National Automated Highway System Consortium C3 Interim Report

NAHSC

Phase 1
October 1996 to March 1998

National Automated Highway System Consortium
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Section 1 - Executive Summary

This was a year of transition. This Interim Report covers the first year, from October 1996 through December 1997, of the C3 task, titled "Develop an AHS System Design". During this period, the Automated Highway System (AHS) Program was changed by a fundamental shift in the USDOT's policy for implementing highway automation. The Program, as initially defined by the USDOT, was intended to promote the implementation of highway automation by having the National AHS Consortium (NAHSC) build a prototype of an AHS in which fully automated vehicles would operate on a dedicated lane. The NAHSC was also asked to prepare a deployment plan describing the likely steps that needed to be taken, both by government agencies and by private industry, to lead to deployment of this, and all other likely forms of an AHS. This had been the direction of the program since its inception, and the initial task plans for Task C3 were developed with this purpose in mind.

In March of 1997, about six months into the first year of the C3 Task, the USDOT introduced a new policy for implementing highway automation. The USDOT was concerned, for some time, that the planned AHS prototype was too much of a "conceptual leap" for most stakeholders. They decided that the NAHSC should shift its focus towards building prototypes of systems which, they felt, must exist along the deployment path towards full automation. This policy would find and promote these smaller steps towards automation which they felt the stakeholders would be more willing to embrace.

The NAHSC began to implement this new policy by identifying services which seemed likely candidates for such steps. This effort was labeled a progressive deployment task and formed the basis for much of the subsequent effort in the C3 Task. By the end of the year, the NAHSC had identified a rich set of almost 100 candidate services which appeared to be possible deployment steps towards full automation. In the next year, the NAHSC intended to work to better understand these candidates , to evaluate their costs and benefits and determine the time frame in which they would likely be feasible. From the best, the NAHSC and the USDOT would then have selected candidates for near, medium and long term prototype and operational test development.

The consequences of implementing the new USDOT policy on the C3 task were profound.

- The benefits to be derived from these smaller steps are considerably less than the benefits to be derived from full automation making each a more marginal improvement over what had come before.
- The benefits will be more in terms of safety than congestion relief or capacity enhancement.
- Integration of the driver into the system is considerably more important, and more difficult, than with full automation.

SUBTASK AREAS

Introduction

In the context of the original NAHSC work plan, the C3 Task was the third and final stage of concept development, during which a concept was to be selected for prototype design, development and testing. It was preceded by two concept development phases (C1 and C2), each of which narrowed the focus towards the single selected concept. In the course of working its way through these two previous stages, the NAHSC discovered that the single concept had to be very flexible in order to meet the wide variations in requirements; it must include both partial and full automation, near and long term deployment considerations and embrace a variety of stakeholder needs with configurations tailorable to the application. These requirements have remained valid, even as the focus of the NAHSC shifted from a full automation prototype to near term partial automation operational tests. However, the realization that the NAHSC must seek a flexible, multi-variant concept rather than a single purpose design has been a significant factor in our thinking since the very first year of our concept development effort. The March redirection by the FHWA changed our prototype aims, but not our concept goals.

Architecture Development

This C3 task had the goal of producing an initial functional specification of a mature AHS. To start, the team first wrote an operational description of the system. By starting with an operators view of the system (with the operator primarily being the driver), a very top level description could be written. This description then formed a basis for a more detailed functional description. The system described had the constraints levied in the USDOT *Request for Applications*: full automation on dedicated lanes. However, for operational and application flexibility, the team decided to include both a dedicated lane version and a mixed traffic version. The functional description divided the system into four major functional areas:

- Initiating Automated Operations – checking in the vehicle for proper operation, selecting a route to an exit from the automated highway, selecting an alternate exit if necessary, and transferring control from the driver to the automated vehicle
- Disengaging Automated Operations – determining that the selected exit is near, alerting the driver and assessing driver readiness to resume control of the vehicle, parking the vehicle if the driver does not take control, transferring control to the driver, and selecting alternate routes due to unavailability of portions of the automated highway
- Moving Under AHS Control – managing lateral and longitudinal movement of the vehicle, sensing the environment of the vehicle, and making tactical decision on the type of maneuvers to be made, including merge, demerge, passing, and evasive maneuvers

- Managing the AHS – traffic management function for an automated highway, including managing traffic flow, managing incidents, and maintaining the infrastructure

In March, this task was suspended, by direction of the USDOT, and the NAHSC began an analysis of possible partial automation systems which could form a deployment path to this mature AHS.

User Needs and Services

This was one of the tasks which began in March. The desire was to initiate the process of identifying promising deployment steps towards an AHS by starting with a statement of the user services to be provided. The bases for this process were the user services identified at the start of the National ITS Architecture study and the Consortium's *Automated Vehicle Control Services Compendium.* An attempt was made to refine and expand the user services, but the team found it difficult to define a user service that did not sound like a market package. Therefore, the definitions available from the Architecture study were adopted with only slight modifications.

Deployment Strategy

This task, while started at the beginning of this phase of C3, grew into a major area of emphasis at mid-year when the program was re-focused on deployment steps leading to an AHS rather than on the AHS itself. The effort began by identifying the many partial automation systems which might be precursors to full automation and the range of possible full automation systems. These were documented in the *Automated Vehicle Control Services (AVCS) Compendium*, which identified a variety of warning, temporary control, and full time control systems utilizing mixtures of lateral and longitudinal control approaches. In the second half of this phase of C3, when major emphasis was directed on the deployment steps towards AHS, this work was expanded into an extensive list of Market Packages. (The Market Package terminology came from the ITS National Architecture.) The Market Packages were divided into three categories: warning systems with no control features, emergency avoidance systems which exercise temporary control of either brake or steering, and full time control systems including Automated Highway Systems. These three categories became the three levels of the Intelligent Vehicle Initiative. Within each category a range of systems was described from very simple to quite complex, such as systems which would assess the vehicle's environment and develop complex maneuvers such as passing slower vehicles in heavy traffic. It was at this point that the "Protected Lane" concept was developed which might allow safe mixing of automated and manual vehicles on a single lane with barriers on both sides. This approach could potentially allow the gradual introduction of automated vehicles without the necessity of dedicating a lane.

In addition to identifying likely Market Packages, the task looked at different deployment strategies and developed deployment roadmaps for some of these strategies. The roadmaps showed possible deployment sequences of Market Packages, where each Market Package was a logical extension of Market Packages which came before it.

Feasibility Analyses

The feasibility analyses were the most intense analytical efforts carried out during this phase of the C3 Task. Some were a continuation, or refinements, of previous work. Others were new investigation initiated in response to the FHWA's direction to focus more strongly on partial automation and early deployment systems.

- Pipeline AHS Throughput Evaluation -- A new and more accurate estimation of the distribution of braking rates for light-duty vehicles was developed from Consumer Reports data and used to refine the estimates of capacity obtainable under different vehicle separation algorithms. The effect of using uniform and non-uniform separation algorithms was studied in detail. These analyses confirmed that the capacity of a dedicated AHS lane could be two or three times the capacity of a lane with manually driven vehciles.
- Pipeline Throughput in Mixed Traffic – Analysis of mixed traffic performance, in this case of capacity or throughput, became much more important as the NAHSC took a closer look at possible deployment steps towards AHS. In these studies, the effect of increasing levels of market penetration of vehicles equipped with automatic vehicle separation control systems, combined with aggressive ranges of vehicle separation, showed that improved throughput performance can be expected only with high levels of market penetration.
- Effects of Merging on Throughput – This analysis was conducted for the Houston Metro case study. It analyzed some rather simple merge protocols for fully automated vehicles to determine the impact on pipeline throughput and on entry ramp length. It was shown that entering (and exiting) vehicles decrease pipeline capacity.
- Environmental and Energy Consumption Effects of AHS – These studies looked at the effect of smoother traffic flow, which could be provided by continuous stream of automated vehicles, over the stop-and-go behavior of manually driven vehicles in congested traffic. Significant decreases in fuel consumption and emissions were indicated.
- Safety Evaluations – An attempt was made to investigate the increase in safety that a partial automation frontal collision avoidance systems may offer. Establishing truly definitive results was hampered by the difficulty of modeling human driver responses. However, a methodology for evaluating these safety benefits was developed by the team.
- Mixed Traffic Operations – A limited analysis of mixed traffic operations concluded that the design of fully automated vehicles capable of operating in today's multiple lane limited access highways would be technologically very ambitious. However, development of a cooperative highway to protect the vehicles would make mixed operations much more likely. Key aspects of such protected lanes would include

single lane operation, barriers between this lane and adjacent manual lanes, obstacle mitigation policies, and infrastructure-to-vehicle communications.

- Highway Management Studies – An intensive analysis of GES data on accidents caused by obstacles on the roadway, including an in-depth look at the source data for the GES database, yielded a categorization of the most common and most dangerous obstacle types. The seven most serious obstacles are: tires, tire debris, wheels, wood, metal scrap, vehicle debris, and pedestrians. This effort provided direction to the development of requirements for obstacle detection sensors and for obstacle exclusion features.
- Driver Involvement Studies – The change in emphasis to partial automation systems with the driver remaining responsible for some degree of vehicle control raises a host of critical issues which were not of concern with fully automated operations. Specifically, for any partial automation system where some manual control responsibility is left to the driver, it must be ensured that the driver can still meet that responsibility as effectively as conventional drivers do now. Decreasing driver vigilance as the driving task is automated is a primary area of concern. During this phase, both literature searches and driver simulation experiments indicated a reduction in driver intervention capability when hands-off, feet-off control was introduced. These results lead to the tentative recommendation that high levels of automated control should be introduced either as background collision avoidance systems, which will keep the driver active in the control loop, or as part of a fully automated vehicle. Otherwise, the driver may not remain vigilant enough to detect and avoid hazards on the roadway as well as conventional drivers do now. Because of the potential serious impact of this recommendation, any partial automation product, and especially products that involve steering control, need to be carefully studied for changes in the driver's ability to intervene.

Case Studies

Case Studies represent the application of Automated Highway System concepts, as well as preceding partial automation and warning systems, to a real world application. The studies looked at the issues from a variety of view points; from needs to deployment, costs, and/or benefits. To conduct a case study, the NAHSC first identified a regional entity (generally a regional transportation planning organization) who was interested in working with the Consortium to study the application of automation services to transportation problems such as congestion in their locale. In general, each study followed a process of assessing the need of a particular location (usually determined by the local organization), identifying automation products which might address that need, developing a concept for their application, and analyzing the costs and benefits of that application.

Two case studies were active during this phase of the C3 task: the Houston Metro case study, and the Western Transportation Institute case study. Several others were in the planning stages, including case studies for the Southern California ITS Priority Corridor

Steering Committee, for Virginia DOT, for the Gary-Chicago-Milwaukee ITS Priority Corridor Committee, for Minnesota DOT, and for Michigan DOT.

Houston Metro Case Study -- This study was focused on the capacity increases (from application of automation) which could be obtained on the existing HOV lanes. In particular it addressed the impact of entering and exiting vehicles on the theoretical, or pipe-line, capacity. Houston Metro set three capacity goals (for three points of time). The analysis by the NAHSC involved developing various merging strategies and various vehicle separation strategies that could be shown, using the SmartAHS tools, to meet the capacity requirements. The results showed that automated merge, demerge, and separation protocols could achieve the capacities desired.

Western Transportation Institute Case Study -- The need this study addressed was to increase safety on rural mountainous highways in and near Yellowstone National Park. The study looked at both the safety problems of large numbers of summertime visitors and at the needs of winter travelers in severe weather conditions. The automation products were the more simple warning and emergency braking systems which have been identified as deployment steps towards full automation. The safety studies were meant to begin in the next phase of the C3 task.

The other pending case studies can be briefly described:

- Minnesota DOT -- This study intended to look at partially automated snow plows.
- Southern California ITS Priority Corridor Steering Committee -- This study intended to look at use of automation to reduce congestion and improve air quality.
- Gary-Chicago-Milwaukee ITS Priority Corridor Committee -- This study intended to look at use of automation in Commercial Vehicle Operations. One such automation system was to be truck platooning.
- Michigan DOT -- This study intended to look at the use of automation in CVO and transit operations. The automation services of interest had not yet been identified.
- Virginia DOT -- This study intended to look broadly at the use of automation in work zone safety and control, traffic safety, trucking issues, and intercity traveler needs.

National Consensus

The NAHSC held a second stakeholder forum during this time period. The primary purpose was to discuss with the stakeholders our recent work on User Needs and Market Package development. In two sessions, these topics were discussed with five different working groups: Consumers, Transit, Commercial Vehicle Operations, Infrastructure, and Cross Cutting Users. After seeing the work done for both sessions, many stakeholders were enthusiastic about the variety of market package ideas. In general, they found certain market packages which satisfied a real need that they, as representatives of stakeholders, could see.

Section 2 - Introduction

This report provides the summary of work performed during the first year of the "Develop Candidate System Designs" task, which the NAHSC designates as task C3. The task was planned as a three year activity to develop and document an AHS system design. The Consortium's previous work determined that the AHS system design must support partially and fully automated driving, near term and long term deployment considerations, and embrace stakeholder needs with tailorable application configurations. The system design will support a technically, socially, and economically feasible AHS implementation. The task products will facilitate specification of the prototype AHS to be developed during the E-leg tasks of the NAHSC program. Figure 2-1 illustrates WBS C3 in context with the AHS program plan.

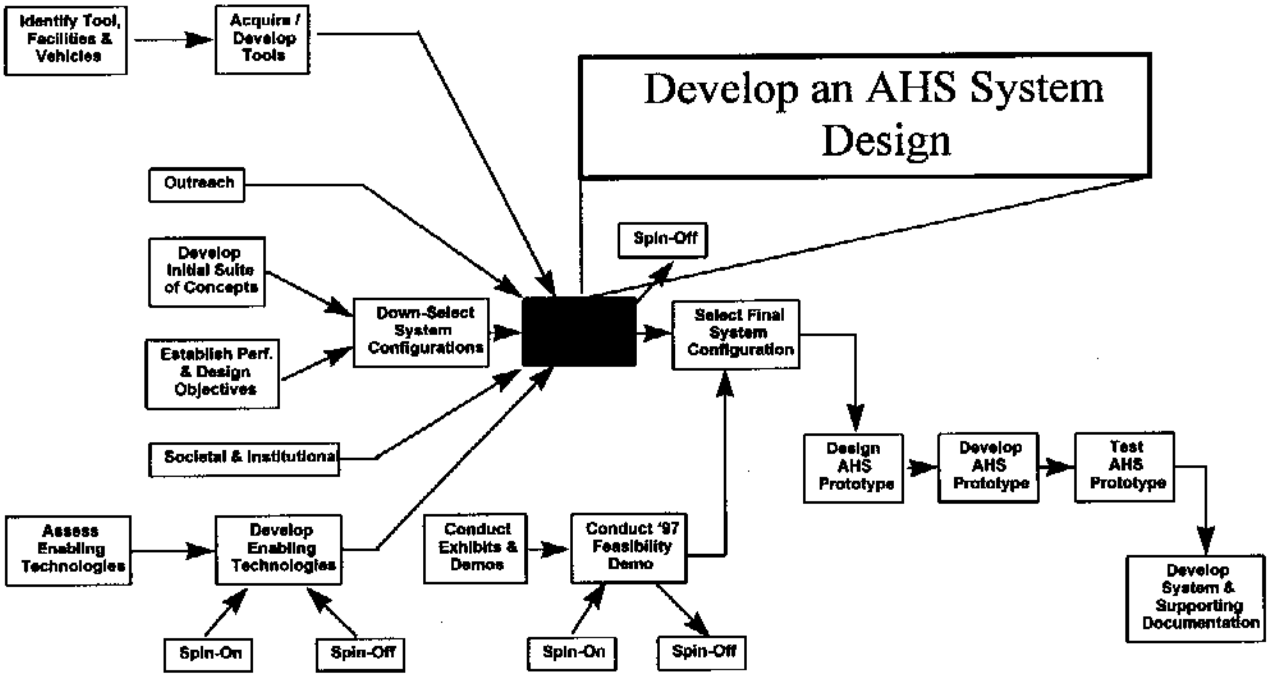

Figure 2-1, NAHSC Task Context Diagram

The work of C3 integrates the accomplishments of the preceding C1 and C2 tasks, as well as leveraging the application of the Modeling and Simulation tools (B5), recommendations of the Societal and Institutional Analyses (B6) and knowledge of Technology Developments (B3). This perspective formed the foundation of the work plan, and hence the structure of this report.

A note on replanning. Midway through this first year task plan, the program emphasis was refocused toward near term deployment of AHS technologies. Interspersed throughout this report are references to this refocus and resulting shift in work emphasis.

This report is structured to provide clarity to results and progress of the following task domains:

- Section 3 provides a report on the progress toward architecture definition.
- Section 4 addresses the User Needs and Services assessment.
- Section 5 addresses substantially all new work in the area of Deployment Strategy.
- Section 6 provides a summary of the numerous analytical analyses and critical design issues.
- Section 7 addresses our work with various regional AHS Case studies.
- Section 8 documents the views we have collected through several stakeholder forums.
- Section 10 is the collection of appendices further supporting the summary sections numbered 3 through 9.

Section 3 - Architecture Development

Architecture Development Process and Relationship to Other Tasks

The AHS Architecture task is one of three Architecture Definition Tasks of the C3A WBS. These tasks continue the concept definition work of C1 and C2 to establish: what is an AHS, how does it operate, and how may it be deployed.

The objectives of this task are:

1. Develop the AHS operations concept, functional and logical architecture for the "mature" AHS:
   - a) Integrate the results of the issue teams and produce/update the baseline AHS architecture;
   - b) Identify/prioritize which issues need to be addressed for architecture development;
   - c) Integrate the results of the Evaluation tasks to provide a feasible architecture.
2. Facilitate system specification and requirements development.
3. Develop a consistent architecture to describe both a dedicated lane AHS and a mixed traffic AHS.
4. Describe and specify the AHS architecture sufficiently to develop an AHS prototype.

This task is planned as a three year activity; during this first year, the focus was on development of the Operations Concept and Functional Architecture. Development of the Operations Concept and Functional Architecture was only partially completed in accordance with the USDOT's request to focus resources toward development of the Deployment Strategy to support the emerging Intelligent Vehicle Initiative (IVI) perspective.

Process

The AHS architecture is developed utilizing previous products from the consortium concept definition tasks (C1 and C2), the ITS National Architecture and non-U.S. consortia. Incorporating the expertise of internal core and associate resources, outlines and drafts of the operations concept and functional decomposition were created. These documents are subject to revision as policy shifts and results from other subtasks substantiate change.

For each of the documents, an outline was prepared and themes coordinated. Domain experts provided draft text and, as appropriate to the content and progress, the C3 subtask leads, the C3 advisory panel and PMC reviewed and commented on the documents.

The Architecture team is the Systems Integrator of the concept development process. Relying upon the products of the Critical Issues analysts and the Evaluation teams, the Operations Concept and Functional Architecture are developed as a compatible, compliant, feasible and deployable system. As the architecture development progresses, the architecture team defines relevant issues: assessing what needs to be resolved to refine or substantiate the system architecture. Based on optimizing the overall system architecture, the preferred or optional solutions will then be incorporated into the system documents, causing an update from the previous baseline.

Successful performance of the system architecture development task is inherently reliant on the complement of the C3 tasks, as well as the products of the other major Consortium tasks: Program Office Systems Engineering, Outreach, Technology Development, Tools, Societal & Institutional and the 1997 Technology Feasibility Demonstration. The architecture team identifies needs and incorporates results from each of these domain experts in the system integration process.

AHS Operations Concept

The Operations Concept captures and establishes boundaries for the concept development process. This document provides answers to the following:

a) what is an AHS,

b) what it does, and

c) in what environment.

Included in this operations concept is a brief description of the expected or desired deployment approach. The consortium is developing a separate document specifically focused on AHS deployment strategy.

The AHS Operations Concept is a work in-process. The current draft, Version 2, dated April 4, 1997, is provided as appendix 10.1.1. This work was performed primarily during the period of October through December 1996, with minor revisions incorporated in March 1997. The Operations Concept documents the vision for the AHS and serves as the baseline for the Functional and Logical Architecture development.

The Operations Concept provides the vision of what is an AHS, with particular emphasis on two evaluatory operating modes. It provides a bridge from the System Objectives and Characteristics document to facilitate the development of the functional and physical architecture (design).

To support the AHS goals as a national, interoperable system, two operating modes have been defined; they are referred to as the Dedicated Lanes operating mode (operating mode A) and the Mixed Traffic Lanes operating mode (operating mode B). Both operating modes are based on fully automated vehicle control, providing improvements in safety, trip time, economy and user convenience. The AHS concept is described by these two mainstream operating modes to assist the NAHSC in the development of a feasible system architecture. These operating modes showcase solutions of deployment, technology, roadway needs, cost and safety. Operating Mode A encompasses the segregated operation of fully automated vehicles on dedicated lanes. Operating Mode B allows manually driven and fully automated vehicles to operate simultaneously on specially equipped lanes. As work progresses on the development of the AHS architecture, these two operating modes may be revised or combined. Evaluations of variations within each of these operations concepts is intrinsic to the concept development process. Performance evaluations, supported by site specific case study data, will facilitate refinement of the concept.

The Operations Concept addresses the "mature" Automated Highway System and potential deployment paths. Plans for prototype and operational tests may be derived from this concept.

These AHS operating modes share some common ground rules, boundaries, and assumptions. The AHS is developed for completely automated driving on limited access, multi-lane highways. While engaged in the AHS, the system provides full control of the vehicle; no driver intervention or monitoring is required. Partial automation systems may provide part of the evolutionary deployment path to AHS, but these are not defined here.

The vehicle systems will include steering, braking and throttle actuators, sensors, and the associated control systems. AHS components will be incorporated into future production models of automobiles, trucks and buses; although some of the vehicle systems may be available as after market installations.

Incremental deployment paths facilitate the implementation of either operating mode. The AHS may use other ITS services; and some components may provide driver assistance on any highway.

Functional Decomposition

The Functional Decomposition document further defines the AHS architecture by describing what operations need to be performed. Work accomplished to date provides an AHS Context Diagram and a functional decomposition defining four primary functions. Each of the primary functions have been refined to the second, third, or fourth levels. The interfaces between the functions are assigned unique names and are also described. This legacy material will be modified and further developed based on modification of the Operations Concept, and results of critical issues analyses and performance evaluations.

The Functional Decomposition for the Automated Highway System is being developed to support both the derivation of performance requirements and the design of the logical architecture. A thorough and well structured model will facilitate completeness, work organization and efficiency of the detailed architecture development. A hierarchical modeling technique was selected, wherein each function and the interfaces between the functions are described.

The AHS Functional Decomposition is a work in-process. The initial draft (reference AHS Functional Decomposition, dated March 31, 1997, and attached as appendix 10.1.2 to this report) was prepared primarily during the period of January through March 1997. It is based on the previous work of the consortium (inclusive of tasks B1, C1 and C2), the AHS Precursor Studies, and incorporates new work in consonance with both the Dedicated Lane and Mixed Traffic (automated vehicles sharing the lane with manually driven vehicles) Operating Modes described in the AHS Operations Concept. The Functional Decomposition facilitates the development of the logical architecture for an Automated Highway System.

The four primary functions, and their respective sub-functions, are:

1. Initiate Automated Operation
    Provide Initiate User Interface
    Power Up
    Assess AHS Availability
    Transfer Control
2. Disengage Automated Operation
    Availability Assessment Execution
    Plan/Manage Park Maneuver
    Qualify Driver to Control Vehicle
    Transfer Control to Driver

  Verify Driver Control
  Route Planning

3. Moving Under AHS Control
   Vehicle Maneuver Management
   Vehicle Control and Sensing
   Tactical Planning

4. Managing the AHS
   Manage Traffic Flow
   Maintain AHS Infrastructure
   Manage Incidents
   Managing AHS Infrastructure Enhancements.

Section 4 User Needs and Services

As the direction of the NAHSC has turned towards safety, infrastructure based applications, and near term effects, efforts have increased to identify User Services and Market Packages based on user needs and keeping in mind a future vision of where AHS wants to be.

NAHSC believes that an AHS must be designed with those in mind who will implement, manage, use and be affected by the system. Ideas, critique, and input from AHS stakeholders are essential to make the dream of AHS a practical reality. A goal of NAHSC is to seek consensus among stakeholders on all facets of AHS. Accordingly, NAHSC has made stakeholder involvement fundamental to every aspect of our work.

The National ITS Architecture offers a great heritage of information that is useful for AHS. Its goal is to promote compatibility and synergy among transportation systems in every region of the nation. It also emphasizes developing a regional big picture and assessing user needs, then determining market packages to provide the most appropriate solutions for a regions transportation needs.

AHS must be compatible with the National ITS Architecture to be successfully implemented nationally. To achieve this, NAHSC is examining previous work on the Architecture, assessing user needs and developing AHS User Services to address those needs. NAHSC has included the entire bundle of Advanced Vehicle Control and Safety Systems (AVCSS) User Services for this reason. Simultaneously, NAHSC is developing AHS Market Packages based on current and emerging technology and a system architecture that incorporates those Market Packages to provide the User Services identified for AHS. Prior to the NAHSC defining these User Services, the National ITS Architecture only showed a heading for AHS User Services. These new User Services were developed based on information gathered from NAHSC workshops and forums and reflect the needs of a broad group of AHS stakeholders. As work continues under the program, it is expected that continuous stakeholder and user involvement will influence the evolving definition of User Services.

User Services are concise descriptions of what the system has to do, or provide if it is going to be successful from the users point of view. How to provide the User Service is provided by market packages. User Services encapsulate user preferences, needs, objectives, and issues. Users in this case may include, but are not limited to, private car drivers, commercial vehicle operations (drivers, managers, dispatchers, shippers), transit operations (drivers, managers, dispatchers, riders), and traffic managers (traffic engineers, transportation planners, highway operations specialists). It is important to separate this from how to provide the user service, which is provided by Market Packages in order to allow deployment flexibility.

User Services are composed of User Service Requirements or shall statements. Additionally, they must be detailed enough to address all requirements and be concise enough to be useful in guiding an ITS framework and system development. User Service Descriptions are composed of two components:

- a label that identifies the User Service and gives an indication of its nature;
- a description that provides the material required to explain and confirm the User Service to the user and to the developer.

The process starts with the collection and assembly of a variety of data and information describing the users initial perceptions of needs. This will be drawn from previous consortium work and further direct contact with users. It will include the following:

- user problems - what transportation problems do the users perceive as important, taking into account their lifestyles, interests, backgrounds and organizational affiliations?
- user objectives - what goals or objectives from both personal and organizational perspectives do the users want to have addressed by the ultimate AHS?
- user issues - what issues are associated with the satisfaction of stated needs and what factors may have to be taken into account when identifying and developing potential solutions?
- user preferences - what preferences do the users exhibit when they tell us what they want?

Note that this initial collection of needs information is typically unstructured with input in many shapes and forms. In many cases users will expound what they want by describing a potential solution or telling you how they would address the underlying need, issues, or problem. It is also likely that conflicting, incompatible or mutually exclusive needs will emerge, especially as AHS Users represent a wide range of interests. The AHS User Service definition process will have to encompass a mechanism for supporting user convergence to a single consensus set of needs.

The User Service Development Process

The AHS User Services have been developed by the NAHSC in the context of the National ITS Architecture, from the framework of the Advanced Vehicle Control and Safety Systems in Appendix A of the Traceability Document, January 1997 version.

The AHS User Services do not repeat any of the other User Services in the National Architecture. Rather, they are developed to allow for synergy with the other services to provide travelers and service providers with comprehensive services and economical use of infrastructure and data communications. For example, the non-AHS User Service of in-vehicle signing (under En-Route Driver Information) can be used synergistically in AHS to set the maximum speed of Adaptive Cruise Control. Another example is the provision of roadside pollution assessment data (under Emissions Testing and Mitigation User Service) to the Automated Highway System Management System.

Definition of User Services involves the following steps:

1. Identify user requirements - This step only involves the collection of requirements identified by the users. These take the form of problems, objectives, issues, needs, and preferences. It is these requirements which must be determined in order to develop User Services. They are typically unstructured comments or statements and may even be stated by the user in the form of a solution.
2. Develop user service labels - This step involves the creation of a user service label and description. These identify the service and allow for detailed requirements development. To distinguish the user service label they always begin with a verb.
3. Perform "so what" analysis - This step involves the decomposition of the user services, identification of potential benefits to the user and identification of irreducibles or goals which the User Service addresses. This is done by asking "so what?" of the User Service. Asking "so what?" assists in determining detailed requirements and describing benefits, or what the system will provide from the users point of view. The final result of this process is the irreducible or goal which serves to validate that the User Service is appropriate in the context of the overall goals for AHS. The "so what" analysis should involve experienced stakeholders and domain experts to deepen their mutual understanding of user needs.
4. Develop "shall" statements - This step involves taking the user requirements and developing "shall" statements to encapsulate them. "Shall" statements are structured statements which describe what needs to be provided. These may be very high level, (e.g., It shall provide traffic surveillance) or more detailed, (e.g., It shall determine actions necessary to maintain the vehicle at a safe distance behind a lead vehicle). The key in developing these is not stating how it will be done.

User Services, while documented here and identified in the National ITS Architecture, may be modified or developed to specifically address stated needs.

Next Steps

The development of User Services will need to be a continuous process through the NAHSC Program and through the national deployment of AHS. User Services and Market Packages should be developed iteratively, along with technical demonstrations, so that stakeholders can provide more meaningful and imaginative ideas about User Services based on some real experiences and improved understanding of new AHS technologies. In other words, the needs of users will evolve as stakeholders and users know more, and technology evolves.

Current work-plans of the NAHSC include active participation by the Stakeholder representatives and their respective communities in the development and review of User

Services. Various formal and informal meetings, publications, and presentations to the various stakeholder trade group meetings are also anticipated.

AHS User Services

The current set of AHS User Service Labels and Descriptions is listed below. The User Services are based on the Advanced Vehicle Control and Safety Systems (AVCSS) User Services of the National ITS Architecture, and are slightly modified. The detailed User Service Requirements are provided as appendices 10.2.1, 10.2.2 and 10.2.3.

Avoid Longitudinal Collision - This User Service provides vehicle operators with assistance in avoiding longitudinal collisions to the front and/or rear of the vehicle. The driver is assisted by: (1) sensing potential and/or impending collisions or threats to the front or rear of the vehicle; (2) eliciting proper collision avoidance actions from the driver; and/or (3) providing temporary automatic control of the vehicle to assist the driver in avoiding the potential collision situation. This service includes four types of longitudinal collision avoidance:

1. Rear-end Collision Warning and Control will, through driver notification and possibly partial vehicle control, help avoid collisions with the rear-end of either a stationary or a moving vehicle or object.
2. Adaptive Cruise Control (ACC) will allow the driver to select a cruise control feature that tracks the vehicle in front of it and automatically maintains a desired spacing between that vehicle and the one ahead. In more advanced systems, leading vehicles will transmit information on vehicle dynamics to following vehicles. This subservice would allow vehicles to travel in cooperative platoons.
3. Head-on Collision Warning and Control will detect an impending collision with a vehicle moving in the opposite direction in the same lane.
4. Backing Collision Warning would detect slow moving or stationary objects, vehicles, livestock, and pedestrians in the path of a vehicle when backing.

Avoid Lateral Collision - This service augments the vehicle operators ability to avoid collisions by: (1) providing information, (2) if a crash situation is imminent, providing warnings and/or assuming temporary control of the vehicle. This service reduces the number and severity of lateral collisions. This service includes two types of avoidance:

1. Lane Change/Blind Spot Situation Display, Collision Warning and Control will provide information about the presence of vehicles in the drivers blind spots, actively warn of potential collisions due to lane change or merging, and ultimately, assume temporary control of vehicle steering, braking and/or throttle to avoid collisions.
2. Lane/Road Departure Warning and Control would assist in maintaining the vehicle in its proper lane of travel through driver warnings, advice on necessary actions, and eventually, assuming temporary control of vehicle steering and throttle to avoid a lane/road departure incident.

Avoid Intersection Collision - This service provides vehicle operators with assistance in avoiding collisions at intersections. Situations addressed include vehicles improperly violating the right-of-way of another vehicle, or when the right-of-way is not clear. This service will provide warnings of imminent collisions with crossing traffic, and warnings of stop sign and signal control of downstream intersections.

Enhance Vision for Crash Avoidance - This service reduces the number of vehicle crashes that occur during periods of poor visibility by improving the ability of the driver to perceive the roadway surface and objects on and along the roadway. This will allow the driver to avoid potential collisions with other vehicles, fences and railings, pedestrians, wildlife and livestock, or obstacles in the line of travel; and would assist the driver in complying with traffic control devices.

Provide Safety Readiness - This service provides drivers with warnings regarding their own driving performance, the condition of the vehicle, and the condition of the roadway as sensed from the vehicle. Advanced safety readiness systems will also include the ability to assume temporary, partial control of the vehicle in highly hazardous situations. These services include:

- Impaired Driver Warning and Control Override to monitor driver performance and either warn of impaired driver condition or take temporary control of the vehicle to prevent or discourage continued driving.
- Vehicle Condition Warning to monitor the performance of components, such as tires and brakes, whose degradation could have a significant impact on the safe operation of the vehicle, and warn of their imminent failure.
- In-Vehicle Infrastructure Condition Warning to detect and warn the driver of unsafe conditions on the roadway or bridge infrastructure, such as the presence of ice or water.

Deploy Pre-Crash Restraint - This User Service will reduce the number and severity of injuries caused by vehicle collisions. The service is accomplished by anticipating an imminent collision and activating passenger safety systems prior to the actual impact.

Automate Vehicle Operation - This service is a vehicle-highway system that will substantially improve the safety and efficiency of highway travel in all weather conditions, greatly enhance driver comfort, and help reduce air pollution. This service provides automated (hands off, feet off) operation of multiple types of equipped vehicles on dedicated highway lanes. This means that steering, acceleration, and braking of vehicles are controlled automatically. Equipped vehicles may also be capable of automated operation on some specially equipped highway lanes inter-mixed with manually driven vehicles.

This service builds on the other user services including Avoid Longitudinal Collision and Avoid Lateral Collision. The service consists of six major functions:

1. Automated Check-In will (1) check the eligibility of the vehicle and driver, (2) accept or reject vehicles for operation in the AHS lanes, and (3) divert disapproved vehicles back to the non-AHS lanes and assume control of approved vehicles.
2. Automated Vehicle Control assumes control of an approved vehicle and moves it onto an AHS lane, merging it with the other AHS traffic. Vehicles are safely controlled in the context of the traffic flow; and when the destination is reached, the system moves the vehicle to an off-ramp.
3. Automated Check-Out occurs with the exiting of the vehicle from the AHS lanes, resuming control by the vehicle driver. This function may include a means to manage the flow of vehicles onto the adjacent surface street system.
4. Low Speed Maneuvering And Parking provides assistance to special vehicles. This includes transit vehicles approaching curbs, commercial vehicles approaching loading docks, operation of snowplows, and movement of vehicles within parking and maintenance areas.
5. AHS Management provides monitoring and oversight of AHS performance, sets operational parameters, and exercises policy level control of the AHS operation.
6. Coordination and Compatibility Between AHS Management and ITS Center Subsystems provides synergy and interoperability between AHS and other ITS Services, (e.g., Travel and Traffic Management, Public Transportation Management, Commercial Vehicle Operations).

Section 5 Deployment Strategy

The systems the Consortium develops must be deployable, and to ensure that they are, the Consortium must also produce a deployment plan. The C3 efforts to assure deployability, and move towards a deployment plan were embodied in the Deployment task during the first half of Phase I, and the Progressive Deployment task during the second half of Phase I. The main change between these two tasks was that Deployment initially focused more on general deployability issues and strategies, while Progressive Deployment folded in the C3 Architecture efforts and focused on developing a set of candidate systems, "market packages," that spanned the range of potential deployable systems, from early warning and advice systems all the way to full automation.

A major early focus was to consider deployment in the light of many stakeholder suggestions that a dedicated-lane, high-capacity AHS was "too big a step" and "undeployable," and that nearer term systems should be more attractive. This led to two efforts. The first was an attempt to determine if there really was "gold in the gap" between today's systems, with the driver fully engaged, and a full AHS. This effort created successive drafts of the Automated Vehicle Control Services (AVCS) Compendium (Appendix 10.3.9). The second effort was to create a range of deployment strategies, some of which looked for creative ways to deploy a dedicated lane facility, in order to grapple with different deployability arguments.

The vision was that the different deployment strategies could be merged into a unified map of all potential deployment strategies. This would be similar to the Reactive Adaptive Management Portfolio (RAMP) described in "Decision Support for Automated Highway System Development and Deployment," Lathrop and Michael, from the 7th Annual Meeting and Exposition of ITS America. RAMP envisions an integrated decision tree for deployment and development decisions, but no such comprehensive decision tree has yet been built.

In the second half of Phase I, efforts moved to more fully model work in the mold of the ITS National Architecture. This led to the explicit creation of User Services and Market Packages as the conceptual building blocks for defining and deploying AHS and related systems. Appendix 10.3.6 describes these concepts in detail.

While the User Needs and Services group within C3 focused on getting to user services, Progressive deployment focused on developing market packages. Since both are to be developed in mutual iteration, they could be launched in parallel for downstream comparison and revision. Having these defined was critical to the rest of C3 because it defined the subjects for analysis of subsequent partial automation. The AVCS Compendium helped quickly start the identification of market packages. Also helpful was the development of the Issues, Constraints, Guidelines and Policy document (Appendix 10.3.7), which provided guidance for developing market packages.

As a step in that direction towards building something like the RAMP decision tree, the Deployment Map (Appendix 10.3.4) was developed. It was intended to explicitly capture the viable alternate paths of deployment through the set of market packages.

Deployment Strategies

Each deployment strategy was a scenario, an imagined sequence of events, that led to the deployment of AHS. They were not meant to be exclusive, but it was hoped that they would be nearly exhaustive in spanning the range of possible deployments. It was clear from the stakeholders that the deployment strategy had to answer not only how the systems were deployed, but also how and why they would be supported when needed by their key stakeholders, and how the development of systems would be strung together.

The deployment strategies generated are briefly summarized below and are described in detail in Appendix 10.3.8 Deployment Strategies.

Smooth Evolution to Mixed Traffic AHS. Starting with today's vehicles, increasing levels of automation are added to vehicles. These are attractive because they progressively relieve the driver of his workload, and increase driver convenience. At some intermediate point the vehicles automate all ordinary functions, leaving the driver only responsible for the occasional, extraordinary occurrence. Figure 6-1 illustrates this smooth transition of functions from the driver to the vehicle. This strategy is believed infeasible, as described in section 7.2 of the AHS Milestone 2 Report, and was included specifically to illustrate the "forbidden zone" within partial automation, to anchor the range of deployment strategies, and to test assessments of the feasibility of deployment strategies.

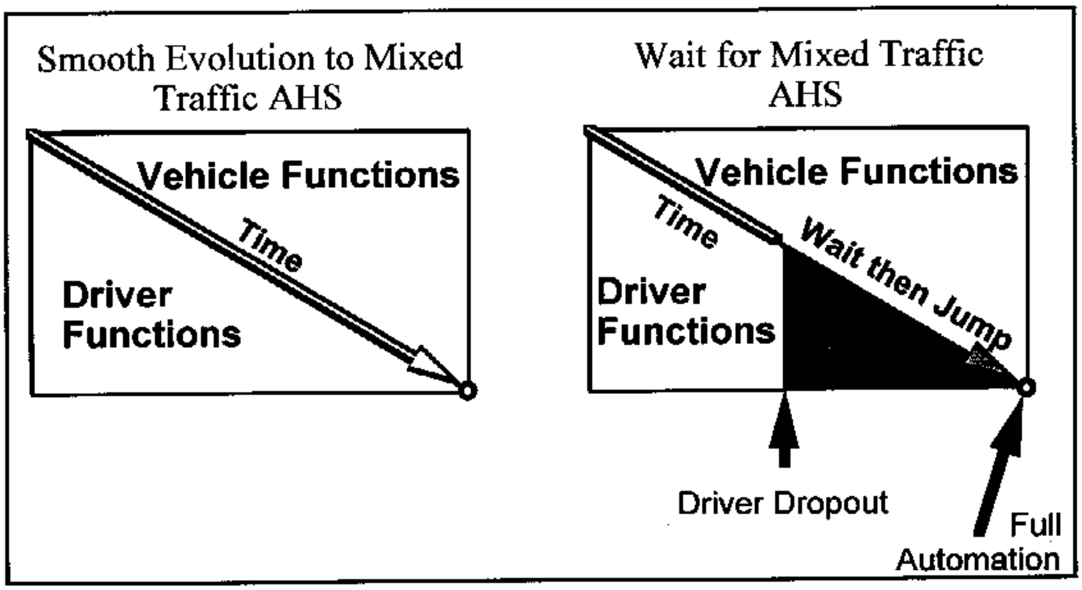

Figure 1. "Smooth Evolution" strategy relies on no gap in capability, while "Waiting for Mixed Traffic" strategy crosses the gap in one jump, once technology is sufficiently advanced.

Driver-Engaged AHS Data Collection. This strategy was driven by a premise that we lack adequate data on driving environments, particularly regarding a great number of potential improbable events that are handled almost unconsciously by current drivers, but that would be difficult for automation to respond to properly. The key stage in this strategy is the deployment of many partial automation systems, which also provide the benefit of extensive data collection on real-world driving situations. That information is fed into the development of full automation systems. Somewhat later but in parallel, protected roadways designated to allow, and increasingly dedicated, to fuller automation.

"Policy-Driven." This was one of three deployment strategies presented at Workshop #3 in C2, and carried into C3. The focus was on creating a dedicated-lane high-capacity AHS, and then expanding the number of highways and the lane miles dedicated to AHS, with downstream deployment of mixed AHS capability when that later became technically feasible.

"Market-Driven." This was the second of three deployment strategies presented at Workshop #3 in C2, and carried into C3. The focus was on deploying partial automation systems for use on ordinary lanes, moving to full automation on ordinary lanes, and once there is a sufficient market penetration of automated vehicles, then dedicating lanes to full automation.

"Bootstrapping." This was the third of three deployment strategies presented at Workshop #3 in C2, and carried into C3. The focus was on creating designated lanes, protected but allowing manually driven vehicles, and then fielding increased automation on these protected lanes.

Start with driver Engaged Mixed Operations. This was an intricate strategy with 8 assumptions, 6 inferences, 6 derived requirements, and 4 market packages. It focused on limited partial automation systems for use mixed in manual traffic, with an explicit deferral of further decisions until after lessons from these deployments become available.

Wait for Mixed Traffic AHS. This was predicated on the dual assumptions that initial deployment of dedicated-lane AHS would be excessively challenging, and that with time, AHS mixed with manual traffic would become feasible. Figure 6-1 illustrates that this occurs when the vehicle can perform all the driving function. The strategy was to wait for that feasibility, and only move to dedicated lanes after significant market penetration of AHS vehicles.

Dedicated Lane Operational Test Showcase. This strategy was similar to policy driven, in that a Federally led effort developed a prototype AHS, and then deployed it as one or more operational tests. The supposition here is that the operational tests will be successful, after which AHS will be an ordinary candidate in major investment studies (MIS's). Due to the high performance and very high cost effectiveness on high-demand corridors, this results in dedicated lane, high capacity AHS becoming widespread.

Dedicated Lane Operational Test Seedlings. This was similar to the Dedicated Lane Operational Test Showcase. In this case, however, the hurdle to deploying a high-capacity, dedicated lane AHS is prohibitive, or nearly so, in locations where there is no pre-existing installed base of vehicles to use those lanes (and whose owners would call for such lanes). Thus, these lanes are built and expanded at the edges of where they have already been deployed. The operational tests thus work like "seedlings," helping to initiate this positive feedback of deployment leading to more deployment. This is the strategy modeled in the dedicated lane portion of "Modeling National Deployment of an Automated Highway System," McKendree, from the 7th Annual Meeting and Exposition of ITS America.

Dedicated as a Stepping-Stone to Dual-Capable. This is something of the obverse of Waiting for Mixed Traffic AHS. Here, dedicated-lane AHS systems are deployed early, because of their greater technical ease, as a way to foster AHS, leading to the vision of full automation, mixed with manual traffic on ordinary lanes and on dedicated lanes for high capacity.

Foreign Leadership Through Risk-Taking. This approach is to leave the hard problems for some other nation to solve, and to then import their system once it is demonstrated and developed to the point where it becomes attractive for the US.

Communications Policy Driven Approach on Mixed Dedicated Lanes. This focuses on deploying and extending ITS vehicle to vehicle and vehicle to roadside communications for driver information, warning and advice, and once these standards are deployed, encouraging partial and then full automation and ultimately dedicating lanes for greater safety and capacity.

Highway Block Downgrades. This strategy was not developed, but would involve setting a very high standard for roadways that allow automation. Then, as technology progresses, there would be block "downgrades" to the roadway requirements. With each downgrade, dedicating and designating automation lanes would become more affordable and prevalent, while older vehicles would still be able to operate automatically on the more stringently supporting roads they were purchased for.

There was some desire to create a deployment roadmap, that would merge all of these, and other, possible deployment strategies. That idea evolved into the deployment map, discussed in 5.3.

Market Packages

Appendix 10.3.2, Automated Highway System Market Packages lists all the currently defined market packages, and their descriptions. Each is meant to be a system, including the vehicle and possibly the roadway and/or traffic management infrastructure, to provide some full or partial automation benefit(s). Appendix 10.3.3 contrasts each market package across seven broad characteristics. Appendix 10.3.6 Defining and Developing AHS Market Packages provides a more detailed description of what is intended by market packages, and why they are important. Appendix 10.3.12 describes an architectural framework as a step towards locating other candidate market packages from various system architectures.

Warning & Advice and Temporary Control Market Packages

"Warning & Advice" market packages provide information and guidance to the driver, but do not provide any control actuation. Temporary Control market packages are those in which the vehicle is maneuvered briefly (over a few seconds) in limited, well-defined situations. In the current list, all but one of these are Temporary Emergency Control market package--the vehicle intervenes, after alerting the driver, when the driver does not respond to an impending emergency situation. All of these market packages vary on three main issues, what situation is handled, do the vehicles use communications, and what is the response.

The situations handled currently span the following range:

- Frontal Collision
- Curve Overspeed
- Blind Spot Collision
- Side Collision
- Lane Change Collision
- Lane Departure
- Road Surface Conditions
- Traffic Situation
- Unsafe Driving Situation
- Merge Maneuver
- Lane Change Maneuver
- Vehicle Condition
- Driver Condition
- Road Management Situation
- Intersection Crossing
- Railroad Crossing

Vehicle Communications can be either:

- Autonomous Vehicles (no formal communications channel)
- Cooperative Vehicles (communications with other vehicles and/or the infrastructure.)

Vehicle Response can be:

- Warning and Advice

- Temporary Control
    - May subdivide further, based on differing human factors interfaces. For example, full-authority control versus partial authority control, or avoidance actuation versus control resistance to disfavored driver action only.

Almost every intersection is a feasible and interesting market package. The full list is in Appendix 10.3.2.

Market Packages Providing Control of Ordinary Driving Actions

These market packages provide ongoing automation (actuation) of one or more driving function. The simplest example is adaptive cruise control, which acts like ordinary cruise control, but will slow down behind slower moving traffic. (Advanced) Adaptive Cruise Control (A)ACC, but able to operate all speeds, including braking from full speed for stopped vehicles, and cruising automatically in stop-and-go traffic. Lane keeping automatically holds the vehicle in its lane, but leaves maintenance and control of velocity, acceleration and braking to the driver.

An interesting combination for use on ordinary lanes is (A)ACC, Forward Collision Avoidance (FCA), and Side Collision Avoidance (SCA) using the brake and throttle only. This leaves the driver to steer, but is an even more capable longitudinal cruise. One market package adds to this driver initiated, automated lane changes, while another market package adds instead lane keeping and driver alertness monitoring (to assure that the driver remains engaged in the driving situation). To this latter combination, the next market package adds vehicle initiated automated lane changes. Finally, there is a market package that adds automated merge/demerge capability.

An alternate approach would improve ACC by adding cooperation (so vehicles can space themselves based on estimated braking capabilities, and respond more quickly to slow-downs more than one vehicle ahead of them). This cooperative ACC could be improved to Cooperative (A)ACC. There is then a market package of Cooperative (A)ACC and FCA in mixed traffic on a protected lane. Another market package adds to this lane keeping, which is safe because of the protected lane, and the vehicle's ability to hear and respond to cooperative warnings. Another market package adds to this merge/demerge capability.

Control of ordinary driving actions leds to some market packages that allow the driver to disengage in special, limited circumstances. More robust capability is the provenance of full AHS.

AHS Market Packages

These market packages provide robust driver-disengaged capabilities, in what are intended to be robust and eventually wide-spread environments. One version is full automation able to drive mixed with manual traffic on ordinary lanes, but not offering vehicle communications. One version is a dedicated-lane system, providing high-capacity such as through platooning, but not offering full automation on ordinary lanes. Finally, one version is a merged capability, wherein vehicles could operate in high-capacity dedicated lanes, and mixed with manual traffic on ordinary lanes.

Specialized Application Market Packages

AHS technology, once developed could be applied to many special purposes. The intent of the Specialized Applications, however, was to identify particular market packages that could be deployed before the corresponding AHS market package, and thus provide a stepping stone towards deployment of those AHS market packages. Each candidate ended up being a somewhat idiosyncratic special case. They are summarized below.

Automated Bus Movements in the Maintenance Area would apply vehicle automation to move buses at low speeds to relieve maintenance workers from long walks between buses. This would deploy bus automation in a controlled environment, laying the groundwork for further bus automation. A Bus Docking Aid would automatically park a bus at a very low speed, at designated stops, allowing it to park very close without hitting the curb.

Automated Snowplows would follow some lane markings (e.g., magnetic tape) in poor weather. Following the road in bad weather is a necessary function for snowplows, and this would deploy lane marking that could be used for other automation.

Truck Convoy with Driver in Leading Truck would allow truck automation, laying the groundwork for further automation, while leaving a professional driver alert and in charge of the situation. Truck Safety System is not really a specialized application, but instead a recognition that many systems may be cost effective for trucks, and deployed there, first.

Automated Container Movement (Within Terminal) is the automation of trucks for operation in terminal areas, such as the loading of trains and trucks at ports. The vehicles can travel at less than highway speeds, and the environment can be more closely monitored and controlled than a public highway.

Interterminal Passenger Shuttle is something like an airport shuttle, running on a fully defined route, under automated control.

Coordinated Startup (From a Stop Light) deploys vehicle cooperation to allow vehicles to respond evenly to a stop light turning green.

Deployment Map

Appendix 10.3.4 presents the current detailed Deployment Map. The purpose of this map is to demonstrate the feasibility of deployment, and to capture the full range of alternate paths. It is also to provide the "master copy" of the results of discussions with stakeholders regarding deployment of particular market packages. The document itself is <u>not</u> intended to be a stakeholder friendly representation of deployment paths--translation into stakeholder friendly term is expected.

Each circle represents the actual deployment of a market package. Arrows indicate the flow between market packages. "Or"s indicate that there is a choice of precursors, and thus any particular market package feeding into an "or" is optional. Ultimately, for each set of incoming arrows to a market package there should be a description of how deployment of that market package would be achieved, given the prior deployment of those specific precursor market packages. Appendix 10.3.5, Transitions Document, provides an initial draft of 13 of these descriptions.

Appendix 10.3.10, Functional Evolution of an AHS for Incremental Deployment, explores the question of deployment from a functional point of view. This appendix identifies the significant functions needed for AVCSS and looks at their dependencies. Especially interesting is the impact of cooperation on the introduction of various functions. Appendix 10.3.11, Orthogonal Capability Building Blocks for Flexible Deployment, proposes an approach to identifying deployment steps by combining orthogonal functions. Orthogonal functions are those which could be deployed independently of each other.

Demo '97 Support

The most visible Consortium effort during C3 Phase I was the 1997 Demonstration of Technical Feasibility. Progressive Deployment performed several efforts in support of that demonstration.

An illustrated, full-color version of the Deployment Roadmap, simplified to be a friendly to the general public, was developed as a hand out. Appendix 10.3.1 is a black-and white version.

Another handout was prepared, to illustrate the top-level traceability between Market Packages to User Services. The matrix in 10.3.7 is a more comprehensive version. The theme of one AHS booth, "Driving Toward the Future," was subsequent development and deployment of intermediate systems and AHS.

Section 6 Feasibility Analyses

Introduction

The Feasibility Analyses represent a diverse combination of activities carried forward from Task C2. These include evaluations of performance and safety of AHS concepts and studies of critical issues that were identified during Task C2. In the middle of the first year of Task C3 this work became considerably more complicated when the scope was expanded beyond AHS to include a full range of warning and control assistance services that may precede the introduction of AHS. The result of this is that the activities that are grouped together here include some completed studies of AHS issues, some completed studies of pre-AHS issues and some partially completed studies of both (either interrupted in mid-course or started late enough that they could not be completed within this initial year of Task C3). The remainder of this Section is subdivided into reports on the results of the evaluation studies and reports on the critical issues studies.

Performance and Safety Evaluations

Pipeline AHS Throughput Evaluation

Task C2 included extensive estimates of the pipeline throughput that could be achieved by AHS based on a variety of system design and operating assumptions. These evaluations were extended in Task C3 to include more parametric variations and a new set of more optimistic base case assumptions. The most important change was in the distribution of braking rates for the vehicle population. The new distribution is based on the braking rates of 96.9% of the 1995 and 1996 new-vehicle population (for light-duty vehicles) as reported in Consumer Reports, without any derating for wear and aging. This produces a significantly narrower distribution of braking rates, which leads to the possibility of smaller longitudinal spacings between AHS vehicles, producing higher pipeline capacities. Appendix 10.4.1, Analysis of AHS Pipeline Analysis, contains the full report on the evaluation of AHS pipeline throughput.

The pipeline capacity estimates reported here are higher than those reported in Task C2, especially for the non-platooned cases. For operations at a nominal speed of 30 m/s and with 3.2% of the vehicle population excluded (those with the poorest braking capabilities), the new pipeline estimates for an AHS lane with dry pavement carrying only light-duty passenger vehicles are:

- 3939 for autonomous vehicle following
- 4327 for low-cooperative vehicle following
- 4817 for high-cooperative vehicle following
- 10,425 for platoons of ten vehicles.

For a case in which the traffic flow includes 6% heavy trucks and 1% transit buses, with 93% light-duty passenger vehicles, the corresponding pipeline estimates are approximately:

- 3100 for autonomous vehicle following
- 3300 for low-cooperative vehicle following
- 3500 for high-cooperative vehicle following
- 4300 for platoons of ten light-duty vehicles (with buses and trucks able to form separate, but short, platoons)

The pipeline analyses were also extended to more detailed evaluations of non-uniform spacing cases, in which the spacing between vehicles is based on real-time knowledge of the braking capabilities of one or both vehicles. This strategy provides the opportunity to further reduce separations between vehicles.

Pipeline Throughput in Mixed Traffic

The Task C2 analysis of pipeline throughput in mixed traffic was extended to take account of the new nominal safe separations between automated vehicles, and some other assumptions were relaxed as well. Parametric studies were conducted in Task C3 (see Appendix 10.4.2, Mixed Traffic Throughput Analysis) for a wider range of operating characteristics, including non-uniform separation between automated vehicles, but the fundamental character of the results was not changed from that reported in Task C2. The results show that under most assumptions about minimum safe separations between vehicles, the introduction of automated vehicles does not decrease the effective throughput of a lane. However, they also show that the automated vehicles can produce only small increases in lane throughput (up to 15%) when they represent less than 30% of the population of vehicles using the lane. Significant increases in lane throughput (30% or more) generally require market penetrations in the range of 50% of the vehicle population in the lane. The analyses assume that the automated vehicles have the ability to follow non-automated vehicles at time gaps of less than 1 second, which is less than contemplated in the designs of adaptive cruise control systems (and less than half the time gap of the ACC recently announced by Toyota, which would significantly *reduce* lane throughput).

Effects of Merging on Throughput

The effects of merging of entering traffic on AHS throughput were evaluated for the Houston case study, in order to produce realistic estimates of the throughput that would be achievable on the Katy Freeway HOV facility. This study considered three different levels of travel demand and infrastructure development, together with four different distributions of intelligence. Simulations were used to estimate the maneuver ramp lengths needed to accommodate the merging under each level of demand and distribution of intelligence, allowing for 96% light-duty vehicles and 4% buses in the traffic mix. Since maneuver ramp lengths needed to be constrained to distances compatible with feasible construction in Houston (typically no more than 1 or 2 km), the effective throughput had to be derated to the levels that could be achieved at these ramp lengths.

These studies showed the following effective merge derating factors, leading to effective throughput values of :

	Derating Factor	Pipeline Capacity	Effective Throughput (veh/hr)
Autonomous vehicle following	25%	3783	2837
Low-cooperative vehicle following	10%	4115	3704
High-cooperative vehicle following	10%	4534	4081
Platooning	20%	7838	6270

Environmental and Energy Consumption Effects of AHS

The detailed SmartAHS simulations of the Houston Katy Freeway HOV case study were applied in conjunction with a state-of-the-art model of modal emissions and fuel consumption using the latest EPA driving cycles for different congestion levels to predict the effectiveness of AHS compared to other alternatives (do nothing or use conventional technology to widen the Katy Freeway). The results of this preliminary evaluation (see Appendix 10.4.9, Preliminary Emissions and Fuel Consumption Evaluation of Automated Highway Systems) showed that an AHS has slightly lower average fuel consumption than a non-automated highway operating at free-flow, which would require the construction of additional lanes to accommodate the traffic demand on the Katy. However, the AHS on the Katy would have much lower average fuel consumption (47% lower) than the heavily-congested Katy would have without AHS or any other enhancement. In both cases, the AHS advantage is attributable to smoother speed control, eliminating the transients that lead to enrichment events (when the engine control system applies a "richer" fuel/air mixture to meet power demand, thereby increasing fuel consumption and emissions).

The HC and NOX emissions were also shown to be substantially lower for AHS than for congested manual driving, but the CO emissions were actually least in congested traffic because of its much lower travel speed. When AHS was compared to freely-flowing manual traffic (representing the addition of lanes to the Katy), all emissions were lower for AHS than for the manual traffic because of the smoothing of transient maneuvers.

The AHS cases that included use of platoons provided an additional 5% to 15% savings in fuel and emissions due to the aerodynamic drafting associated with the close separation between the vehicles.

Safety Evaluations

The safety analyses are considerably more complicated, and depend on the need to make more assumptions, than the throughput analyses. The safety analyses in Task C2 addressed in great depth rear-end collisions between an abruptly decelerating lead vehicle and a following vehicle that is trying to avoid hitting it. In Task C3, the scope of safety issues has been broadened considerably, but these have been addressed with less depth and detail than in the earlier task. More attention has been devoted to partially-automated AVCSS systems that could be precursors to AHS, including Adaptive Cruise Control and forward collision warning systems. For these systems, the effective safety is heavily dependent on the responses of the driver, and modeling of the driver responses remains quite primitive at this stage.

A general methodology (Appendix 10.4.14, Benefit Evaluation of Crash Avoidance Systems) has been developed to frame the analyses that can predict the safety benefits of AVCSS based on their technical capabilities. A first example has been implemented for a forward collision avoidance system, using a kinematic analysis of vehicle motions to study Leading Vehicle Decelerating collisions (Appendix 10.4.12, Design of Emergency Maneuvers for AHS) and to study Leading Vehicle Not Moving collisions (Appendix 10.4.14, Benefit of Crash Avoidance Systems).

The Task C2 analysis (Appendix 10.4.13, Multiple Collision Analysis and Inter-Vehicle Spacing) of hard braking to avoid colliding with a decelerating lead vehicle was extended to include the possibility of multiple collisions within a platoon (rather than only the first collision, which was addressed in Task C2). The new analysis shows that the frequency and severity of intra-platoon collisions increase with platoon length, nominal intra-platoon spacing, the breadth of the braking distribution and the elasticity of the collisions. This kind of analysis can be used to develop recommendations regarding both intra- and inter-platoon safe separations, based, for example, on results showing significantly lower collision velocities for 1m separations than 2m separation within platoons. The extended analyses of hard braking also produced a first estimate that the rate of rear-end crashes with automatic vehicle following could be reduced to 16% of that for manual driving under the same traffic flow conditions. This analysis is contained in Appendix 10.4.11, AHS Rear-end Crash Mitigation Benefits.

Relationship of Safety and Congestion

There have been many anecdotal statements regarding the relationship between traffic safety and congestion, but there appear to be few if any quantitative studies of that relationship. Such an investigation has been initiated, to explore whether the existing traffic congestion or safety data can be used to draw any significant conclusions. For example, most estimates of the annual costs of traffic congestion in the United States are in the range of $50 to $100 billion, but NHTSA's estimate of the congestion cost attributable to traffic crashes is only $4.4 billion. The congestion estimates typically indicate that at least half of the congestion delay is attributable to non-recurring causes, which include not only crashes but also construction and maintenance activities, adverse weather conditions, special events, and law enforcement actions. It would be useful to be able to isolate the portion that should really be attributable to crashes so that the benefits of crash avoidance systems can be estimated more realistically.

Similarly, there have been anecdotal claims that congestion leads to increases in crashes, but the available data need to be explored carefully to establish what statistical support exists for this kind of a causal relationship. An initial look at some of these issues surrounding this relationship can be found in Appendix 10.4.3, The Connection Between Safety and Congestion).

Studies of Critical Issues

The evaluations of AHS concepts in Task C2 led to the identification of the critical issues that needed to be studied in order to support the selection of a final AHS concept or concepts. Most of those issues are addressed here (with the exception of progressive deployment strategies, which has its own Section 5). In addition, the extension of the program's scope to issues of AHS precursors such as driver warning and control assistance systems created a need to develop a better understanding of the hazards that are responsible for the crashes that occur today on our interstate highways.

Driving Environment Hazard Analysis

The existing published analyses of causes of traffic crashes are based on consideration of crashes that occur in all types of road environments. Since AHS and its precursors focus more specifically on travel on limited-access highways, it is important to understand the causes of crashes that occur in that specific environment so that we have a reasonable baseline for comparison. The GES database maintained by NHTSA contains samples of all crashes in the country, but it is possible to sort it to identify and focus on the crashes that occur on Interstate Highways, which are all limited access. Although the interstate highway crashes are only about 6% of the total of crashes reported to police, they can be used to represent the crashes that occur on all limited access highways.

Two-thirds of the interstate highway crashes were found to be attributable to speed differences, driver loss of control, lane changes, and obstacles, in that order of importance. The conditions that most often contributed to these crashes were lighting condition, road surface, visibility and speeding or reckless driving, again in that order. Although driver inattention is known to be a critical factor in many of these crashes, it is not explicitly coded in the GES database so it does not show up in these tabulations. The most frequent crash geometries were rear-end, road departure/vehicle avoidance, sideswipe, angle and object/vehicle impact, together comprising two-thirds of all interstate highway crashes.

These data provide encouragement that AHS can make a significant contribution to reducing crashes, because the large majority of the crash causes are factors that could be eliminated or greatly reduced by the use of automation technology. An excellent analysis of the causes of crashes on limited access highways is found in Appendix 10.4.4.1, Driving Environment Hazard Analyses.

Mixed Traffic Operations

When this study (see Appendix 10.4.7, Mixed Traffic Analyses) was initiated, it focused on evaluating the potential for operation of fully automated vehicles mixed freely with manually driven vehicles on highways. This included identifying the driving hazards that the automated system would need to handle safely and seeking means of using some of the drivers' capabilities to augment the automated system performance under those hazard conditions. It became apparent that today it would be very difficult to develop an automated system that could respond safely to the full range of possible driving hazards, so intermediate approaches were then sought, in which automated and manual vehicles might mix under some carefully constrained conditions.

One of the key issues underlying the challenges to fully automated mixed traffic operations is the finding that the driver cannot be relied upon to act as a hazard monitor if the moment-to-moment vehicle control is taken away from him. This means that any system that supports full-time automation of both lateral and longitudinal vehicle motions must also include fully-capable monitoring, situation awareness, hazard recognition and response.

The development of the catalog of hazards was particularly useful in highlighting the kinds of information that the automated vehicle would need to have in order to drive safely. It became apparent that today it would be very difficult to acquire all this information from vehicle mounted sensors. This led to the requirement for some degree of cooperation on the part of the highway and perhaps other vehicles as well, which means that the automated driving would need to be restricted to specially designated roads, where the non-automated vehicles might also be required to have some special equipment (reflectors or transponders).

The requirements that were identified for a mixed-traffic AHS are:

- The AHS must support prevention of or response to virtually all hazards without manual intervention;
- The AHS must react safely in the presence of arbitrary manual vehicles, even if the road is somehow restricted;
- The AHS must react safely and efficiently in the presence of manual or semi-automated vehicles that meet the specified roadway restrictions;

- The AHS must ensure that the vehicle has all of the roadway information that is available to a manual driver through signage and other visual means (e.g., cones, flares, highway patrol manual signals, exit signs, lane ending signs);
- The automated vehicles must operate in any common weather conditions in which manual vehicles can operate, with at least the same level of safety;
- The AHS must provide acceptable levels of liability exposure for all parties.

Dedicated Lane Operations

AHS operations in dedicated lanes are the counterpart to mixed traffic AHS operations. Studies in this area were de-emphasized after the middle of the first year of work on Task C3 following the request of USDOT. Nevertheless, studies were produced on the interactions between roadway geometric design and sensor characteristics and on the means for excluding obstacles from a dedicated AHS lane (which will be described later in the section on obstacle management).

Existing roadway geometric design standards are based on assumptions about the visibility needs of drivers who must look ahead to see hazards. These assumptions need to be re-examined when the hazards are being sought by electronic sensors mounted low on the vehicles. For example, an existing forward-looking radar being studied at CMU, based on a design from the Technical University of Munich, has a horizontal field of view of 12 degrees, which could be extended to 16 degrees. This was found to be adequate for use with the curves encountered on normal highways and on high-speed ramps (designed for speeds up to 50 mph). However, it would not be able to detect all objects in the vehicle's lane on an interchange loop ramp posted for 30 mph. For these tighter curves, it would be necessary to reduce speed below the current posted value, increase the radar field of view, or provide a steerable radar, which would need preview information about upcoming curves (from GPS plus map database, roadside beacon or information coded in magnetic markers or tapes).

Obstacle Management Studies

Two primary studies were conducted on the issue of roadway obstacles, one of which identified the obstacles currently found on highways (Appendix 10.4.4.2, Driving Environment Obstacle Analyses) and the other (Appendix 10.4.8, Dedicated Lanes Analysis) developed conceptual designs for obstacle-excluding infrastructure (fences). Appendix 10.4.6, Obstacle Management Analysis, is a summary of these two reports.

The driving environment obstacle analyses used data from the GES database to identify the frequency of occurrence and severity of crashes associated with various types of roadway obstacles. Obstacles were found to cause about 6% of the crashes on interstate highways and about 15% of crashes on all highways with speed limits of 55 mph and above (the non-interstates tending to be not as well fenced or barriered as the interstates). The seven major types of obstacles were found to be:

intruders from the environment (deer, rocks, etc.)	42.3%
vehicle loads	18.7%
vehicle components (tires, mufflers, etc.)	17.9%
other/unknown	14.7%
highway components (expansion joints, etc.)	4.2%
people (pedestrians, workers, occupants of disabled vehicles)	1.2%
malicious mischief	1.1%

Although people were a small percentage of the total, they ranked highest in terms of total injuries and injuries per crash, presumably because they were severely injured by being hit by the vehicles. The ten obstacle types that rank in the top dozen for both injury and property damage per crash were:

- ladders
- tires
- tire debris
- wheels
- wood
- metal scrap
- vehicle debris
- vehicle loads
- unknown objects
- unknown debris

The most common types of obstacle motion were found to be: entering the roadway under their own power (38%), lying in traffic lanes (27%), falling/separating from a vehicle (16%), and bouncing or thrown up by a vehicle (12%). Most obstacles originated from the surroundings (42%), from another vehicle or trailer (37%) or an unknown source (15%). The obstacles were first seen: in the same lane as the vehicle involved in the crash (41%), in an unknown location (23%), coming from the opposite direction lanes (17%), from the shoulder in the same direction (13%), or from one lane over (6%).

In order to fully address the kinds of obstacles identified in this study, an obstacle detection and tracking system for an AHS vehicle would need to have the following characteristics:

- wide field of view both horizontally and vertically
- rapid update rate
- ability to determine quickly and precisely what objects are on the roadway and what objects are off, even on curved sections of highway
- ability to make a gross determination of object size
- ability to quickly establish a track on obstacles with regular motion
- ability to quickly recognize that an obstacle is moving erratically.

Since this is a challenging combination of attributes, it is necessary also to consider means of excluding obstacles from entering the AHS lanes. These would need to:

- provide a means of keeping animals and objects from the surroundings off the highway
- require methods of vehicle inspection and self-monitoring to keep vehicle components from separating from the vehicle while in operation
- enforce a policy regarding vehicle loads, backed up by inspection, which greatly reduces the probability that cargo will be ejected from a vehicle during operation on AHS lanes
- keep people who do not belong on the AHS off the roadway, and safeguard those who do belong there.

Obstacle-excluding fence configurations were devised for a wide variety of highway environments, including overcrossings, undercrossings, interchanges, frontage roads, entry and exit ramps and deer crossing areas on open highways. These involved use of conventional chain-link fence construction, with finer mesh (1") at locations where vandals might deliberately try to introduce debris onto the AHS roadway and coarser mesh (2.5") at locations where it is only necessary to prevent animal intrusions (deer). Costs were estimated for each of the environments, including multiple approaches for some of them. Simply fencing the sides of the ramps at overcrossings, undercrossings and interchanges was estimated to cost only a few thousand dollars per location. However, providing a full fence enclosure (with fencing over the top of the automated and adjacent manual lanes) could cost from $68 thousand to $141 thousand per location, depending on whether there are four or eight lanes to be spanned. Fencing along the side of an open highway, for example to prevent deer from crossing, costs in the range of $12 per linear foot. For more details on obstacle exclusion techniques see Appendix 10.4.8, Dedicated Lanes Analyses.

Driver Involvement Studies

The role of the driver was identified as a key issue in Task C2, and has become an even more important issue in Task C3, with the expansion of consideration to driver warning and control assistance systems. The work conducted thus far in Task C3 (see Appendix 10.4.5, Driver Involvement Analyses) has consisted of: a driver-in-the-look simulation study to investigate the influence of automated driving conditions on driver vigilance (10.4.5, Appendix A,), a human factors assessment of two background collision avoidance system concepts (10.4.5, Appendix B), and a literature review on human factors issues in automated and partially automated vehicle/highway systems (10.4.5, Appendix C). Some of the primary findings thus far include:

- The supervisory control literature indicates that a disengaged operator will not intervene as quickly or as appropriately as an engaged operator, because of reduced situation-specific awareness. In partially automated systems, it is recommended that the driver retain usual steering responsibilities until the system can provide adequate hazard avoidance and safety without driver intervention.

- The vigilance and monitoring literature suggests that with disengagement a driver might show worse obstacle detection due to lowered alertness. A driving simulation study will be conducted to investigate whether detection of infrequent obstacles is impaired by decreasing physical involvement in driving.

- The driver workload in using an automation feature should at no time exceed the driver workload in using conventional cruise control. Any automation or partial automation system should include a set of automated functions that is useful and immediately intelligible as a group, so that the driver perceives its activation or deactivation as a single action. This is essential in order to avoid confusion by the driver about what features are automated and what features remain his responsibility.

- System designers should use the fewest possible number of warnings, and the warnings should only be presented when the driver has sufficient time to respond effectively. The costs of both false alarms and failures to warn of genuine hazards need to be considered carefully.

- Fallback schemes may be complex in terms of their dependence on the traffic situation, but choices must be easy to understand and simple to execute from the driver's point of view.

- The AHS should be able to accept inputs from the driver (such as a panic input) but should not depend on driver inputs. However, there needs to be systematic study of the appropriate system response to driver inputs (particularly panic inputs) in specific traffic situations. System responses may be complex in terms of their dependence on the traffic situation, but should be easy to understand from the driver's point of view.

Section 7 Case Studies

Introduction

The National Automated Highway System Consortium (NAHSC) is involved in partnerships with many public and private stakeholders across the nation in what are called case studies. Case studies might be described as turn-key planning analyses where we take a region's transportation challenges and needs and apply ideas based on the integration of highway and vehicle technologies to develop realistic solutions - many of which the NAHSC hopes to prototype and demonstrate in field operational tests in the near future. The intent of Case Studies is to determine:

- what automated highway systems (AHS) look like in a real world context;
- what effect those implementations will have on the rest of the system;
- how do we deploy these systems over time;
- what are the benefits, costs, and tradeoffs; and
- how do AHS compare to other possible transportation alternatives.

In addition, case studies are being used to evaluate the institutional factors that surround AHS implementation and deployment and to establish regional consensus by engaging participants at the state and local levels. The funding of NAHSC case studies illustrates the partnership aspect and varies anywhere from eighty percent to thirty percent federal funds (with most studies at around the fifty percent level) with the balance of funds coming from State and regional agencies and potentially from the private sector.

In order to gain a perspective on what automation means at a national level, case studies were selected to examine everything from specific corridors to entire transportation networks in rural, suburban, and urban settings looking at all vehicle classes from maintenance and operations vehicles to buses to trucks to passenger vehicles.

There are currently seven case studies underway across the nation with many different types of partners including: State DOTs, regional governments, and research institutes (It should be noted that there are many additional partners that were brought into the study by the prime contracting agency and include representatives from transit, commercial trucking, private industry, law enforcement, and cities and counties).

Below is a table that highlights the primary partners, location, and focus for each NAHSC Case Study

Table 7-1 Summary of NAHSC Case Studies

Principal Partner	Location	Classification
Houston Metro	Katy Freeway HOV/Transit Lanes	Transit/HOV - improve capacity and safety
Western Transportation Institute	Greater Yellowstone Rural ITS Priority Corridor	Light Vehicles - Rural two lane highway safety plus maintenance and operations
Southern California ITS Priority Corridor Steering Committee	Southern California ITS Priority Corridor	Light Vehicles & Trucks - Large urban system - Safety and operational efficiency
Virginia Tech Virginia DOT	I-81 Corridor Virginia	Trucks - Intercity / rural interstate commercial vehicle operations
Gary-Chicago-Milwaukee ITS Priority Corridor Committee	Gary-Chicago-Milwaukee ITS Priority Corridor	Trucks - Urban commercial vehicle operations
Minnesota DOT	Minnesota	Special Vehicles - Medium Urban System - automating snowplows and other maintenance operations
Michigan DOT	I-94 Michigan	Trucks & Transit - Urban/Intercity commercial vehicle operations and transit

Background

NAHSC began FY 97 with a emphasis on a longer term end-state AHS and original case study objectives reflected this perspective. The focus was on providing data and feedback for AHS Architecture evaluation, studying the major issues relevant to a given AHS end-state scenario (i.e., urban, intercity, mixed traffic, dedicated lanes, etc.), and determining the viable deployment sequence(s). Secondary emphasis was given to near-term deployment(s), providing feedback to stakeholders regarding the viability of a "real world" AHS, and looking at AHS as an alternative to other transportation modes.

Two case studies were already underway in October 1996: The Houston Metro study was well established and the Western Transportation Institute contract had just been finalized. In order to expand and facilitate the case study process, a request for information (RFI) was written in December asking for interest and qualifications from potential case study candidates. The RFI was sent out in January to several agencies that had indicated previous interest in Consortium activities and was also advertised in the Commerce Business Daily (CBD). This Request for Information can be found in Appendix 10.5.1.

In March five replies were received and evaluated according to the criteria that were laid out in the RFI. Also in March, because of direction from U.S. DOT, Consortium efforts began to shift from end-state automated highway system prototype development to near-term development of smaller or precursor automated highway systems as part of the Intelligent Vehicle Initiative (IVI).

In April, letters of interest were sent by the Consortium to the five sites indicating NAHSC interest in pursuing a case study with each of those agencies. At the same time that letters of interest went out, each of the five agencies were contacted and asked to participate in the August 1997 AHS Proof of Technical Feasibility Demonstration held in San Diego California by developing a booth for the exhibition hall describing the role and potential for AHS in their region.

Phase I contracts were written for each of the five new sites to 1) produce presentation materials for Demo '97 and to 2) develop a statement of work (SOW) defining the focus of the case study by vehicle platform and roadway setting (urban, intercity, rural) including detailing the specific tasks and activities for each study. In general, each case study includes problem definition, corridor or site selection, data gathering, corridor analysis, service definition and development, and service performance evaluation.

Because of funding constraints due to the delayed federal budget process and uncertainties about the direction of IVI, NAHSC case studies are continuing without federal dollars on a cost-share basis where the state or regional agency and the Consortium are providing labor to continue case study activities like workshops, SOW development, regional analysis,.

The Case Studies

Houston Metro

- Houston METRO
- Houston-Galveston Area Council
- TxDOT
- Wilbur Smith Assoc
- FTA

Houston Metro was established in 1979 to deal with the increasing transportation and mobility problems of the Houston - Galveston region which is the fourth largest metropolitan area in the United States and one of the nationally designated ITS priority corridors.

Houston Metro currently defines a HOV as two or more persons per vehicle. Metro estimates that within the next few years the usage of the regions HOV facilities will increase such that on some facilities the HOV definition will change to three or more persons per vehicle. This study is a high level analysis of how automation might increase the capacity of their dedicated transit/high occupancy vehicle (HOV) lanes in order to keep the HOV facilities at the two plus person per vehicle level. The study focused on vehicle entry into the system, merging with other vehicles, and reducing the spacing between vehicles to increase capacity.

Discussions with Houston Metro lead to the following findings:

* The public is fairly accepting of new transportation technologies, however these technologies must be proven, cost effective, and show travel time savings.

* Metro expects AHS to increase capacity and safety and to pay for itself. In addition, any systems developed within the Case Study should be applicable to the entire region.

* In order to be incorporated into the region's planning process AHS must demonstrate feasibility and must be tangible enough to determine what should be done now to prepare for AHS in fifteen or twenty years.

The case study centered around four tasks:

1. Assemble and Organize Data to Support Analysis
2. Develop Detailed Description of AHS Transit/HOV Application
3. Assess Performance of AHS Transit and HOV Application
4. Evaluate Societal and Institutional Factors Affecting AHS

Several different analyses were performed using tools, models and computer simulations, developed primarily under the NAHSC B5 Tools task. The types of investigation included: top level analysis, localized merge and queuing analysis, corridor-wide merge simulation, corridor-wide capacity analysis, and emissions and fuel consumption evaluation.

The results indicate that in order to meet the future increases in demand on the Houston area Transit/HOV lanes (as forecast by Houston Metro), automation is necessary (i.e., automation is defined to include AVCS with vehicle to vehicle and vehicle to roadside communication and cooperation). The emissions and fuel consumption evaluation indicates that automation - assuming close spacing between vehicles - will lower emissions on at least a per capita basis and perhaps a corridor basis. Phase II of the case study will involve defining the specific AHS systems (services) and supporting technologies, identifying the potential services and locations for demonstration and testing, and performing cost/benefit/tradeoff analysis.

Western Transportation Institute

- Western Transportation Institute
- Montana State University
- 3-M Corporation
- Montana DOT
- Idaho DOT
- Wyoming DOT
- Yellowstone/Grand Teton National Parks

The Western Transportation Institute (WTI) was established in 1994 as a national and international center for rural transportation research. WTI's testbed is the Greater Yellowstone Rural ITS Priority Corridor (GYRITS) which is an 800-mile rural corridor situated between Bozeman, Montana; Idaho Falls, Idaho; and Jackson, Wyoming and includes: Montana, Idaho, Wyoming, and Yellowstone and Grand Teton National Parks. The Corridor includes typical two-lane rural highways as well as rural interstates.

The primary focus of the case study is on enhancing the safety of rural two lane roadways. Preliminary investigation indicates that up to 82% of the corridor's crashes can be addressed by automation.

Through crash analysis, AHS countermeasure concepts have been developed for each corridor crash trend as shown in Table 7-2 below.

Table 7-2 Corridor Services vs. Accident Trend

AHS Countermeasure (service)	Accident Trend
Lane Detection/Warning/Keeping	Single Vehicle Run-Off-Road
Friction/Ice Detection	Overdriving on Slippery/Icy Roads
Headway Control	Rear-End Collisions
Detection of Vehicle Presence on Major Approach	Failure to Yield R/W
Detection of Objects in the Roadway	Animal-Vehicle Conflicts

Services will be phased in through the following incremental approach:
1. Develop corridor concepts;
2. Segment testing and demonstration;
3. Near term solutions - driver aids (infrastructure based);
4. Short term solutions - warning systems (integrating infrastructure and/or smart vehicles);
5. Intermediate term solutions - mixed automated and manual control (more smart vehicle based); and
6. Long term solutions - full automation.

The next step in the case study includes a phase II detailed development of corridor concepts and identification of sites suitable for field operational tests and demonstrations leading to deployment.

Minnesota Department of Transportation

- Minnesota DOT
- University of Minnesota
- Minneapolis-Saint Paul Metropolitan Council
- 3-M Corporation

The Twin Cities metropolitan region consists of seven counties which surround Minneapolis and Saint Paul. Over 2.2 million people - about half the state's population - live in Minnesota's only large metropolitan area. Because of the state's northern location and the impact on travel from heavy snow, blowing snow, and ice - winter maintenance operations are a major concern in Minnesota. These impacts include accidents, stalls and stranded travelers, abandoned vehicles, travel delays and increased time for emergency vehicles to respond to incidents. The societal costs, including deaths, injuries, property damage, lost productivity, etc., of these impacts are significant. The Minnesota DOT case study is looking at automating snow plows for operation within the greater Minneapolis/Saint Paul region which includes both urban and rural settings.

The Case Study will evaluate the potential benefits of using technology packages (e.g., services) which assist snow plow operators to "see" the road edges and obstacles (such as, other vehicles, roadside appurtenances and large snow drifts) in extreme low visibility conditions. The Case Study will determine if these services will increase snow plow productivity during the worst conditions and, therefore, reduce accidents, incidents, delays, etc. The Case Study will attempt to assess the potential safety and operational costs, benefits, and tradeoffs of various levels of market penetration of these services. The study will also examine the potential longer term impacts of an established lateral support and communications infrastructure given the expectation that spin-off applications may be relevant to other maintenance operations like striping, paving, and crack-sealing and may eventually lead to applications for commercial trucks, transit and passenger vehicles

This study is part of a larger nationwide effort to form a national consortium of DOTs and others. Using a combination of Pooled funds, State-only, and NAHSC funds the snowplow consortium will demonstrate automated snowplow technologies through FOTs in different locations around the country in the winter of 98/99, less than a year and a half away. The primary technologies showcased are expected to be lane keeping; frontal, side, and rear collision warning; and HMI heads-up display(s).

Southern California ITS Priority Corridor Steering Committee

- Southern California ITS Priority Corridor Steering Committee
- NAHSC
- San Diego Area Governments (SANDAG)
- California Highway Patrol (CHP)
- Southern California Economic Partnership
- Southern California Area Governments (SCAG)
- Calif. State Automobile Association (AAA)
- California Alliance for Advanced Transportation Systems
- Regional Transportation Technology Alliance (San Diego)

Southern California has long been known for its system of freeways and for some of the negative impacts the transportation system has induced including congestion and reduced air quality. The Southern California Corridor is one of the four corridors identified under ISTEA as a location for a more complete showcasing and deployment of ITS technologies. The Corridor runs from the northern boundary of Los Angeles County down to the United States border with Mexico and from the Pacific Ocean to roughly the middle of the state.

The goals of the priority corridor include:

- Increasing the efficiency without construction of new facilities
- Enhancing safety
- Facilitating commercial vehicle operations
- Maximizing capital investment
- Creating innovative public-private partnerships
- Reducing environmental impact

The Southern California ITS Priority Corridor Steering Committee wants to look at automation as a potential tool to help alleviate their congestion and environmental challenges, given that in many locations throughout the region, conventional solutions have proved to be inadequate. Congestion as well as safety are key elements that will be addressed from both a microscopic as well as a system or corridor perspective. One of the major themes underlying the Study is that AHS solutions should be needs and data driven not concepts driven. A draft of the statement of work for the next phase was recently developed to investigate the viability of AHS through: identification of Corridor problems and needs, identification of underlying causes, development of services to address the needs, assessment of concepts and services, and evaluation of AHS systems through FOTs.

In addition to increasing overall system efficiency, the corridor has an interest in addressing the special transportation challenges related to the international border, intermodal freight, commercial vehicles and transit vehicles

Gary-Chicago-Milwaukee ITS Priority Corridor - I-94

- Gary-Chicago-Milwaukee ITS Priority Corridor Committee
- Illinois DOT
- Indiana DOT
- Wisconsin DOT
- ITS America & ITS Midwest
- FHWA Region 5 & OMC
- Illinois Toll Collection
- BRW Inc.
- Cambridge Systematics
- Bulkmatic Transport Company
- Wisconsin State Patrol
- Illinois State Police
- International Road Dynamics

The GCM Corridor is one of the four corridors in the United States which is designated as a national ITS priority corridor. The GCM Corridor is 130 miles long, home to 10 million people, provides an employment base of 4 million people, and is the major distribution center for the Midwest. The GCM Corridor faces some of the toughest transportation challenges in the nation, including a mix of extreme traffic density, ozone non-attainment, complex travel patterns, and an inability to significantly expand existing transportation facilities.

The economic vitality of the GCM Corridor is highly dependent on Commercial Vehicle Operations (CVO). The GCM Corridor's transportation systems ability to add capacity is very limited which in turn threatens the cost effectiveness, efficiency, and safety of CVO activities in the Corridor. The Corridor Steering Committee believes that potential solutions may be found in innovative concepts like Automated Highway Systems and assessing AHS's potential role for reducing congestion and pollution along with increasing safety The GCM Corridor has completed a draft statement of work for a four phase case study that will look at increasing the safety and capacity through services like automated truck following and will lead to a FOT in three years.
The tasks include:

1. Identify Potential FOT sites & collect data;
2. Assess Institutional & Societal Aspects;
3. Assess Legal Barriers & Propose Workable Solutions;
4. Assess Potential AHS Impact;
5. AHS Operations in the Corridor and;
6. Motor Carrier Participation.

The primary concept being studied consists of a specially trained licensed commercial driver operating a commercial vehicle that has been specially equipped with advanced technology. This specially equipped vehicle will serve as a "lead vehicle" for other commercial vehicle operators who wish to follow behind and relinquish control to the lead vehicle (e.g., electronic coupling). The vehicles will be assisted by infrastructure support and information systems. The overall goal established for the GCM AHS Case Study is to ... provide useful information on the impact that AHS initiatives utilizing commercial vehicle could have on the GCM Corridors transportation system. The findings from the Study are also expected to be useful to other regions considering AHS and utilizing commercial vehicles.

Michigan DOT - I-94

- Michigan Department of Transportation
- Parsons Brinckerhoff - Michigan
- Southeast Michigan Council of Governments (SEMCOG)
- Eaton Vorad
- Hubbell, Roth & Clark
- General Motors - Michigan
- FHWA - OMC
- University of Michigan
- City of Detroit
- Road Commissions of Oakland, Wayne, and Macomb Counties
- ITS Michigan

The Michigan Department of Transportation (MDOT) is experiencing several problems with the current transportation system. Numerous routes are in need of increased capacity due to the excessive commercial and passenger vehicles traveling in Detroit and the surrounding areas. Limited space prohibits construction of new facilities and due to limited resources, several of these areas are in need of significant maintenance and reconstruction. MDOT's first priority is to improve the operation of existing facilities and believes that AHS may provide some improvement where conventional measures and even mainstream ITS technologies fall short.

The I-94 Corridor stretches from Detroit to Chicago and beyond and serves as a major link for commercial and interstate transit vehicle traffic. It is a vital link for the Big Three automakers and is critical to the international trade route between Canada and Mexico.

Due to the high percentage of commercial and fleet vehicle use on the I-94 Corridor, the MDOT-NAHSC Case Study will focus and CVO and transit applications. Michigan DOT plans on conducting their AHS case study in parallel with a current MIS that is being conducted on the I-94 in and near Detroit.

The study is being set up to address several critical issues that will define the market for AHS like:

1. What will be the benefits to carriers and shippers?
2. What will the costs be for automating the vehicles? the infrastructure? How will these costs be paid for?
3. What will be the mode of operations for the automated trucks? Will they operate as single vehicles or as platoons of two or more?
4. What is a reasonable timeframe to bring AHS to the consumer market?
5. What are the safety implications of operating automated trucks in either mixed traffic or in dedicated lanes?
6. What will be the regional impact on the level of congestion and incidents?

The next steps include: gathering data, performing analysis, identifying and developing AHS, and evaluating the systems and their costs and benefits.

Virginia Tech - Virginia DOT - I-81

- Virginia Polytechnic Institute
- Virginia Department of Transportation
- ITS Virginia
- Virginia Trucking Association

Interstate 81 connects the six states of Tennessee, Virginia, West Virginia, Maryland, Pennsylvania, and New York. Geographically, it is a main connection between the southern economic hubs of Atlanta, New Orleans, Houston, and Dallas to the

Northeastern United States. In Virginia, the I-81 Corridor traverses the western part of the state and is located between the Blue Ridge and Allegheny Mountains. The 325 mile interstate serves a predominantly rural region.

Besides providing an important transportation link to the economic hubs and markets of the eastern United States, I-81 also serves a large number of commuters between Christiansburg and Roanoke. As a result of the varied uses, the corridor is characterized by a high percentage of commercial vehicles in addition to many daily commuters. The rolling terrain presents long upgrades which further complicate traffic conditions along the corridor. Additionally, the heavy truck volumes effectively use up the capacity of the right lane and thus severely limits the capacity of the facility during peak hours. This road section is frequently referred to as a "one lane road" because trucks are perceived as using up one full lane of the capacity of the dual lane roadway

A preliminary study of the Corridor was performed and revealed four issues of concern: work zone safety and control, traffic safety, trucking issues, and intercity traveler needs. Phase I and Task A of the Case Study is to build upon the preliminary work by assembling and organizing existing data. Task B will identify those Corridor issues and needs that lend themselves to AHS applications and describe those applications. Through the use of a focus group with various key players within the Corridor, Task C will generate acceptance for and further refine the regions identified needs and potential solutions.

Under Phase II the AHS concepts will be further defined and performance evaluations will be performed along with a benefit-cost-tradeoff analysis to estimate the potential benefit to the Corridor. Lastly, those AHS systems that hold the most promise will potentially be developed under IVI as prototypes for FOTs and demonstrations.

Other potential Sites

I-95 Coalition

The I-95 Coalition is currently putting together a proposal for a joint Coalition-NAHSC Case Study. The study would focus on systems wide effects of applications of new technologies given the complex multi-modal nature of the corridor and might possibly include transit, carpools, and commercial vehicles as well as light passenger vehicles.

Section 8 National Consensus

Stakeholder Forum Summary

The second annual Stakeholder Forum took place in Washington, D.C. on June 5th and 6th, 1997. The timing was designed to take advantage of the ITS America Annual Meeting, which ended at 11:30 AM on June 5th. The Forum planners hoped that interested attendees would stay an additional day to participate in the Forum.

While only 56 people pre-registered to attend the Forum, 99 people actually participated. Of this group, 48 represented Associate Participants, 33 were from the Core Participants, and 18 were other interested stakeholders. Each of the nine stakeholder groups was represented, with the exception of the Environmental Interests group.

The agenda included presentations on some of the ongoing concept development work and a preview of the contents of Demo 97. It also included three breakout sessions, two covering technical issues related to concept development and one dedicated to stakeholder organization. Participants for the two technical sessions were separated into the following five categories: Consumers, Transit, Commercial Vehicle Operations, Infrastructure, and Cross Cutting Users. The organizational session split the participants according to the traditional nine stakeholder categories.

The first technical breakout session took place immediately after a presentation to the Plenary on User Needs/User Services by Bob McQueen, Jim Reynold, Chris Bausher, and Evelyn Wagner. Participants were given materials listing user needs and example user services related to the associated breakout category that they attended. They were asked to list additional user needs or modify the ones already identified. The group then analyzed one of the example user services to demonstrate that it satisfied one or more of the needs that were identified for their category. A Moderator, Note-taker, and Domain Expert assisted the participants in completing the exercise.

The second technical breakout session took place on Friday after a presentation to the Plenary on Market Packages by Tom McKendree. Tom demonstrated the relationship between the User Services, which tell what the AHS should do, and the Market Packages, which tell how it should be done and lead to potential deployment sequences. In this session, participants examined five example market packages to determine what characteristics they considered important in describing a market package. Once again, a Moderator, Note-taker, and Domain Expert assisted during the exercise.

The organizational breakout session was intended to allow the nine stakeholder groups to select a new representative, if necessary. The groups also used the time to identify issues unique to their group. Note-takers captured the results of these meetings to help report them back to the Plenary.

The final event of the Forum was to report on the results of each breakout session. Volunteers from each group presented the notes to the Plenary session. These notes have been integrated into a final report that is included in section 10.6.1 in the Appendices of this document.

The Forum was a success. Attendance at the event was close to what was expected. It gave the Consortium an excellent opportunity to demonstrate the new emphasis on a user-driven, market-driven approach to concept development. Some attendees were unhappy with the seemingly academic nature of the user service analysis, but they were enthusiastic about discussing the market packages and market package sequences. They asked that the Consortium mail out presentation materials ahead of time so that they have a chance to review them prior to the event. They also expressed concern about being separated in a manner different from the traditional nine categories during the breakout sessions. This concern will be addressed in future Consortium-sponsored events.

A complete review of the Washington Stakeholder Forum is contained in the Forum Summary Report in Appendix 10.6.2.

Another measure of National Consensus was made in a survey of AHS riders taken during the NAHSC's August 1997 Demonstration in San Diego. During this four-day demonstration of automated vehicle and highway technologies, a survey was made of the riders in those vehicles. The purpose of this survey was to gain insights into their perceptions of these technologies. The riders filled out this survey immediately after their rides. The survey covered four areas: 1) what did they like and dislike about the AHS technologies, 2) what are the perceived benefits of AHS, 3) what concerns do they have with AHS, and 4) for what kind of driving would they use AHS. A complete report on the survey and the results is contained in Appendix 10.6.3.

C3 Interim Report
March 1998

Appendix 10.1 Architecture

Includes:
10.1.1 AHS Operations Concept
10.1.2 Functional Decomposition Document

NAHSC

10.1.1 AHS Operations Concept

Jerome. F. Sobetski
for the AHS Architecture Development Team

Preface

This version of the AHS Operations Concept is a work in-process. This work was performed primarily during the period of October, 1996 through December 1996, with minor revisions incorporated in March, 1997. The Operations Concept documents the vision for the AHS and serves as the baseline for the Functional and Logical Architecture development.

Introduction

The Operations Concept provides the vision of what is an AHS, with particular emphasis on two evaluatory operating modes. It provides a bridge from the System Objectives and Characteristics to facilitate the development of the functional and physical architecture (design). The AHS System Specification is the program document providing the AHS performance requirements.

Purpose

The Operations Concept captures and establishes boundaries for the concept development process. This document provides answers to the following:

a) what is an AHS,

b) what it does, and

c) in what environment.

Included in this operations concept is a brief description of the expected or desired deployment approach. The consortium is developing a separate document specifically focused on AHS deployment strategy.

Scope

This document describes two operating modes for an automated highway system. Both operating modes support the AHS goals as a national, interoperable system. Operating Mode A encompasses the segregated operation of fully automated vehicles on dedicated lanes. Operating Mode B allows manually driven and fully automated vehicles to operate simultaneously on specially equipped lanes. As work progresses on the development of the AHS architecture, these two operating modes may be revised or combined. Evaluations of variations within each of these operations concepts is intrinsic to the concept development process. Performance evaluations, supported by site specific case study data, will facilitate refinement of the concept.

This document addresses the "mature" Automated Highway System and potential deployment paths. Plans for prototype and operational tests may be derived from this concept.

Operating Modes

Two operation operating modes are described; they are referred to as the dedicated lanes operating mode (operating mode A) and the mixed traffic lanes operating mode (operating mode B). Both operating modes of the concept are based on fully automated vehicle control, providing improvements in safety, trip time, economy and user convenience. The AHS concept is tentatively described by these two mainstream operating modes to assist the NAHSC in the development of a feasible system architecture. These operating modes showcase solutions of deployment, technology, roadway needs, cost and safety.

Common Assumptions

These AHS operating modes share some common ground rules, boundaries, and assumptions. The AHS is developed for completely automated driving on limited access, multi-lane highways. While engaged in the AHS, the system provides full control of the vehicle; no driver intervention or monitoring is required. Partial automation systems may provide part of the evolutionary deployment path to AHS, but these are not defined here.

The vehicle systems will include steering, braking and throttle actuators, sensors, and the associated control systems. AHS components will be incorporated into future production models of automobiles, trucks and buses; although some of the vehicle systems may be available as after market installations.

Incremental deployment paths facilitate the implementation of either operating mode. The AHS may use other ITS services; and some components may provide driver assistance on any highway.

Dedicated Lanes Operating mode - Operating mode A

The dedicated lanes operating mode of AHS is predicated upon physical segregation of manually driven vehicles from automated vehicles. The AHS lanes are separated by grade, barrier or geography from roadway used by manually driven vehicles. Entry and exit to and from the arterial roadways is via dedicated ramps or special transition lanes. The operation of the roadway, control system, vehicle separation policy, deployment strategy and user/operator environment are described in the following paragraphs.

Roadway and TMS

The roadway and TMS subsystems for the dedicated lanes operating mode is similar to today's high occupancy vehicle (HOV) lanes, supplemented by sensor elements and an infrastructure control system. The lanes are restricted to properly equipped and operating AHS vehicles. Physical barriers prevent intrusion of manually driven vehicles or large debris hazards onto the AHS dedicated lanes.

Control

The vehicle and TMS subsystems provide the sensing and processing capability to maintain safe vehicle spacing and speed, minimize the occurrence of, detect, and avoid obstacles; and perform lane change maneuvers. Automated highway entry merge and exit functions are performed by the AHS. Transition from manual to automated control is similar to engaging cruise control on today's automobiles or autopilot systems on sea faring vessels and jet aircraft. Prior to engaging, the AHS will automatically verify the ability of the vehicle AHS subsystems and the system interfaces to perform the vehicle control functions. The transfer of control zones are designated on the automated highway entry and exit ramps or special transition lanes. Control variations include optimization of flow control.

Vehicle Separation Policy

A platoon vehicle separation policy may be used to maximize throughput for heavy traffic corridors; individual vehicle spacing may be the preferred policy in lower traffic volume venues or in mixed vehicle class environments. Platoon speed and vehicle separation distance is controlled for each of the automated vehicles to synchronize maneuvers and to minimize trip time.

Deployment Strategies

The deployment of a dedicated lane operating mode of AHS could be accomplished by building dedicated lanes or converting existing HOV facilities. Initial implementation projects must be a careful balance, large enough to justify the costs, but small enough to be an achievable step. Fleet purchases of AHS vehicles can help boost initial AHS usage. As interest and use of AHS increases, additional dedicated AHS facilities would be implemented across the country.

An alternative approach is to dedicate lanes for any vehicles above a certain technical threshold, short of full AHS (e.g., all vehicles with at least adaptive cruise control). Subsequent transition to full AHS would be realized as the vehicle technology becomes sufficiently advanced and the infrastructure elements are installed.

Environment

Route guidance and other ITS services are integrated into the AHS. The dedicated lane traffic option may be implemented in any geographic environment (rural, inter city, urban, mountains, plains); limited only by availability of right of way, environment impact and construction cost.

Operations and Maintenance

Operations and maintenance functions will be responsible for providing a safe, functional environment in which automated vehicle operations can occur. Operations will be primarily concerned with the daily tactical activities of the roadway, while maintenance will be a more preventive activity. Where a TMS (Traffic Management System) exists today, the AHS will be integrated into that system. Where none exists today, the AHS will provide the impetus to establish a regional TMS.

Operations - The degree of centralized operational control exerted on the AHS will depend greatly on the amount of functionality placed on the roadway versus the vehicle. At a minimum however, it is expected that operations will monitor the AHS system at a macro (regional) level and provide status information that will be available to drivers, vehicles, and non-AHS TMS. Monitoring will be accomplished through roadway sensors, vehicle communications, and video, as well as outside sources such as weather reports. Information will be provided through radio broadcasts, variable or changeable message signs, and vehicle communications. In a fully automated AHS lane, the operations function will provide specific vehicle guidance. An additional requirement of operations will be to provide system operating policy such as speed limits, vehicle separation, and entry / exit data based on current conditions of the system.

Maintenance - The AHS will require regularly scheduled preventive maintenance to insure high availability to the users of the system. Because it is anticipated that the system will be highly automated, this maintenance will include electronic as well as physical elements of the AHS. Vehicle maintenance will be the owners responsibility; but, roadway and infrastructure will be the responsibility of the AHS operator. Incident management will also invoke maintenance assistance when an incident has affected some element of the infrastructure.

Mixed Traffic Lanes Operating Mode

The mixed traffic lanes AHS operating mode allows the mixing of automated vehicles and manually driven vehicles within the same highway lanes. The AHS unique roadway features, control system, vehicle separation policy, deployment strategy and user/operator environment are described in the following paragraphs.

Roadway and TMS

The highway lanes may be specially equipped, restricted, or designated to support the vehicle control systems.

Roadway variations for the Mixed Traffic Lanes operating mode include requiring significant or minimal roadway enhancements (sensors, references, control, or physical construction):

1) The roadway may be equipped with obstacle detection systems, transmitting hazard data to the automated vehicles.
2) The roadway may be enhanced with fencing or other barriers to exclude hazards from the travel lanes.
3) The automated vehicles may be restricted to operate in physically segregated lanes, shared with manually driven vehicles (similar to HOV lanes).
4) Sensor references may be installed on the roadway to support lane demarcation.
5) Communication systems may be installed on the roadway to facilitate automated vehicle control and traffic flow control.
6) The lanes may be restricted (by law) to exclude certain classes or types of vehicles.

Control

Each automated vehicle contains the sensing and processing capability to maintain safe vehicle separation and speed, detect and avoid obstacles, travel within a lane, and perform lane change maneuvers. Transition from manual to automated control is similar to engaging cruise control on today's automobiles or autopilot systems on sea faring vessels and jet aircraft. A driver request for transfer to automated control is accepted and executed by the AHS vehicle subsystems after verification by the system that operational control conditions are satisfied; e.g. sensors functional, road surface conditions adequate, vehicle control systems operational. System design and transfer of control analyses may dictate the implementation of "transfer of control" zones: designated areas of the highway where topography or additional sensors provide for optimal control transition.

Architecture variations will be evaluated to support technical feasibility and deployment evaluations. Other configurations of control include communication between other automated vehicles and/or roadside equipment to facilitate automated entry, exit, merge, or emergency maneuvers.

Vehicle Separation Policy

Individual vehicle separation distance is maintained for each of the automated vehicles dependent on their sensing, control, and braking capability (a function of speed and surface friction).

Vehicle Separation Policy variations may include:

1) Driver selection of speed and separation distance from a predetermined menu (similar to some current designs of Adaptive Cruise Control).
2) A platoon policy, supported by communication between automated vehicles, both those preceding and those following.
3) Cooperatively spaced vehicles (a variant between the platoon and individual vehicle separation policies), potentially using vehicle to vehicle communications.

Deployment Strategy

Once technically, institutionally, and economically feasible, AHS equipped vehicles could be marketed as an option on higher-cost vehicles. As production costs fall with increasing volume, experience and advancing technology, the market penetration would envelope the moderate and lower price automobiles. Infrastructure improvements would be planned to accommodate the regional use needs.

Alternative deployment strategies will explore how intermediate systems can spur the development of incremental systems leading to full driver-disengaged mixed traffic AHS.

Environment

Route guidance and other ITS services may be integrated into the AHS system; however, the AHS is not dependent on these services. The mixed traffic operating mode may be implemented in any geographic environment (rural, inter urban, urban, mountains, plains).

Manual driver behavior associated with heavy traffic volume and inclement weather conditions may prove to be unsuitable operating environments for automated vehicle control. In these stressing operating environments, the driver of an AHS equipped vehicle may benefit from the partial automation features of AHS (lane keeping, obstacle detection, and adaptive cruise control).

Operations and Maintenance

Operations and maintenance in a mixed traffic environment will be very similar to that of a dedicated AHS environment for monitoring and information dissemination. The system will provide status, speed limit and access information, but will initiate limited direct vehicle control. Maintenance will be required for the electronic infrastructure as well as the roadways. Vehicle maintenance will remain the responsibility of the vehicle owner.

Automated Highway System Functional Decomposition

Version 2
DRAFT
March 1997

Jerome F. Sobetski
for the AHS Architecture Development Team

Preface

The AHS Functional Decomposition is a work in-process. This initial draft was prepared primarily during the period of January, 1997 through March, 1997. It is based on the previous work of the consortium (inclusive of tasks B1, C1 and C2), the AHS Precursor Studies, and incorporates new work in consonance with both the Dedicated Lane and Mixed Traffic (automated vehicles sharing the lane with manually driven vehicles) operating modes described in the AHS Operations Concept (see separate document, latest draft annotated as version 2, March 28, 1997). This document facilitates the development of the logical / physical architecture for an Automated Highway System.

Introduction

The Functional Decomposition for the Automated Highway System is being developed to support both the derivation of performance requirements and the design of the logical / physical architecture. A thorough and well structured model will facilitate completeness, work organization and efficiency of the detailed architecture development. The modeling technique applied is to develop a hierarchical model, wherein each function and the interfaces between the functions are described.

The functional decomposition defines four major internal functions and recognizes interfaces to external elements, including the driver and regional Transportation Management System. The internal functions are decomposed two to three levels, as deemed appropriate to the complexity and likely physical allocation of each specific function. The interfaces between the functions are assigned unique names and are also described. The four primary functions are:

1) Initiate Automated Operation
2) Disengage Automated Operation
3) Moving Under AHS Control
4) Managing the AHS.

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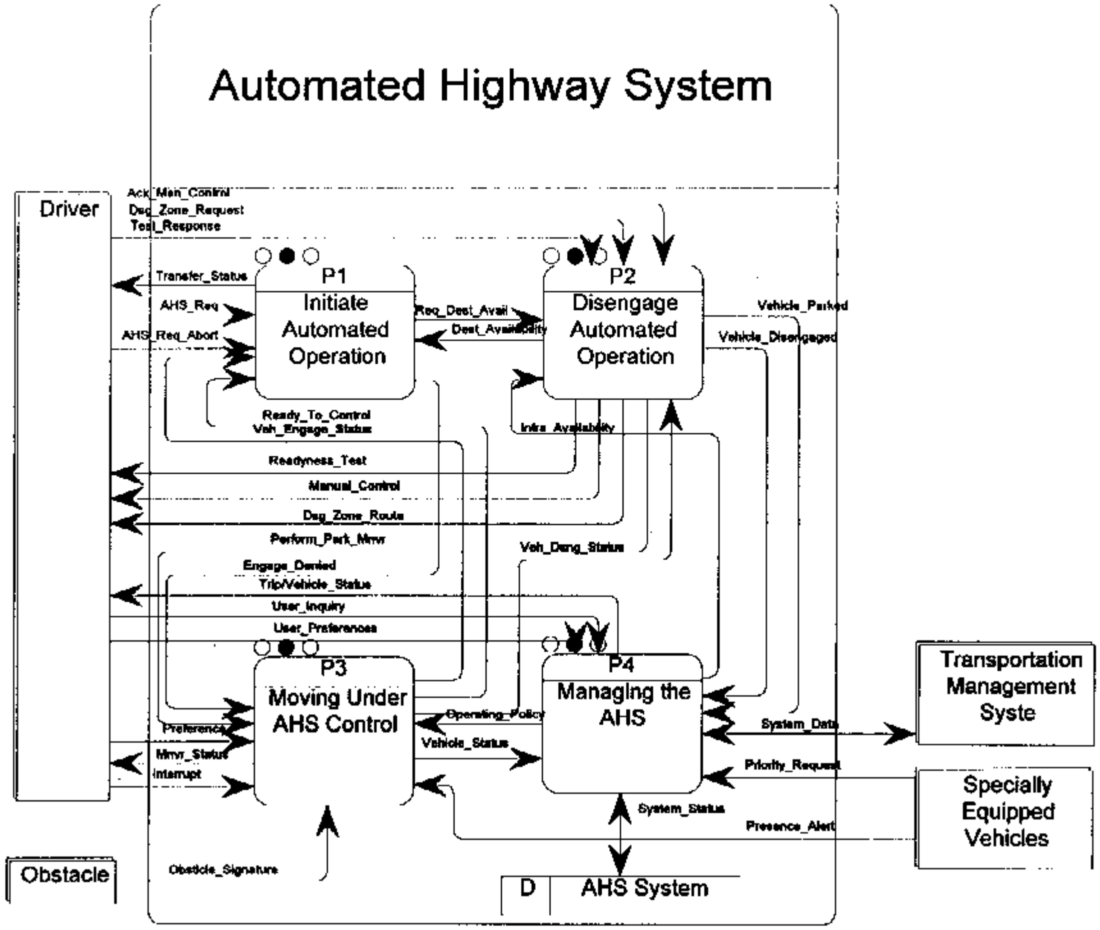
0. TOP LEVEL DIAGRAM



0.1. Driver Interface

- Driver starts a trip with a destination in mind where AHS can facilitate the trip
- Driver drives vehicle to an AHS engage zone
- AHS drives vehicle from engage zone to selected disengage zone
- Driver can change route and disengage zone during the trip
- As vehicle approaches disengage zone driver is notified and prompted to validate cognizance
- If driver demonstrates ability to control vehicle, AHS returns manual control.

Driver Interfaces	**Included messages**	**From**	**To**
Driver		1.x	Driver
Transfer_Status	Transfer Status	1.x	Driver
Dsg_Zone_Route	Display of trip route and destination	2.6	Driver
Manual_Control	Display indicating automated control not engaged	2.4	Driver
Readiness_Test	Interactive display for determining if driver is alert and ready	2.3	Driver
Mnvr_Status	Maneuver Status	3.x	Driver
Trip/Vehicle_Status	Obstacle Data Traveler & Freight Info Emergency Incident Data AHS Data/Data Requests Construction & Maintenance Info and Requests	4.x	Driver
AHS_Req_Abort	AHS Request Abort	Driver	1.1
AHS_Req	Request to initiate automated operations of vehicle AHS disengage zone (destination)	Driver	1.1
Ack_Man_Control	Acknowledge Manual Control	Driver	2.4
Dsg__Zone_Request	Disengage Zone Request	Driver	2.6
Test_Response	Test Response	Driver	2.3
Interrupt	Driver Interrupt	Driver	3.x
User_Preference	Driver Preference	Driver	4.x
User_Inquiry	User inquiries	Driver	4.x

0.2. Traffic Management System Interface

A significant role of the Automated Highway System (AHS) will be to provide an information interchange with other Traffic Management Systems (TMS). These "external" systems will consist of jurisdictional traffic operations or management centers (TOC/TMC), Advanced Traveler Information Systems (ATIS), as well as local radio, TV, law enforcement, and emergency services. In this manner, coordinated regional traffic management plans will be developed between the operating agencies. External agencies will supply information that will be important to the daily operations and planning of the AHS. A combination of these external systems and the AHS capabilities will keep the traveling public informed regarding the status of the AHS.

Examples of information provided by external sources are:

- Weather data.
- Planned traffic events (i.e. sporting events, parades, holidays).
- Emergency situations (fire, hurricane, flood)

Examples of data provided to external agencies are:

- AHS system and roadway status
- Entry and exit information
- AHS system configuration (Roadmap)
- Maintenance activities on the roadway
- Emergency activities on the roadway
- Traffic flow data

AHS Database

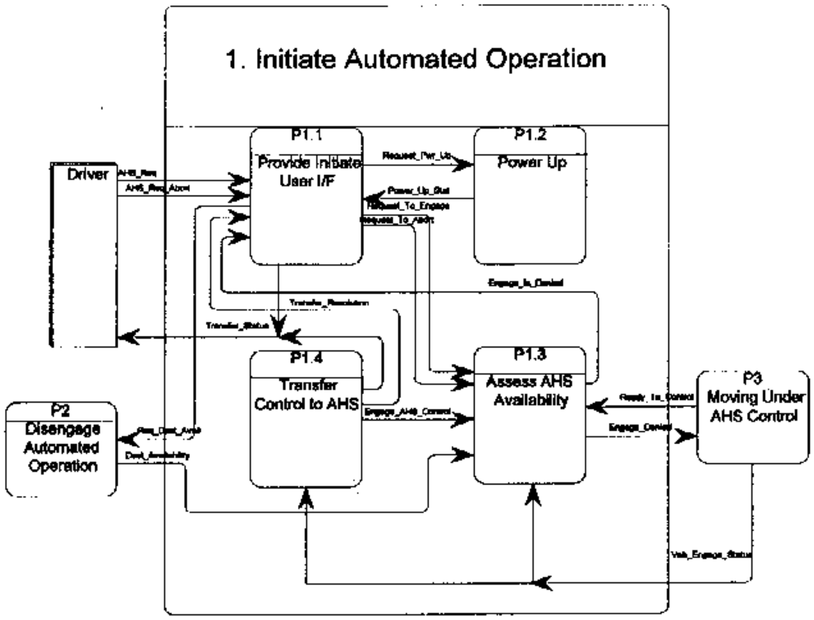
Input Signal	Included messages	From	To
Vehicle_Status_Data	From each power supply an indication it is working properly From each subsystem an indication it is on and operating properly From each software component an indication it has initiated correctly From each subsystem an indication cyclic diagnostics have detected no problems	All sub-systems	1.x
	Absence Data Non AHS Roadway Data Traveler & Freight Information Emergency Incident Data AHS Data/Data Requests Construction & Maintenance Information & Requests Weather Forecast Operating Parameters	TMS	P4.x
System Data	Weather	TMC/ Internal	4.x
	Planned traffic events	TMC/ Internal	4.x
	Surface conditions	TMC/ Internal	4.x
System Data	Traffic Information	TMC/ Internal	4.x
System Data	Traffic Data	Internal	4.x
System Data	Traffic Information	Various System Sources	4.x
System Data	Location	Various System Sources	4.x
System Data	Resource Availability/Unavailability	TMS / Internal	4.x
	Deterioration report	External	4.x
	Deterioration report	IDV	4.x
	External alert	External TMS/ Weather	4.x
	Incident response report	response teams	4.x
	Damage assessment	response teams	4.x
	Incident response time goals	Internal/ External	4.x
	Planned Roadway Expansion	FDOT	4.x
	Planned disengage zone / Entrance change	FDOT /DOT	4.x
	Technology advancements	External	4.x
	System software improvements	Internal	4.x
	Computer functionality requests	Internal/ External	4.x

1. INITIATE AUTOMATED OPERATION

This function takes vehicles not under automated control, and transitions them to automated control at the request of the driver, when the vehicle is at an AHS roadway and at a location where initiation of automated operations is permitted.

It comprises four sub-functions:

1.1 Provide "Initiate" User Interface
1.2 Power Up
1.3 Assess AHS Availability
1.4 Transfer Control



Input Signal	Included messages	From	To
AHS_Req	AHS Request	Driver	1.1
AHS_Req_About	AHS Request Abort	Driver	1.1
Ready_to_Control	Ready to automatically control vehicle, yes or no	3.x	1.3
Veh_Engage_Status	Health and Working Order of AHS Equipment	3.x	1.3 & 1.4

Output Signal	Included messages	From	To
Transfer_Status	See Section 1.1	1.1	Driver
Req_Dest_Available	See Section 1.3	1.1	2.x

1.1. Provide "Initiate" User Interface

SUMMARY: This function provides and manages the interface to the driver for the other Initiate Automated Operations functions. (Note: Driver specifies destination in function 2.6.)

DESCRIPTION: This function shall ensure vehicle readiness:

- Generate a "Request Power Up" to the vehicle subsystem.
- Based on the "Power Up Status" message, generate and display a message to the driver.
- Receive an "AHS Request" from the driver to initiate automated operations, or, (for dedicated lane operations only) detect that the vehicle has entered the entry station and has reached the location within the entry station where transfer to automated operations must occur.
- Generate a "Request to Engage" message.
- Receive from the driver an "AHS Request Abort" requesting that initiation of automated operations be aborted.
- Based on receipt of "Engage Automated Operations Denied," display to the driver notification that automated operations could not be initiated and the reason why. Generate, for dedicated lane operations only, instructions to the driver on how to manually exit this entry station.
- Based on receipt of "Transfer Resolution" indicating a successful transfer to automated operations, display to the driver notification that transfer to automated operations was completed.
- Based on receipt of "Transfer Resolution" indicating that the transfer to automated operations was not successful and was aborted, display to the driver that transfer to automated operations was aborted, the reason why, and instructions on how to regain manual control of the vehicle, and, for dedicated lane operations only, generate and display instructions on how to manually exit this entry station.

Input Signal	**Included messages**	**From**	**To**
Power_Up_Stat	From each vehicle power supply an indication it is working properly From each vehicle subsystem an indication it is on and operating From each vehicle software component an indication it has initiated correctly From each vehicle subsystem an indication cyclic diagnostics have detected no problems	1.2	1.1
Engage_Denied	Automated operations cannot be initiated Reason why automated operations cannot be initiated	1.3	3.x
Engage_Is_Denied	Automated operations cannot be initiated Reason why automated operations cannot be initiated	1.3	1.1
Transfer_Resolution	Transfer of vehicle to automated operations was successful, or Transfer to automated operations was aborted -Reason why transfer to automated operations was aborted -Instructions to the driver on how to regain manual control of the vehicle	1.4	1.1
AHS_Req	Request to initiate automated operations of vehicle AHS disengage zone (destination)	Driver	1.1
AHS_Req_Abort	About request to transfer to automated operations (before transfer has completed)	Driver	1.1

Output Signal	Included messages	From	To
Request_Pwr_Up	See Section 1.2	1.1	1.2
Request_to_Engage	See Section 1.3	1.1	1.3
Request_to_Abort	See Section 1.3	1.1	1.3
Req_Dest_Avail	Request destination availability	1.1	2.x
Transfer_Status	Notification that power up or initiation failed Notification that cyclic diagnostics detected a failure Notification that automated operations could not be engaged Reason why automated operations could not be engaged Notification that transfer to automated operations is completed Notification that transfer to automated operations was aborted Reason why transfer to automated operations was aborted Instructions to the driver on how to regain manual control of the vehicle Instructions to the driver on how to leave this entry station (dedicated lane operations only)	1.1	Driver

1.2. Power Up

SUMMARY: This function will cause all components of the vehicle AHS subsystem to power up, to initialize their software, and to run any cyclic diagnostics. The function then collects status from each of these components and collects status on any detected failures.

DESCRIPTION: This function shall:

- Based on the "Request Power Up", generate a signal to all vehicle power supplies to turn on, and generate a signal to all vehicle subsystems to initiate operations and to begin cyclic diagnostics.
- Receive status information from all vehicle subsystems and in the event of notification of any failures which would inhibit automated operations,
- Generate the "Power Up Status" message.

Input Signal	Included messages	From	To
Request_Pwr_Up	Request to turn on power to all vehicle subsystems, to initiate software components, and to initiate cyclic diagnostics	1.1	1.2
Vehicle_Status_Data	From each power supply an indication it is working properly From each subsystem an indication it is on and operating properly From each software component an indication it has initiated correctly From each subsystem an indication cyclic diagnostics have detected no problems	All sub-systems	1.2

Output Signal	Included messages	From	To
Power_Up_Stat	See 1.1	1.2	1.1

1.3. Assess AHS Availability

NOTE: There is not an output from 1.3 to 1.1 to notify the driver that "yes, automated operations are engaging." Rather, the message is sent from 1.4 that "yes, automated operations engaged".

SUMMARY: Function 1.3 decides whether or not to engage AHS once such an engagement has been requested. It receives the request to engage, processes it, and either engages 1.4 Transfer of Control, or sends a message to 1.1 explaining why not.

DESCRIPTION: Once invoked by 1.1, continuously assess the availability to engage. Availability requires that:

- 3.x indicates it is ready to control. (This implies that 3.x: does not detect any precluding anomalies; assesses the vehicle as in proper working order; sees the vehicle is in the proper infrastructure environment to engage AHS and that conditions allow automated operations; and recognizes a safe traffic pattern to engage into.)
- 2.x indicates that it has an acceptable disengage zone. (Note, this means that 2.x has an acceptable route to the disengage zone, and thus has confirmed that the route conforms to function 4.x constraints.)
- 1.3 determines that any required, entry peculiar immediate environment is available.
- For each, possible states include not yet assessed ("Working"), available ("Yes"), and not available--rejected ("No"). Some concerns may also admit a state of not available--momentarily ("No" with temporary reasons appended).
- If 2.x gives a "No," or 3.x gives a "No" with a reason that means engagement is rejected, then 1.1 is notified that AHS is not available, along with the reason why. For 2.x, the most likely reason would be that particular needed road elements are not available, and why.
- On receipt of the request to engage, if all the components are available, then 1.4 is engaged. If any component is "Working," or "Not Available Momentarily," then 1.3 waits. Certain TBD conditions after 1.3 has been waiting would cause 1.3 to declare "not available-rejected." 1.1 would be notified of this failure and its reason. Such conditions include a time-out after waiting too long, and the vehicle not being accepted on a dedicated ramp before reaching its last chance to abort. Other design-specific conditions, depending on proper human factors in the driver interface, may be added.

Input Signal	Included messages	From	To
Request_to_Engage	Desire to Engage, Yes	1.1	1.3
Request_to_Abort	Desire to Engage, No	1.1	1.3
Dest_Availability	Yes Working Not Available Momentarily and Reason(s) No and Reason(s)	2.x	1.3
Ready_to_Control	Safe Solution, Ready to Engage, Yes Safe Solution, Ready to Engage, Working Safe Solution, Ready to Engage, Not Available Momentarily and Reason(s) Safe Solution, Ready to Engage, No plus Reason(s)	3.x	1.3
Veh_Engage_Status	Health and working order of AHS equipment (including devices for transitioning to automated control)	3.x	1.3

Output Signal	Included messages	From	To
Engage_is_denied	See Section 2.x	1.3	1.1
Req_Dest_Avail	See Section 2.x	1.3	1.1
Engage_AHS_Control	See Section 1.4	1.3	1.4
Engage_Denied	See Section 1.1	1.3	3.x

1.4. Transfer Control

SUMMARY: Vehicles should begin 1.4 with all ordinary automated subsystems except physical actuators fully engaged, and in a situation where automated control can immediately take over. The function 1)enables the automated actuators while disabling manual control, 2)monitors for correct transfer, and 3)notifies both 1.1 Provide "Initiate" User Interface, and 3.x Moving Under Automated Control (micro), when the transition is complete. 1.4 also aborts transfer and notifies 1.1 when transfer fails.

DESCRIPTION: This function will perform operations as follows;

- The first action is to confirm from 3.x that the physical status of the vehicle supports immediate AHS engagement, and on approval, command the actuators to assume the state of being responsive to control signals generated by 3.x.. Details depend on the control device designs, and appropriate human factors.
    - If an error is detected in the transfer of actuation, 1.4 aborts the process, executing a series of actions to the actuators, appropriate to the state of the vehicle, to return the vehicle to complete manual control. A message is sent to 3.x and 1.4 indicating abort status.
    - Upon successful transfer of control, 1.4 concludes by sending a message to 3.x that changeover is complete, and sending a second message to 1.1 that the vehicle has completed transfer to automated operations.

Input Signal	**Included messages**	**From**	**To**
Veh_Engage_Status	Health and working order of devices for transitioning to automated control Effective Controller State of actuators	3.0	1.4

Output Signal	**Included messages**	**From**	**To**
Engage_AHS_Control	Command to Engage Automated Control	1.4	1.3
Transfer_Resolution	Transfer to Automated Operations Automated Operations Abort and reason(s)	1.4	1.1

2. DISENGAGE AUTOMATED OPERATION

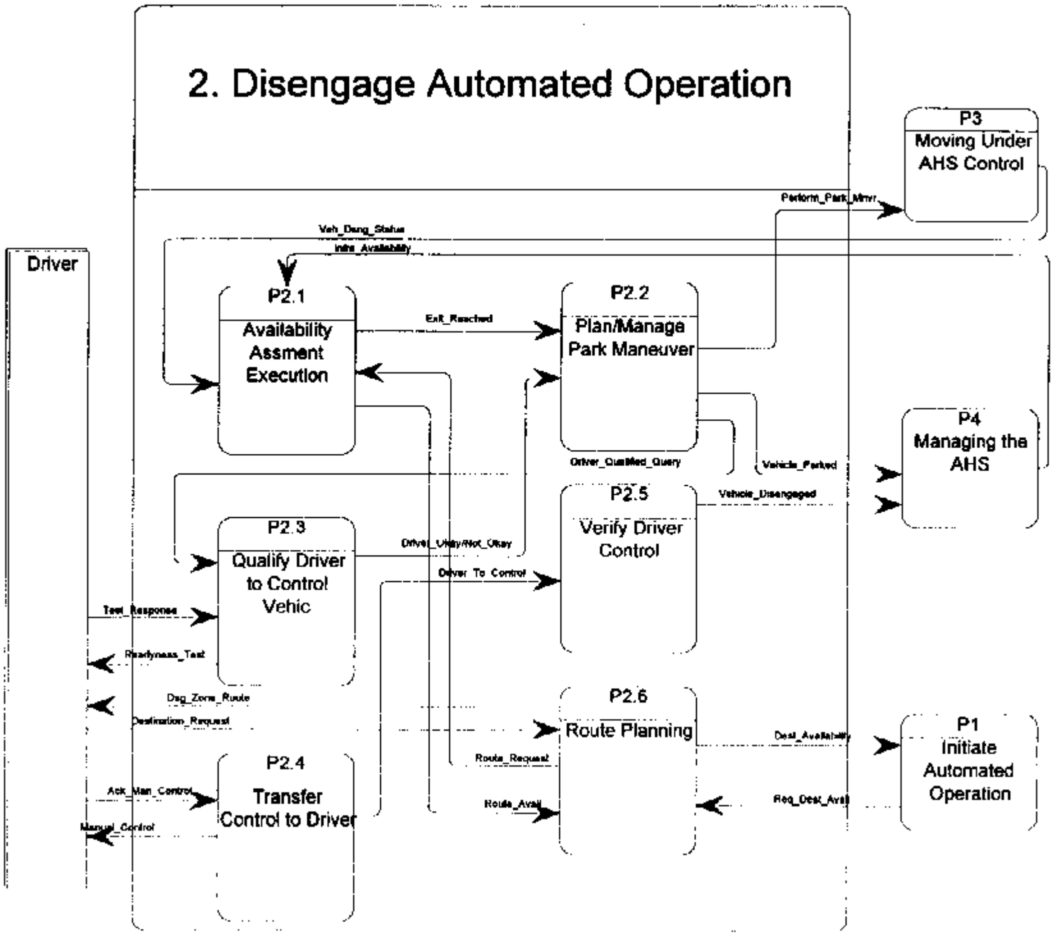
The AHS provides the capability to disengage automated operation, transfer vehicle control from automated to manual, maneuver exiting vehicles and safely park vehicles (when disengage automated criteria are not met).

The scenario associated with disengage automated operation starts with a dialog between the driver and the AHS system that continues until a desired and available disengage zone is agreed upon. The vehicle will proceed on AHS until it reaches the agreed upon location.

When the vehicle approaches the disengage zone the system alerts the driver and determines if he is ready to take over control of the vehicle. When the driver is alert and responsive he will drive off of the AHS. When the driver is not ready to take over the vehicle the system drives the vehicle to a park facility and dispatches driver aid.

The major sub-functions of this section are;

- 2.1 - Availability Assessment Execution
- 2.2 - Plan / Manage Park Maneuver
- 2.3 - Qualify Driver to Control Vehicle
- 2.4 - Transfer Control to Driver
- 2.5 - Verify Driver Control
- 2.6 - Route Planning



Input Signal	Included messages	From	To
Ack_Man_Ctrl	Acknowledge Manual Control	Driver	2.4
Dsg_Zone_Req	Disengage zone Request	Driver	2.6
Test_Respnse	Test Response	Driver	2.3
Req_Dest_Avail	Request disengage zone Availability	1.x	2.6
Veh_Dsng_Status	Vehicle Status	3.x	2.1
Infra_Availability	Infrastructure Availability	4.x	2.1

Output Signal	Included messages	From	To
Dsg_Zone_Route		2.6	Driver
Manual_Control		2.4	Driver
Readiness_Test		2.3	Driver
Dest_Availability	Yes disengage zone is available Working on disengage zone availability Not Available Momentarily and Reason(s) No and Reason(s)	2.6	P1.x
Perform_Park_Mnvr	Perform the park maneuver	2.2	3.x
Route_Vehicle	Route Vehicle	2.1	3.x
Vehicle_Parked	Vehicle has been parked and needs emergency attention Location Vehicle has been parked Driver emergency alert	2.2	4.x
Vehicle_Disengage		2.5	4.x

2.1. Availability Assessment Execution

SUMMARY: Availability Assessment Execution provides for processing of vehicle routing to assure that the disengage zone and all roadway segments between current location (or origin) and the disengage zone are available. This includes checking for current highway conditions.

DESCRIPTION:

- Prior to allowing a vehicle to disengage automated operation, the AHS verifies the condition and availability of the requested disengage zone.
- Verify vehicle disengage zone criteria includes vehicle capability (i.e., enough fuel) to make it to the disengage zone.
- Verify vehicle disengage zone criteria includes vehicle capability (i.e. has enough fuel) to make it to a parking facility if the driver is not available to resume vehicle control at selected disengage zone.
- If primary disengage zone not available, AHS determines if there is an alternative disengage zone which is:
    - within an acceptable distance of the requested disengage zone
    - operational
    - connected to the requested disengage zone by an operational AHS lane
    - within the vehicle's reach
- The AHS will notify the driver prior to arrival at the selected disengage zone.
- If the driver's requested disengage zone becomes unavailable, (at the time that the vehicle is predicted to arrive at the requested disengage zone) the AHS informs the driver that the requested disengage zone is no longer available and displays alternatives.
- If all disengage zone criteria are not met, the AHS denies the vehicle disengage zone request. If the vehicle state is not within acceptable limits for a safe disengage zone, the AHS routes the vehicle to the next available safe disengage zone, and notifies the driver what that disengage zone is.
- If all disengage zone criteria are not met, the AHS denies the vehicle disengage zone request. If the requested disengage zone condition is not acceptable or the requested disengage zone is not available, the AHS has the capability to route the vehicle to the next available disengage zone and identify the disengage zone to the driver.

Input Signal	**Included messages**	**From**	**To**
Vch_Dsng_Status	Vehicle Status	3.x	2.1
Infra_Availability	Infrastructure Availability	4.x	2.1
Route_Request	Route Information	2.6	2.1

Output Signal	**Included messages**	**From**	**To**
Route_Avail	See Section 2.6	2.1	2.6
Exit_Reached	See Section 2.2	2.1	2.2

2.2. Plan/Manage Park Maneuver

SUMMARY: Plan/Manage Park Maneuver provides processing necessary to direct the vehicle to a safe stopping place after it has been determined that the driver is not available to safely assume control of the vehicle.

DESCRIPTION:

- Requests the parking of the vehicle (executed by 3.x)
- Permits qualified driver (2.3) to resume manual control.
- When there is degradation of vehicle performance this task will reassess disengage zone to determine the best way to disengage if required.

Input Signal	**Included messages**	**From**	**To**
Driver_Okay/Not_Okay	Driver has been tested and is ready to assume control of vehicle	2.3	2.2
Exit_Reached	The vehicle is approaching the disengage zone - start disengage process	2.1	2.2

Output Signal	**Included messages**	**From**	**To**
Perform_Park_Mnvr	Perform the park maneuver	2.2	3.x
Vehicle_Parked	Vehicle has been parked and needs emergency attention Location Vehicle has been parked Driver emergency alert	2.2	4.x
Driver_Qualified_Query	Driver is or is not qualified	2.2	2.3

2.3. Qualify Driver to Control Vehicle

SUMMARY: Qualify Driver to Control Vehicle provides processing to interact with the driver and assure driver is available to safely assume control of the vehicle.

DESCRIPTION:

- Verify the capacity and readiness of the driver to resume manual control of the vehicle.

Input Signal	**Included messages**	**From**	**To**
Test_Resp	Test Response	Driver	2.3
Driver_Qualified_Query	Interaction with driver to verify driver is alert and ready to drive	2.2	2.3

Output Signal	**Included messages**	**From**	**To**
Readiness_Test		2.3	Driver
Driver_Okay/Not_Okay		2.3	2.2

2.4. Transfer Control to Driver

SUMMARY: Transfer control to Driver provides processing to interact between the driver and automated control of the vehicle to assure smooth transition at disengage zone between vehicle AHS operation and control of the vehicle by the driver.

DESCRIPTION:

- Notify the driver to take control as vehicle reaches the disengage zone
- Relinquish automated control system (manual control enabled to override automated control functions)
- Validate Automated to Manual Control Transfer

Input Signal	**Included messages**	**From**	**To**
Ack_Man_Control	Acknowledge Manual Control	Driver	2.4

Output Signal	**Included messages**	**From**	**To**
Manual_Control	Driver in control	2.4	Driver
Driver_To_Control	Driver to control	2.4	2.5

2.5. Verify Driver Control

SUMMARY: Verify Driver Control provides processing to analyze driver performance (derived from information available through sensors). Reaction is situation and implementation dependent.

DESCRIPTION:

- The AHS validates transfer of vehicle control from automated to manual.

Input Signal	Included messages	From	To
Driver_To_Control		2.4	2.5

Output Signal	Included messages	From	To
Vehicle_Disengaged		2.5	4.x

2.6. Route Planning

SUMMARY: Route Planning provides processing to interact with the driver and determine the disengage zone for the trip.

DESCRIPTION:

- Work with the driver and 4.x - Managing the AHS to develop a route.
- Consider engage location, route options, disengage zone accessibility, and traffic conditions.
- When the driver does not help plan the route, a default route will be selected by this task.
- The AHS provides the capability for the driver to select a disengage zone.
- The AHS notifies the driver of the assigned disengage zone.

Input Signal	Included messages	From	To
Destination_Request	Disengage zone request	Driver	2.6
Rq_dest_Avail	Request disengage zone availability	1.x	2.6
Route_Avail	Query to determine if the potential route is available	2.1	2.6

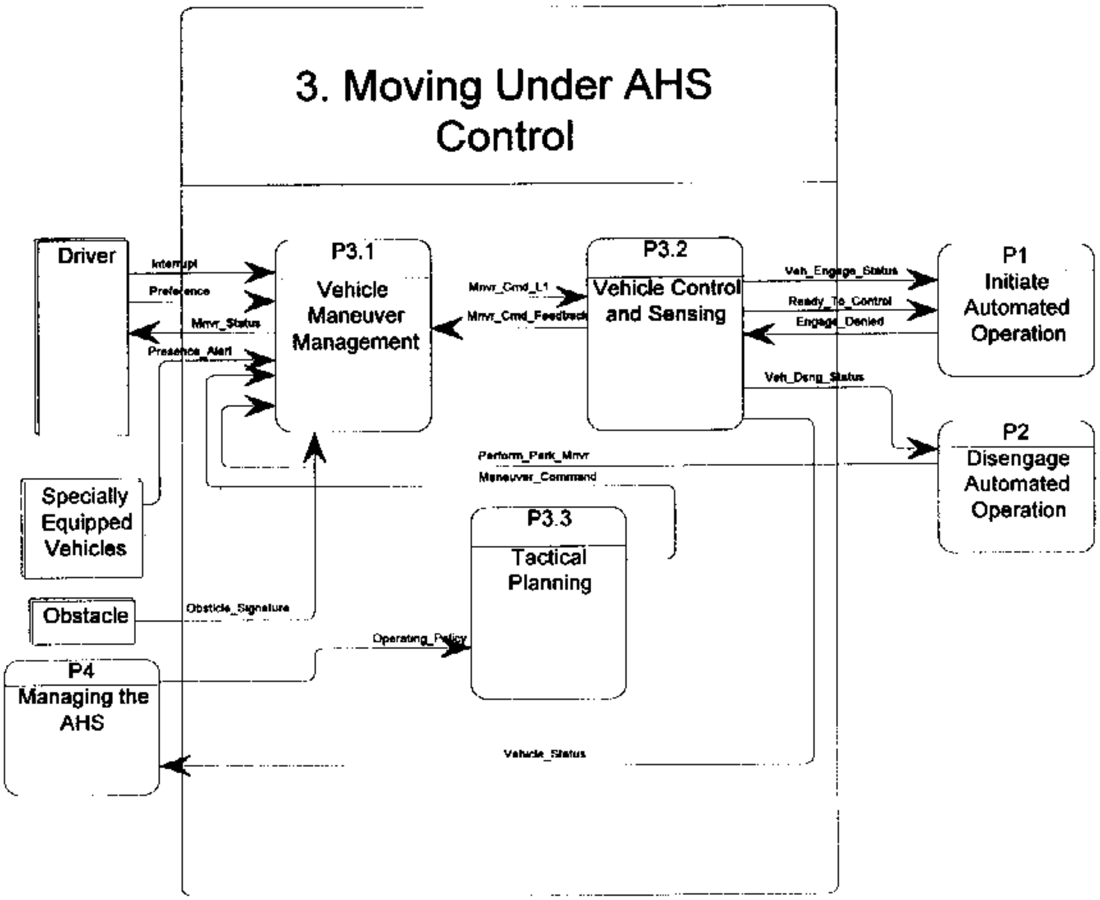
Output Signal	Included messages	From	To
Dsg_Zone_Route	Destination Route	2.6	Driver
Dest_Availability	Yes disengage zone is available Working on disengage zone availability Not Available Momentarily and Reason(s) No and Reason(s)	2.6	1.x
Route_Request	Route Request	2.6	2.1

3. MOVING UNDER AHS CONTROL

This function encompasses all vehicle control sub-functions that move vehicles under full automation along a designated lane or lanes. The scope of this function is defined by the "micro" or tactical movements of any vehicle or group of vehicles traveling on the AHS, from the point that control is transferred from the driver (Function P1) through the point that control is relinquished back to the driver (Function P2). This function does not include the "macro" or strategic highway link or network traffic management strategies (Function 4.x) that affect "moving under AHS control", although these strategies or policies are locally implemented in this function.

There is a set of hierarchical "executive-supervisor-worker" roles which delineate the three sub-functions of 3. In this hierarchy, the Tactical Planning (3.3) function serves as the local decision maker, or executive, and calls upon the menu of maneuvers contained in the Vehicle Maneuver Management (3.1), or supervisor, function, which in turn calls upon Vehicle Control Execution (3.2), or worker, sub-function to enact the actual vehicle controls, communication and self- and external-sensing devices to move the vehicle. All the further decomposed sub-functions described herein fit into this decision flow model.

The sub-functions of this section are;
- 3.1 - Vehicle Maneuver Management
- 3.2 - Vehicle Control Execution
- 3.3 - Tactical Planning



Input Signal	Included messages	From	To
Interrupt	Driver Interrupt	Driver	3.x
Preference	Driver Preference	Driver	3.x
Engage_Enable	Engage Enable	1.x	3.x
Transfer_Cntl	Transfer Control	1.x	3.x
Perform_Park_Mnvr	Perform the park maneuver	2.2	3.x
Route_Vehicle	Route Vehicle	2.x	3.x
Operating_Policy	Operating Policy - speed, class, lane usage	4.x	3.x

Output Signal	Included messages	From	To
Mnvr_Stat		3.2	Driver
Vehicle_Engage_Status		3.1	1.x
Ready_To_Control		3.2	1.x
Engage_Denied		3.2	1.x
Veh_Dsng_Status		3.2	2.x
Degraded_Performance	Indication of need to disengage vehicle for a vehicle system problem	3.2	2.2
Operating_Policy		3.2	4.x

3.1. Vehicle Maneuver Management

This function directs, monitors and supervises local vehicle movements, based on commands from the Tactical Planning (3.3) function and feedback from the Vehicle Control Execution (3.2) function.

Input Signal	**Included messages**	**From**	**To**
Maneuver_Command	Perform Specific Maneuver	3.3	3.1
Mnvr_Cmd_Feedback	Feedback from Lower Level Controllers and In-Vehicle State	3.2	3.1
Perform_Park_Mnvr	Perform the Park Maneuver	2.2	3.1.5
Presence_Alert	Notification that an emergency vehicle is in the area	Sp Vch	3.1
Obstacle_Signature	Signature of obsticle	Obstacle	3.1
Preference	Driver's preferences	Driver	3.1
Interrupt	Override the Maneuver	Driver	3.1.5

Output Signal	**Included messages**	**From**	**To**
Mnvr_Cmd_Ll	Command Lower Level Controllers	3.1	3.2
Mnvr_Status	Status of Maneuver	3.1	Driver

3.1.1. Merge

SUMMARY: This sub-function governs the automated joining of two flows of traffic at a fixed point on the highway, such as at the intersection of on-ramp traffic onto the main line or the flow through a highway-to-highway interchange.

DESCRIPTION: This sub-function is a coordinated maneuver invoked by 3.3.1, and it consists of the following operations :

- Accept transfer of control. This operation accepts automated vehicles from 1.3. It supervises communication of vehicle and local traffic condition, and places automated vehicles onto the merge ramp or ramp queue.
- Detect gaps. The "detection" process can be AHS sensors (in a purely autonomous case), vehicle communications, or likely, some combination of the two.
- Negotiate gaps. Communication is required to determine which vehicles are to accelerate and decelerate, by how much and for how long. Communication is also required to ensure that only one vehicle move in per designated safe space.
- Align gaps. In this step, communication is supplemented by sensing to verify that gaps exist.
- Determine merge trajectory. This step calculates the lane-to-lane routing, speed, and acceleration profiles necessary to complete the merge within ramp constraints. (Ramp constraints include standard highway topography constraints, in addition to the possibility of on-ramp metering of automated vehicles.)
- Move in. This step invokes 3.2 to execute the merge. Continuous feedback is received from process input information, and adjustments to the "determine merge trajectory" and "move in" functions can be made.
- Close gap. This final step adjusts the gap to eliminate any "excess" space over the minimum safety distance *if* the AHS operating policy and local traffic conditions require this.
- Process input information. Higher level processing and monitoring of these inputs is performed to carry out the elemental merge functions described above, particularly in determining and supervising the merge trajectory.
    - Vehicle self state (from 3.2.4) - to determine values for own-vehicle acceleration, velocity and yaw.
    - State of neighboring vehicles (from 3.2.5) - to determine target values for neighboring-vehicle acceleration and velocity.

3.1.2. Demerge

SUMMARY: This sub-function governs the automated separation of a single lane of traffic into two separate flows of traffic at a fixed point on the highway, such as at an off-ramp.

DESCRIPTION: This sub-function is a coordinated maneuver and is invoked by 3.3.1, and it consists of the operations defined below:

- Detect distance to demerge location . The "detection" process can be either sensor-based (in a purely autonomous case), communications-based, or likely, some combination of the two. This distance and the companion vehicle speed information from "process input information" provides the time constraint for all subsequent movements to be conducted.
- Negotiate additional near-vehicle separation distance, if any, required for the demerge to be safety executed (requires processing of input information, particularly adherence to "macro" policy or emergency constraints). Communication is required to determine which vehicles are to change speed , by how much and for how long.
- Detect spacing/gaps in demerge lane (requires processing of input information, described in the last bullet of this function). The "detection" process can be either sensor-based (in a purely autonomous case), communications-based, or likely, some combination of the two.
- Negotiate gaps in demerge lane (requires processing of input information, particularly adherence to "macro" policy or emergency constraints). Communication is required to determine which vehicle(s) are to accelerate and decelerate, by how much and for how long.
- Align gaps. In this step, communication is supplemented by sensing to verify that gaps exist.
- Determine demerge trajectory. This step calculates the lane-to-lane routing.
- Move in. This step invokes 3.2 to execute the merge. Continuous feedback is received from process input information, and adjustments made as required.
- Close gap. This final step adjusts the gap to eliminate the newly created empty space, as allowed by the AHS operating policy and local traffic conditions.
- Process input information. Higher level processing and monitoring of vehicle status is performed to carry out the elemental demerge functions described above, particularly in determining and supervising the demerge trajectory.
    - * Vehicle self state (from 3.2.4) - to determine values for own-vehicle acceleration, velocity and yaw.
    - * State of neighboring vehicles (from 3.2.5) - to determine target values for neighboring-vehicle acceleration and velocity.

3.1.3. Lane Change

SUMMARY: This sub-function conducts vehicle travel between lanes which does not fall into the merge or demerge categories. In this function, the lane change may occur at any time or as a precursor to disengage (e.g., "weave"). The motivation behind this maneuver is to allow lateral movements needed for local implementation of a strategic (i.e., commanded from a TMS) lane balancing or flow management tactic or strategy. For example, this function addresses the lateral component of any sorting (by destination or class).

DESCRIPTION: This sub-function is a coordinated maneuver and is invoked by 3.3.1, and it consists of the operations defined below:

- Detect gaps. The "detection" process can be either sensor based (in a purely autonomous case), communications-based, or likely, some combination of the two.
- Negotiate gaps. Communication is required to determine which merge vehicles are to change speed , by how much and for how long. Communication is also required to ensure that only one vehicle move in per designated safe space.
- Align gaps. In this step, communication is supplemented by sensing to verify that gaps exist.
- Determine lane change trajectory. This operation calculates the lane-to-lane routing, and speed and acceleration profiles necessary to complete the lane change within any traffic flow, density, or safety constraints. As an extreme case, with only one car in a highway link, the entire link length could plausibly be used to complete the lane change; alternately, with nearly full AHS capacity, this lane change would occur rather quickly within safety constraints to minimize any disruptions to the traffic flow. It is important to note that if multiple trajectories are planned, as in the application of a sort-by-lane policy, lane change trajectories will also be time constrained.
- Move in. This step invokes 3.2 to execute the lane change. Continuous feedback is received from process input information, and adjustments made as required.
- Close gap. This final step adjusts the gap to eliminate the newly created empty space, as allowed by the AHS operating policy and local traffic conditions.
- Process input information. Higher level processing and monitoring of these inputs is performed to carry out the elemental lane change functions described above, particularly in determining and supervising the lane change trajectory.
    - Vehicle self state (from 3.2.4) - to determine values for own-vehicle acceleration, velocity and yaw.
    - State of neighboring vehicles (from 3.2.5) - to determine target values for neighboring-vehicle speed changes.

3.1.4. In-Lane Travel

SUMMARY: This sub-function consists of operations conducting "normal" (i.e., non-contingency) travel within a lane. Lane keeping, vehicle separation and speeds are managed within this function. This function also addresses the longitudinal component of any sorting (by destination or class). This would include the platoon-specific functions of splitting and joining.[1] Finally, any implementation of a mixed traffic "zone of control transfer", where the manual-to-automated control is executed in-lane as part of function 1.x, is handed off in this function.

DESCRIPTION: As with other 3.1 sub-functions, this sub-function is a coordinated maneuver and is invoked by 3.3.1. The degree of coordination in this function is highly dependent on prevailing traffic and on design-specific control architectures. Each of the operations is defined below:

- Lane keeping. The vehicle will be kept in the lane center, or if desired, at some prescribed displacement off-center of the highway lane. Lane geometry preview for 3.2 is essential, along with knowledge of the state variables of the lateral dynamic system such as lateral velocity, lateral acceleration and yaw rate.
- Speed supervision. The speed is governed, based on speeds of vehicles in the immediate surround, particularly by the vehicle in front, or in the platoon case, by the lead vehicle. The speed is constrained by the upper and lower limits of the global speed policy currently dictated by 4.x, in addition to local safety requirements derived from knowledge of local road geometry's and conditions from 3.2.
- Inter-vehicle separation supervision. This operation implements the global safe separation policy for the specific local condition. The type of implementation depends on the information structure and content, closeness of spacing, prevailing speed, vehicle class, and control of separation by fixed distance or time command.
- Platoon splitting and joining. This operation is applied only with AHS platoon operations. The formation and dissipation of platoons is governed by this operation. These operations require a high degree of coordination between platoon leaders. The platoons must check that their combined size will not be above the global policy of maximum platoon size and that they are not involved in any other maneuver at that time, then execute the particular maneuver.
- Start of automated travel. This operationis applied only with mixed traffic utilizing a "zone of control" to engage automated operations. This operation interfaces with 1.3, supervising communication of the vehicle and local traffic states. Vehicles are accepted on the fly, placing a premium on inter-vehicle separation enforcement within this subfunction.
- End of automated travel. This operation is applied only with mixed traffic operations utilizing a "zone of control" to disengage automated operations. This sub-function interfaces with 2.2, supervising communication of the vehicle and local traffic states. The driver takes over on the fly, so graceful transition with full status information made available to the vehicle, and eventually the driver, is important.
- Process input information. Higher level processing and monitoring of these inputs is performed to carry out the elemental in-lane travel functions described above.
    - Vehicle self state (from 3.2.4) - to determine values for own-vehicle acceleration, velocity and yaw.
    - State of neighboring vehicles (from 3.2.5) - to determine target values for neighboring-vehicle speed changes.

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[1] A platoon is strictly defined as a coordinated group of vehicles, with the coordination arising from control enacted with velocity and acceleration information from the lead vehicle. Thus, individual vehicles which communicate to other individual vehicles, can be regarded as one-vehicle platoons; and join and split maneuvers are possible with one-vehicle platoons either comprising the initial or final condition, depending on the maneuver.

3.1.5. Contingency Handling

SUMMARY: This sub-function handles the safety-oriented vehicle maneuvers in response to disturbances. These disturbances are classified by source -- external, internal and driver -- because the contingency responses are different for each. For each category of disturbance, the objective is to address the impact in a "graceful" manner, allowing for quick recovery. This function does *not* address inclement weather, unless very extreme, as the response to this does not constitute emergency handling.

DESCRIPTION:

- Emergency handling - system intrusion and other external sources. This operation covers the response, or graceful degradation, to external-to-AHS sources that would result in an unsafe or inefficient (i.e., low throughput) operation without the appropriate emergency handling response. Operations to handle the presence of obstacles and other roadway hazard handling, are defined to be equivalent and are shown below.
    - Obstacle management handling. These comprise emergency maneuvers required to avoid any perceived obstacle which is determined to be an AHS vehicle hazard (either because it is in-lane or with a projected trajectory that could bring the obstacle in-lane). Within 3.x, the presence of obstacles indicates failure of any infrastructure-based obstacle exclusion measures; hence, the function defined here describes a response to and not the totality of managing obstacles. Examples of obstacles include non-communicating vehicles, sudden appearance of debris, or animals. This includes rogue vehicles with potentially malicious intent. Examples of roadway hazards include black ice.
        - ◊ Detect, classify and verify obstacles. This process invokes 3.2, using sensing technologies and/or communications with 4.x. A policy on acceptable detection probabilities and to what extent obstacles must be classified and verified must be in place before the onset of emergency maneuvers.
        - ◊ Decision strategy. The specific obstacle avoidance maneuver is an input from 3.3, but the supervision of the execution of this maneuver, including vehicle trajectory assessment, comes from this function.
        - ◊ Hard braking. This operation is a potential maneuver strategy and would work as follows. Prior to hard braking, provide broadcast of braking capability. This may be in the form of communicating a nominal braking capability; given technology advances, it may take the form of real time updates of the current braking capability as a function of the road condition. With hard braking, the vehicle brakes to the maximum extent allowed by AHS policy. (This might not be maximal braking if high braking performance vehicles are involved, or if brake amplification along a string of vehicles are a concern.) At the onset of hard braking, the vehicle locally communicates: the fact that braking occurs and at a minimum, the degree of braking effort applied; if technologically possible, the vehicle communicates also the trajectory resulting from the measure.
        - ◊ Maneuver around the obstacle. This operation is a sequential application of 3.1.2 (Demerge) and 3.1.1 (Merge), the differences being that here, the coordination with adjoining vehicles is minimal, if at all, and inter-vehicle separation criteria for normal operations would probably be violated. The execution of the 3.1.1 function is optional, and may not constitute an emergency maneuver per se.
- Emergency handling - malfunctions (internal sources). This operation comprises the response, or graceful degradation, to any vehicle- or infrastructure-based failure that would result in an unsafe or even inefficient (i.e., low throughput) operation without the appropriate critical malfunction response countermeasure. The malfunction source is either in-vehicle or on the roadway.

  - Determine, classify and identify failure source. Real time diagnostics are applied to quickly identify potential and emergent failures. A minimum classification of failure would be the required time to respond: immediate or later.
  - An immediate response would dictate:
    - Hard braking. (See above.)
    - Maneuver to side of road.
    - Mayday signal. Sent to neighborhood vehicles and infrastructure, and passed on to Function 4.x.
  - A "later" response would dictate 3.3 to invoke any of the 3.1.1 - 3.1.4 functions or to advise the driver to fix the malfunction once he or she leaves the AHS. This could invoke the Park Maneuver (contained in this function).
- Driver Handling
  - Emergency interrupt. This sub-function handles the response to any "emergency" driver-initiated action or inaction which either constitutes or is in response to a disturbance (in terms of safety or efficiency) to the automated highway control system. A probable implementation is a "panic button" override (e.g., hard braking response to driver-detected obstacle). Operations include those under emergency handling and also: determination of severity, system notification (interfacing to 4.x), and proceed to park maneuver.
  - Preference Interrupt. This function is the response to any "non-emergency" driver-initiated action or predetermined preference (e.g., headway policy, lane change preference). During execution of any of the 3.1.1 - 3.1.4 maneuvers, the driver may indicate a preference, which is then transmitted to 3.3.1 for a decision. If the preference is accepted, an alternate executive command is proffered or the initial command is revoked; if the preference is not accepted, the initial command is executed. In any event, the driver is notified, along with the reason.
  - Park Maneuvers. This function comprises the potentially complex set of maneuvers required to control a vehicle from the stream of highway traffic, slowing it to a stop. This maneuver can be called by 3.3.1 while the vehicle is in the mainline traffic, by 1.x if the cause for park maneuver is on the merge lane due to rejection at check-in, or by 2.x if the cause is on the demerge lane due to lack of response at check-out. In any case, 3.1.2 (Demerge) is called because the park maneuver must be executed at a fixed point, then the vehicle is either parked on the roadside shoulder or guided through a series of maneuvers in 3.1.4 (In-Lane Travel) toward a more elaborate storage facility. In any case, Function 2.2 is called.

3.2. Vehicle Control and Sensing

This function directs, monitors and supervises local vehicle movements, based on commands from the Tactical Planning (3.3) function and feedback from the Vehicle Control Execution (3.2) function.

Input Signal	Included messages	From	To
Mnvr_Cmd_Ll	Feedback from Lower Level Controllers and In-Vehicle State	3.1	3.2
Engage_denied	Request to engage is denied	1.x	3.2

Output Signal	Included messages	From	To
Ready_to_Control	Ready to Control	3.2	1.x
Veh_Eng_Status	Denial of Engagement Due to Local Conditions	3.2	1.x
Veh_Dsng_Status	Status of Vehicles to be Disengaged	3.2	2.x
Vehicle_status	Vehicle operational status	3.2	4.x
Mnvr_Cmd_Ll	Command Lower Level Controllers	3.2	3.1
Mnvr_Cmd_Feedback	Status of maneuver	3.2	3.1

3.2.1. Control Powertrain

SUMMARY: This sub-function controls transmission and throttle actuators.

DESCRIPTION: Longitudinal vehicle velocities and accelerations (changes in speed) are controlled in this sub-function. Positive velocities and accelerations are entirely controlled in this sub-function, and negative values are arrived at in potential combination with 3.2.2, depending on the commanded rate; higher deceleration rates will require 3.2.2.

3.2.2. Control Brake

SUMMARY: This sub-function controls brake actuators.

DESCRIPTION: Longitudinal vehicle velocities and accelerations will be controlled in this sub-function, depending on the deceleration rate and whether the vehicle must be stopped.

3.2.3. Control Steering

SUMMARY: This sub-function controls steering actuators

DESCRIPTION: Lateral vehicle velocities and accelerations (changes in direction) are controlled in this sub-function. These control higher level outputs as yaw angle and yaw rate.

3.2.4. Determine Vehicle Status

SUMMARY: This data collection sub-function provides vehicle operational health and motion state vectors (including location, vehicle or O-D identification and whether parked).

DESCRIPTION: This sub-function is defined to the extent of the particular data requirements of the interfaces, which will vary between AHS concepts. A primary external interface of 3.2.4 data is 1.x, specifically with ready_to_control, engage_denied, vehicle_designation_status signals, which affect engaging with the AHS. Another external interface is the transmittal of locally detected anomalies (i.e., beyond defined norms) to 4.x. The remaining interfaces are to confined to 3.3.1 (executive decision maker) and 3.1 (supervisor) to provide information needed to assess maneuver tactics. Sub-functions are:

- On-Vehicle Status. In this sub-function, on-vehicle operational heath, position and dynamics are sensed, recorded and communicated to 3.1 (for supervision) and 3.3 (for decision making). Specific parameters include vehicle identification (which could be a simple as a counter) and kinematic items as actual positions, velocities, accelerations and yaw. These parameters are presented alone and relative to the reference, or commanded values. Diagnostics/health information include system monitoring (brake, tire pressures, operational checks on various AHS devices).
- Nearby Vehicle Status. With this function, the operational heath, position and dynamics of vehicles in the "immediate surround" (to be defined) are sensed, recorded and communicated to 3.1 and 3.3. This includes relative positions, velocities and accelerations. Again, these parameters are presented alone and relative to the reference, or commanded values. The presence of and actions as a result of contingencies is also reported. The collection and compact expression of prevailing local traffic conditions (speed and densities) is another important element of this sub-function, as it directly affects the execution of many of the maneuvers in 3.1. Finally, note that sensing and communication devices are required to fulfill this sub-function.

3.2.5. Determine Other Status Items

SUMMARY: This data collection sub-function provides non-vehicle operational health and status information.

DESCRIPTION: This function is defined to the extent of the particular data requirements of the interfaces, which will vary by AHS design. A primary external interface is to 1.x, specifically with ready_to_control, engage_denied, vehicle_designation_status signals, which affect engaging with the AHS. Another external interface is the transmittal of locally detected anomalies (i.e., beyond defined norms) to 4.x. The remaining interfaces are to confined to 3.3.1 (executive decision maker) and 3.1 (supervisor) to provide information needed to assess maneuver tactics. Sub-functions are:

- Road geometry recognition. Highway topographical information such as curvature, banking, elevation, occlusion and lane width is provided by this sub-function.
- Local climate and road condition monitoring. Climate and road conditions which are projected by AHS designers to affect sensing and communication phenomenology and vehicle dynamics are provided by this sub-function.
- Emergency detection/monitoring. The presence, severity and response to contingencies is provided by this function.
- Driver status monitoring.

Sensing and communication devices are required to fulfill all these sub-functions.

3.3. Tactical Planning

This function makes decisions on local vehicle movements. The extent of the implied tactical planning region (by geography or car count) is TBD, contingent on the AHS operational concept, and command and control system.

Input Signal	Included messages	From	To
Operating_Policy	System_Wide Policies	4.x	3.3.2

Output Signal	Included messages	From	To
Maneuver_Command	Perform Specific Maneuver	3.3.2	3.1

3.3.1. Maneuver Decision

SUMMARY: This sub-function chooses from the maneuver functions of 3.1. In other words, 3.3.1 is the decision agent, or executive, that balances the individual vehicle travel goals (taken to be to minimize travel time within comfort and safety constraints.) with 4.xrequirements and the "good of the tactical planning region" – ensuring smooth traffic flows through compatible and coordinated execution of maneuvers. The necessary decision constraints arrive from 3.3.2 (Situational Assessment) function.

DESCRIPTION: The decision and sequencing of functions in 3.1 – merge, demerge, lane change, in-lane travel, and contingency handling – are specifically determined by this sub-function, based on inputs from 3.3.2.

3.3.2. Situation Assessment

SUMMARY: Coordination between the roadside infrastructure (to the extent that it exists) and other vehicles is ensured by this function, based on the "situational awareness" feedback from the Vehicle Control Execution (3.2) function.

DESCRIPTION: This sub-function performs the following:

- The onset, local effects of and predicted global effects of any contingency event is provided to 4.x.
- Global policies are periodically reported from 4.x to 3.3.2, and reported on demand or at higher frequencies if global emergencies or other TMS-dictated adverse conditions exist. Policies to be reported (by class, link, lane) include: speed limits, inter-vehicle separation limits, comfort (jerk) limits, platoon size, allowable obstacle detection error thresholds, and hard braking rate limitations.
- Local climate and road conditions are periodically reported to 4.x, whether or not they adversely affect traffic flow.
- Status inputs from 3.2.4 and 3.2.5 processed by this function at request or periodic intervals during steady state (in-lane) travel, at higher frequencies or on demand during other maneuvers or during contingency operations.
- 3.3.1 accepts 3.1 requests to execute maneuvers, providing specific trajectory information. The basis for 3.1 requests is "optimizing" individual vehicle travel behaviors (minimizing travel time while adhering to safety policy constraints). Based on current 4.x policies and on the awareness of status from 3.2.4.5, 3.3.1 makes a "yes", "no", "modify to" decision, which 3.1 is compelled to command 3.2 to execute. An input to these requests is the 2.x individual vehicle routing information, as 3.1 must allow for maneuvers leading to egress or digress to occur. (Not doing so will lead to no allowable merges and demerges if any mainline slowing occurs!)
- Processes the specific input information necessary to make these decisions which are architecture- or design-dependent, but fall into six categories which can be generally described below:

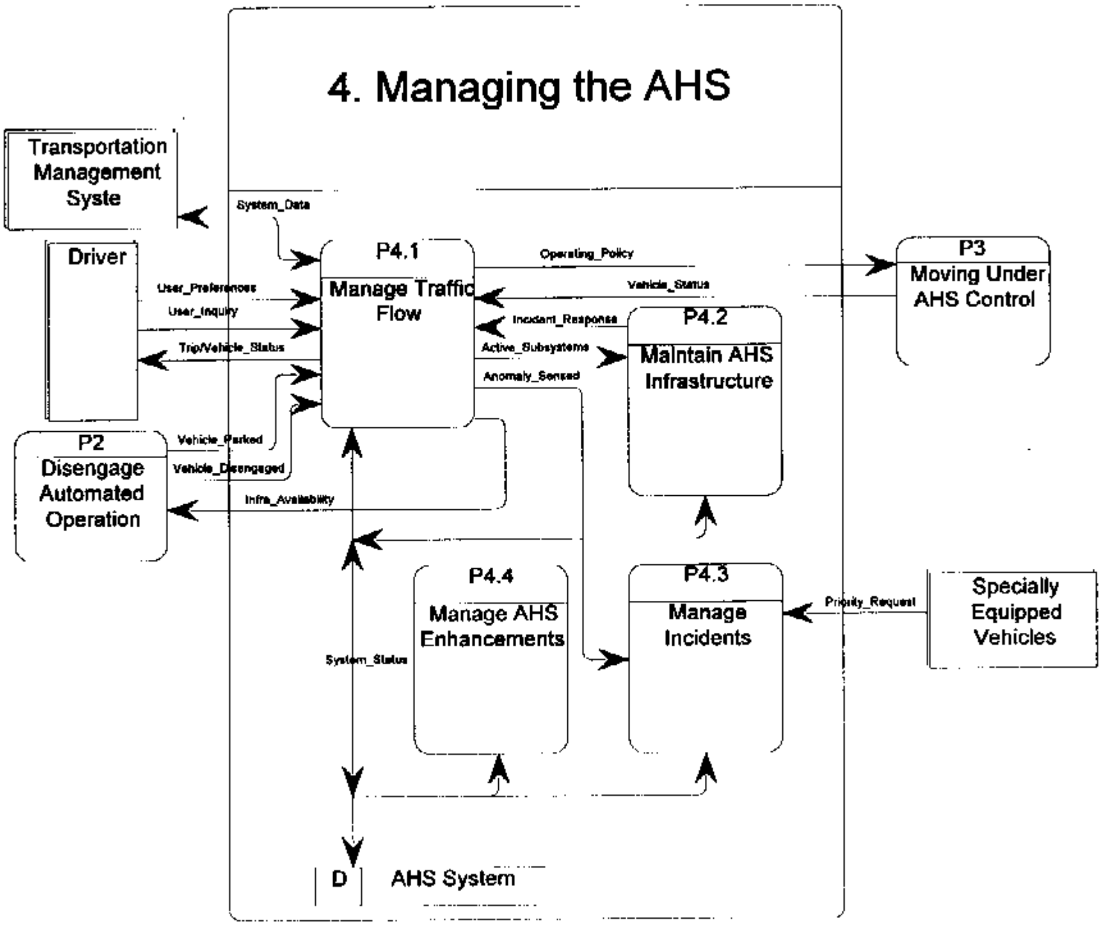
  - Vehicle self state (from 3.2.4) - to determine values for own-vehicle state (e.g., velocity, acceleration)
  - State of neighboring vehicles (from 3.2.5) - to determine target values for neighboring-vehicle state; this is related to the next item below but differs in that these are discrete in-vehicle data whereas item 3 consists of traffic flow data.
  - Intent of neighboring vehicles (from 3.2.5) - to determine expected disturbances to in-lane travel.
  - Prevailing in-lane local traffic conditions (from 3.2.5 -- speed and density).
  - State of local roadway (from 3.2.5) - to determine curvature, banking, elevation, occlusion and road surface condition constraints to potential changes in vehicle state.
- "Macro" policy or emergency conditions - (from 4.x) to determine allowable ranges of in-lane speeds.

4. MANAGING THE AHS

This section describes the macro level management functions performed for the AHS by the Traffic Management System (TMS). The functions represented in this section are those that will have a system wide impact and require a global view of the AHS. Managing the AHS represents the operations and maintenance of the systems infrastructure for the benefit of other system functions (1.x - 3.x). Infrastructure is defined as the physical and data elements required to perform the daily systems functions. Examples of infrastructure are: roadways, CMS signs, map data bases, system status, and systems performance data. The AHS management function will provide input to drivers on system availability, driving conditions, and emergency situations. This will be in the form of HAR, message signs, or other ATIS methods. Direct vehicle communications will be through the other system functions (1.x -3.x).

This section is currently broken down into four major subcomponents

4.1. Manage Traffic Flow
4.2. Maintain AHS Infrastructure
4.3. Manage Incidents
4.4. Manage AHS Enhancements



Input Signal	Included messages	From	To
Vehicle_Parked	Vehicle has been parked and needs emergency attention	2.x	4.x
Vehicle_Disengage	Vehicle Disengaged and has left AHS (at a specific location)	2.x	4.x
Vehicle_Status	Vehicle Management Status Emergency Notification	3.x	4.x
Priority_request	Priority request	Veh	4.x
User_Preferences	User preferences	Driver	4.x
User_Inquiry	User inquiries	Driver	4.x
System Data	Absence Data Non AHS Roadway Data Traveler & Freight Information Emergency Incident Data AHS Data/Data Requests Construction & Maintenance Information & Requests Weather Forecast Operating Parameters	TMS	4.x

Output Signal	Included messages	From	To
Operating_Policy	Operating policies - link speed limit - headway policy by vehicle class	4.1	3.x
Infra_Availability	All information needed for vehicle to plan a route - route link capacity/utilization - exit availability	4.1	2.x
System_Data	Absence Data Non AHS Roadway Data Traveler & Freight Information Emergency Incident Data AHS Data/Data Requests Construction & Maintenance Information & Requests Weather Forecast Operating Parameters	4.1	TMS

4.1. Manage Traffic Flow

This function is the nerve center of macro level traffic management. It provides all the functionality required to operate and adjust system operational parameters, lane usage management, entry/exit management and data management. Inputs to this function are internal and external as well. Matrix below gives a overview of all the processes and inputs/outputs associated with them.

	Input	Function	Output
4.1.1.	System Data	Determine System Operational Status	Change of System Status
4.1.2.	System Data	Adjust System Operational Parameters	Optimized System Ops Parameters
4.1.3.	Traffic Data	Manage Lane Usage	Optimized Lane Usage Parameters
4.1.4.	Traffic Data	Manage Entry Traffic Flow	Optimized Entry Traffic Flow Parameters
4.1.5.	Traffic Data	Manage Exit Traffic Flow	Optimized Entry Traffic Flow Parameters

4.1.1. Determine System Infrastructure Operational Status

SUMMARY: This function is responsible for monitoring system operational status and to trigger function 4.1.2 provided operational parameters are detected to be out of predefined range.

DESCRIPTION: All the sub-functions associated with this functions are described below:

- Check weather conditions. This sub-function will monitor parameters associated with weather conditions like temperature, rain, fog, etc. If any of the weather condition parameter goes out of the pre specified range, this sub-function will trigger sub-function 4.1.2.
- Check surface conditions. This sub-function will monitor highway surface conditions like ice, water, hazardous spill, etc. Input to this sub-function are binary in nature. If any change in surface conditions are detected, this sub-function will trigger sub-function 4.1.2.
- Check Traffic conditions. This sub-function is responsible to monitor global traffic conditions (density and speed). Once any traffic parameter goes out of a pre specified range, sub-function 4.1.2 will be triggered.
- Check incident impact report. This sub-function is responsible to monitor conditions which arises due to an incident on the highway. Once the incident is reported it will trigger sub-function 4.1.2.
- Check fault (4.2) impact report. This sub-function is responsible to monitor conditions which arises due to a fault on the highway. Once a fault is reported it will trigger sub-function 4.1.2.

Input Signal	Included messages	From	To
System Data	Weather	TMC/ Internal	4.1.1
	Traffic Conditions	TMC/ Internal	4.1.1
	Surface conditions	TMC/ Internal	4.1.1
Incident Response	Traffic impact assessment	P4.3.1	4.1.1
Subsystem Health & Status	Fault impact assessment	P4.3.2	4.1.1

Output Signal	Included messages	From	To
Changed Status	Changed operational status	4.1.1	4.1.2

4.1.2. Adjust System Infrastructure Operational Parameters

SUMMARY: This function is responsible for adjusting global operational parameters once abnormal conditions are detected on the highway. Abnormal conditions can arise from changed weather conditions, changed surface conditions, incidents and faults. This function will check the cause of abnormality and generate adjusted global operating parameters for amended operating mode. This function will also notify external TMC's of altered traffic conditions.

DESCRIPTION: All the sub-functions associated with this functions are described below:

- Generate weather related operational parameters: This sub-function will generate optimized operating parameters (speed, headway distance) based on the degree of abnormality in weather. This sub-function will also issue procedures for highway usage like chains required, head lights on.
- Generate surface related operational parameters: This sub-function will generate optimized operating parameters (speed, headway distance) based on the surface conditions on highway. This sub-function will also issue procedures for highway usage like change route, lane X not available.
- Generate congestion related operational parameters: This sub-function will generate optimized operating parameters (speed, headway distance) based on recurring highway congestion. This sub-function will also issue traffic congestion notifications and possible alternate routing..
- Generate operational parameters for planned traffic events: Based on pre programmed information this sub-function will generate optimized operating parameters (speed, headway distance). This sub-function will also issue notifications and procedures for alternate routing of traffic.
- Generate congestion related operational parameters: This sub-function will generate optimized operating parameters (speed, headway distance) based on recurring highway congestion. This sub-function will also issue procedures to evade traffic congestion.

Input Signal	Included messages	From	To
System Data	Weather	TMC/ Internal	4.1.2
	Changed Operational Status	4.1.1	4.1.2
	Planned traffic events	TMC/ Internal	4.1.2
	Surface conditions	TMC/ Internal	4.1.2
	Recurring Traffic congestion	TMC/ Internal	4.1.2
Incident Response	Traffic impact assessment	4.2.2	4.1.2
Subsystem Health & Status	Fault impact assessment	4.3.1	4.1.2

Output Signal	Included messages	From	To
Change parameters	Adjust traffic flow	4.1.2	3.x
	AHS traffic information	4.1.2	TMC/ ext

4.1.3. Manage Lane Usage

SUMMARY: This sub-function will check traffic information (example - number of vehicles per lane per hour, vehicle class, lane availability) and issue parameters to 3.x to optimize lane usage based on local traffic management preferences. In certain areas it might be required to keep long haul traffic on lane #1 and to keep all the other traffic on other lanes. In some areas local authorities might want to provide a corridor to trucks in certain hours of the day.

DESCRIPTION: This sub-function will perform the following:

- Monitor lane congestion and usage based on data received internally.
- Compare usage to predetermined traffic parameters.
- Generate new lane usage parameters.

Input Signal	Included messages	From	To
System Data	Traffic Information	TMC/ Internal	4.1.3
System Status	Lane availability	4.2.2	4.1.3
	Lane availability	4.3.1	4.1.3
	Vehicle data	3.x	4.1.3

Output Signal	Included messages	From	To
Update lane usage	Lane usage parameters	4.1.3	3.x

4.1.4. Manage Entry Point Traffic Flow

SUMMARY: This sub-function will check traffic information (Number of vehicles requesting a particular entry,

traffic condition on AHS system in near vicinity of the entry, vehicle data, entry availability) and issue parameters to optimize entry usage based on local traffic management preferences. If number of vehicles requesting a particular entry point is in excess of capacity or AHS lane is congested close to entry point then this sub-function will give options regarding availability of other entry points in near vicinity and delay time at the entry point requested.

DESCRIPTION: This sub-function will provide the following:

- Provide capability to limit usage of an entry point to certain classes of traffic for certain time periods.
- Notify system and external TMC's of entry point restrictions.
- Set parameters to alleviate congested conditions around entry point.

Input Signal	Included messages	From	To
System Data	Traffic Information	TMC/ Internal	4.1.4
System Status	Entry availability	4.2.2	4.1.4
	Entry availability	4.3.1	4.1.4
	Vehicle data	3.x	4.1.4

Output Signal	Included messages	From	To
System parameters	Traffic control parameters	4.1.4	3.x
System conditions	Adverse traffic conditions	4.1.4	TMC/ ext

4.1.5. Manage Disengage Zone Traffic Flow

SUMMARY: This sub-function will check traffic information (Number of vehicles requesting to use a particular disengage zone, vehicle class, exit availability) and issue parameters to optimize disengage point usage based on local traffic management preferences. This function will also notify the system and external TMC's of disengage point restrictions.

DESCRIPTION: This sub-function will provide the following:

- Alter system parameters in order to alleviate congestion or anticipated disengage point abnormality.
- Provide information regarding delay time and availability of other disengage points in near vicinity.
- Provide ability to limit usage of a disengage point for certain time periods.

Input Signal	**Included messages**	**From**	**To**
System Data	Traffic Information	TMC/ Internal	4.1.4
System Status	Disengage zone availability	4.2.2	4.1.4
	Disengage zone availability	4.3.1	4.1.4
	Vehicle data	3.x	4.1.4
Parked Vehicle	Location	2.x	4.1.5

Output Signal	**Included messages**	**From**	**To**
System status	Traffic flow parameters	4.1.5	3.x
	Traffic flow information	4.1.5	Driver

4.2. Maintain AHS Infrastructure

This function will detect and verify system faults. A system fault is defined as a defect in the infrastructure that may or may not generate an incident (4.3). Once faults are detected this function will generate and execute a response plan. This function will also monitor system deterioration and schedule preventive maintenance plans. Matrix below gives a overview of all the processes and inputs/outputs associated with them.

	Input	**Function**	**Output**
4.2.1.	System Data	Detect Infrastructure Faults	Change of System Status
4.2.2.	System Data	Verify and Identify Infra. Faults	Confirmed fault type
	System Status		No-fault
	Location		
4.2.3.	Confirmed Fault Type	Generate system faults response plan	Response plan
	Resource Availability	Fault impact assessment	
4.2.4.	Response plan	Execute System Faults Response Plan	Status to macro traffic management
			Inadequate response plan
4.2.5.	System Data	Monitor system deterioration	Status to macro traffic management
			Inadequate response plan
4.2.6.	Ranking report	Generate system deterioration response plan and schedule	Status to macro traffic management

4.2.1. Detect Infrastructure System Faults

SUMMARY: This function will receive and interpret infrastructure related data from various sources, both internal and external. When an input is suspected to represent a fault the information will be catalogued, stored, and passed to 4.2.2 for additional processing.

DESCRIPTION: This function will perform the following:

- Receive infrastructure related information from internal and external sources.
- Determine if an infrastructure fault may be involved.
- Pass the suspected fault information to 4.2.2
- Maintain a data base of the reported information for subsequent processing or reporting

Input Signal	**Included messages**	**From**	**To**
System Data	Traffic Information	Internal/ext.	4.2.1

Output Signal	**Included messages**	**From**	**To**
Fault alert	Fault report data	4.2.1.	4.2.2

4.2.2. Verify & Identify System Infrastructure Faults

SUMMARY: This sub-function will verify the type of fault and determine severity. Once the fault is verified this function will generate a confirmed fault type and generate fault impact traffic report.

DESCRIPTION: This sub-function will perform the following:

- Determine type and severity of fault.
- Pass information to 4.2.3 for action
- Notify 4.1 of possible effects on traffic flow.

Input Signal	**Included messages**	**From**	**To**
System Data	Changed Infrastructure Status	4.2.1	4.2.2

Output Signal	**Included messages**	**From**	**To**
Confirmed Fault type	Fault data	4.2.2	4.2.3
Fault Impact analysis	Fault impact data	4.2.2	4.1

4.2.3. Generate/Execute System Infrastructure Faults Response Plan

SUMMARY: Based on the confirmed fault type this sub-function will check resources availability and will execute a response plan based on best suited response from the response plan database Execution could mean dispatching a team to fault site for proper repairs or running a corrective software. This sub-function will also check if resources available are enough to take care of the fault in a timely manner. If resources available are not enough then this function will generate a request for additional resources to proper authorities.

DESCRIPTION: This sub-function will perform the following:

- Update the response plan database for new faults.
- Determine and execute best response plan.
- Request additional resources if required.

Input Signal	Included messages	From	To
Confirmed Fault Type	Faulty system/subsystem	4.2.2	4.2.3
System Data	Resource Availability/Unavailability	TMS/ Internal	4.2.3

Output Signal	Included messages	From	To
Execute response plan	Fault data and plan implementation	4.2.3	Int./Ext.
Resource Request	Resources required	P4.2.3	Ext.

4.2.4. Monitor System Infrastructure Deterioration

SUMMARY: This sub-function will generate an infrastructure ranking report based on the reports from both external and internal sources such as, component/subsystem/system failure history and data available from Infrastructure Diagnostic Vehicle (IDV).

DESCRIPTION: The following operations will be performed:

- Review maintenance logs and fault reports in order to create preventive maintenance schedules.
- Create preventive and scheduled maintenance plans to insure infrastructure viability.
- Ensure resources are appropriate and available.
- Maintain a database of infrastructure inventory and scheduled maintenance history.

Input Signal	Included messages	From	To
Scheduled review	Deterioration report	Ext.I	4.2.4
	Deterioration report	IDV	4.2.4

Output Signal	Included messages	From	To
Scheduled Maintenance	Maintenance data	4.2.4	4.2.5

4.2.5. Execute Scheduled Maintenance Plan for Infrastructure

SUMMARY: This sub-function executes the schedule maintenance for the system infrastructure. This includes ensuring appropriate resources are available and notifying 4.1 of any anticipate traffic flow impact.

DESCRIPTION: This sub-function will perform the following:

- Execute and monitor scheduled maintenance activities.
- Anticipate traffic flow impact and notify 4.1 of timing and impact.
- Update Maintenance logs to indicate results of scheduled maintenance.

Input Signal	Included messages	From	To
Maintenance request	Plan/available resources	4.2.4	4.2.5

Output Signal	Included messages	From	To
Traffic flow alert	Scheduled maintenance impact	4.2.5	4.1

4.3. Manage Incidents

An incident is defined as any anomaly or abnormal condition that may impact the normal traffic flow and operations of the AHS. Incidents can be both traffic and/or infrastructure related occurrences that are out of the normal operational expectations. The processes within this function will receive incident reports from both within and external to the system. This function will verify the type of incident, severity, and execute an appropriate response plan as described in 4.3.2. The processes within the function are:

4.3.1. Verify and Classify Incident Activity or Report

4.3.2. Initiate and Monitor Incident Response

4.3.3. Catalog and Report Incident Data

4.3.4. Create and Update Response Plans.

4.3.1. Verify and Classify Incident Activity or Report

SUMMARY: This sub-function will receive the report of an incident from either internal sensors, or other AHS functions that control moving vehicles, (i.e. 2.x, 3.x), or external alerts from other TMS or Traveler information systems such as weather. Some incidents may be automatically responded to when the system can determine this is appropriate. An example would be a machine malfunction that can be electronically sensed and the appropriate maintenance crew notified electronically. This sub-function (4.3.1) would be "copied" and would classify and record the incident for tracking purposes.

DESCRIPTION: This sub-function shall perform the following:

- The incident shall be classified by type, such as; vehicular accident, vehicular accident with injury, system malfunction, roadway obstacle, etc.
- Generate an internal incident alert and/or assign an "incident ID" for tracking purposes.
- The alert will be passed to 4.3.2 for action.
- In case of a parked vehicle in an emergency area due to a non-responsive driver this function will notify the system of the emergency area and vehicle attributes (registration number, color etc.)

Input Signal	Included messages	From	To
Vehicle_Parked	Driver emergency alert	2.x	4.3.1
	Vehicle emergency alert	3.x	4.3.1
	Roadway hazard alert	3.x	4.3.1
Parked Vehicle	Location	2.x	4.1.5
	External alert	TMC/ ext.	4.3.1

Output Signal	Included messages	From	To
Incident alert	Incident ID and data	4.3.1	4.3.2

4.3.2. Initiate and Monitor Incident Response

SUMMARY: Based on the severity of the incident as reported by 4.3.1, notices are sent out and progress tracked. Perhaps most important will be the emergency response plan that shall include local or AHS emergency crews, ambulances, fire trucks, and appropriate law enforcement personnel depending on the incident classification

DESCRIPTION:

- This sub-function will select a response plan based on the alert type.
- A traffic flow impact assessment will be sent to 4.1 (manage flow) to allow for adjustments to overall traffic flow parameters in the affected area.
- An emergency response notice will be sent to P2 and P3 if immediate action such as "stop all vehicles" is required
- A traveler advisory messages shall be posted on CMS or VMS signs, transmitted via HAR, and regional ATIS (Radio and TV) systems notified.
- A notification will be made to maintain the AHS (4.2) and a maintenance response team will be dispatched if necessary based on severity.
- Incident status will be posted for internal tracking purposes.

Input Signal	Included messages	From	To
	Classified incident alert	4.3.1	

Output Signal	Included messages	From	To
Flow Alert	Traffic flow impact data	4.3.2	4.1
Information update	Traveler advisory information	4.3.2	Ext.
Emergency Alert	Request for immediate action	4.3.2	2.x/3.x

4.3.3. Catalog and Report Incident Data

SUMMARY: This sub-function shall represent a repository of the incident information that is gathered both before and after the incident in order to provide data to those services requiring it.

DESCRIPTION:

- This sub-function shall maintain a data base by type of incident, number of incidents, damages sustained, and circumstances, response, and result of response to the incident.
- Reports will be made available on request to external users such as insurance companies and other agencies that may have a lawful need for this information.

Input Signal	Included messages	From	To
	Initial incident data	4.3.1	4.3.3
	Incident response report	External	4.3.3
	Damage assessment	External	4.3.3

Output Signal	Included messages	From	To
Data request	Incident report	4.3.3	Ext.

4.3.4. Create and Update Response Plans

SUMMARY: This process will be a continuous planning and review mechanism for aggregating the incident data from the other functions and updating the response plans in order to improve safety and availability of the AHS.

DESCRIPTION:

- Incident reports and results from the "current" response plans will be reviewed for areas of improvement.
- New technologies shall be reviewed order to assess improvements to incident responses.
- This function shall recommend improvements to the infrastructure in order to prevent incidents.
- Response plans shall be reviewed, tested and updated as, required, annually.

Input Signal	**Included messages**	**From**	**To**
	Incident data base	4.3.3	4.3.4
	Incident response time goals	Int./Ext.	4.3.4
	Enhancement Notification	4.4	4.3.4

4.4. Manage AHS Infrastructure Enhancements

The manage enhancements function shall be a planning process for incorporating improvements to the system in a non-disruptive, safety oriented method. Improvements may be structural (new roadways or exits), electronic (signs, computer systems, sensors), or traffic flow related and of long term duration. Sub-functions involved are:

4.4.1. Manage Structural Enhancements
4.4.2. Manage Electronic Enhancements
4.4.3. Establish Staffing and Training Requirements

4.4.1. Manage Structural Enhancements

SUMMARY: This sub-function shall manage the introduction of new system structural enhancements such as additional roadway, upgraded lanes, and new entry / disengage points. These introductions must be managed to insure least disruption to the "in place" system while maintaining the safety and integrity of the system.

DESCRIPTION:

- Implementation plans for system enhancements will be generated and monitored for compliance.
- System data bases will be updated to reflect the new infrastructure model
- The AHS system shall provide long range planning and coordination activities

Input Signal	**Included messages**	**From**	**To**
	Request for upgrade	4.3	4.1.1
	Planned Roadway Expansion	External	4.1.1
	Planned Disengage zone / Entry point change	External	4.1.1

Output Signal	**Included messages**	**From**	**To**
Implement enhancement	Enhancement data elements	4.4.1	Int.

4.4.2. Manage Electronic Enhancements

SUMMARY: This sub-function shall be responsible for introduction of upgrades to the "system" aspects such as computers, sensors, detectors, and other new or improved electronic equipment that will enhance the AHS operations.

DESCRIPTION: This sub-function shall perform the following:

- Provide for testing and monitoring before and during implementation of new system enhancements.
- Provide notification to all affected internal and external processes.
- Insure safe implementation of these changes.

Input Signal	Included messages	From	To
	Technology advancements	External	4.4.2
	System software improvements	Internal	4.4.2
	Computer functionality requests	Internal/ External	4.4.2

Output Signal	Included messages	From	To
Implement enhancement	new functionality and availability	4.4.2	Ext./Int

4.4.3. Establish Staffing and Training Requirements

SUMMARY: This sub-function shall have the responsibility to establish skills and personnel requirements for new enhancements that are added to the AHS system. This sub-function will also establish training requirements for existing personnel in order to best utilize the new enhancements.

DESCRIPTION: This sub-function shall perform the following:

- Establish personnel staffing requirements
- Establish personnel skill requirements

Input Signal	Included messages	From	To
	Enhancement Plan	4.4.1	4.4.3
	Personnel Req.s	4.4.1	4.4.3
	Skill Requirements	4.4.2	4.4.3

Output Signal	Included messages	From	To
Personnel/skill request	requirements and justifications	4.4.3	Ext.

C3 Interim Report
March 1998

Appendix 10.2 User Needs

Includes:
10.2.1 User Services Part 1
10.2.2 User Services and Market Package Methodology
10.2.3 AHS User Services

NAHSC

AUTOMATED HIGHWAY SYSTEM (AHS)

NAHSC
National Automated Highway System Consortium

USER SERVICES
PART 1
(DRAFT)

Authors: Jim Reynold, Steve Mortensen

August, 1997

Purpose

The purpose of this document is to formalize the User Services for the National Automated Highway System (AHS). These User Services reflect the needs of a broad group of AHS stakeholders. As work continues under the program, it is expected that continuous stakeholder and user involvement will influence the definition of User Services.

Introduction

NAHSC believes that AHS must be designed by and for those who will implement, manage, use and be affected by the system. Ideas, critique, and input from all AHS stakeholders are essential to make the dream of AHS a practical reality. A goal of NAHSC is to seek consensus among stakeholders on all facets of AHS. Accordingly, NAHSC has made stakeholder involvement endemic to every aspect of our work.

User Services are concise descriptions of 'what' the system has to do, or provide if it is going to be successful from the user's point of view. User Services encapsulate user preferences, needs, objectives, and issues. It is important to separate this from 'how' to provide the user service, which is provided by Market Packages in order to allow deployment flexibility. Market Packages are presented in a separate document.

The National ITS Architecture offers a great heritage of information that is useful for AHS. Its goal is to promote compatibility and synergy among transportation systems in every region of the nation. It also emphasizes developing a regional 'big picture' and assessing user needs, then determining market packages to provide the most appropriate solutions for a region's transportation needs.

AHS must be compatible with the National ITS Architecture to be successfully implemented nationally. To achieve this, NAHSC is embracing previous work on the Architecture, assessing user needs and developing AHS User Services to address those needs. NAHSC has included the entire bundle of Advanced Vehicle Control and Safety Systems (AVCSS) User Services for this reason. Simultaneously, NAHSC is developing AHS Market Packages based on current and emerging technology and a system architecture that incorporates those Market Packages to provide the User Services identified for AHS.

The User Service Development Process

The AHS User Services have been developed in the context of the National ITS Architecture, from the framework of the Advanced Vehicle Control and Safety Systems in Appendix A of the Traceability Document, January 1997 version.

The AHS User Services do not repeat any of the other User Services in the National Architecture. Rather, they are developed to allow for synergy with the other services to provide travelers and service providers with comprehensive services and economical use of infrastructure and data communications. For example, the non-AHS User Service of in-vehicle signing (under En-Route Driver Information) can be used synergistically in AHS to set the maximum speed of Adaptive Cruise Control. Another example is the provision of roadside pollution assessment data (under Emissions Testing and Mitigation User Service) to the Automated Highway System Management System.

Definition of User Services involves the following steps:

1.) Identify user requirements - This step only involves the collection of requirements identified by the users. These take the form of problems, objectives, issues, needs, and preferences. It is these requirements which must be determined in order to develop User Services. They are typically unstructured comments or statements and may even be stated by the user in the form of a solution.

2.) Develop user service labels - This step involves the creation of a user service label and description. These identify the service and allow for detailed requirements development. To distinguish the user service label they always begin with a verb.

3.) Perform 'so what' analysis - This step involves the decomposition of the user services, identification of potential benefits to the user and identification of irreducibles or goals which the User Service addresses. This is done by asking 'so what?' of the User Service. Asking 'so what?' assists in determining detailed requirements and describing benefits, or what the system will provide from the users point of view. The final result of this process is the irreducible or goal which serves to validate that the User Service is appropriate in the context of the overall goals for AHS. The 'so what' analysis should involve experienced stakeholders and domain experts to deepen their mutual understanding of user needs.

4.) Develop 'shall' statements - This step involves taking the user requirements and developing 'shall' statements to encapsulate them. Shall statements are structured statements which describe what needs to be provided. These may be very high level, (e.g., It shall provide traffic surveillance) or more detailed, (e.g., It shall determine actions necessary to maintain the vehicle at a safe distance behind a lead vehicle). The key in developing these is not stating 'how' it will be done.

User Services, while documented here and identified in the National ITS Architecture, may be modified or developed to specifically address stated needs.

Next Steps

The development of User Services will need to be a continuous process through the NAHSC Program and through the national deployment of AHS. User Services and

Market Packages should be developed iteratively, along with technical demonstrations, so that stakeholders can provide more meaningful and imaginative ideas about User Services based on some real experiences and improved understanding of new AHS technologies. In other words, the needs of users will evolve as stakeholders and users know more, and technology evolves.

Current work-plans of the NAHSC include active participation by the Stakeholder representatives and their respective communities in the development and review of User Services. Various meetings formal and informal, publication, and presentations to the various stakeholder member professional or trade group meetings are also anticipated.

AHS User Services

The current set of AHS User Service Labels and Descriptions is listed below. The User Services are based on the Advanced Vehicle Safety Systems (AVSS) User Services of the National ITS Architecture, and are slightly modified. The detailed User Service Requirements are provided as Part 2 of this document.

Avoid Longitudinal Collision – This User Service provides vehicle operators with assistance in avoiding longitudinal collisions to the front and/or rear of the vehicle. The driver is assisted by: (1) sensing potential and/or impending collisions or threats to the front or rear of the vehicle; (2) eliciting proper collision avoidance actions from the driver; and/or (3) providing temporary automatic control of the vehicle to assist the driver in avoiding the potential collision situation. This service includes four types of longitudinal collision avoidance:

- Rear-end collision warning and control will, through driver notification and possibly partial vehicle control, help avoid collisions with the rear end of either a stationary or a moving vehicle or object.
- Adaptive Cruise Control (ACC) will allow the driver to select a cruise control feature that tracks the vehicle in front of it and automatically maintains a 'desired' spacing between that vehicle and the one ahead. In more advanced systems, leading vehicles will include transmission of information on vehicle dynamics to following vehicles. This subservice would allow vehicles to travel in cooperative platoons.
- Head-on collision warning and control will detect an impending collision with a vehicle moving in the opposite direction in the same lane.
- Backing collision warning would detect slow moving or stationary objects, vehicles, livestock, and pedestrians in the path of a vehicle when backing.

Avoid Lateral Collision –This service augments the vehicle operator's ability to avoid collisions by: first providing information, second, if a crash situation is imminent, providing warnings and/or assuming temporary control of the vehicle. This service reduces the number and severity of lateral collisions. This service includes two types of avoidance:

- Lane Change/blind spot situation display, collision warning and control will provide information about the presence of vehicles in the driver's blind spots, actively warn of potential collisions due to lane change or merging, and ultimately, assume temporary control of vehicle steering, braking and/or throttle to avoid collisions.
- Lane/road departure warning and control would assist in maintaining the vehicle in its proper lane of travel through driver warnings, advice on necessary actions, and eventually, assuming temporary control of vehicle steering and throttle to avoid a lane/road departure incident.

Avoid Intersection Collision -- This service provides vehicle operators with assistance in avoiding collisions at intersections. Situations addressed include vehicles improperly violating the right -of-way of another vehicle, or when the right-of-way is not clear. This service will provide warnings of imminent collisions with crossing traffic, and warnings of stop sign and signal control of downstream intersections.

Enhance Vision for Crash Avoidance -- This service reduces the number of vehicle crashes that occur during periods of poor visibility by improving the ability of the driver to perceive the roadway surface and objects on and along the roadway. This will allow the driver to avoid potential collisions with other vehicles, fences and railings, pedestrians, wildlife and livestock, or obstacles in the line of travel; and would assist the driver in complying with traffic control devices.

Safety Readiness – This service provides drivers with warnings regarding their own driving performance, the condition of the vehicle, and the condition of the roadway as sensed from the vehicle. Advanced safety readiness systems will also include the ability to assume temporary, partial control of the vehicle in highly hazardous situations. These services include;

- Impaired driver warning and control override to monitor driver performance and either warn of impaired driver condition or take temporary control of the vehicle to prevent or discourage continued driving.
- Vehicle condition warning to monitor the performance of components, such as tires and brakes, whose degradation could have a significant impact on the safe operation of the vehicle, and warn of their imminent failure.
- In-vehicle infrastructure condition warning to detect and warn the driver of unsafe conditions on the roadway or bridge infrastructure, such as the presence of ice or water.

Deploy Pre-Crash Restraint – This User Service will reduce the number and severity of injuries caused by vehicle collisions. The service is accomplished by anticipating an imminent collision and activating passenger safety systems prior to the actual impact.

Automate Vehicle Operation – This service is a vehicle-highway system that will substantially improve the safety and efficiency of highway travel in all weather conditions, greatly enhance driver comfort, and help reduce air pollution. This service provides automated (hands off, feet off) operation of multiple types of equipped vehicles on dedicated highway lanes. This means that steering, acceleration, and braking of vehicles are controlled automatically. Equipped vehicles are also capable of automated operation on some specially equipped highway lanes inter-mixed with manually driven vehicles. This service builds on the other user services including Avoid Longitudinal Collision and Avoid Lateral Collision. The service consists of six major functions:

- Automated check-in will (1) check the eligibility of the vehicle and driver, (2) accept or reject vehicles for operation in the AHS lanes, and (3) divert disapproved vehicles back to the non-AHS lanes and assume control of approved vehicles.

- Automated vehicle control assumes control of an approved vehicle and moves it onto an AHS lane, merging it with the other AHS traffic. Vehicles are safely controlled in the context of the traffic flow; and when the destination is reached, the system moves the vehicle to an off-ramp.

- Automated check-out occurs with the exiting of the vehicle from the AHS lanes, resuming control by the vehicle driver. This function may include a means to manage the flow of vehicles onto the adjacent surface street system.

- Low speed maneuvering and parking provides assistance to special vehicles. This includes transit vehicles approaching curbs, commercial vehicles approaching loading docks, operation of snowplows, and movement of vehicles within parking and maintenance areas.

- AHS management provides monitoring and oversight of AHS performance, sets operational parameters, and exercises policy level control of the AHS operation.

- Coordination and compatibility between AHS management and ITS center subsystems provides synergy and interoperability between AHS and other ITS Services, (e.g., Travel and Traffic Management, Public Transportation Management, Commercial Vehicle Operations).

10.2.2 User Services and Market Package Methodology

Author Bob McQueen

Discussion Note 1

Background

This discussion note is the first in a family of three, designed to provide guidance and explanation on applying the concepts of ITS User Services and ITS Market packages to the work of the NAHSC. This note, number 1, discusses the overall methodology and how the user fits within the overall process. Notes 2 and 3 address the ITS User Services and ITS Market Packages concepts in more detail.

Intended Audience For The Discussion Notes

The family of discussion notes is intended to support the needs of three audiences as described below. While it is intended that the notes be provided to all three audiences, each note will have a primary focus on one of the audience groups and will have appropriate content, format and style for that audience group. Primary focus for each discussion note is indicated.

1. **Stakeholder Groups And Stakeholder Representatives** - working within the consortium and representing the interests of the following primary user groups:

- private car driver
- commercial vehicle operations
  - drivers
  - fleet managers
- transit
  - drivers
  - fleet managers
- traffic manager
  - traffic engineers
  - transportation planners
  - highway operations specialists

It is anticipated that this audience will primarily be interested in using discussion note 2 as an aid to defining suggested AHS User Services for input to the consortium. Consequently this is the primary focus for Discussion Note 2 - AHS User Services

2. **NAHSC User Needs Team** - those technical analysts within the consortium holding primary responsibilities for activities associated with identification and analysis of user needs, including stakeholder consensus, outreach and case studies. It is anticipated that this group will use Discussion Note 2 as a primary tool for supporting the development of

AHS User Services, in collaboration with the users themselves. This audience should also find Discussion Notes 1 and 3 to be of value in setting out the context within which AHS User Services will be defined and utilized and ultimately translated into AHS market Packages. This audience is the primary focus for Discussion Note 1 - Methodology

3. **NAHSC Progressive Deployment Team** - Those technical analysts within the consortium with primary responsibilities for defining the big future picture or the ultimate AHS and illuminating feasible deployment paths from the existing situation today, to the future. It is anticipated that this audience will find most value in Discussion Note 3 on AHS Market Package definition, as an aid to the development of the fundamental building blocks to be utilized in planning and explaining the deployment paths and the future picture . This audience is the primary focus for Discussion Note 3 - AHS Market Packages

What's In This Document?

In this discussion note, you will find answers to the following questions:

- What are we trying to accomplish in utilizing AHS User Services and Market Packages?
- How do we plan to go about it ?
- Why are we doing it this way?
- What happens next?

What Are We Trying To Accomplish In Utilizing AHS User Services And AHS Market Packages?

There are a number of objectives for applying the concepts of AHS User Services and AHS Market Packages as follows:

- **Building on Previous Work**

An important objective of adopting the AHS User Service and AHS Market Package tools is to fully exploit all previous work that has been carried out by the consortium in identifying user needs and developing technological solutions. This will be achieved through the use of the techniques to structure needs and solutions to provide optimum support for a productive and meaningful dialogue between the users and the technical analysts within the overall framework of the consortium.

- **Putting the user in the driving seat**

We want to help invoke user-driven development, supported by clear communication of needs, objectives, technology capabilities and effects. We want to help the technical analysts within the consortium to develop a focus on the needs, objectives and issues that are important to the user by providing a simple methodology and supporting tools. These will support the identification, exploration, analysis and confirmation of user needs and preferences in collaboration with the users

To do this successfully, we also need to provide the users with the necessary information to make informed decisions regarding technology choices and deployment sequences. This information will be packaged in straightforward terms to facilitate explanation of how the AHS will operate, the likely effects and the potential benefits.

We also want to highlight the direct correlation between what the user expects and how the automated highway system will work, setting the scene for the upcoming Stakeholder Forum in June and the San Diego Automated Highway System demonstration in August through the development and provision of explanatory support material.

- **Sharpening the near term focus**

Although it remains important that we define and explain the future big picture or the ultimate target that we intend to progressively deploy towards, it is vital that we support the users and the technical analysts working within the consortium to develop, detail and agree on the short term components of potential deployment paths

- **Defining, describing and explaining the future big picture**

As discussed above, it is important that we define the ultimate goal from two primary perspectives - the user objectives, problems and issues that will be addressed and the proposed technological solution. Both need to be explained in terms of an integrated holistic approach that maximizes synergy, minimizes duplication of data input and equipment procurement and provides a coherent framework at technical and institutional/organizational levels. This should also illustrate automated highway systems within the context of integrated intelligent transportation systems, particularly with respect to infrastructure deployment and operation.

How Do We Plan To Go About It?

Probably the best way to explain our proposed approach is to illustrate it with a simple process diagram as shown in figure 1

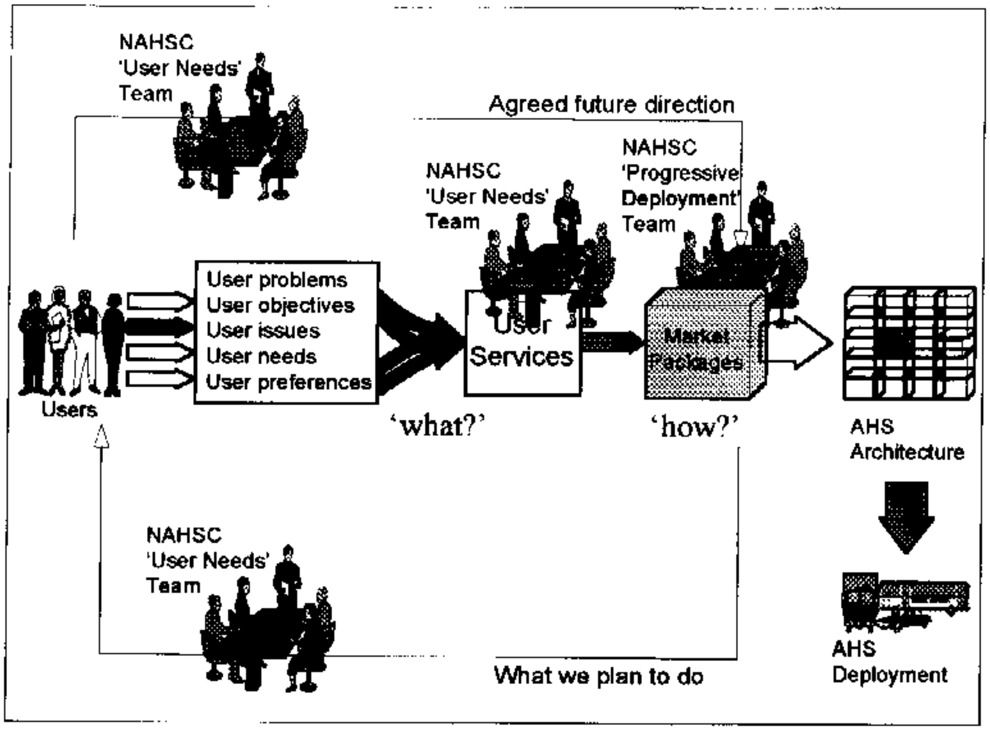


Figure 1 - How We Plan To Go About It

The process starts with the collection and assembly of a variety of data and information describing the users initial perceptions of needs. This will be drawn from previous consortium work and further direct contact with users. It will include the following:

- user problems - what transportation problems do the users perceive as important, taking account of their lifestyles, interests, backgrounds and organizational affiliations ?
- user objectives - what goals or objectives from both personal and organizational perspectives do the users want to have addressed by the ultimate AHS?
- user issues - what issues are associated with the satisfaction of stated needs and what factors may have to be taken into account when identifying and developing potential solutions?
- user preferences - what preferences do the users exhibit when they tell us what they want?

Note that this initial collection of needs information is typically unstructured with input in many shapes and forms. In many cases users will expound what they want by describing a potential solution or telling you how they would address the underlying need, issues or describing a potential solution or telling you how they would address the underlying need, issues or problem. It is also likely that conflicting, incompatible or mutually exclusive needs will emerge, especially as AHS Users represent a wide range of interests. The AHS User Service definition process will have to encompass a mechanism for supporting user convergence to a single consensus set of needs.

User Services

These are concise encapsulations of what the users are asking for. They summarize what the ultimate deployment will have to do, or provide, if the system is to be considered a success by the users. AHS User Services will fulfill the following roles:

- provide the basic materials, describing user needs, problems, objectives and issues, to be used to guide the NAHSC technical analysts in the progressive deployment team in identifying, defining and developing appropriate solutions

- provide a simple tool to be utilized by the user needs team in collaboration with users, to confirm that all user requirements have been discovered, understood and correctly interpreted.

- answer the question so what? for the user.

AHS User Services are described in more detail, with examples in discussion Note 2 - AHS User Services.

Market Packages

These are from a system planning perspective, the basic building blocks of intelligent transportation systems and AHS. They consist of groups or bundles of technologies that collectively address one or more user services, providing tangible, measurable benefits for users. These Lego blocks can be assembled into system frameworks or architectures describing the big future picture in simple terms.

They can also be sequenced over time and space as a way of explaining possible deployment paths from today s transportation context, to the final, future deployment. This will help us to achieve the following:

- Characterize how the AHS is going to meet user requirements
- List the products and features and how each addresses a specific objective, need, or issues or solves a specific problem
- Illustrate how the AHS will provide tangible measurable benefits to the various users

- Explain possible incremental deployment sequences taking account of market influences, technology constraints, standees development, strategic investment and other factors

AHS Market packages are explained in detail, with examples in Discussion Note 3 - AHS Market Packages

What's In The Other Two Documents ?

As indicated above, the second box in the process User Services, is explained in detail in Discussion Note 2 - AHS User Services. The activities required to develop and define user services are explained.

The third box in the process Market Packages is explained in detail in Discussion Note 3 - AHS Market Packages , including information on how to define market packages and examples of market packages.

Why Are We Doing It This Way?

Support of the cycle between what? and how? is a vital part of our proposed approach. We want to ensure that the users are given full opportunity to revise their initial stated requirements in the light of new knowledge about technological capabilities provided in the AHS Market Packages.

To do so effectively, requires that we maintain a clear separation of what and how until the users real needs become clear. This enables the technology experts to concentrate on what they know best, i.e. the how , ensuring that the most appropriate technology grouping are defined and examined.

It also ensures that the users focus on what they know best, i.e. the what , avoiding unproductive how discussions that may be based on misconceptions or misunderstandings regarding technology capabilities and constraints. This also has the benefit of concentrating user resources on agreeing on a collective view of what they want. This might otherwise be difficult, given the widely varying nature of the users.

We have also created three separate discussion notes to make them easier to use for different groups.

Summary

Parsons Brinckerhoff has utilized the User Services and Market Packages concept in project work in the USA, Europe, the Middle East and South East Asia, confirming that the concepts are a proven approach to efficient, effective management of the user requirements analysis process with the context of intelligent transportation systems development. This note describes the intended audience for the discussion notes, explains the objectives, the approach being adopted and the likely benefits of taking such an approach.

We are confident that the adoption and correct utilization of the User Services and Market Packages concepts in tandem will enable us, as a consortium, to fully support a user driven approach to AHS development by facilitating the desired requirements/solution cycle.

Next Steps

Based on the guidance provided by the family of three discussion notes, NAHSC technical analysts within the user needs team can work with users to define a range of AHS User Services. These can then be used by technical analysts within the progressive deployment team to influence the definition and selection of appropriate solutions characterized by AHS Market Packages.

As indicated in figure 1, we expect to support a feedback loop from the initial set of AHS Market Packages (how?) back to the user, leading to consequential changes in the AHS User Services (what?). This will probably lead, in turn, to further modifications, revisions and additions to the AHS Market Packages. We would expect that the Stakeholder Forum in June and presentations in connection with the San Diego demonstration in August will act as major pivot points for this what and how requirements cycle.

10.2.3 AHS User Services

Author Chris Bausher

Automated Highway Systems User Services

Introduction

As the direction of the NAHSC has turned towards safety, infrastructure based applications, and near term deployment, efforts have increased to identify User Services and market packages based on user needs and keeping in mind a future big picture of where AHS wants to be. This is the second of three papers and provides guidance on what a User Service is and how to develop User Services for AHS. Additional papers in this set are available for market package definition and the methodology on AHS User Service and market package development.

Often, as in the National ITS Architecture, the names and terms used to characterize User Services and market packages are the same and lead to confusion. The guidance provided in these documents will assist in clarifying the difference between user services and market packages and will assist in developing clearly defined User Services and market packages.

What is a User Service?

User Services are concise descriptions of what the system has to do, or provide if it is going to be successful from the user s point of view. How to provide the User Service is provided by market packages. User Services encapsulate user preferences, needs, objectives, and issues. Users in this case may include, but is not limited to, private car drivers, commercial vehicle operations (drivers, managers, dispatchers, shippers), transit operations (drivers, managers, dispatchers, riders), and traffic managers (traffic engineers, transportation planners, highway operations specialists). User Services are composed of User Service Requirements or shall statements. Additionally, they must be detailed enough to address all requirements and be concise enough to be useful in guiding an ITS framework and system development. User Service Descriptions are composed of two components:

- a label that identifies the User Service and gives an indication of it s nature
- a description that provides the material required to explain and confirm the User Service to the user and to the developer

History of ITS User Services

National ITS Architecture User Services

The User Service concept was first introduced in the National ITS Program Plan in 1995. Since then the National ITS Architecture development teams have adopted and developed the National ITS Architecture around them. At present there are 30 User Services. These are listed below:

Table 1 - User Services

User Service Bundle	User Service
Travel and Transportation Management	En-Route Driver Information Route Guidance Traveler Services Information Traffic Control Incident Management Emissions Testing and Mitigation Highway - Rail Intersection
Travel Demand Management	Pre-Trip Travel Information Ride Matching and Reservation Demand Management and Operations
Public Transportation Operations	Public Transportation Management En-Route Transit Information Personalized Public Transit Public Travel Security
Electronic Payment Services	Electronic Payment Services
Commercial Vehicle Operations	Commercial Vehicle Electronic Clearance Automated Roadside Safety Inspection On-Board Safety Monitoring Commercial Vehicle Administrative Processes Hazardous Material Incident Response Commercial Fleet Management
Emergency Management	Emergency Notification and Personal Security Emergency Vehicle Management
Advanced Vehicle Control and Safety Systems	Longitudinal Collision Avoidance Lateral Collision Avoidance Intersection Collision Avoidance Vision Enhancement for Crash Avoidance Safety Readiness Pre-Crash Restraint Deployment Automated Highway Systems

Example from the National ITS Architecture

As an aid to understanding the User Service concept, here is an example taken from the National ITS Architecture development program. This is an excerpt of the description for the Route Guidance User Service:

> 1.3 ROUTE GUIDANCE
>
> 1.3.0 IVHS shall include a Route Guidance (RG) function. Route Guidance will provide travelers with directions to selected destinations. Four functions are provided which are (1) Provide Directions, (2) Static Mode, (3) Real-Time Mode, and (4) User Interface.
>
> 1.3.1 RG shall include the capability to Provide Directions to travelers.
>
> 1.3.1.1 The Provide Directions function shall provide travelers with directions to their selected destination locations.

1.3.1.2 The Provide Directions function shall issue directions to travelers that is based on information about current conditions of transportation systems.
1.3.1.2.1 Current transportation system conditions upon which directions to travelers is based shall include, but not be limited to, the following:
  1.3.1.2.1(a) Current traffic conditions.
  1.3.1.2.1(b) Status of transit systems.
  1.3.1.2.1(c) Schedules of transit systems.
  1.3.1.2.1(d) Events taking place that influence travel routes.
  1.3.1.2.1(d).1 Street closures.
  1.3.1.2.1(d).2 Pedestrian events.
  1.3.1.2.1(d).3 No pedestrian zones.
1.3.1.3 The Provide Direction function shall issue traveler directions that are simple and easy to understand in the form of arrow displays or voice messages providing turning instructions of which way to turn onto including, but not limited to, the following:
  1.3.1.3(a) Particular streets.
  1.3.1.3(b) Roads.
  1.3.1.3(c) Walkways.
  1.3.1.3(d) Transit facilities.

Defining and Developing User Services

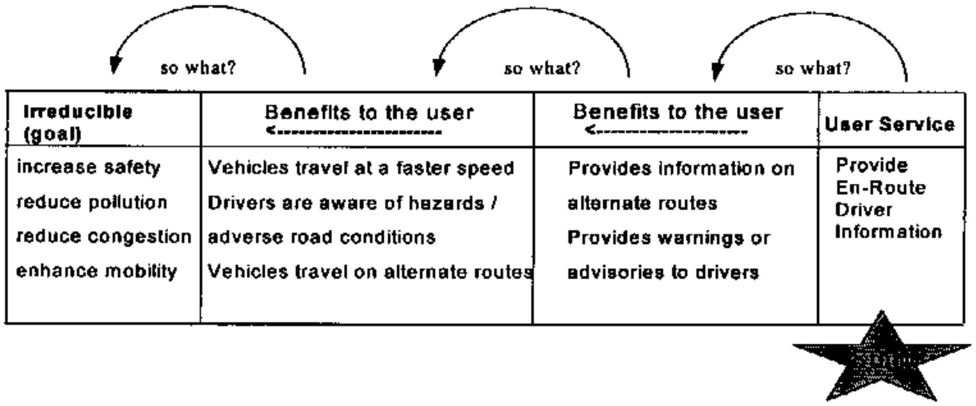
User Services, while identified in the National ITS Architecture, may be modified or developed to specifically address stated needs. We need our User Service definitions to be more than just abstract labels, they need to have enough detail to enable the user to really relate to the User Service, being able to see exactly what s in it for them. The following process has been found to be useful in generating User Services in a simple, structured way:

1.) Develop a label. In order to make a clear distinction between User Service and Market Package labels all User Service labels start with a verb. This label gives some indication of the nature of the User Service, but does not convey all the descriptive information.

2.) Identify user requirements. This step involves the collection of requirements identified by the user. These may take the form of problems, objectives, issues, needs, and preferences. It is these requirements which must be determined in order to develop User Services. They are typically unstructured comments or statements and may even be stated by the user in the form of a solution.

3.) Develop shall statements. This step involves taking the user requirements and developing shall statements to encapsulate them. Shall statements are structured statements which describe what needs to be provided. These may be very high level (e.g. it shall provide traffic surveillance) or more detailed (e.g. it shall determine actions necessary to maintain the vehicle at a safe distance behind a lead vehicle). The key in developing these is not stating how it will be done. The shall is often dropped from the statement to avoid repetition, if this is done then it is important to ensure that the remaining statements start with a verb.

4.) Perform "So what?" analysis. This step involves the generation of further descriptive information required to fully explain the User Service, through identification of potential benefits to the user and identification of irreducibles or goals which the User Service addresses. This is done by asking "so what?" of the User Service. Asking "so what?" assists in describing benefits to the user or what the system will provide from the users point of view. The final result of this process is the irreducible or goal and a set of intermediate information forming the basis for the description of the User Service. An example of this is shown below in Figure 1.



Irreducible (goal)	Benefits to the user <--------------------	Benefits to the user <------------------	User Service
increase safety reduce pollution reduce congestion enhance mobility	Vehicles travel at a faster speed Drivers are aware of hazards / adverse road conditions Vehicles travel on alternate routes	Provides information on alternate routes Provides warnings or advisories to drivers	Provide En-Route Driver Information

Figure 1 - So What? Analysis

It is important to note that the irreducibles are the final product of the process, but not the real focus. The real aim is to develop the material in the middle columns into useful User Service descriptions.

The following are the goals or irreducibles which may result from the so what? analysis:

- **Increase operational efficiency and capacity of the transportation system.** A central goal of ITS, including AHS, is to better utilize the capacity and increase the operational efficiency of the surface transportation system. In fact, this goal actually underlies and enables attainment of several of the other ITS goals. Reducing congestion, providing reliable information on which travelers can make better travel decisions, eliminating the delays of toll collection, and more traffic-responsive coordination of traffic lights all contribute to enhanced effective capacity and efficiency, as well as to general mobility, productivity, more efficient use of resources, and reduced environmental impact.

- **Enhance personal mobility and the convenience and comfort of the transportation system.** Goal 1 makes a major contribution toward this, as will public transportation systems that are more convenient and cost-effective. New control systems will increase transit automation and predictability. Intermodal management services will improve connections between modal systems and increase trip end opportunities. Increased availability of high-fidelity traveler information will enable better informed travelers to make the best transportation choices.

- **Improve the safety of the Nation s transportation system.** There is need for safety improvement, particularly in overcoming human error in vehicle operation, preventing or reducing the severity of injuries in collisions, and enhancing traveler security in all transportation modes. Safety is a key consideration in the implementation of all AHS and ITS services, but the most dramatic gains are expected to derive from the Advanced Vehicle Control and Safety Systems.

- **Reduce energy consumption and environmental costs.** Our ability to use energy more efficiently and reduce environmental costs will depend, in part, on the technologies applied through the ITS program. More efficient energy use and improved air quality can be achieved by services which encourage public transportation use, increase average vehicle occupancy, smooth traffic flow, and manage travel demand. Better use of existing transportation resources will positively impact land use by reducing requirements for new infrastructure.

- **Enhance the present and future economic productivity of individuals, organizations and the economy as a whole.** Transportation is an integral part of nearly all productive processes, and making transportation more efficient (Goal 1) lets all these processes be more efficient. This applies as well to individuals in their daily lives: commuting, shopping, socializing. Thus more efficient routing, reduced travel times, and more efficient administration of the transportation system will enable productivity gains across the spectrum of the economy.

When defining a User Service one must include the following:

- Listing of raw user requirements
- The User Service label , beginning with a verb
- Shall statements defining what is needed
- So what? analysis to determine benefits to the user and goals addressed

The following statements may be used as a checklist to assist in definition of User Services and to ensure they fulfill their purpose.

- User Services are user driven (stakeholders and consumers)
- User Services are based on understanding stakeholder needs
- User Services describe WHAT , not HOW
- User Services explain and capture what the system has to provide in order to be considered successful by the stakeholder or user of the system
- User Services are clear concise statements of user needs
- User Services may build upon National ITS Architecture work

- User Services are technology independent
- User Services are derived from user problems, objectives, issues, needs, and preference

Conclusion

Given this guidance, User Services may be developed which draw upon the user stated requirements and provide relevant information for the identification and development of market packages. Following is an example of an AHS User Service as well as a template to develop others.

C3 Interim Report

Appendix 10.3 Deployment Strategy

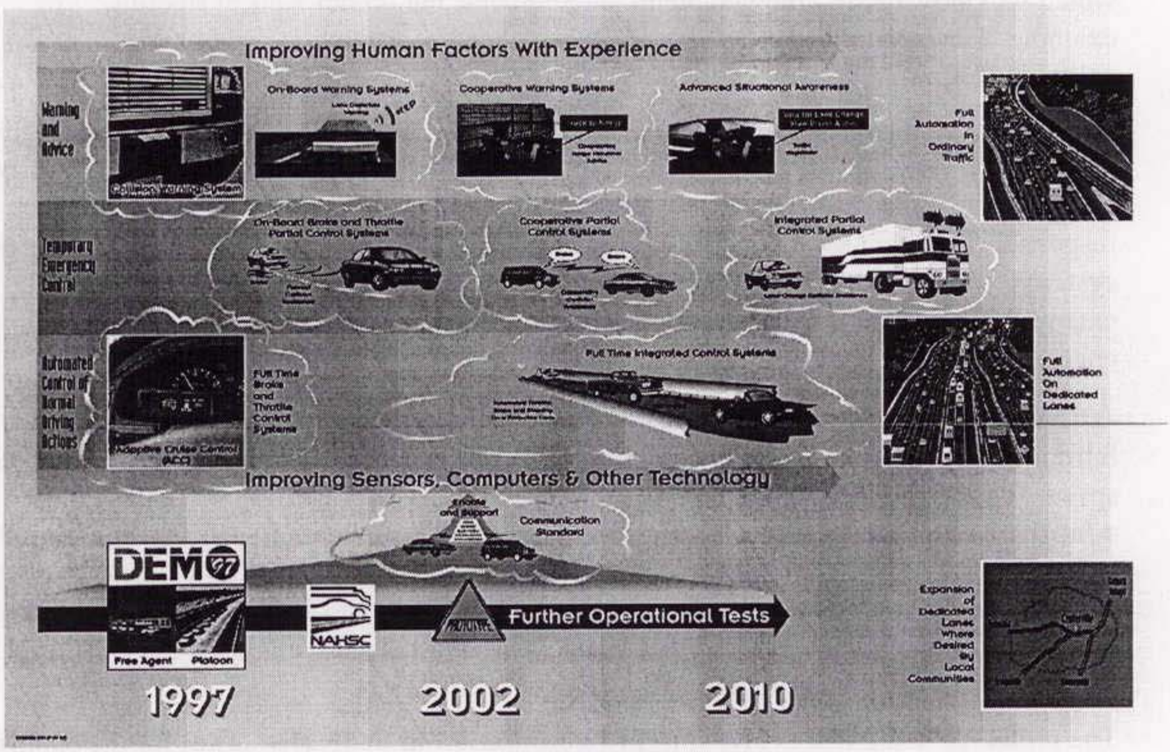
Includes:
10.3.1 Demo '97 Deployment Roadmap
10.3.2 Automated Highway Systems Market Packages
10.3.3 Market Package Matrix
10.3.4 The Deployment Map
10.3.5 Transitions
10.3.6 Defining and Developing AHS Market Packages
10.3.7 Issues, Constraints, Guidelines and Policies
10.3.8 Deployment Strategies
10.3.9 AVC Services Compendium
10.3.10 Functional Evolution of an AHS for Incremental Deployment
10.3.11 Orthogonal Capability Building Blocks for Flexible AHS Deployment
10.3.12 A Hybrid Human-Computer Autonomous Vehicle Architecture

NAHSC

10.3.1 Demo '97 Deployment Roadmap

Tom McKendree, Author

The following figure was handed out at the 1997 Demonstration of Technical Feasibility as the main content of a flier entitled "Deployment Roadmap: From Warning and Control to Full Automation." The text, which was on the back of the flier, is repeated below.



The Automated Highway System will grow from technologies being developed or currently on the road. The Federal Highway Administration (FHWA), the National Highway Traffic Safety Administration (NHTSA), the Office of Motor Carriers (OMC), the Federal Transit Administration (FTA) and many vehicle makers are all doing research or developing products. These products will provide three levels of automated driver assistance leading towards full automation of throttle, brake and steering.

Warning and Advice - The first level of driver assistance is **on-board warning systems.** A **collision warning system** for trucks has been available since 1994 [Editor's Note: the picture is from Eaton-Vorad]. Other on-board warning systems will be developed as the industry gains human factors experience with warning systems. For example, a **lane departure warning** product will detect the lane boundaries and alert the driver if the vehicle drifts out of the lane.

As computers and communications become more capable and less costly, the next generation of warning products will incorporate electronic information from the roadside or other vehicles. Because they share information, these systems are called **cooperative warning systems**. They will grow into highly sophisticated **advanced situational awareness** systems that keep the driver appraised of the overall driving situation. They will fuse information from sensors, from other vehicles and from the roadside to warn the driver of potential problems and to improve driving efficiency.

Temporary Emergency Control - These not only detect potential problems, but automatically react to them. They take advantage of the reliable, fast and precise reactions of automated systems, but allow the driver full control of ordinary driving actions. The earliest will be **on-board brake and throttle partial control systems**, which will slow or stop the vehicle in emergencies, but do not control steering. For example, **forward collision avoidance** looks ahead of the vehicle and brakes if a collision is imminent.

As in the warning systems, the next generation will incorporate communications to give **cooperative partial control systems**. An example is **cooperative collision avoidance**, in which the vehicles inform each other of their actions, giving a faster, more precise response. The most sophisticated emergency systems will be **integrated partial control systems**, which control steering as well as brakes and throttle in an emergency. For example, **lane change collision avoidance** will automatically abort an unsafe lane change.

Automated Control of Normal Driving Actions - These products will introduce full time control of the vehicle. Today's cruise control automatically controls speed. The next generation of **full time brake and throttle control systems**, called **adaptive cruise control**, now under development, will maintain a safe distance from the vehicle ahead. The first vehicles to include automated steering will provide **automated throttle, brake and steering on a protected lane**. Protected lanes have barriers to keep out obstacles and vehicles from other lanes. These protected lanes would also be used by conventional vehicles during the early years of automation.

The protected lanes will evolve into **full automation in dedicated lanes** for the exclusive use of AHS vehicles, when there are enough automated vehicles to make this practical. Operating only automated vehicles in dedicated lanes will allow doubling or tripling the lane capacity. As automate technology matures, **full control in ordinary traffic** eventually will be possible.

Also, the AHS will grow geographically from **expansion of dedicated lanes where desired by local communities**. The map shows a community that started with automation on one heavily congested highway, from Suburbia to downtown Centerville, and later extended automation to other areas.

The **National Automated Highway Systems Consortium (NAHSC)** was formed in 1994 by a cooperative agreement between FHWA and a partnership of government, university and industry to bring automation to America's highways. The Consortium's **Demo97** is currently showing a range of automated vehicles on an HOV lane. By 2002, the Consortium will build an automated highway **prototype**. This will be followed by **further operational tests** of automated highway systems.

To **enable and support** deployment of automated highway systems, the Consortium will provide demos, prototypes, operational tests, standard, specifications and deployment plans. One example is **communications standards**, which define how vehicles communicate with each other and with the roadside for seamless implementation across the country.

This **Deployment Roadmap** shows that the Automated Highway System is a range of technologies and products to meet many driving needs. Some products are available now, some in a few years, and all lead to safer, more efficient and more comfortable highway travel for everyone.

Automated Highway System Market Packages

24 September 1997

NAHSC
C3 Progressive Deployment Team

(Lead Author, Tom M^{c}Kendree)

Introduction

This document provides a quick overview of the various market packages that have been defined to date as part of the AHS Progressive Deployment effort.

It is recognized that the following list of market packages may be too detailed to carry over to the ITS Architecture as top level market packages. Thus, these market packages may be grouped, with the current "market packages" being finer gradations of some final list of market packages.

A Warning and Advice Market Packages

[Note: The general warning format, audible, visual, kinesthetic, etc., as well as the detailed human interface design, remains largely TBD.]

A.1 Autonomous Warning and Advice Market Packages

A.1.a Frontal Collision Warning without Communication

A frontal collision warning (FCW) system without communication warns the driver of an impending frontal collision when the time to collision with the preceding vehicle exceeds a predefined limit, when there is a violation of the minimum allowable headway distance to the preceding vehicle, or when there is a threatening forward obstacle. The system relies solely on sensing the state (e.g., range, range rate, and velocity) of the preceding vehicle.

A.1.b Curve Overspeed Warning

The vehicle monitors its speed, and knows about impending curves. (Possible approaches include on-board sensors, and on-board navigation combined with a map database.) When the vehicle is approaching a curve at a potentially excessive speed, the vehicle alerts the driver about the situation and to slow down. The alarm threshold could be adjustable to promote customer acceptance.

A.1.c Blind Spot Warning

Blind Spot Warning provides the driver with an indication that there is a vehicle in an adjoining lane, in close proximity to the subject vehicle.

A.1.d Side Collision Warning

Side Collision Warning notifies the driver that a collision with a vehicle in an adjoining lane is likely. This system is designed to respond to two conditions: 1) The driver is drifting or swerving toward vehicles in an adjoining lane, or 2) a vehicle in an adjoining lane is drifting or swerving too close to the subject vehicle—invading the "safe space bubble".

A.1.e Lane Change Collision Warning

Lane Change Collision Warning notifies the driver of the presence of overtaking vehicles as well as vehicles in the adjacent lane. This system is enabled concurrent with the lane change ("turn signal") indicator. If vehicle sensors detect a vehicle in the adjoining lane, or sense a vehicle quickly approaching (which would endanger the lane change) an alarm would notify the driver of the hazardous condition.

A.1.f Lane Departure Warning

Sensors would detect the position of the vehicle relative to the lane boundaries and/or roadway shoulders. The driver would be warned when the vehicle approached and/or exceeded the lane boundaries. Warnings could be graduated so that they increase in intensity as the lane edge is breached.

A.1.g Autonomous Road Surface Condition Warning

Sensors on-board the vehicle would detect when the tire-to-road surface coefficient of friction is reduced due to water, ice or road surface condition. The driver would be warned of reduced traction; this warning could increase as the severity of the loss of friction increases. The capability of this service could vary substantially from a simple lamp that warns of possible traction loss (as some vehicles have today) to an indication of the percent of traction loss; this could be needed with systems that control the vehicle response to the traction loss.

[A desirable but challenging extension would be on-board ability for vehicles to determine preview road surface conditions.]

A.1.h Traffic Situation Awareness

The vehicle fuses data from multiple on-board sensors to create a detailed picture of the immediately surrounding traffic situation, and presents that information to the driver on an ongoing basis. It is left to the driver to decide on how to act on the information. The human interface is TBD, but for high-end systems could be significant. Not overwhelming the driver is a significant concern. Many output characteristics may be customizable, to promote customer acceptance.

A.1.i Unsafe Driving Situation Warning

This capability is based on having tactical layer intelligence, reasoning about traffic as individually moving vehicles with a time horizon of many seconds, coupled with an array of sensors that detect the surrounding traffic. This capability could have many permutations, from a head-up advisory that indicates where all surrounding traffic is and accelerator pedal signal if the closing rate to other vehicles is too high to driver warnings and suggestions about the traffic scene. The intention is for this capability to go beyond detecting existing situations and moving into an arena of predicting the traffic scene forward in time. Probabilistically analyzing these projections may enable "proactive defensive driving," which identifies dangerous driving situations before they unfold and can be detected by sensors alone.

The human interface to best use this information is likely to be a subject of substantial research, with the utility of warning and advice, versus temporary control and versus ongoing control being an important subject to resolve.

A.1.j Merge Maneuver Advisor

This capability is based on having tactical layer intelligence coupled with an array of sensors that detect the surrounding traffic. A possible version of this is to have a head-up display indicating the viable and the best gaps to merge into, as well as an indication of unacceptable gaps. This capability is based on in-vehicle intelligence which takes information about surrounding-vehicle motion, predicts the motion of these vehicles forward in time, and takes into account the limits of the vehicle and the driving style of the individual driver that it is advising. The interface must be capable of directing the driver to accelerate and merge at the proper times, with consideration for all forward vehicles and for the ramp length.

A.1.k Lane Change Maneuver Advisor

Lane change maneuver advice is more simple than merge maneuver advice, in that the same capability is provided without the added restraint of the lane ending. Otherwise, this is similar to Merge Maneuver Advice.

A.1.l Traffic Negotiator

Negotiating through traffic (in the sense of maneuvering a vehicle through other vehicles, not bargaining with other vehicles), is a particularly difficult problem, requiring an array of sensors and tactical layer reasoning. This capability could be used to work across several lanes of traffic to get to an exit point, or to negotiate out of a "boxed in" driving situation, for example. This is an extension of the capabilities outlined in Autonomous Defensive Driving Advisory, and Autonomous Merge Maneuver Advisory, given a particular intent on the part of the driver (e.g., maneuver to exit in 2 miles).

A.1.m Vehicle Condition Warning

Today's vehicles have some form of vehicle condition monitoring such as oil pressure and coolant temperature. This service would go a step further and monitor the vehicle's safety related functions. Examples of conditions monitored include tire pressure, sensor and actuator performance, and communication system. The warnings would be given to the driver, or for those cases involving some form of automated control, the warnings/notices would be given to the system.

A.1.n Driver Condition Warning

Driver condition is monitored on-board the vehicle; if the driver is detected drowsy or otherwise incapacitated, warnings would be given to the driver to stop until the condition was overcome or the vehicle was turned off. Detection may be based on driving performance, psychophysiological measures of alertness, or both.

A.2 Cooperative Warning and Advice Market Packages

A.2.a Cooperative Frontal Collision Warning

A frontal collision warning (FCW) system with communication warns the driver of an impending frontal collision when either the time to collision with the preceding vehicle exceeds a predefined limit, when there is a violation of the minimum allowable headway distance to the preceding vehicle, or when there is a threatening forward obstacle. An FCW with communication provides for the exchange of vehicle state information (e.g., range, range rate, and velocity), via point-to-point or broadcast transmission, between the preceding and following vehicles, and for cooperative alerting of obstacles. The system does not preclude the use of sensing: sensing can be used in parallel with communication to provide for redundancy in case of failure of the communication subsystem, and sensing can be used to acquire select vehicle-state information in order to minimize the bandwidth and other performance requirements placed on the communication subsystem.

A.2.b Cooperative Curve Overspeed Warning

The vehicle monitors its speed, and knows about impending curves, including location, curve radius, potentially super-elevation, and potentially road surface information. The knowledge of impending curves can come from other vehicles or infrastructure outside the vehicle. When the vehicle is traveling through a curve, it will broadcast the fact of that curve to other vehicles. Thus, an on-board ability to predict curves is not required. Local highway authorities may choose to deploy curve warning beacons at notable locations. This could be integrated with Cooperative Road Surface Conditions Warning to alert about things like ice on curves. When the vehicle is approaching a known curve at a potentially excessive speed, the vehicle alerts the driver about the situation and to slow down. The alarm threshold could be adjustable to promote customer acceptance. The vehicle will also broadcast its performance in this maneuver, and will alert other vehicles if it may be traveling too fast for a curve.

A simplified version of Cooperative Curve Overspeed Warning has been suggested, which does not include the ability of vehicles to autonomously determine that a curve is impending. While such a simplified version may be deployable sooner, the version described here is also desirable, as some curves will not be marked with an infrastructure broadcast, nor immediately traveled by a broadcasting lead vehicle.

A.2.c Cooperative Blind Spot Warning

Same as Blind Spot Warning, except that communication systems are used to supplement or replace vehicle sensors. For example, vehicles may broadcast "I am here" messages, describing their position and immediate trajectory.

A.2.d Cooperative Side Collision Warning

Same as Side Collision Warning, except that communication systems are used to supplement or replace vehicle sensors.

A.2.e Cooperative Lane Change Collision Warning

Same as Lane Change Collision Warning, except that communication systems are used to supplement or replace vehicle sensors.

A.2.f Cooperative Lane Departure Warning

Same as Lane Departure Warning, except that communication systems are used to supplement or replace vehicle sensors. For example, the infrastructure or other vehicles may inform the vehicle they detect the vehicle drifting in its lane.

A.2.g Cooperative Road Condition Warning

Sensors on-board the vehicle would detect when the tire-to-road surface coefficient of friction is reduced due to water, ice or road surface condition. This information would be broadcast to other vehicles in the vicinity, provide them early warning. Warnings can also come where intelligence infrastructure is deployed, both roadside sensors and broadcasts directed by the roadway operators. The drivers would be warned of reduced traction; this warning could increase as the severity of the loss of friction increases. The capability of this service could vary substantially from a simple lamp that warns of possible traction loss (as some vehicles have today) to an indication of the percent of traction loss; this could be needed with systems that control the vehicle response to the traction loss.

A.2.h Cooperative Traffic Situation Awareness

The vehicle fuses data from multiple on-board sensors to create a detailed picture of the immediately surrounding traffic situation. With other vehicles [and optional infrastructure] their shared local traffic pictures are fused, and digests of the immediate situation are broadcast up and down stream. When the information is available, the span of interest for each vehicle extends at least as far forward as the gentle stopping distance of the vehicle, and far enough back to include all vehicles where it is within their gentle stopping distance. The vehicle probably tracks farther out in less detail, where available, such as all lane blockages out to the next exit.

The vehicle presents the local traffic picture to the driver on an ongoing basis. It is left to the driver to decide on how to act on the information. The human interface is TBD, but for high-end systems could be quite extensive. Many output characteristics may be customizable, to promote customer acceptance.

The full communications standard included in this package should be designed to support, or grow to support, the full requirements for vehicle communications across all the market packages.

A.2.i Cooperative Defensive Driving Advisory

Communication adds another element to Autonomous Unsafe Driving Situation Warning, by providing additional information about the surrounding traffic scene. Vehicle-to-vehicle communication could provide pre-brake warnings, hazardous object warnings, and accident warnings. Infrastructure-to-vehicle communication likewise can provide hazardous object warnings, roadway condition warnings, etc. These data, by providing additional information to the vehicle, supplement the capability suggested in Autonomous Unsafe Driving Situation Warning.

A.2.j Cooperative Merge Maneuver Advisory

Several possibilities exist for enhanced merging assistance when communications are enabled. First, potential communication with other vehicles enables those vehicles to provide assurances as to the maintenance of gaps in the main-line (or the creation of gaps, if necessary). This vehicle-to-vehicle communications may provide higher safety margins given the increased knowledge, and influence which gaps are recommended given these assurances. Given that communications may not be enabled on all surrounding vehicles, Autonomous Merge Maneuver Advisor capability would need to be fully operational within the vehicle.

A second possibility exists with infrastructure-based merge support once communications is enabled. The infrastructure may also look for gaps in upstream traffic, negotiate the creation of gaps, etc., and "launch" merging vehicles into traffic when gaps are available. This could be particularly useful on older roadways where a number of blind merges make traffic dangerous and congested. On any roadway it should provide smoother traffic flow.

A.2.k Cooperative Lane Change Maneuver Advice

Lane change maneuver advice with communication enables vehicle-to-vehicle negotiation in searching for an acceptable gap to merge into. These assurances may provide additional information and may influence which gap the vehicle recommends. Infrastructure support is less likely than for Cooperative Merge Maneuver Advice, since lane changes may happen along the full length of multiple lanes.

A.2.l Cooperative Traffic Negotiator

Enabling communication between vehicles provides additional information that the vehicle folds into the decision-making process. Otherwise this is like Autonomous Traffic Negotiator.

A.2.m Cooperative Vehicle Condition Warning

Same as Vehicle Condition Warning with two differences. First, communications could be used to supplement vehicle sensors, for example by detecting loose wheels or erratic behavior. Second, vehicles would broadcast any weakened vehicle conditions so that other traffic could take precautions.

A.2.n Driver Condition Warning (with communications)

Same as Driver Condition Warning. In addition, a warning may be given to other vehicles and/or to the roadside.

A.2.o Road Management Situation Warning (RMSW)

This warning system will warn the driver of on-coming road hazards such as construction, maintenance, accidents, the presence of active emergency vehicles on the freeways, or any situation that would bring out a roadcrew. Information regarding these planned (maintenance and construction) or unplanned (accidents and/or presence of active emergency vehicles) events will be provided to each vehicle equipped with this system provided this vehicle is approaching the event site in next TBD seconds. Information may consist of location, type of event, time to clear the event, available exits, temporary speed limit, etc.

Information could be transferred from intelligent warning signs to the vehicles in case of planned events. In case of unplanned events, vehicle will pass the information to other vehicles after detecting it.

A.2.p Cooperative Intersection Warning

The vehicle would receive communications from other vehicles and/or the infrastructure alerting the driver both to when the driver is handling the intersection improperly, and when another vehicle threatens the instrumented vehicle at an intersection.

A.2.q Cooperative Railroad Crossing Warning

The vehicle would receive communications from the railroad and potentially other vehicles alerting the driver of trains in the area.

B Market Packages Providing Temporary Emergency Control

B.1 Autonomous Emergency Control Market Packages

B.1.a Frontal Collision Avoidance of Obstacles and Vehicles (brake only)

A frontal collision avoidance (FCA) system maintains a safe longitudinal separation between the preceding and following vehicles via background monitoring with intervention, through a warning, and if necessary, automatic braking, in response to a system-perceived crash threat (i.e., obstacle or another vehicle). While engaged, the system monitors the area in front of the vehicle for obstacles and other vehicles—both stationary and moving. The system relies solely on sensing of vehicle-in-front state information (e.g., range, range rate, and velocity) and obstacle detection and state information.

Note, frontal collision avoidance of vehicles is provided as part of the (Advanced) Adaptive Cruise Control package.

B.1.a' Frontal Collision Resistance of Obstacles and Vehicles (brake only)

A frontal collision resistance (FCR) system maintains a safe longitudinal separation between the preceding and following vehicles via background monitoring with intervention, through a warning, and if necessary, automatic braking, in response to a system-perceived crash threat (i.e., obstacle or another vehicle), and driver-engaged automatic maintenance of speed, headway, or path control. While engaged, the system monitors the area in front of the vehicle for obstacles and other vehicles—both stationary and moving. The system relies solely on sensing of vehicle-in-front state information (e.g., rate, range rate, and velocity) and obstacle detection and state information. During system intervention, the system applies *partial-authority* braking: the driver can override the automatic control system's actions at any time.

B.1.b Curve Overspeed Avoidance

The vehicle monitors its speed, and knows about impending curves. (Approaches include on-board sensors, and on-board navigation combined with a map database.) When the vehicle is approaching a curve at a potentially excessive speed, the vehicle alerts the driver about the situation and to slow down. This may be done with upward force on the accelerator pedal, "nudging" the driver to take the desired action. If the driver does not respond, the vehicle will slow down on its own. In *extremis*, the vehicle may engage its brakes to slow down to a safe speed for the curve. The alarm threshold might be adjustable to promote customer acceptance.

B.1.b' Curve Overspeed Resistance

The vehicle monitors its speed, and knows about impending curves. (Approaches include on-board sensors, and on-board navigation combined with a map database.) When the vehicle is approaching a curve at an excessive speed, the vehicle alerts the driver about the situation and to slow down. If the driver tries to accelerate to an excessive (or more excessive) speed for an impending curve, the vehicle's accelerator provides significantly greater than normal resistance to discourage this, although it still may be overridden. The alarm threshold might be adjustable to promote customer acceptance.

B.1.c Blind Spot Collision Avoidance

Blind Spot Collision Avoidance determines when there is a vehicle in an adjoining lane, in close proximity to the subject vehicle. If the driver indicates and starts to execute a lane change into where there is an adjacent vehicle and, the subject vehicle, under temporary emergency control, will change trajectory to avoid moving into the vehicle in its blind spot. The driver may override this. Driver warnings with appropriate human factors would also be integrated into this market package.

B.1.c' Blind Spot Collision Resistance

Blind Spot Collision Resistance determines when there is a vehicle in an adjoining lane, in close proximity to the subject vehicle. If so, the vehicle controls will provide increased resistance to commands that would drive the vehicle into the detected vehicle. The driver may override the system. Driver warnings with appropriate human factors would also be integrated into this market package.

B.1.d Side Collision Avoidance

Similar to Side Collision Warning except that in the event that the driver does not respond sufficiently to eliminate the threat of a collision the control of the vehicle is subsumed by automated vehicle controls. The driver can override the automated control.

B.1.d' Side Collision Resistance

Similar to Side Collision Avoidance except that instead of the control of the vehicle being subsumed, the driver is alerted through haptic feedback resisting the wheel turn, discouraging continuing the collision course.

B.1.e Lane Change Collision Avoidance

Similar to Lane Change Collision Warning except that in the event that the driver does not respond sufficiently to eliminate the threat of a collision the control of the vehicle is subsumed by automated vehicle controls. The driver can override the automated control.

B.1.e' Lane Change Collision Resistance

Similar to Lane Change Collision Avoidance except that instead of the control of the vehicle being subsumed, the driver is alerted through haptic feedback resisting the wheel turn, discouraging continuing the collision course.

B.1.f Lane Departure Avoidance

Similar to Lane Departure Warning except that in the event that the driver does not respond sufficiently to eliminate the threat of a collision the control of the vehicle is subsumed by automated vehicle controls. The driver can override the automated control.

B.1.f' Lane Departure Resistance

Similar to Lane Departure Avoidance except that instead of the control of the vehicle being subsumed, the driver is alerted through haptic feedback resisting the wheel turn, discouraging continuing the collision course.

B.1.g Autonomous Road Surface Condition Emergency Control

Sensors on-board the vehicle would detect when the tire-to-road surface coefficient of friction is reduced due to water, ice or road surface condition. In addition to warning the driver as in Part A, if the system determines that the vehicle is traveling too fast for the measured coefficient of friction, the power to the drive wheels would be reduced. In dire conditions, brakes would be applied (but only if the vehicle is equipped with differential braking capability).

B.1.n Driver Condition Mitigation - Avoidance

If the monitoring of the driver's condition indicates drowsiness or other incapacitation, then this service would respond to reduce possible incident occurrence. The vehicle response would depend on the vehicle's control sophistication and the driver's involvement. If the driver was responsible for driving functions at the time that the incapacity was detected, then at the least, the system would attempt to alert the driver while simultaneously slowing the vehicle and activating its warning lights. An advanced form of this service might be Integrated Background Longitudinal and Lateral Warning with Temporary Emergency Control, (service 6.4 in AVC Services Compendium); this service could maintain full vehicle control if the driver was incapacitated. There is a concern expressed in the Compendium about whether service 6.4 would attempt to park the vehicle or continue to "herd" the vehicle along the lane. Effective driver condition mitigation requires the capability to provide fully automated operation in mixed traffic.

B.1.n' Driver Condition Mitigation - Resistance

It may be that a similar sort of humans factors difference, like the Avoidance-Resistance distinction that seems relevant to other temporary emergency control market packages, may be relevant for Driver Condition Mitigation. Driver Condition Mitigation - Resistance is reserved for this purpose.

B.2 Cooperative Emergency Control Market Packages

B.2.a Cooperative Frontal Collision Avoidance of Obstacles and Vehicles (brake only)

A cooperative frontal collision avoidance system maintains a safe longitudinal separation between the preceding and following vehicles via background monitoring with intervention, through a warning, and if necessary, automatic braking, in response to a system-perceived crash threat (i.e., obstacle or another vehicle), and driver-engaged automatic maintenance of speed, headway, or path control. While engaged, the system monitors the area in front of the vehicle for obstacles and other vehicles—both stationary and moving. The system relies on sensing *and* communication of vehicle-state information (e.g., range, range rate, and velocity) and obstacle detection and state information.

B.2.a' Cooperative Frontal Collision Resistance of Obstacles and Vehicles (brake only)

A cooperative frontal collision resistance system maintains a safe longitudinal separation between the preceding and following vehicles via monitoring with intervention, through a warning, and if necessary, automatic braking, in response to a system-perceived crash threat (i.e., obstacle or another vehicle), and driver-engaged automatic maintenance of speed, headway, or path control. While engaged, the system monitors the area in front of the vehicle for obstacles and other vehicles—both stationary and moving. The system relies on sensing and communication of vehicle-in-front state information (e.g., range, range rate, and velocity) and obstacle detection and state information. During system intervention, the system applies *partial-authority* braking.

B.2.b Cooperative Curve Overspeed Avoidance

The vehicle monitors its speed, and knows about impending curves. The knowledge of impending curves can come from other vehicles or infrastructure outside the vehicle. When the vehicle is traveling through a curve, it will broadcast the fact of that curve to other vehicles. Thus, an on-board ability to determine when curves are impending may not be required. Nonetheless, for robustness in an actuated vehicle system, some on-board means of determining approaching curves is very desirable as a backup and redundant check.

Local highway authorities may choose to deploy curve warning beacons at notable locations. This could be integrated with Cooperative Road Surface Conditions Avoidance. When the vehicle is approaching a known curve at a potentially excessive speed, the vehicle alerts the driver about the situation and to slow down. This may be done with upward force on the accelerator pedal, "nudging" the driver to take the desired action. If the driver does not respond, the vehicle will slow down on its own. In extremis, the vehicle may engage its brakes to slow down to a safe speed for the curve. The proper human interface is TBD. The alarm threshold might be adjustable to promote customer acceptance.

The vehicle will also broadcast its performance in this maneuver, and will alert other vehicles if it may be traveling too fast for a curve.

B.2.b' Cooperative Curve Overspeed Resistance

The vehicle monitors its speed, and knows about impending curves. The knowledge of impending curves can come from other vehicles or infrastructure outside the vehicle. When the vehicle is traveling through a curve, it will broadcast the fact of that curve to other vehicles. Thus, an on-board ability to determine when curves are impending may not be required. Nonetheless, for robustness in an actuated vehicle system, some on-board means of determining approaching curves is very desirable as a backup and redundant check.

Local highway authorities may choose to deploy curve warning beacons at notable locations. This could be integrated with Cooperative Road Surface Conditions Resistance. When the vehicle is approaching a known curve at a potentially excessive speed, the vehicle alerts the driver about the situation and to slow down. If the driver tries to accelerate to an excessive (or more excessive) speed for an impending curve, the vehicle's accelerator provides significantly greater than normal resistance to discourage this, although it still may be overridden. The proper human interface is TBD. The alarm threshold might be adjustable to promote customer acceptance.

The vehicle will also broadcast its performance in this maneuver, and will alert other vehicles if it may be traveling too fast for a curve.

B.2.c Cooperative Blind Spot Collision Avoidance

Determines when there is a vehicle in an adjoining lane, in close proximity to the subject vehicle, through sensors and/or communications. If there is an adjacent vehicle and the subject vehicle is moving towards it, the subject vehicle, under temporary emergency control, will avoid moving into the vehicle in the blind spot, broadcasting to the immediate vicinity its change in trajectory. The driver may override the system. Driver warnings with appropriate human factors would also be integrated into this market package.

B.2.c' Cooperative Blind Spot Collision Resistance

Determines when there is a vehicle in an adjoining lane, in close proximity to the subject vehicle, through sensors and/or communications (including "I am here" and "I see a vehicle there" messages). If so, the vehicle controls will provide increased resistance to commands that would drive the vehicle into the detected vehicle. The driver may override this resistance, in which case the subject vehicles would broadcasting to the immediate vicinity its change in trajectory and impending collision. Driver warnings with appropriate human factors would also be integrated into this market package.

B.2.d Cooperative Side Collision Avoidance

Same as Side Collision Avoidance except that communication systems are used to supplement or replace vehicle sensors.

B.2.d' Cooperative Side Collision Resistance

Same as Side Collision Resistance except that communication systems are used to supplement or replace vehicle sensors.

B.2.e Cooperative Lane Change Collision Avoidance

Same as Lane Change Collision Avoidance except that communication systems are used to supplement or replace vehicle sensors.

B.2.e' Cooperative Lane Change Collision Resistance

Same as Lane Change Collision Resistance except that communication systems are used to supplement or replace vehicle sensors.

B.2.f Cooperative Lane Departure Avoidance

Same as Lane Departure Avoidance except that communication systems are used to supplement or replace vehicle sensors.

B.2.f' Cooperative Lane Departure Resistance

Same as Lane Departure Resistance except that communication systems are used to supplement or replace vehicle sensors.

B.2.g Cooperative Road Surface Condition Avoidance

Sensors on-board the vehicle would detect when the tire-to-road surface coefficient of friction is reduced due to water, ice or road surface condition. This information would be broadcast to other vehicles in the vicinity, to provide earlier warning to them. In addition to warning the driver as in Part A, if the system determines that the vehicle is traveling too fast for the measured coefficient of friction, the power to the drive wheels would be reduced. In dire conditions, brakes would be applied (but only if the vehicle is equipped with differential braking capability).

[Editor's Note: May also include infrastructure based sensors of road surface conditions, broadcasting that information to vehicles.]

B.2.g' Cooperative Road Surface Condition Resistance

Similar to Cooperative Road Surface Condition Avoidance, but with a Resistance human factors interface.

B.2.j Cooperative Merge Maneuver Execution

Temporary Control, <u>not</u> emergency control. At driver's request and specified merge locations, the vehicle automatically merges with another traffic scheme.

B.2.n Cooperative Driver Condition Mitigation

Similar to Driver Condition Mitigation but with communications possible with other vehicles and/or roadside.

If the monitoring of the driver's condition indicates drowsiness or other incapacitation, then this service would respond to reduce possible incident occurrence. The system response would depend on the system's control sophistication and the driver's involvement. If the driver was responsible for driving functions at the time that the incapacity was detected, then at the least, the system would attempt to alert the driver while simultaneously slowing the vehicle, activating its warning lights, and/or communicating with other vehicles and/or roadside. An advanced form of this service would be Fully Automated Background Control in Mixed Traffic with Cooperative Vehicles (service 6.5, AVC Services Compendium); that service would maintain full control and attempt to park the vehicle until the driver was determined to be alert, or the driver turned the service off. This latter service would require the capability to provide fully automated operation in mixed traffic.

B.2.o Road Management Situation Avoidance (RMSA)

This package is a logical step forward after RMSR. This package will not only provide warning to the driver but it will avoid the hazard in case a driver intentionally or unintentionally tries to run into a hazard. Initially the system will warn the driver but if the driver persists, the system will take control and perform TBD evasive maneuvers to avoid the hazard. This system will use throttle, brakes and steering to avoid the hazard.

B.2.o' Road Management Situation Resistance (RMSR)

This package is a logical step forward after RMSW. This package will not only provide warning to the driver but also provides resistance in case a driver intentionally or unintentionally tries to run into a hazard. If the driver persists, s/he will be able to override the resistance. This resistance is applicable to throttle and steering only.

B.2.p Cooperative Intersection Collision Avoidance

The vehicle would receive communications from other vehicles and/or the infrastructure alerting the driver both to when the driver is handling the intersection improperly, and when another vehicle threatens the instrumented vehicle at an intersection. The vehicle would maneuver on its own initiative to avoid collisions if the driver does not respond to warnings.

B.2.p' Cooperative Intersection Collision Resistance

The vehicle would receive communications from other vehicles and/or the infrastructure alerting the driver both to when the driver is handling the intersection improperly, and when another vehicle threatens the instrumented vehicle at an intersection. The vehicle would use this information to increase the resistance to pedal and steering motions that the system believes would be unwise for the circumstances.

B.2.q Cooperative Railroad Crossing Avoidance

The vehicle would receive communications from the railroad, and potentially other vehicles, alerting the driver of trains in the area. The vehicle would intervene to avoid hitting a train, or maneuvering such that it would be stranded on a train track.

B.2.q' Cooperative Railroad Crossing Resistance

The vehicle would receive communications from the railroad and potentially other vehicles alerting the driver of trains in the area. The vehicle's steering and pedals would resist driver commands that would result in a collision at the railroad crossing.

C Market Packages Providing Control of Normal Driving Actions

C.1 Autonomous Normal Driving Market Packages

C.1.a Adaptive Cruise Control

This market package represents what is expected to be the high-end first-generation Adaptive Cruise Control system. Using this system, the driver will be able to set a cruising speed (as in today's cruise control systems) and this vehicle will maintain that speed to the limit of its performance capabilities. However, forward looking sensors will be able to detect vehicles ahead and, if the vehicle ahead is in the same lane and is moving slower, will adjust the speed of this vehicle to match the speed of the vehicle ahead. Speed control will involve use of both the throttle and the brake to achieve a comfortable deceleration. Once the vehicle ahead is no longer in the lane of this vehicle (due to a lane change or an exiting vehicle), this vehicle will automatically resume the set cruising speed. The system will not operate below a fixed design speed and is not expected to detect stopped vehicles ahead or any obstacle ahead. It is however, expected to detect any type of moving vehicle including motorcycles and trucks. This market package is in late stage development by many car makers and is included here as the second expected step in normal driving longitudinal control (the first step being ordinary cruise control).

C.1.b (Advanced) Adaptive Cruise Control

This market package extends the capabilities of an ACC system so that this vehicle is capable of detecting a vehicle ahead in the same lane which may be traveling at any speed, including fully stopped. Furthermore, this vehicle will automatically stop without colliding with the vehicle ahead as long as the vehicle ahead is not hidden from view of this vehicle's sensors (for instance, around a blind curve). A full range of braking capability is available to the automated vehicle, including hard braking. In addition, the system provides longitudinal control at any vehicle speed, that is, automated longitudinal control is provided even in stop and go traffic. Although obstacle detection is not a prime objective, some obstacles would be detected and avoided by this system. This market package is a critical stepping stone towards market package Cooperative (A)ACC, FCA, and Lane Keeping in Mixed Traffic on a Protected Lane, in which a disengaged driver is assured the system will prevent a collision with any vehicle ahead.

C.1.c Lane Keeping (proposed)

This has been proposed as an additional market package. It allows the vehicle to automatically stay within their lanes, while the driver controls the longitudinal acceleration and braking. The driver can take lateral control at any time. This market package explicitly excludes simultaneous cruise control, and may exclude vehicles which have cruise control. It remains TBD whether this is on designated lanes (with lane markings such as magnets or radar reflective stripes), or on any well-marked lane.

C.1.d (A)ACC, FCA and SCA (Brake and Throttle Only)

This is a robust capability for longitudinal partial automation, in ordinary limited access lanes, with the potential for manually-driven vehicles in the traffic flow. The vehicle will cruise without hitting vehicles or obstacles in front, and will brake (or accelerate) to avoid a side collisions.

C.1.e (A)ACC, FCA, SCA (Brake and Throttle Only) and Driver Initiated Lane Changes

This is the robust capability for longitudinal partial automation with the added feature of driver initiated lane changes. These are temporary (non-emergency) control maneuvers, where the driver requests a lane change, and once the situation is appropriate, the vehicle moves laterally into the new lane. The vehicle provides a lateral control input for no more than a couple of seconds.

C.1.f (A)ACC, FCA, SCA (Brake and Throttle Only) and Lane Keeping with Driver Alertness Monitoring

This is the robust capability for longitudinal partial automation, integrated with simultaneous lane keeping. A driver-alertness monitoring insures that the driver remains engaged in the driving operations, in order to respond to unusual circumstances.

Human factors challenges may limit this market package to drivers with special training.

C.1.g (A)ACC, FCA, SCA (Brake and Throttle Only), Lane Keeping with Driver Alertness Monitoring and Vehicle Initiated Lane Changes

This is the robust capability for longitudinal partial automation, integrated with simultaneous lane keeping, and with the added feature of lane changes selected and performed by the vehicle. A driver-alertness monitoring insures that the driver remains engaged in the driving operations, in order to respond to unusual circumstances.

Human factors challenges may limit this market package to drivers with special training.

C.1.h (A)ACC, FCA, SCA (Brake and Throttle Only), Lane Keeping with Driver Alertness Monitoring, Vehicle Initiated Lane Changes and Automated Merge/Demerge

This is the robust capability for longitudinal partial automation, integrated with simultaneous lane keeping, with lane changes selected and performed by the vehicle, and with the added feature of automated merging and demerging (lane changes at designated points). A driver-alertness monitoring insures that the driver remains engaged in the driving operations, in order to respond to unusual circumstances.

Human factors challenges may limit this market package to drivers with special training.

C.2 Cooperative Normal Driving Market Packages

C.2.a Cooperative Adaptive Cruise Control

In this market package, the cruise control capability is identical to that in market package Adaptive Cruise Control. However, the information available to this vehicle is augmented by information communicated from either other vehicles or from the infrastructure. Information from other vehicles could include a braking indication (for quicker reaction) and braking rate capability (to allow adjustment of following distance). However, this vehicle would have to know the relative location of the vehicle transmitting in order to use this information. Information from the infrastructure could include warning of congestion, incidents or weather ahead (for anticipatory slowing), speed restrictions (for curves, for instance), or preferred operating speed (to smooth the flow of traffic). To use the information from the infrastructure, this vehicle would have to know its location, or the infrastructure transmitters would have to have a very short range.

C.2.b Cooperative (Advanced) Adaptive Cruise Control

As in Cooperative Adaptive Cruise Control, this market package supplements the capabilities of market package (Advanced) Adaptive Cruise Control with vehicle-to-vehicle and infrastructure-to-vehicle communications. The information from other vehicle is the same as in Cooperative Adaptive Cruise Control, that is, braking and braking rate information. The information from the infrastructure is also the same, information on traffic, incidents, and weather, speed restrictions, and preferred speed settings.

C.2.c Cooperative (Advanced) Adaptive Cruise Control and Frontal Collision Avoidance in Mixed Traffic on a Protected Lane

This market package combines the cooperative (advanced) cruise control capabilities of market package Cooperative (Advanced) Adaptive Cruise Control with an initial capability to detect obstacles. This capability is meant to be a very early and initial capability to detect obstacles. Two conditions are incorporated in the market package to ease the performance requirements on this initial capability. The first is that the driver is still steering the vehicle and therefore is continuously in the driving loop. If the obstacle sensors fail to detect an obstacle, the driver can be expected to, and to avoid collision with that obstacle. Secondly, the vehicle is only operated in this mode on a protected lane. In this case, a protected lane might be like today's HOV lane but at least with barriers between it and the normal lanes. These barriers will help to keep some kinds of obstacles and erratically driven vehicles out of the roadway. In addition, infrastructure sensing can be employed to supplement the capabilities of on-vehicle sensors. Equipped vehicles will also have the capability of passing on information about obstacles to both the infrastructure and to other equipped vehicles. The purpose of this market package is to introduce and further a capability to detect obstacles, so it will become as well as needed for the next market package.

C.2.d Cooperative (A)ACC, FCA, and Lane Keeping in Mixed Traffic on a Protected Lane

This market package adds to the capability of market package Cooperative (Advanced) Adaptive Cruise Control and Frontal Collision Avoidance in Mixed Traffic on a Protected Lane the fundamental capability of lane keeping. One of the goals of this market package is to enable the introduction of lane keeping as early as possible, because of its substantial safety and convenience benefits. This market package is also based on the assumption that introduction of lane keeping will result in a significant loss of driver vigilance and to partial driver disengagement from the driving task. Therefore, it is designed to provide the necessary capabilities, and to provide a safe enough environment, so that driver disengagement can be tolerated. On the other hand, the protected lane is designed to allow mixing of automated and manually driven vehicles even though the drivers in the automated vehicles may have become much less vigilant than under normal driving conditions. This allows market penetration of the automated vehicles to follow building of the lane. In this market package, the protected lane might be even more restrictive than in Cooperative (Advanced) Adaptive Cruise Control and Frontal Collision Avoidance in Mixed Traffic on a Protected Lane. Here it is a single lane, with solid barriers, and with only one entrance and one exit (like an express lane), and may need to include infrastructure-based obstacle detection. Automated operation can't be initiated until the vehicle is already on the lane and must be terminated before the vehicle exits the lane. If the driver does not resume control of the vehicle, it must be automatically moved into a temporary parking area and held until the driver does resume control. For the drivers of the automated vehicles, the usual response of the system to an emergency is to keep the vehicles safe (including an emergency stop if necessary) until the driver would resume manual control. In fact, the purpose of this style of protected lane is ensure that any hazard that a manual driver could cause can be safely handled by the following vehicle by performing an emergency stop. Capacity improvements are not expected but significant safety and driving comfort improvements, for the occupants of the automated vehicles, are.

C.2.e Cooperative (A)ACC, FCA, LK, and Merge/Demerge Capability in Mixed Traffic on a Protected Lane

This market package adds incrementally to market package Cooperative (A)ACC, FCA, and Lane Keeping in Mixed Traffic on a Protected Lane the ability to build multiple entries and exits into the protected lane. The vehicles would still have to be under manual control to either enter or exit the protected lane. However, automated vehicles already on the lane could handle the entry and exit of the manual vehicles. Safe protocols and carefully designed entries and exits would limit the hazards that a manual driver could create. Temporary storage points for non-responsive drivers would still be required. This market package is the final step before evolving to full automation on dedicated lanes when significant capacity improvements can start to be realized.

C.2.f Lane Keeping and (Advanced) Adaptive Cruise Control With Driver Alertness Monitoring

Lane keeping and (Advanced) Adaptive Cruise Control are integrated for simultaneous operation on a vehicle. A driver-alertness monitoring insures that the driver remains engaged in the driving operations, in order to respond to unusual circumstances.

Human factors challenges may limit this market package to drivers who have undergone special training.

D Automated Highway Systems

The AHS is developed for completely automated driving on limited access, multilane highways. While engaged in the AHS, the system provides full control of the vehicle; no driver intervention or monitoring is required. Other market packages describe driver aids and partial-automation systems supporting the progressive deployment path to AHS.

The vehicle systems will include steering, braking and throttle actuators, sensors, and the associated control systems. AHS components will be incorporated into future production models of automobiles, trucks and buses; although some of the vehicle systems may be available as after-market installations.

The AHS may use other ITS services; and some components may provide driver assistance on any roadway.

It has been suggested that Cooperative AHS in Mixed Traffic should be added to the list of market packages below.

D.1.a Autonomous AHS in Mixed Traffic

The Autonomous AHS in Mixed Traffic market package allows the mixing of automated vehicles and manually driven vehicles within the same highway lanes. The automated vehicles may be supported by minimal infrastructure improvements and other ITS services; however, vehicle control is not supported by communication systems.

D.2.a Cooperative AHS in Dedicated Lanes

The Cooperative AHS in Dedicated Lanes market package is predicated upon physical segregation of manually driven vehicles from automated vehicles. The AHS lanes are separated by grade, barrier or geography from roadway used by manually driven vehicles. Entry and exit to and from the arterial roadways is via dedicated ramps or special transition lanes. The roadway and the vehicles are equipped with sensors and communication equipment, providing the most comprehensive vehicle control and traffic flow control.

D.2.b Cooperative AHS in Mixed or Dedicated Lanes

The Cooperative AHS in Mixed or Dedicated Lanes market package provides the most comprehensive control and user flexibility. Automated vehicles, supported by communication with other vehicles and roadside systems, can be operated on dedicated lanes OR share lanes with manually operated vehicles.

Specialized Applications

Automated Bus Movement In The Maintenance Area

The transit group at the Stakeholder Forum found this very promising. If buses were to be automated (e.g., for Houston Metro), they could also operate in automated mode in the maintenance barn. Maintenance people must now walk as much as 20 miles a day, so this would speed and simplify the process. This could also be a preliminary use of automation in a low-speed, controlled environment before the automated buses are used by the public. A fixed route is marked (e.g., by magnetic markers, magnetic stripes or painted lines), with fixed maintenance stations. The buses are equipped to follow the route at low speed (about 5 mph) and stop at the stations, without a driver. They will also detect and stop for other buses, large objects and people that are on the path. Furthermore, they may be stopped remotely by an operator (e.g., by a hand held device). Once they are stopped, they must be started by an operator. The maintenance people have automated vehicle location to find and send for buses needing service. Another approach is to use automated guided vehicles to tow the buses. Using automated buses, this is most like Cooperative AHS in Dedicated Lanes, because it does not operate in mixed traffic, but has full control. It is simpler since it is a small area, a small number of vehicles, low speeds and a controlled environment.

Automated Snowplows

This would allow the plows to sense the edge of the road and parked cars in heavy snow, and maintain a proper distance from them. The motivation is improved safety for plow operators, by preventing them from leaving the road. The plows would be partially automated, guided by signals fed from lane sensors and side vehicle detectors. Selected problem roads would be instrumented with a marker that can be detected through heavy snow. The driver maintains longitudinal (throttle and brake) control, while the automated system maintains lateral control (steering). The automated system will detect the lane and any parked cars or other large obstacles under the snow. It will follow the lane unless it detects an obstacle, in which case it will avoid it if possible. If the system determines that the obstacle cannot be passed safely, it will stop and return control to the driver. The driver will also look for obstacles and can take control at any time. The system will alert the driver to any obstacles it detects. This is most like Lane Departure Avoidance. It is simpler since it is low speeds, a lone vehicle, and a specially trained driver.

Truck Convoy With Driver In Leading Truck

This is a possible precursor to platooning systems, while maintaining an alert lead driver. The application is to fleets, in which a team of drivers take turns leading and resting. Ideally, but not necessarily, the trucks in the convoy would be similar in capabilities (especially braking) and load. The driver of the lead vehicle drives his truck or bus normally and is responsible for and leads the convoy. He is continually under alertness monitoring and will be awakened by some means if he gets drowsy. If he fails to respond, the vehicle will be brought to a stop and the other drivers alerted. Also, all vehicles have sensors and logic to determine whether a lane change is safe, and the results will be communicated to the lead vehicle. Before the convoy can change lanes, the lead driver must turn on his signal and all vehicles must respond that it is safe to change lanes. Each of the following vehicles is in communication with the lead as well as with those in front of and behind itself. They do coordinated longitudinal control, and road following lateral control. During a lane change both lateral and longitudinal control are coordinated so they change lanes as a unit. This is similar to Cooperative (A)ACC, FCA, LK, and Merge/Demerge Capability in Mixed Traffic on a Protected Lane, in that it includes automation of all essential driving functions, but with a provision to avoid unusual problems. In Cooperative (A)ACC, FCA, LK, and Merge/Demerge Capability in Mixed Traffic on a Protected Lane, the problems are avoided by using a protected lane (including infrastructure warning of obstacles). In this package, they are avoided by the alert lead driver.

Truck Safety System

The trucking stakeholders were interested in becoming the initial users of general purpose warning and safety systems. Such systems will be cost-effective for them before they are for the general public, due to the significantly greater number of miles driven and economic value of each shipment. This is not a distinct user service except in its application to CVO only. It is essentially all of the safety support up through emergency control, but relying on full driver alertness. Specifically, it includes the following market packages that are described elsewhere: frontal collision avoidance, curve overspeed avoidance, blind spot collision avoidance, side collision avoidance, lane change collision avoidance, lane departure avoidance, road surface conditions avoidance. These are integrated into a single package with a common interface. This package does not depend on cooperation of the infrastructure or other vehicles. This package is essentially (A)ACC (which includes Frontal Collision Avoidance of stopped vehicles), Frontal Collision Avoidance of Obstacles and Vehicles, Curve Overspeed Avoidance, Blind Spot Collision Avoidance, Side Collision Avoidance, Lane Change Collision Avoidance, Lane Departure Avoidance, and Road Condition Emergency Control. It may be easier economically for many packages to deploy first on trucks, due to the high value of freight and trucks, and their many hours of use. Later, as prices drop, these products will be bought by the general public.

Bus Docking Aid

The transit group at the Stakeholder Forum would like docking assistance of buses at the curb while picking up and dropping off passengers. One reason is to support wheelchairs. Another is to save the considerable expense of wear on tires due to scraping the curb. Automation can position the bus very precisely relative to the curb. The driver maneuvers the bus into the loading area and then turns it over to automation. Sensors continually determine the lateral distance to the curb, front and rear, and the longitudinal distance to the end of the bus loading area. The automation will steer the bus toward the curb and straighten out to get both front and rear of the bus within the prescribed distance of the curb and with the wheels straight. It will abort if the longitudinal motion will take it beyond the end of the loading zone. It will then revert to manual mode and the driver will back the bus and try again. The driver can override at any time by operating brakes or steering, and is expected to monitor the situation and take emergency action if necessary (for example, if a pedestrian steps in front of the bus). When the bus is properly docked, it will stop, open the doors and revert to manual control. This uses the same technology as Cooperative Lane Change Collision Avoidance to take temporary control to keep the vehicle at a particular lateral position. This could appear earlier since it is not emergency control like Cooperative Lane Change Collision Avoidance, and so does not have to meet such high reliability standards. Also, due to high maintenance costs from scraping the curb, the bus companies may find even a fairly expensive system cost-effective.

Automated Container Movement (within terminal)
This specialized application consists of using vehicle automation technologies to move containers within rail-, truck-, or ship-yards or other centralized facility to the next stage or to storage. This can be viewed as an "automated forklift." The motivation is labor savings and high accuracy. The origins and destinations can be dynamically reconfigured to high precision, so fixed guide ways are not sufficient. The automated forklifts will move containers to the proper destinations safely (requiring some combination of protected area and obstacle detection's) and with high lateral and longitudinal accuracy (requiring preview detection scheme). The destinations are programmed and communicated, as are the inter-container spacings (which might be small and moving at relatively high throughputs). The aggregation of these automated technologies may parallel and maybe feed into AHS, albeit in a considerably more controlled environment.

Interterminal Passenger Shuttle
Newark airport has a driverless shuttle (rubber tire) between its terminals; Dallas has had one for years as do others. This is a similar system where in addition to the inter-terminal shuttle, driven shuttles (such as from the car rental companies, hotels, limos, etc.) would also be able to pull onto the "dedicated" guideway and be automatically controlled while in the airport. The drivers of these shuttles would be able to resume control at a few designated exits and continue their trip under manual control. This is an early form of "fully automated"; it would be in a very controlled environment and the vehicle fleet would also be tightly controlled.

Coordinated Startup (from a stop light)
This application uses inter-vehicle communication to perform coordinated starts (and for that matter, stops). In this manner, traffic movements can occur with considerably smaller delays than the additive lags of strings of humans reacting to signals. In the coordinated startup mode, a transfer of control issue must be solved, as the vehicles would start in an automated fashion, then at a prescribed speed and distance (or headway) from the preceding vehicle, it would revert to manual control. In the coordinated stop mode, the vehicle would assume control (much as in a FCA system, although the stop would be gradual as it would not necessarily be an emergency) but need not relinquish control until after the vehicle is stopped. In either case, the enabling signal would be synched with and might emanate from the traffic light or traffic sign. In the coordinated startup mode, the primary motivation would be traffic efficiency at intersections; in the coordinated stop mode, the primary motivation would be safety at intersection stops,

although traffic efficiency would still provide some of the motivation for this market package.

10.3.3 Market Package Matrix

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Market Package	Level of control	Situations controlled	Type of control	Area of concern	Required knowledge	Appli-cation	Level of coordination
A.1.a Frontal Collision Warning without Communications	Warning	Avoid obstacle or vehicle	Warning	Own lane immediately ahead	Range, range rate, velocity of vehicle ahead	General	None
A.1.b Curve Overspeed Warning	Warning	Avoid entering a curve at too high a speed	Warning	Curvature of own lane immediately ahead	Own speed, radius of curvature (and optionally banking) of road ahead	General, with suitable lane markings or database	None
A.1.c Blind Spot Warning	Warning	Prevent lane change into vehicles in blind spot	Warning	Adjacent lane, close proximity to own vehicle	Presence of vehicle in the zone of interest	General	None
A.1.d Side Collision Warning	Warning	Avoid drifting; avoid other vehicle drifting into own lane	Warning	Adjacent lane within about 5 meters	Relative lateral distance and velocity	General	None
A.1.e Lane Change Collision Warning	Warning	Avoid vehicles in lane change	Warning	Adjacent lane, all vehicles that would have difficulty avoiding a collision if you entered the lane	Intent to change lanes, position and velocity of vehicles in zone of interest	General	None
A.1.f Lane Departure Warning	Warning	Avoid leaving lane without driver's knowledge	Warning	Lane edge, both sides	Vehicle position relative to lane edge	General, with suitable road markings	Vehicle reads infrastructure

Market Package	Level of control	Situations controlled	Type of control	Area of concern	Required knowledge	Application	Level of coordination
A.1.g Autonomous Road Surface Condition Warning	Warning	Avoid or compensate for road conditions that decrease COF, cause driver discomfort or steering problems	Warning	Own lane, surface below own vehicle; surface ahead in advanced system	Tire-to-road surface coefficient of friction; existence of poor conditions ahead in advanced system	General	None
A.1.h Traffic Situation Awareness	Warning	Avoid potentially hazardous situations	Warning	All lanes, large enough area to include several vehicles ahead and behind	Traffic picture (TBD)	General	None
A.1.i Unsafe Driving Situation Warning	Warning	Defensive driving advisor. Optimize own vehicle speed and position relative to surrounding vehicles, for safety	Warning, Recommendations	Near region, especially all adjacent vehicles	Movements of surrounding traffic, prediction of traffic situation, tactical reasoning for proactive defensive driving.	General, but with highway configuration info available	None
A.1.j Merge Maneuver Advisor	Warning	Assist entering vehicle to line up with gaps in the mainstream traffic	Recommendations	Ramp, mainline traffic upstream	Position and velocity of mainline vehicles in the merge area; own vehicle, driver characteristics	General, with mainline visibility from entry ramp	None

Market Package	Level of control	Situations controlled	Type of control	Area of concern	Required knowledge	Application	Level of coordination
A.1.k Lane Change Maneuver Advisor	Warning	Assist vehicle making a lane change into traffic; avoid other vehicle entering own lane	Recommendations	Adjacent lane, all vehicles that may enter point immediately adjacent or change lanes into own vicinity	Positions and velocities of own and surrounding vehicles	General, with road markings	None
A.1.l Traffic Negotiator	Warning	Assist vehicle in safely weaving through traffic	Recommendations	Region around and ahead of vehicle	Current and predicted traffic picture	General	None
A.1.m Vehicle Condition Warning	Warning	Detect unexpected vehicle failures	Warning, maintenance recommendations	Own vehicle	Status of own vehicle safety-related functions	General	None
A.1.n Driver Condition Warning	Warning	Alert driver if he shows signs of not being capable of driving safely	Warning	Own vehicle	Driving performance and/or psycho-physiological measures of alertness	General	None
A.2.a Cooperative Frontal Collision Warning	Warning	Avoid obstacle or vehicle	Warning	Own lane immediately ahead		General	Broadcast from vehicles--here I am, this is what I am doing

Market Package	Level of control	Situations controlled	Type of control	Area of concern	Required knowledge	Appli-cation	Level of coordination
A.2.b Cooperative Curve Overspeed Warning	Warning	Avoid entering a curve at too high a speed	Warning	Curvature of own lane immediately ahead	Own speed, radius of curvature (and optionally banking) of road ahead	General, with suitable lane markings or database	Curve information sent from vehicles just ahead or from infrastructure
A.2.c Cooperative Blind Spot Warning	Warning	Prevent lane change into vehicles in blind spot	Warning	Adjacent lane, close proximity to own vehicle	Presence of vehicle in the zone of interest	General	Broadcast from vehicles--here I am, this is what I am doing
A.2.d Cooperative Side Collision Warning	Warning	Avoid vehicles in lane change	Warning	Adjacent lane within about 5 meters	Relative lateral distance and velocity	General	Broadcast from vehicles--here I am, this is what I am doing
A.2.e Cooperative Lane Change Collision Warning	Warning	Avoid vehicles in lane change	Warning	Adjacent lane, all vehicles that would have difficulty avoiding a collision if you entered the lane	Intent to change lanes, position and velocity of vehicles in zone of interest	General	Broadcast from vehicles--here I am, this is what I am doing
A.2.f Cooperative Lane Departure Warning	Warning	Avoid leaving lane without driver's knowledge, including preventive measures	Warning	Lane edge, both sides	Vehicle position relative to lane edge	General, with suitable road markings	Vehicle reads infrastructure, speed, curve, weather warnings

Market Package	Level of control	Situations controlled	Type of control	Area of concern	Required knowledge	Application	Level of coordination
A.2.g Cooperative Road Condition Warning	Warning	Avoid or compensate for road conditions that decrease COF, cause driver discomfort or steering problems	Warning	Own lane, ahead	Tire-to-road surface coefficient of friction; existence of poor conditions ahead in advanced system	General	Warnings from infrastructure (ice, snow, water, loose gravel), vehicle-vehicle comm of loss of traction
A.2.h Cooperative Traffic Situation Awareness	Warning	Avoid potentially hazardous situations	Warning	All lanes, large enough area to include several vehicles ahead and behind	Traffic picture (TBD)	General	None
A.2.i Cooperative Defensive Driving Advisory	Warning	Optimize own vehicle speed and position relative to surrounding vehicles, for safety	Warning, Recommendations	Near region, especially all vehicles within gentle stopping distance	Movements of surrounding traffic, prediction of traffic situation, tactical reasoning for proactive defensive driving.	General	Vehicle-vehicle and/or infrastructure vehicle comm of braking, hazards, etc.
A.2.j Cooperative Merge Maneuver Advisory	Warning	Assist entering vehicle to line up with gaps in the mainstream traffic	Recommendations	Ramp, mainline traffic upstream	Position and velocity of mainline vehicles in the merge area; own vehicle, driver characteristics	General, with entry ramp knowledge	Roadside-vehicle comm on ramp, vehicle-vehicle comm to assist merge

Market Package	Level of control	Situations controlled	Type of control	Area of concern	Required knowledge	Appli-cation	Level of coordination
A.2.k Cooperative Lane Change Maneuver Advice	Warning	Assist vehicle making a lane change into traffic; avoid other vehicle entering own lane	Recom-men-dations	Adjacent lane, all vehicles that may enter point immediately adjacent or change lanes into own vicinity, and all that could be nearby before the lane change is completed	Positions and velocities of own and surrounding vehicles (up to 2 lanes over)	General, with road markings	Vehicle-vehicle comm and coordination
A.2.l Cooperative Traffic Negotiator	Warning	Assist vehicle in safely weaving through traffic	Recom-men-dations	Region around and ahead of vehicle	Current and predicted traffic picture	General	State of vehicles in the region
A.2.m Cooperative Vehicle Condition Warning	Warning	Detect unexpected vehicle failures or potential failures	Warning, main-tenance recom-men-dations	Own vehicle	Status of own vehicle safety-related functions	General	Warning to other vehicles and/or roadside; possibly inputs from vehicles or roadside
A.2.n Driver Condition Warning (with communications)	Warning	Alert driver if he shows signs of not being capable of driving safely	Warning	Own vehicle	Driving performance and/or psycho-physiological measures of alertness	General	Warning to other vehicles and/or roadside

Market Package	Level of control	Situations controlled	Type of control	Area of concern	Required knowledge	Appli-cation	Level of coordination
A.2.o Road Management Situation Warning (RMSW)	Warning	Avoid disruptive or hazardous temporary situations, such as construction, accident, emergency vehicle	Warning	Near region (100 meters or so)	Warnings or instructions from manually set or placed roadway devices	General, with instru-mented lanes	Emitters or electronically readable tags on warning signs, emergency vehicles, cones, etc. Vehicle-vehicle comm warnings, infrastructure smart signs
A.2.p Cooperative Intersection Warning	Warning	Avoid collision with another vehicle at an intersection	Warning	Intersection or crossing and anything that might enter it	Position, velocity and intentions of nearby vehicles, status of signals	Instru-mented inter-sections	Negotiations among vehicles
A.2.q Cooperative Railroad Crossing Warning	Warning	Avoid collision with a train at a railroad crossing	Warning	Crossing and any trains that might enter it	Position, velocity and intentions of nearby trains, status of signals	Railroad crossings	Warnings about approaching train from train or other vehicles
B.1.a Frontal Collision Avoidance of Obstacles And Vehicles (brake only)	Avoid-ance	Avoid obstacle or vehicle	Braking	Own lane immediately ahead	Range, range rate, velocity of vehicle or obstacle ahead	General	None
B.1.a' Frontal Collision Resistance Of Obstacles And Vehicles (brake only)	Resis-tance	Avoid obstacle or vehicle	Braking	Own lane immediately ahead	Range, range rate, velocity of vehicle ahead	General	None

Market Package	Level of control	Situations controlled	Type of control	Area of concern	Required knowledge	Application	Level of coordination
B.1.b Curve Overspeed Avoidance	Resistance, then avoidance	Avoid entering a curve at too high a speed	Throttle	Curvature of own lane immediately ahead	Own speed, radius of curvature (and optionally banking) of road ahead	General, with suitable lane markings or database	None
B.1.b' Curve Overspeed Resistance	Resistance	Avoid entering a curve at too high a speed	Throttle	Curvature of own lane immediately ahead	Own speed, radius of curvature (and optionally banking) of road ahead	General, with suitable lane markings or database	None
B.1.c Blind Spot Collision Avoidance	Avoidance	Prevent lane change into vehicles in blind spot	Steering	Adjacent lane, close proximity to own vehicle	Presence of vehicle in the zone of interest, movement of own vehicle towards it	General	None
B.1.c' Blind Spot Collision Resistance	Resistance	Prevent lane change into vehicles in blind spot	Steering	Adjacent lane, close proximity to own vehicle	Presence of vehicle in the zone of interest, movement of own vehicle towards it	General	None
B.1.d Side Collision Avoidance	Avoidance	Avoid drifting into vehicles in adjacent lane	Braking, throttle, steering	Adjacent lane within about 5 meters	Relative lateral distance and velocity	General	None
B.1.d' Side Collision Resistance	Resistance	Avoid drifting into vehicles in adjacent lane	Braking, throttle, steering	Adjacent lane within about 5 meters	Relative lateral distance and velocity	General	None

Market Package	Level of control	Situations controlled	Type of control	Area of concern	Required knowledge	Application	Level of coordination
B.1.e Lane Change Collision Avoidance	Avoidance	Avoid vehicles in lane change	Steering	Adjacent lane, all vehicles that would have difficulty avoiding a collision if you entered the lane	Presence of vehicle in the zone of interest	General	None
B.1.e' Lane Change Collision Resistance	Resistance	Avoid vehicles in lane change	Steering	Adjacent lane, all vehicles that would have difficulty avoiding a collision if you entered the lane	Presence of vehicle in the zone of interest	General	None
B.1.f Lane Departure Avoidance	Avoidance	Avoid leaving lane without driver's knowledge	Steering	Lane edge, both sides	Vehicle position relative to lane edge	General, with suitable road markings	None
B.1.f' Lane Departure Resistance	Resistance	Avoid leaving lane without driver's knowledge	Steering	Lane edge, both sides	Vehicle position relative to lane edge	General, with suitable road markings	None
B.1.g Autonomous Road Surface Condition Emergency Control	Avoidance	Avoid or compensate for road conditions that decrease COF, cause driver discomfort or steering problems	Throttle, possibly braking	Own lane, ahead	Tire-to-road surface coefficient of friction; existence of poor conditions ahead in advanced system	General	None

Market Package	Level of control	Situations controlled	Type of control	Area of concern	Required knowledge	Application	Level of coordination
B.1.n Driver Condition Mitigation - Avoidance	Avoidance	Alert driver if he shows signs of not being capable of driving safely; take over if necessary	Warning and throttle; full	Own vehicle	Driving performance and/or psycho-physiological measures of alertness	General	None
B.1.n' Driver Condition Mitigation - Resistance	Resistance	Alert driver if he shows signs of not being capable of driving safely	Warning, throttle	Own vehicle	Driving performance and/or psycho-physiological measures of alertness	General	None
B.2.a Cooperative Frontal Collision Avoidance of Obstacles and Vehicles (brake only)	Avoidance	Avoid obstacle or vehicle	Warning, then braking (no override)	Own lane immediately ahead within graceful braking distance	Positions and velocities of own and surrounding vehicles	General	Broadcast from vehicles--here I am, this is what I am doing (state information)
B.2.a' Cooperative Frontal Collision Resistance of Obstacles and Vehicles (brake only)	Resistance	Avoid obstacle or vehicle	Warning, then braking (with override)	Own lane immediately ahead within graceful braking distance	Current and predicted traffic picture	General	Broadcast from vehicles--here I am, this is what I am doing (state information)
B.2.b Cooperative Curve Overspeed Avoidance	Avoidance	Avoid entering a curve at too high a speed	Throttle, possibly braking	Curvature of own lane immediately ahead	Own speed, radius of curvature (and optionally banking) of road ahead	General, with suitable lane markings or database	Curve warnings to other vehicles or roadway

Market Package	Level of control	Situations controlled	Type of control	Area of concern	Required knowledge	Appli-cation	Level of coordination
B.2.b' Cooperative Curve Overspeed Resistance	Resis-tance	Avoid entering a curve at too high a speed	Throttle	Curvature of own lane immediately ahead	Own speed, radius of curvature (and optionally banking) of road ahead	General, with suitable lane markings or database	Curve warnings to other vehicles or roadway
B.2.c Cooperative Blind Spot Collision Avoidance	Avoi-dance	Prevent lane change into vehicles in blind spot	Steering	Adjacent lane, close proximity to own vehicle (blind spot)	Presence of vehicle in the zone of interest	General	"I am here"
B.2.c' Cooperative Blind Spot Collision Resistance	Resis-tance	Prevent lane change into vehicles in blind spot	Steering	Adjacent lane, close proximity to own vehicle (blind spot)	Presence of vehicle in the zone of interest	General	"I am here"
B.2.d Cooperative Side Collision Avoidance	Avoid-ance	Avoid drifting into vehicles in adjacent lane	Braking, throttle, steering	Adjacent lane within about 5 meters	Relative lateral distance and velocity	General	Broadcast from vehicles--here I am, this is what I am doing
B.2.d' Cooperative Side Collision Resistance	Resis-tance	Avoid drifting into vehicles in adjacent lane	Braking, throttle, steering	Adjacent lane within about 5 meters	Relative lateral distance and velocity	General	Broadcast from vehicles--here I am, this is what I am doing
B.2.e Cooperative Lane Change Collision Avoidance	Avoid-ance	Avoid vehicles in lane change	Steering	Adjacent lane, all vehicles that would have difficulty avoiding a collision if you entered the lane	Presence of vehicle in the zone of interest	General	Broadcast from vehicles--here I am, this is what I am doing

Market Package	Level of control	Situations controlled	Type of control	Area of concern	Required knowledge	Appli-cation	Level of coordination
B.2.e' Cooperative Lane Change Collision Resistance	Resis-tance	Avoid vehicles in lane change	Steering	Adjacent lane, all vehicles that would have difficulty avoiding a collision if you entered the lane	Presence of vehicle in the zone of interest	General	Broadcast from vehicles--here I am, this is what I am doing
B.2.f Cooperative Lane Departure Avoidance	Avoid-ance	Avoid leaving lane without driver's knowledge, including preventive measures	Steering	Lane edge, both sides	Vehicle position relative to lane edge	General, with suitable road markings	Vehicle reads infrastructure, speed, curve, weather warnings
B.2.f' Cooperative Lane Departure Resistance	Resis-tance	Avoid leaving lane without driver's knowledge	Steering	Lane edge, both sides	Vehicle position relative to lane edge	General, with suitable road markings	Warnings from infrastructure (ice, snow, water, loose gravel)
B.2.g Cooperative Road Surface Conditions Avoidance	Avoid-ance	Avoid or compensate for road conditions that decrease COF, cause driver discomfort or steering problems	Warning, throttle, possibly braking	Own lane, ahead	Tire-to-road surface coefficient of friction; existence of poor conditions ahead in advanced system	General	Warnings from infrastructure or other vehicles (ice, snow, water, loose gravel)
B.2.g' Cooperative Road Surface Condition Resistance	Resis-tance	Avoid or compensate for road conditions that decrease COF, cause driver discomfort or steering problems	Brakes, steering, throttle	Own lane, ahead	Tire-to-road surface coefficient of friction; existence of poor conditions ahead in advanced system		Warnings from infrastructure or other vehicles (ice, snow, water, loose gravel)

Market Package	**Level of control**	**Situations controlled**	**Type of control**	**Area of concern**	**Required knowledge**	**Application**	**Level of coordination**
B.2.j Cooperative Merge Maneuver Execution	Temporary control (non-emergency)	Control entering vehicle to line up with gaps in the mainstream traffic and execute a safe merge	Brakes, steering, throttle	Ramp, mainline traffic upstream	Position and velocity of mainline vehicles in the merge area; own vehicle	General, with entry ramp knowledge	Roadside-vehicle comm on ramp, vehicle-vehicle comm to assist merge
B.2.n Cooperative Driver Condition Mitigation	Avoidance	Alert driver if he shows signs of not being capable of driving safely	Warning and throttle; full	Own vehicle	Driving performance and/or psycho-physiological measures of alertness	General	Warning to other vehicles and/or roadside
B.2.o Road Management Situation Avoidance (RMSA)	Avoidance	Avoid disruptive or hazardous temporary situations, such as construction, accident, emergency vehicle	Warning, braking, throttle, steering	Near region (100 meters or so)	Existence and location of situation	General, with consistent use of at least portable instrumentation	Emitters or electronically readable tags on warning signs, emergency vehicles, cones, etc. Vehicle-vehicle comm warnings, infrastructure smart signs

Market Package	Level of control	Situations controlled	Type of control	Area of concern	Required knowledge	Application	Level of coordination
B.2.o' Road Management Situation Resistance (RMSR)	Resistance	Avoid disruptive or hazardous temporary situations, such as construction, accident, emergency vehicle	Warning, braking, throttle, steering	Near region (100 meters or so)	Existence and location of situation	General, with consistent use of at least portable instrumentation	Emitters or electronically readable tags on warning signs, emergency vehicles, cones, etc. Vehicle-vehicle comm warnings, infrastructure smart signs
B.2.p Cooperative Intersection Collision Avoidance	Avoidance	Avoid collision with another vehicle at an intersection	Brake, throttle, steering	Intersection or crossing and anything that might enter it	Position, velocity and intentions of nearby vehicles, status of signals	Instrumented intersections	Negotiations among vehicles
B.2.p' Cooperative Intersection Collision Resistance	Resistance	Avoid collision with another vehicle at an intersection	Steering, throttle	Intersection or crossing and anything that might enter it	Position, velocity and intentions of nearby vehicles, status of signals	Instrumented intersections	Negotiations among vehicles
B.2.q Cooperative Railroad Crossing Collision Avoidance	Avoidance	Avoid collision with a train at a railroad crossing, or becoming stranded on track	Brake, throttle, steering	Crossing and any trains that might enter it	Position, velocity and intentions of nearby trains, status of signals	Railroad crossings	Warnings between vehicles and trains
B.2.q' Cooperative Railroad Crossing Collision Resistance	Resistance	Avoid collision with a train at a railroad crossing, or becoming stranded on track	Steering, throttle	Crossing and any trains that might enter it	Position, velocity and intentions of nearby trains, status of signals	Railroad crossings	Warnings between vehicles and trains
C.1.a Adaptive Cruise Control	Full time	Maintain proper speed and distance from moving vehicles	Throttle, soft braking	Own lane, ahead, moving vehicles only	Speed and position of the vehicle ahead	General, but not stop-and-go traffic	None

Market Package	Level of control	Situations controlled	Type of control	Area of concern	Required knowledge	Appli-cation	Level of coordination
C.1.b (Advanced) Adaptive Cruise Control	Full time	Maintain proper speed and distance from moving or stalled vehicles	Throttle, braking	Own lane, ahead	Speed and position of the vehicle ahead	General	None
C.1.c Lane Keeping	Full time	Keep vehicle within its lane	Steering	Own lane, ahead	Lane edges	General, with suitable lane markings	None
C.1.d (Advanced) Adaptive Cruise Control, Frontal Collision Avoidance, and Side Collision Avoidance (Brake and Throttle Only)	Full time	Maintain proper speed and distance from vehicles and obstacles, avoid side collisions	Brakes, throttle	Own lane, ahead; adjacent lane to the side	Position, velocity of obstacles and of other vehicles ahead and to the side	General	None
C.1.e (Advanced) Adaptive Cruise Control, Frontal Collision Avoidance, and Side Collision Avoidance (Brake and Throttle Only) and Driver Initiated Lane Changes	Full time longitudinal; accepts driver request for lane change, temporary lateral	Maintain proper speed and distance from vehicles and obstacles, avoid side collisions, automate lane changes at driver request	Brakes, throttle; temporary steering	Own lane, ahead; adjacent lane to the side	Position, velocity of obstacles and of other vehicles ahead and to the side	General with suitable lane markings	None

Market Package	Level of control	Situations controlled	Type of control	Area of concern	Required knowledge	Appli-cation	Level of coordination
C.1.f (Advanced) Adaptive Cruise Control, Frontal Collision Avoidance, and Side Collision Avoidance (Brake and Throttle Only) and Lane Keeping with Driver Alertness Monitoring	Full time	Maintain proper speed and distance from vehicles and obstacles, avoid side collisions, maintain position within lane	Brakes, throttle, steering	Own lane, ahead; adjacent lane to the side; lane edges	Position, velocity of obstacles and of other vehicles ahead and to the side, position within lane, driver alertness	General with suitable lane markings	None
C.1.g (Advanced) Adaptive Cruise Control, Frontal Collision Avoidance, and Side Collision Avoidance (Brake and Throttle Only), Lane Keeping with Driver Alertness Monitoring and Vehicle Initiated Lane Changes	Full time	Maintain proper speed and distance from vehicles and obstacles, avoid side collisions, maintain position within lane, change lanes when appropriate	Brakes, throttle, steering	Own lane, ahead; adjacent lane to the side; lane edges	Position, velocity of obstacles and of other vehicles ahead, position within lane, driver alertness, adjacent lanes	General with suitable lane markings	None

Market Package	Level of control	Situations controlled	Type of control	Area of concern	Required knowledge	Appli-cation	Level of coordination
C.1.h (Advanced) Adaptive Cruise Control, Frontal Collision Avoidance, and Side Collision Avoidance (Brake and Throttle Only), Lane Keeping with Driver Alertness Monitoring, Vehicle Initiated Lane Changes and Automated Merge/Demerge	Full time	Maintain proper speed and distance from vehicles and obstacles, avoid side collisions, maintain position within lane, change lanes when appropriate; merge/demerge	Brakes, throttle, steering	Own lane, ahead; adjacent lane to the side; lane edges; entry, exit ramps	Position, velocity of obstacles and of other vehicles ahead, position within lane, driver alertness, adjacent lanes and ramps	General with suitable lane markings	None
C.2.a Cooperative Adaptive Cruise Control	Full time	Maintain proper speed and distance from moving vehicles	Throttle, soft braking	Own lane, ahead, moving vehicles only	Speed and position of the vehicle ahead	General	Infrastructure-vehicle for speed control, warnings; braking indications from vehicles
C.2.b Cooperative (Advanced) Adaptive Cruise Control	Full time	Maintain proper speed and distance from vehicles	Throttle, brake	Own lane, ahead, vehicles	Speed and position of the vehicle ahead	General	Infrastructure-vehicle for speed control, warnings; braking indications from vehicles

Market Package	**Level of control**	**Situations controlled**	**Type of control**	**Area of concern**	**Required knowledge**	**Appli-cation**	**Level of coordination**
C.2.c Cooperative (Advanced) Adaptive Cruise Control And Frontal Collision Avoidance in Mixed Traffic on a Protected Lane	Full time	Maintain proper speed and distance from vehicles and obstacles	Brakes, throttle	Own lane, ahead, lane edges	Position, velocity of obstacles and of other vehicles	Protected lane with barriers	Infrastructure-vehicle for obstacle detection , speed control, etc.
C.2.d Cooperative (Advanced) Adaptive Cruise Control, Frontal Collision Avoidance, and Lane Keeping in Mixed Traffic on a Protected Lane	Full time	Maintain proper speed and distance from vehicles and obstacles, and position in lane	Brakes, throttle, steering (within lane), emergency stop and revert to manual	Own lane, ahead, lane edges	Position, velocity of obstacles and of other vehicles, lane edges	Protected single lane with one entrance, one manual exit, barriers, possibly infra-structure obstacle detection	Vehicle-vehicle; infrastructure-vehicle comm for obstacles and various information
C.2.e Cooperative (Advanced) Adaptive Cruise Control, Frontal Collision Avoidance, Lane Keeping, and Merge / Demerge Capability in Mixed Traffic on a Protected Lane	Full time	Maintain proper speed and distance from vehicles and obstacles, position in lane, and perform safe merge and demerge	Brakes, throttle, steering	Own lane ahead, entry/exit ramps	Position, velocity of obstacles and of other vehicles, lane edges	Protected single lane with carefully designed entries, exits to be nego-tiated auto-matically	Vehicle-vehicle; infrastructure-vehicle for various information, including obstacles

Market Package	Level of control	Situations controlled	Type of control	Area of concern	Required knowledge	Application	Level of coordination
C.2.f Lane Keeping and (Advanced) Adaptive Cruise Control with Driver Alertness Monitoring	Full time with an alert driver who can take over at any time	Driver monitoring, maintain proper speed and distance from moving vehicles, keep vehicle within its lane	Braking, throttle, steering	Nearby vehicles, lane edges	Driver alertness, position, velocity of obstacles and of other vehicles, lane edges	Specially trained drivers who will stay alert	
D.1.a Autonomous AHS in Mixed Traffic	Full time	All	All	Nearby vehicles, hazards ahead (same as for manual driving)	State of nearby vehicles and hazards, lane edges	General with suitable lane markings	None
D.2.a Cooperative AHS in Dedicated Lanes	Full time	All	All	Nearby vehicles, hazards ahead (same as for manual driving)	State of nearby vehicles and hazards, lane edges	Dedicated, protected, dedicated entry and exit	Vehicle-vehicle and/or vehicle-infrastructure; states, status, warnings, etc.
D.2.b Cooperative AHS in Mixed or Dedicated Lanes	Full time	All	All	Nearby vehicles, hazards ahead (same as for manual driving)	State of nearby vehicles and hazards, lane edges	Dedicated or mixed	Vehicle-vehicle and/or vehicle-infrastructure; states, status, warnings, etc.
Automated Bus Movement in the Maintenance Area	Full time	Low speed movement of buses between maintenance stations	All	Specific route within maintenance barn	Route, stop points, obstacles, commands	Transit maintenance facility only	TBD

Market Package	**Level of control**	**Situations controlled**	**Type of control**	**Area of concern**	**Required knowledge**	**Appli-cation**	**Level of coordination**
Automated Snowplows	Full or resis-tance	Follow snow-covered road, avoid abandoned cars; low speed	Lateral	Specific roads	Lane edges, location of abandoned vehicles	Specific roads with lane markings readable through snow	TBD
Truck Convoy With Driver In Leading Truck	Warning for lead, full for follow-ing	Allows trucks of the same fleet to follow each other and the drivers of the following vehicles to rest safely	All	Area surrounding the convoy	Lead driver attentiveness, state of surrounding vehicles and road	Major long-haul trucking routes	Vehicle-vehicle comm
Truck Safety System	As in A or B	Various. Provide warning and or emergency control for truck safety	As in A or B	As in A or B	As in A or B	Long-haul trucking; early deploy-ment of general-purpose market packages	As in A or B
Bus Docking Aid	Tem-porary, full	Maneuver bus near curb	All	Loading area, curb	State relative to leading area, curb	City buses, especiall y for wheel-chairs	None

Market Package	**Level of control**	**Situations controlled**	**Type of control**	**Area of concern**	**Required knowledge**	**Application**	**Level of coordination**
Automated Container Movement (within terminal)	Full	Move containerized cargo within yard; dynamic movements with goal, low speeds	All	Container route	Destination, route, obstacles	Protected area in rail-, train- or shipyards	Infrastructure-vehicle destinations, spacings
Interterminal Passenger Shuttle	Full	Specialized movement within terminal on fixed route	Longitudinal, within lane	Fixed route	Route, stations, status of own and other vehicles	Fixed, protected route, few designated entries and exits	Possible remote commands
Coordinated Startup (from a stop light)	Temporary, full	Automate and coordinate driving from stopped to underway for smooth starts; safe stops	Longitudinal, within lane	Signalized intersection	Signal status, position and velocity of other vehicles in own lane	Signalized intersections	Vehicle-vehicle state infor-mation

10.3.4 Deployment Map

Author: Tom McKendree.

The Deployment Roadmap is the top level central archive capturing how the various market packages are believed to relate to each other in terms of overall deployable sequences. This map should capture every realistic deployment sequence.

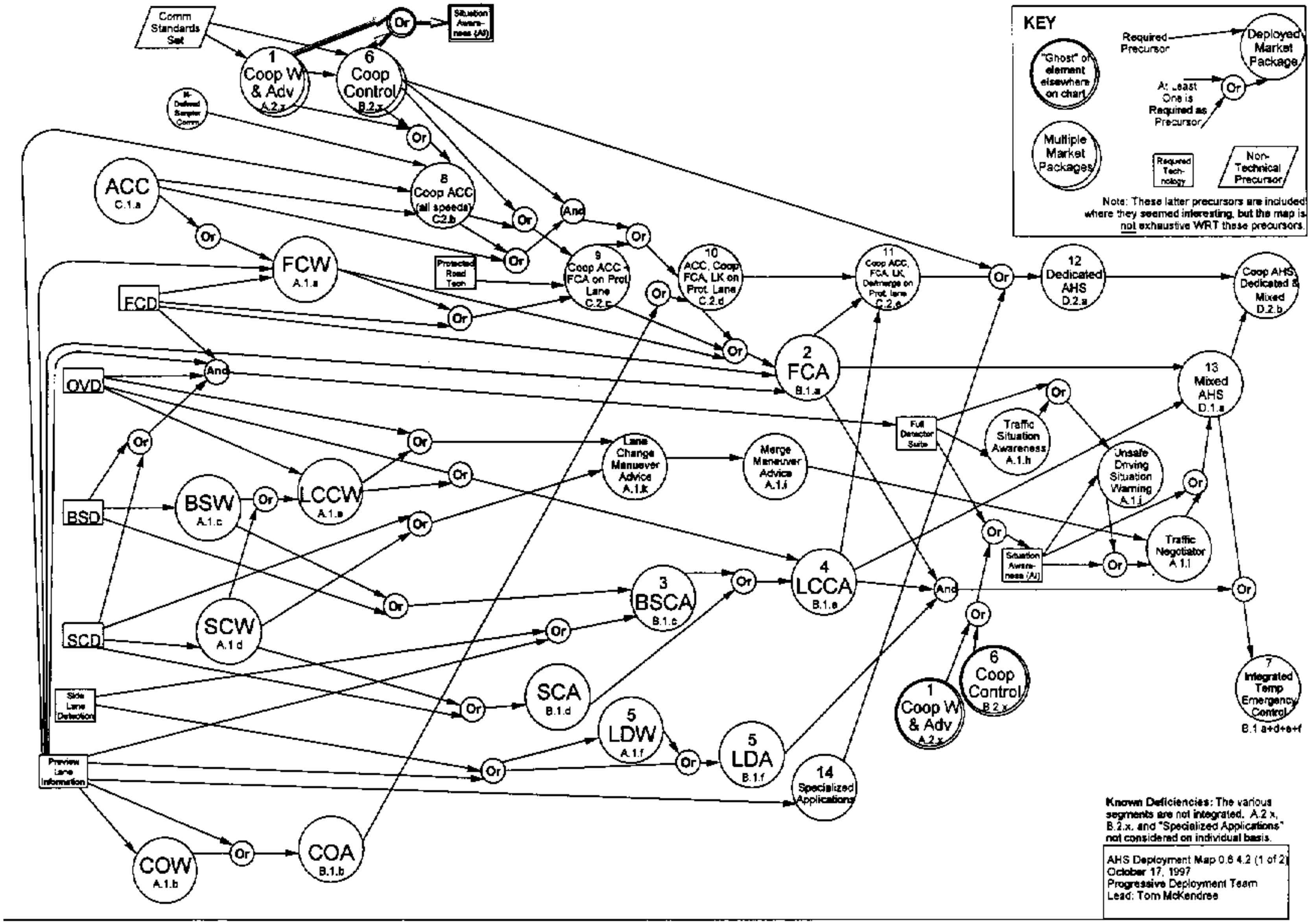
Each circle on the map represents actual deployment of a market package. Each arrow on the map represents a directly sequential deployment step, usually where a deployed market package is leveraged to facilitate the deployment of the next market package. Every arrowhead into a market package must be supported for deployment of that market package to be feasible. Any path into an "or" can continue out to support the downstream market package. Every path is required into an "and" to support a downstream market package.

The deployment of a market package, given a sufficient set of precursors, is called a "transition." Ultimately, every transition in this map should be examined, and its feasibility documented. The current transition write ups are in Appendix 10.3.5 Transitions.

The two basic relationships between two market packages, are sequential, and parallel. "Sequential" means that there is a realistic deployment path that entails having the first market package deployed before deployment of the second market package. Usually, the first deployed market package is used to ultimately facilitate the deployment of the second market package. Two market packages are sequential if there is a line of arrows from one market package to the other. Market packages may be indirectly sequential, with intermediate market packages requiring deployment, as well as directly sequential. "Parallel" means that the deployments of the two market packages are independent--either could be deployed before the other. This is indicated by the fact that there is no line of arrows from one market package to another. Market packages are "optionally sequential" if they are sequential, but there is also a set of transitions deploying the second market package that bypasses the first market package.

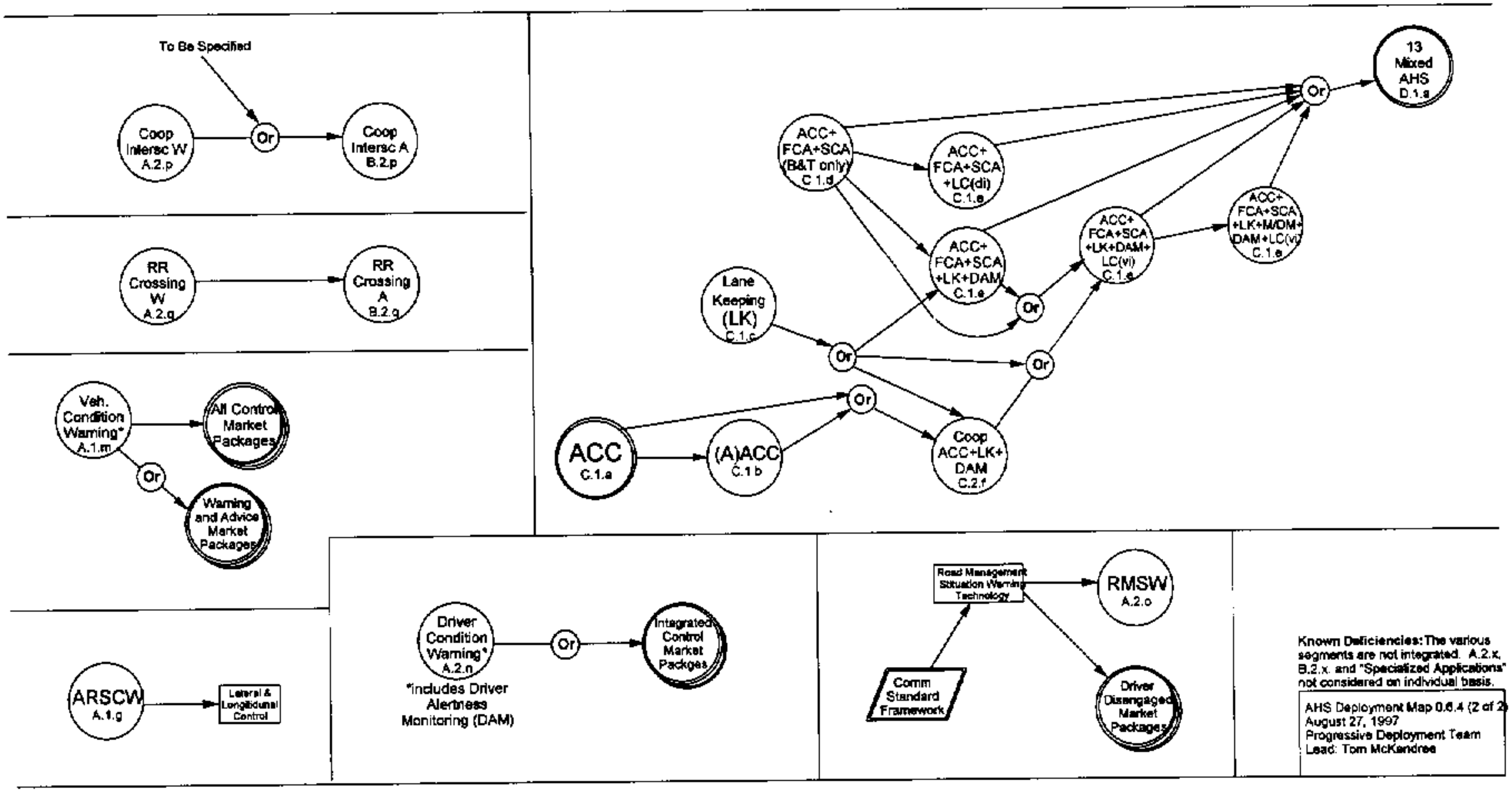
Not every precursor is captured in this map. Where "or"s have a single input, that indicates that the line they are on is useful, but not a necessary precursor, for the deployment of the immediately downstream market package.

The map is fragmented. Each of the eight sections in the current map largely stands alone, but is linked to other sections through "ghosts," which are repeated representations of deployment map elements. The presence of a connection in one section overrules the absence of a connection in another section.



Known Deficiencies: The various segments are not integrated. A.2.x, B.2.x, and "Specialized Applications" not considered on individual basis.

AHS Deployment Map 0.6 4.2 (1 of 2)
October 17, 1997
Progressive Deployment Team
Lead: Tom McKendree



This deployment roadmap illustrates that there are many feasible routes to deployment of AHS and related systems. It provides a basis for further work, ensuring consistency between future efforts that draw on the information contained here.

10.3.5 Transitions document.

Lead author, Tom McKendree

Introduction

This document describes NAHSC 's current, draft opinions regarding transitions leading to the deployment of various market packages. The market package designations (Capital_Letter.number.lower_case_letter) refer to the designations in appendices 10.3.2 and 10.3.3.

Each transition describes a target, starting conditions, what the public sector must do, what the private sector must do, technical requirement, benefits of the transition, alternate paths, and how the market package grows after initial deployment. These are the elements stakeholders have said they need to understand and evaluate a proposed transition.

1. Communications: Warning and Advice

Target

Any A.2.* market package from appendix 10.3.2, with receivers on the vehicle able to receive messages in a protocol that supports all of A.2.a (Cooperative Frontal Collision Warning) through A.2.l (Cooperative Traffic Negotiator) and all of A.2.o (Road Management Situation Warning) though A.2.q (Cooperative Railroad Crossing Warning). The target is deployment (actual sale and use) of vehicles that can receive the entire suite of warning and advice messages, from vehicles or infrastructure, along with the deployment of some system(s) (vehicle or infrastructure) actually broadcasting some useful information. Thus, at least one cooperative warning and advice market package is deployed, and the vehicles deployed contain the communications equipment package necessary to support all the cooperative warning and advice market packages.

Starting Conditions

Some autonomous driver warning systems may be deployed, and others will be in development. Research should already have indicated the benefit of cooperative market packages, and of later market packages enabled by the deployment of cooperative communications.

What Public Sector Must Do

Support the development of the necessary communications standard. Government must allocate RF spectrum necessary for the standard to this use. Some initial (broadcast) service in the standard must be provided, and the public sector is well suited to provide an initial capability (e.g., road surface condition warning, unsafe driving situation warning, merge maneuver advice, road management situation warning).

Special incentives for initial deployment (e.g., demonstration projects, early purchase subsidies) may help greatly with the initial transition.

What Private Sector Must Do

Support the development of the necessary communications standard. Vehicle electronics industry must develop and produce affordable radios that meet the standard. Vehicle manufacturers must integrate the radios into complete vehicle equipment packages. Ideally, they should architect the system so that adding market packages with newer vehicles is as minimal a change as possible. The vehicle electronics and vehicle industries must select these more capable radios, rather than simpler receivers on a smaller protocol that only supports one or a small subset of the market packages. Private transit operators, truckers, and high-end car buyers must begin buying these vehicles. If public information broadcast is not available, then private sector broadcast must also occur. This could be from private information service providers, but it could also be vehicle broadcast functions.

The insurance industry must insure the vehicle electronics industry against liability, possibly the vehicle manufacturers, and possibly localities broadcasting information on the system, (although the latter two might self-insure). The insurance industry must give vehicles with warning and advice communications no-less favorable an insurance rating than comparable vehicles with comparable autonomous warning and advice.

Technical Requirements

A single communications protocol that supports the full set of messages, at necessary bandwidth and ranges, for all the cooperative warning and advice market packages. A high probability of message receipt, and very low probability of forward uncorrected error is needed. The receivers must be usable on vehicles. It should also be an open standard, and expandable to new uses, allowing messages to be added. While not a requirement for <u>this</u> transition, it should be upward compatible to the communications protocol in Cooperative Control (B.2.*, discussed below in section 6).

The protocol may specify broadcast behavior (e.g., announce own operating parameters, digest and rebroadcast information up and down stream) that vehicles broadcasting on the protocol must follow.

Ideally, the protocol would support scaleable radios, so that cheaper, earlier radios could be deployed that would be fully compatible with more robust, later capability, but this may be too optimistic a goal.

Benefits Of Transition

The primary benefit is in the improved utility of driver warning and advice, do to cooperative information. This should be most pronounced for warnings and advice on circumstances at close range (e.g., closer than moderate braking distance), but circumstances that are not visible to the driver or vehicle (e.g., because of intervening traffic, weather, or innately invisible information such as other vehicles' performance capabilities). The incremental benefit should be less for long range warning and advice, since ordinary ITS would handle that adequately, and for advice where autonomous (vehicle mounted) systems are affordable and adequate.

Alternate Paths [Optional]

None currently listed.

How Transition Furthers Overall Deployment

This is perhaps the most critical step in overall deployment. There are a number of potential uses for intervehicle communications, and it becomes critical for very advanced systems, but getting sufficient benefit for initial deployment is a challenge. Once useful cooperative communications is established, it should grow on itself.

How Market Package Grows

The market package grows in two directions. More vehicles are sold with the capability, and more information is broadcast on the channel and used by vehicles. For the former, the standard approach should be adequate; Sell more new vehicles with cooperative communications, reduce costs with experience, and move the new feature down-market until it is available on nearly all new vehicles.

Meanwhile, the increase in information comes about because, as market penetration grows, it becomes increasingly attractive to broadcast additional information. Since this is only a warning and advice system, generally no additional equipment is required for the vehicles to use the information, and thus information services can naturally be added.

Note, some broadcasts should come from vehicles. At least three means exist to motivate the deployment of appropriate vehicle transceivers. The first is for local highway operators to provide some benefit (e.g., preferential lane usage, lower tolls, shoutback of requested information) to vehicles that provide broadcast of useful information. The second is to expand regulation of the communications protocol at a later date, requiring new vehicles sold with the receiver to also broadcast certain useful information. The third is to create a coordinated market push, offering both a new source of information from vehicles, and the means to take special advantage of that information.

2. Forward Collision Avoidance

Target

B.1.a, Forward Collision Avoidance (FCA) of Obstacles and Vehicles (Brake and Throttle Only). The vehicle autonomously senses other vehicle and threatening obstacles forward, and slows down, stopping if necessary, to avoid hitting vehicles or obstacles in its lane. The target is reached when the first consumers equip their vehicles or purchase equipped vehicles with this feature.

Starting Conditions

Forward collision warning is commercially available on private and fleet vehicles and in use on ordinary roads. [The demonstrated warning reliability is very high.] Also, electronic actuators of longitudinal vehicle controls are commercially available to vehicle manufacturers.

What Public Sector Must Do

Perhaps nothing, but public transit operators might buy or install FCA on their buses at higher prices, before the general auto market.

What Private Sector Must Do

Vehicle electronics industry must continue developing and selling sensors for long range, comprehensive vehicle and obstacle detection, and must develop and sell electronic actuators for longitudinal vehicle controls.

Vehicle manufacturers must integrate and sell FCA vehicles. This includes developing an acceptable human factors interface.

Some private vehicle owners must buy and use FCA. This could be private Transit operators, truckers, and/or high-end car buyers.

The insurance industry must insure the vehicle electronics industry against liability, and possibly the vehicle manufacturers (although, the latter may self-insure). The insurance industry must give FCA no-less favorable an insurance rating than comparable vehicles with FCW.

Technical Requirements

Identify vehicles and threatening obstacles at a range sufficient so that the vehicle can stop and avoid a collision even when traveling at highway speed. Note, the sensors should be able to detect any object that threatens the vehicle. Identify whether or not these obstacles are in the vehicle's lane. Do all this with very few false alarms, an extremely high confidence of catching actual threats, and rapidly enough so that the vehicle still has time to brake.

Disengage throttle and activate braking on command.

Support the override defined in the human factors interface (e.g., the signal to disengage the system might be to push back against the accelerator pedal).

Unfortunately, the most difficult obstacles arrive on their own, and we cannot lay requirements on them.

Benefits Of Transition

The primary benefit is a decrease in forward collisions, specifically those in which FCW would have alerted the driver, but the driver would not have responded to the alert adequately.

Alternate Paths [Optional]

Two alternate paths are identified on the Deployment Map, and a third alternate path deserves mention

A. Alternate Path 1 [From FCA on Protected Lanes]

FCA on protected lanes performs the same function, in a limited and restricted environment. The deployment transition consists of developing and selling vehicles that have the broader capability to perform the same function in a more open environment.

1. Differences In Starting Conditions

There is at least one protected lanes in use, and some vehicles travel on those lanes with an adaptive cruise control that has forward collision avoidance. The ACC and FCA may be limited, because this system need not identify which lane a forward obstacle is in, since the protected lane is only one lane wide. (Note, manual vehicles are still allowed on the protected lane.)

2. Differences In Transition

Government-funded and industry research may be needed to expand a single lane FCA system into one that can work in a multi-lane environment. This requires identifying, at range, which lane objects are in (or even if they are not on the road), and solving the human factors issues in the more complex environment where the driver might wish to change lanes to avoid a collision.

The benefit is potentially much greater, as the ability to robustly determine the lane of the object could be added in this transition. If so, then the transition opens up FCA [and incidentally, FCW if preferred] to the vast number of highway that is not protected single lanes.

B. Alternate Path 2 [From FCA + Lane Keeping on Protected Lanes]

This is similar to the previous alternate path, except the protected lane provides obstacle detection, and the system is sufficient to allow drivers to disengage.

1. Differences In Starting Conditions

There is at least one protected lane in use, which has robust obstacle detection from infrastructure sensors. Vehicles may travel on that lane with adaptive cruise control, forward collision avoidance and lane keeping, and the driver is permitted to disengage. The limitation for this system is that is need not identify which lane a forward obstacle is in, because the protected lane is only one lane wide. (Note, manual vehicles are still allowed on the protected lane.)

2. Differences In Transition

Robust obstacle detection from infrastructure sensors is feasible. This may help in the development of robust obstacle detection for vehicles, which must be less expensive, and work from a ground level, mobile platform, possibly at greater range.

As in alternate path 1., government-funded and industry research may be needed to expand a single lane FCA system into one that can work in a multi-lane environment. This requires identifying, at range, which lane objects are in (or even if they are not on the road), and solving the human factors issues in the more complex environment where the driver might wish to change lanes to avoid a collision. All this, of course, must be done with equipment feasible and affordable on vehicles.

C. Alternate Path 3 [Easy FCA Improves With Time]

Rather than evolve from strong (obstacle and vehicle) FCW, strong FCA could come from weak (vehicle only) FCA.

1. Differences In Starting Conditions

There are no FCW systems able to detect all threatening obstacles at range. There are, however, FCA systems that avoid hitting other vehicles, and other obstacles easy for sensors to detect.

2. Differences In Transition

Critical for this transition is continued research so the sensors can detect smaller obstacles at longer ranges. This may be Federally funded, and funded by industry. Regular increases in the things that FCA protects against provide regular, incremental benefits for incremental deployment. It is just rolled into the model years.

Benefits over weak FCA include increased safety by avoiding smaller threatening obstacles as well as vehicles and other large obstacles. This may be of particular help in poor visibility (assuming the sensors work in poor visibility), as FCA will be adequate for poor visibility driving "most of the time," and strong FCA will protect in those exceptions.

How Transition Furthers Overall Deployment

Forward collision avoidance is a critical stepping stone towards robust automated capabilities. It provides long-range, forward obstacle detection, and a simplified avoidance, which can be used for integrated emergency control, and which is necessary for full automation where obstacles may be present.

How Market Package Grows

Early deployment may be on limited markets, such as for buses and trucks. In any case, the first deployment on passenger vehicles would be on the high-end of the market. Sell more new vehicles with FCA, reduce costs (production, liability risk, etc.) with experience, and move the new feature down-market until it is available on nearly all new cars.

3. Blind Spot Collision Avoidance

Target

B.1.c. Simply stated, this is a *blind spot* lane change alarm and steering override system. This Market Package helps—and is intended to prevent—induced collisions resulting from unsafe lane changes. The Blind Spot Collision Avoidance (BSCA) senses or receives information indicating the presence of a vehicle in adjoining lanes and, if the driver fails to respond to warnings, corrects the steering of the vehicle to abort the lane change. The automated steering control would be able to be overridden by the driver.

The BSCA could be engaged by the driver using the "turn signal". Once the turn signal is ON, the BSCA would notify the driver of the presence of a vehicle in the adjoining lane. If the driver attempted to perform the lane change maneuver while the BSCA detected a vehicle in its intended path, the driver would receive progressively stronger audible, visual and kinesthetic stimuli—eventually correcting the vehicle steering to abort the lane change maneuver.

Starting Conditions

Blind Spot Collision Avoidance is an evolutionary step beyond Blind Spot Collision Warning systems (Market Package A.1.c). To achieve successful deployment of BSCA systems, the BSCW systems will be an established and accepted driver aid;

What Public Sector Must Do

No action required unique to the BSCA market package.

What Private Sector Must Do

Continue development and marketing of BSCW systems, gaining larger market share (through cost reduction?). Participate in study and analyses leading toward feasible, marketable BSCA systems, especially in the field of human factors.

Technical Requirements

Not addressed.

Benefits of Transition

Extensive market penetration of BSCA systems should reduce the number of accidents caused by unsafe lane changes. The likely initial target market for the BSCA system are buses and trucks.

Alternate Path

Human factors challenges may prevent the safe and effective warning systems such as BSCW. If so, then there is an alternate path which waits until avoidance can be safe and effective before deploying a Blind-Spot service.

How Transition Furthers Overall Deployment

Developing and deploying Side Collision Avoidance systems provides enhancements beyond simpler driver warning systems--while keeping the driver engaged in the driving task. Acceptance of the BSCA Market Package brings the stakeholder community to greater confidence in IVI technology, supporting evolution to full automated control.

How Market Package Grows

TBD.

4. Lane Change Collision Avoidance

Target

This market package (B.1.c) prevents an unsafe lane change when there is another vehicle approaching fast from the rear in the target lane. This is built upon and includes side collision avoidance. This package will physically prevent a lane change by taking over steering if another vehicle potentially will enter the merge slot. This take over may occur part-way through the merge, and return the vehicle to its original lane. The target is reached when the first consumers equip their vehicles or purchase equipped vehicles with this feature.

Starting Conditions

Side collision avoidance is offered as at least an option on several vehicles, including some low- or mid-range. There have been enough purchases of Side Collision Avoidance (SCA) to demonstrate the market acceptance of side collision avoidance devices. The technology for lane detection and preview is mature, reliable and accepted

What Public Sector Must Do

The government must support research to develop overtaking vehicle collision avoidance. Research organizations must develop sensors and algorithms to detect and identify overtaking vehicles.

What Private Sector Must Do

The vehicle and equipment makers must build and sell Lane Change Collision Avoidance (LCCA). The consumers must purchase LCCA. Fleet operators must equip their vehicles with LCCA.

Technical Requirements

Sensors must be able to detect vehicles in the adjacent lane and far enough behind to detect any vehicles that might come alongside. It must be able to distinguish these vehicles from the background and from vehicles in other lanes. The sensors or associated algorithms must be able to estimate speed with enough accuracy to identify vehicles that may enter the merge zone, but with a low enough false alarm rate that users do not turn it off. Lane detection must be accurate enough to determine whether own vehicle is fully in its lane, in the target lane, or how far through the lane change it has gone. It must also have "postview" capability to determine what lane the following vehicles are in. The control logic must be able to abort a lane change underway and return the vehicle to its original lane.

Benefits Of Transition

The consumers will have a safer vehicle since this will prevent a major cause of lane change accidents that is often difficult to detect visually.

Alternate Paths [Optional]

BSCA (B.1.f) may be an acceptable precursor in lieu of SCA (B.1.d).

How Transition Furthers Overall Deployment

This package fills out the logic to determine when it is safe to make a lane change. The lane change abort capability also provides a foundation for automated lane change. Automated lane change combined with adaptive cruise control and lane keeping (which will presumably be developed first) together automate all normal mainline driving functions. This is the core of the AHS. This package puts initial lane change logic on the road while keeping the driver involved. This allows use history and consumer confidence to be built without the risk of use by a disengaged driver.

How Market Package Grows

Sell more new vehicles with the feature, reduce production cost with experience, and move the new feature down-market until it is available on nearly all new cars.

5. Lane Departure Avoidance

Target

Lane Departure Avoidance and Resistance (LDA, market packages B.1.d and B.1.d'.)

The system is enabled (with some TBD driver interface, containing suitable warning and lane change override features) in the lateral dimension (i.e., steering control) given transition to a TBD defined lateral deviation from a lane edge reference. The control objective should be to keep the car within the lane given TBD lateral acceleration and jerk constraints. The difference between the avoidance and resistance feature is that with avoidance variant, steering control is automatically invoked upon to correct the course; in the resistance variant, the response will be kinesthetic, that is, the wheel beginning to slew back on course but can be overcome by the driver as necessary. The target is reached when the first consumers equip their vehicles or purchase equipped vehicles with this feature.

Starting Conditions

The technology for side lane detection (i.e., look-down sensors mounted on side mirrors a la DASCAR) or forward looking lane detection (i.e., vision system such as CMU's RALPH, the binocular system used in the Honda demonstration, the PATH magnetic reference system, or a radar reflective surface used in the OSU demonstration) must be widely available. Availability is contingent on all-day, all-weather TBD reliability and robustness measures, and TBD affordable installation costs. Additionally, cheap, reliable actuators for steering control must be available, preferably with an electric vehicle control system.

Another important starting condition is that studies must have been conducted to ascertain that drivers will use LDA as a background -- and not primary -- lateral control method. Part of that would be the TBD numbers for jerk and acceleration which could make LDA use for non-emergency vehicle control uncomfortable. These studies must in turn be accepted by Government regulatory agencies, the legal community and by consumers to shield manufacturers from liability due to claims of decreased vigilance and/or safety brought on by the use of LDA systems.

What Public Sector Must Do

The Federal Government must provide a "nurturing" environment: foster research into the aforementioned studies and encourage development -- possibly by financing collaborative research ventures and definitely by not imposing a chilling regulatory environment. The Federal Government might want to encourage use of these devices by regulating them as necessary, but this is a risky proposition as it could meet resistance from the automobile manufacturers and from consumers, who would face higher costs.

What Private Sector Must Do

The vehicle electronics industry must provide robust, low cost sensors for LDA. The vehicle manufacturers should (but not must) provide electric control systems for their products. Research from both the vehicle electronics and manufacturer industry should work on LDA algorithms, controls and displays. The vehicle manufacturers must integrate and sell LDA systems. Private transit operators and CVO interests should purchase and use LDA systems, along with high-end car buyers. The insurance industry must recognize and reward safety features of LDA in the form of lower premiums.

Technical Requirements

Knowledge of the lane boundaries is required; knowledge of the state variables of the lateral dynamical system such as lateral velocity, lateral acceleration and yaw rate could be desired, depending on the LDA algorithm. The driver operates the vehicle, but background lane keeping will be invoked when pre-determined lateral control limits are exceeded. Pre-determined limits will be based on safety considerations. However, within these considerations a driver override capability will be provided. This allows the tactical decision of lane selection, entry and exit decisions, speed and headway distance to be at the drivers' discretion. Although this capability will exist under normal operational conditions, whether the driver has that discretion during an emergency event is TBD (i.e., it may be the difference between introducing lane departure avoidance or lane departure resistance) and may depend on the type and dynamics of the emergency. The automated control features may or may not be preceded by warning(s), depending on human factors considerations and whether the scenario is defined as a normal operating or emergency event. Again, the type and dynamics of the emergency may be important. The system will operate on any non-signalized, access-controlled highway (rural, urban) at any level of congestion. The system will have day-night and all-weather capabilities, although it may work in a degraded mode under off-nominal conditions. The system hardware is contained within the vehicle to which service is being provided. It is assumed that no inter-vehicle or vehicle-roadway communication is required. There may or may not be physical or electronic infrastructure installed to aid lateral and longitudinal control, depending on the technology to be adopted. Equipped and unequipped vehicles will share the same lanes and mix freely. The equipment can be hosted on all classes of vehicles, except motorcycles.

Benefits Of Transition

The primary benefit is a decrease in Single Vehicle Roadway Departure (SVRD) crashes, the most common crash on the roads.

Alternate Paths [Optional]

None yet identified.

How Transition Furthers Overall Deployment

LDA is an essential antecedent for adding the lateral dimension to "any" incarnation of integrated lateral and longitudinal control. Therefore, it is an essential stepping stone to Market Package 7 (Integrated Temporary Emergency Control) and mixed traffic AHS. It is a probable (and likely) stepping stone towards dedicate lane AHS, with a plausible alternate path there being some "special purpose AHS"; however, this special purpose AHS will undoubtedly have developed lateral control elements similar to those features found in LDA.

How Market Package Grows

Early deployment may be on limited markets such as for buses and trucks, especially if the costs are high and the benefits are seen in terms of lower fleet costs. The first deployment on passenger vehicles would probably be on the high-end of the market, again especially since costs will probably still be higher. The next step is to sell more new vehicles with LDA to reduce costs (production, liability risk, etc.) with experience, and move the new feature down-market until it is available on nearly all new cars. If electronic controls are available, LDA could be an after-market add-on, also.

6. Cooperative Control

Target

Cooperative Emergency Control Market Packages (B.2.*)

The system is enabled (with some TBD driver interface, containing suitable warning and possible, TBD driver override features) given system identification of an emergency event. An emergency event is any safety-motivated vehicle maneuver in response to a disturbance to normal operation The control objective is to address the impact in a "graceful" manner, allowing for quick recovery. Both longitudinal and lateral control are implemented, with the magnitude of applied braking force contingent on the "degree of emergency" (i.e., time to collision) if indeed such a range rate input is reliable, accurate and quickly processed. The emergency event is perceived by sensor and/or communications inputs, and the ensuing action is communicated. The target is reached when the first consumers equip their vehicles or purchase equipped vehicles with this feature.

Starting Conditions

Cooperative Systems Control is preceded by Market Package 1, "Warning and Advice from Cooperative Vehicles and/or Cooperative Infrastructure".

What Public Sector Must Do

Since this Market Package intrinsically includes cooperative vehicle and infrastructure systems, an integrated design solution—endorsed by public agencies—is especially important. Standards would need to be developed and approved by numerous *international* standards committees. Finally, similar to most of the other Market Packages which include emergency automated control of vehicles, it is essential to include policy institutions and government agencies in the development and deployment process.

What Private Sector Must Do

The private sector will need to cooperate in research and development to assure a compatible and interoperable architecture.

Technical Requirements

- Vehicle sensors
- Communication protocols
- Message processing protocols
- Collision assessment algorithms
- Capability of full automated control of vehicles: throttle, brake, steering and transmission.

Benefits of Transition

This Market Package uses technology to the fullest extent possible to aid the driver and eliminate most of the accidents: frontal collisions, side collisions, lane departure, and road departure. Through cooperative systems, each vehicle will have even more knowledge of potential dangers than human drivers. Sensor suites supported by communication systems do not have blind spots, or become inattentive due to fatigue or distractions. It would be able to help the driver "see" past the high profile vehicle, over the hill and around the curve. In the event the driver is unable to respond to the danger, the system will prevent (or at least minimize) the collision.

Alternate Paths (Optional)

None identified.

How Transition Furthers Overall Deployment

Successful design, development and deployment of this Market Package will achieve much of the challenges to D.2.a (Dedicated Lane AHS, discussed in section 12.)

How Market Package Grows

Public acceptance, reasonable cost and availability of both "intelligent vehicles" and "intelligent" infrastructure.

7. Integrated Temporary Emergency Control

Target

The Integrated Temporary Emergency Control Market Package encompasses cooperative vehicle and infrastructure sensing and control to:

1) Avoid frontal collisions with vehicles or obstacles,
2) Avoid collisions with vehicles in adjacent lane during lane change,
3) Avoid collision with overtaking vehicle in adjacent lane during lane change,
4) Avoid inadvertent lane departure, and
5) Avoid inadvertent roadway departure.

This Market Package includes communication of information (bi-directional, vehicle to vehicle and vehicle to infrastructure), sensors and processing systems in the vehicle and installed on the roadway.

This is a monitor and override system, using on-vehicle, neighboring vehicles and infrastructure to prevent collisions. Vehicle and obstacle information is sensed and exchanged among neighboring vehicles to support analysis of potential for collision. Vehicle control (steering, throttle and brake) is automated if the vehicle is in peril and the driver is not responding to warnings.

Starting Conditions

The technology for lane departure avoidance, lane change collision avoidance, forward collision avoidance is available, and the systems integration and software technology necessary to fuse these subsystems is also available. Availability of these technologies implies that constituent software, hardware, sensor and communication technologies are available, and that public and private acceptance to automated control is in hand. Given this -- and the obvious benefits from an integrated temporary emergency control -- this technology and all its potential should be an easy sell -- as long as it virtually "never" causes or exacerbates crashes.

A viable starting point would be the pre-existence of Market Package D.1.a (Mixed Traffic AHS discussed in section 13), if the transfer of control to Mixed Traffic AHS is always assumed to be at the drivers' discretion. In that case, the Integrated Emergency Temporary Control would wrest control from the driver, and importantly, potentially return it to the driver -- arguably a more difficult set of transitions.

Another important starting condition is that studies must have been conducted to show that this market package will have a significant positive impact on roadway safety. This must be established to overcome the (we hope) infrequent but newsworthy failures, where the system reacted dangerously to false alarms and caused crashes. (This is projected to be a major study effort, as this would be a major technical challenge.) These studies must in turn be accepted by Government regulatory agencies, the legal community and by consumers to shield manufacturers from liability due to claims of decreased safety brought on by the use of these emergency systems.

What Public Sector Must Do

The Federal Government must provide a "nurturing" environment: foster research into the aforementioned studies and encourage development -- possibly by financing collaborative research ventures and definitely by not imposing a chilling regulatory environment. The Federal Government might want to encourage use of these devices by regulating them as necessary, but this is a risky proposition as it could meet resistance from the automobile manufacturers and from consumers, who would face higher costs.

What Private Sector Must Do

The vehicle electronics industry must provide a significant number of low-cost LDA, LCCA and FCA OEM's. The vehicle manufacturers should (but not must) provide electric control systems for their products. Research from both the vehicle electronics and manufacturer industry should work on emergency algorithms, controls and displays. The vehicle manufacturers must integrate and sell integrated temporary emergency systems. Private transit operators and CVO interests should purchase and use these systems, along with high-end car buyers. The insurance industry must recognize and reward safety features of the integrated temporary emergency systems in the form of lower premiums.

Technical Requirements

Detect, classify and verify obstacles. Have decision strategy algorithms. Determine appropriate maneuver based on degree of knowledge of as much state and intent. Hard braking. Brake to the limits determined by the decision strategy. Maneuver around the obstacle. This could consist of a lane change, or lateral movement within the lane (proceeding left or right with either). If the former, some knowledge of the occupancy of the adjoining lane is preferred, as the ensuing potential crash could be more severe than the crash avoided. With a non-communicating system, this puts particular stress on sensing. Maneuver to side of road. This is an extension of maneuvering around the obstacle. The strategy might be to perform the evasive maneuver, then stop. A mayday signal might be an optional driver input thereafter. Driver-initiated emergency maneuvering. This requirement handles the response to any "emergency" driver-initiated action or inaction which either constitutes or is in response to a disturbance (in terms of safety or efficiency). This could consist of a "panic button" when an emergency is perceived, causing the system to launch into a decision strategy, or simply execute a pre-planned maneuver (e.g., hard braking response, maneuver to side of road). The driver operates the vehicle, but complete background maneuver control will be invoked when pre-determined lateral or longitudinal control limits are exceeded. The system is invoked only under emergency situations, and responses encompass: braking (various rates), lane-change (left or right), off-center lane movement (left or right). Pre-determined limits will be based on safety considerations. The system will differentiate emergency situations from tactical decisions of overtaking slower vehicles, lane selection, entry and exit decisions, speed and headway distance to be at the drivers discretion. The automated control features may or may not be preceded by warning(s), depending on human factors considerations and whether the scenario is defined as a normal operating or emergency event. Again, the type and dynamics of the emergency may be important. The system will operate on any non-signalized, access-controlled highway (rural, urban) at any level of congestion. The system will have day-night and all-weather capabilities, although it may work in a degraded mode under off-nominal conditions. Inter-vehicle or vehicle-roadway communication are required for optimum performance. However, since the system should work with unequipped vehicles and locales with underdeveloped infrastructure the system should work at some degraded (i.e., sensor-only) state. The equipment can be hosted on all classes of vehicles, except motorcycles, and the equipment should work on all roadways in the U.S.A.

Benefits Of Transition

The benefit is a substantial reduction in the frequency of all types of crashes.

Alternate Paths [Optional]

None yet identified.

How Transition Furthers Overall Deployment

This could be the most ambitious market package, considerably more difficult that the dedicated AHS lanes (D.2.a), and potentially more difficult than the mixed traffic AHS vision (D.1.a). As such, it could be an end state -- or "vision" package -- itself.

How Market Package Grows

Early deployment may be on limited markets such as for buses and trucks, especially if the costs are high and the benefits are seen in terms of lower fleet costs. The first deployment on passenger vehicles would probably be on the high-end of the market, again especially since costs will probably still be higher. The next step is to sell more new vehicles with integrated temporary emergency control to reduce costs (production, liability risk, etc.) with experience, and move the new feature down-market until it is available on nearly all new cars.

8. ACC (Adaptive Cruise Control) with Vehicle/Infrastructure Cooperation

Target

This market package (A.1.c) is an adaptive cruise control that can accept and respond to digital signals, commands or data sent it from other vehicles and/or the infrastructure. It does this automatically without any actions from the driver. The messages it must accept include maximum speed, minimum spacing, braking rate of vehicle ahead, warning to slow. The target is reached when such a product is first bought and used by consumers.

Starting Conditions

The transitions described above in sections 1 and/or 6 have been completed. In particular, there are vehicles and/or roadways equipped to send messages and/or control to other vehicles. Note that in practice transitions 1 and 6 will unfold in parallel with this transition, since they are dependent on each other for their usefulness.

What Public Sector Must Do

Message and communications standards must be developed for all messages that the ACC must accept. (This may be done by the manufacturers.) Roadway operators must install communications devices that adhere to these standards and that provide useful information or commands to vehicles. These must be prevalent enough to motivate consumers to buy ACC devices that respond to them.

What Private Sector Must Do

Vehicle or equipment makers must produce the devices. Consumers or fleet operators must buy them and use them. Sufficient vehicles on the road must use cooperative communications equipment (although this may not be necessary if there is sufficient roadside communications to justify purchase of cooperative ACC).

Technical Requirements

The system must accept communications from other vehicles or roadside devices. It must have logic to ignore other parts of the messages that are not applicable (e.g., for driver-readable in-vehicle signing), and to translate relevant messages to commands for the ACC. The ACC must adjust its speed and spacing parameters in real-time in response to digital commands.

Benefits Of Transition

The consumer is safer, and freed from having to adjust the ACC to changing conditions. The roadway operator gains more control over traffic flow, resulting in smoother, safer traffic.

Alternate Paths [Optional]

None currently listed.

How Transition Furthers Overall Deployment

This market package is an early use of cooperation that is so central to the AHS. Specifically, it provides a motivation to equip both vehicles and infrastructure with cooperative communication devices that provide a base for further cooperative features. As the vehicles are equipped, it will justify and motivate further deployment of warning and advice communications (A.2.*) and of Cooperative Control (B.2.*).

How Market Package Grows

Sell more new vehicles with the feature, reduce production cost with experience, and move the new feature down-market until it is available on nearly all new cars.

9. Automatic Cruise Control (ACC), Frontal Collision Avoidance (FCA), with Cooperative Vehicles/Infrastructure in Mixed Traffic on a Protected Lane

Target

This market package (C.2.c) operates with instrumented vehicles, mixed with uninstrumented vehicles, in cooperation with other vehicles and infrastructure on special lanes. Vehicles operate with cruise control on. The vehicles operate at safe but efficient headways increasing highway capacity. Hazards, including stalled vehicles, debris, weather and incidents are detected by vehicles (within range) initiating frontal collision avoidance when necessary. The same roadway incidents are detected by roadway electronic infrastructure, and communicated to vehicles upstream for a gradual slowdown of the traffic stream until the condition is cleared. Steering is controlled manually and driver vigilance is required for lane-keeping and lateral hazards. This market package target is reached when a network of special lanes is available and instrumented vehicles with ACC and FCA are operating in significant numbers.

Starting Conditions

ACC and FCA is prevalent throughout the public and private vehicle fleet. Special lanes have been identified for use by specially equipped vehicles. These are likely to be similar to or the same as the HOV lanes of today. Public agencies operating highways are positioned to manage special lanes.

ITS systems are in place to monitor highway conditions and convey traffic advisories to motorists via roadside and/or in-vehicle signing.

What the Public Sector Must Do

Implement special lanes or adapt existing HOV lanes. Provide operations, maintenance, and policy management of the roadway infrastructure(special lanes and communications). Implement roadside to vehicle communications (probably dedicated short range communications). Integrate special lane management with general highway traffic management.

What the Private Sector Must Do

Develop and implement standards for vehicle to vehicle communications. Develop and implement technology for vehicle to vehicle communications. Foster public understanding and support of the market package enabling sufficient market penetration.

Technical Requirements

Vehicle to vehicle communications is required to:

- Communicate vehicle braking capability
- Communicate obstacle/hazard identification to upstream vehicles

Roadside to vehicle to roadside communications at short intervals(100 to 200m) along roadway is required to:

- Communicate operating speed limit based on policy and real time roadway conditions
- Monitor operating conditions of special lanes
- Facilitate other ITS services that support AHS
- Management
- Management center must be capable of providing surveillance and control of the special lanes through incident detection, and status monitoring

Benefits of Transition

Infrastructure cooperation provides:

- means to set roadway operating speed limit based on geometric constraints and/or actual emissions criteria
- means to communicate to vehicles safe operating speed under actual conditions of traffic volume, weather, incident, and/or hazards on a roadway section

- means to implement electronic toll collection, commercial vehicle operation and/or transit management for instrumented vehicles on the special lanes
- means to provide special traveler information services for instrumented vehicles in the special lanes

Vehicle cooperation provides:

- enhanced stability of traffic flow providing higher capacity and lower fuel use and emissions
- enhanced safety resulting from less hard braking, and potential for loss of control or passenger injury
- means to communicate presence of hazardous obstacle to upstream vehicles and infrastructure
- means to operate system based on individual vehicle's braking capability (rather than conservative assumptions for all vehicles) providing higher capacity and public confidence
- means to segregate the braking capabilities of passenger cars and heavy vehicles rather than aggregating these vehicles braking capability assumptions

Alternate Paths [Optional]

None currently listed.

How Transition Furthers Overall Development

The transition to this market package, ACC, FCA w/ vehicle/infrastructure cooperation demonstrates to industry, government, and the public the benefits of progressive incremental deployment. This will expand public confidence, market penetration, and begin to develop operating experience in the area of partial automation. The bodies influenced by AHS such as the insurance, environmental and political bodies will begin to gain experience with this partial automation and become aware of issues, develop positions and policy to support further progressive deployment.

How Market Package Grows

This market package grows geographically by the provision of special lanes by transportation authorities. The roadside to vehicle communications can either be provided initially to deploy this market package, or initially for other ITS services. In either case both become feasible with this communications resource, allowing growth of AHS and other ITS services.

The package grows over time with increasing market penetration of ACC and FCA on new vehicles and possibly as an aftermarket capability. The market penetration growth will be a function of cost, consumer confidence, realization of benefits, and the degree to which institutional barriers are overcome by region.

10. Advanced Cruise Control (ACC), Frontal Collision Avoidance (FCA), and Lane Keeping (LK) with Cooperative Vehicles and/or Infrastructure in Mixed traffic on a Protected Lane

Target

Market Package C.2.d (Cooperative Advanced Adaptive Cruise Control, Forward Collision Avoidance, and Lane Keeping in Mixed Traffic on a Protected Lane) operates with instrumented vehicles mixed with uninstrumented vehicles in special lanes. Vehicles are equipped with ACC, FCA, and LK Systems providing headway keeping, avoidance of obstacles and vehicle anomalies, and lane keeping. Driver tasks therefore are limited to general surveillance of vehicle and roadway information and conditions. This target is reached when significant numbers of vehicles are equipped and operating with ACC, FCA, and LK in special lanes.

Starting Conditions

ACC, FCA, and LK technology is available in the new vehicle fleet. Special lanes are being identified in various regions. Public agencies operating highways are positioned to manage special lanes.

ITS systems are in place to monitor highway conditions and convey traffic advisories to motorists via roadside and/or in-vehicle signing.

What the Public Sector Must Do

Implement special lanes or adapt existing HOV lanes, including a lane marking system for the LK system. Provide operations, maintenance, and policy management of the roadway infrastructure(special lanes and communications). Implement roadside to vehicle communications (probably dedicated short range communications). Integrate special lane management with general highway traffic management.

What the Private Sector Must Do

Develop the integrated ACC, FCA, and LK systems in the private public and commercial vehicle fleet Foster public understanding and support of the market package enabling sufficient market penetration.

Technical requirements

In-vehicle capability is required to determine presence of vehicles (instrument and non-instrumented) in adjacent lanes within possible trajectory of vehicle.

Vehicle to vehicle communications is required to:

- Communicate vehicle braking capability
- Communicate obstacle/hazard identification to upstream vehicles
- Communicate obstacle avoidance tactics to upstream vehicles
- Roadside to vehicle to roadside communications at short intervals(100 to 200m) along roadway is required to:

- Communicate operating speed limit based on policy and real time roadway conditions
- Monitor operating conditions of special lanes
- Facilitate other ITS services that support AHS
- Communicate presence of obstacle, hazard or vehicle/system anomaly to upstream vehicles

Management

Management center must be capable of providing surveillance and control of the special lanes through incident detection, and system status monitoring

Benefits of Transition

The transition to Market Package C.2.d adds the Lane Keeping system to the vehicle and roadway infrastructure. This feature reduces the drivers role, eliminating steering control and leaving only general surveillance of vehicle and roadway conditions. A safety benefit will be gained by automating the steering function to both avoid run-off-the-road accidents and provide steering maneuvers a means to avoid obstacles and stopped vehicles (rather than stopping in a straight trajectory or other path chosen by the driver.

Alternate Paths [Optional]

None currently listed.

How Transition Furthers Overall Development

The transition to this Market Package, C.2.d, will provide the public, industry and government with the first experience with fully automated vehicles, (i.e. throttle, braking, and steering control). This will expand public confidence, market penetration, and allow for further operational experience by public agencies.

How Market Package Grows

This Market Package grows geographically by the provision of special lanes by transportation authorities. Greater public use will increase market share of AHS equipment reducing unit cost. Greater public use will cause transportation to designate or construct more special lanes to meet the demand and realize the benefits.

The package grows over time with increasing market penetration of ACC, FCA and LK on new vehicles and possibly as an aftermarket capability. The market penetration growth will be a function of cost, consumer confidence, realization of benefits, and the degree to which institutional barriers are overcome by region.

11. Advanced Cruise Control (ACC), Frontal Collision Avoidance (FCA), and Lane Keeping (LK) with Cooperative Vehicles and/or Infrastructure and Merge/Demerge Capability in Mixed traffic on a Protected Lane

Target

The target for this market package (C.2.e) is to establish all the conditions necessary for the implementation of D.2.a (Cooperative AHS in Dedicate Lanes) with the exception of a protected lane meant for fully automated vehicles. This MP is an optional precursor to D.2.a. This MP requires all the functionality of C.2.d, plus merge/de-merge capability. With all the required technologies (mentioned above) in place and infrastructure support this MP will be able to significantly reduce the driving effort while increasing safety. Under automated mode the system will have the prime responsibility of vehicle control. With merge/de-merge capability this MP will be able to improve throughput as well.

Starting Conditions

Some of the ITS services are in place in various parts of the country. Departments of Transportation (DOTs) are providing infrastructure to monitor traffic volumes. This traffic information is available via several outlets (Internet, Commercial radio and TV stations etc.). Similarly weather information is also available.

In some heavily congested areas toll roads are emerging which are being used by a good number of users. High Occupancy Vehicle (HOV; i.e., "Carpool") lanes are also being used by a large number of users and the trend is growing.

What Public Sector Must Do

For this to happen, the government at state and federal level must encourage private sector to help flourishing new business by either adding more toll lanes on existing freeways or build entire new toll freeways. At the same time the government should also encourage the intelligent vehicle users by subsidizing them in some way. The government should also help in setting up standards for design and communications. Also the government should provide funds for more research in the areas of freeway maintenance in general and freeway lane management in particular.

What Private Sector Must Do

Private sector must make investment in the following areas:

1) Research in coming up with different technologies that would help in low cost traffic automation.

2) Advertising that will help people understand the path towards freeway automation.

3) Trigger the bootstrap process, by coming up with gadgets that work in mixed traffic and on dedicated lanes as well, so that the public sector investment becomes justified.

Technical Requirements

Vehicle should be able to sense and/or get the information from the other vehicle:

1) Range and range rate of the vehicle in front.

2) Center of the lane.

3) Capabilities of vehicle in front (Braking and acceleration).

4) Its position independently and with respect to other vehicles.

5) On-coming obstacles and hazards.
6) MP operated or manually driven vehicle.

Vehicle should be able to communicate bi-directionally with

1) Each other
2) Infrastructure

Infrastructure should be able to provide the following information/services to the vehicles:

1) Downstream planned events
2) Downstream unplanned events (accidents etc.).
3) Traffic conditions downstream and on adjacent freeways.
4) Weather
5) Downstream surface conditions.
6) Gaps in the traffic stream on protected lane.
7) Bi-directional, individually addressable voice channel, if bandwidth allows.

Benefits Of Transition

Transitioning to this market package (C.2.e) will add merging/de-merging capabilities. With the addition of merging/de-merging capabilities, safety will improve as the driver does not have to look for gaps in the traffic stream to merge. This will be done by the system automatically. Similarly in case of de-merging, all the driver has to do is to program his/her exit and the system will do the de-merge operation at the requested exit. This MP will also enhance throughput as automated merge/de-merge will be smoother than manual.

Alternate Paths [Optional]

None currently listed.

How Transition Furthers Overall Deployment

Transition to C.2.e with the implementation of merge/de-merge application will prove that actions which are heavily based on coordination between vehicle and infrastructure are possible. This will improve the public confidence on technology and open paths toward full automation.

How Market Package Grows

Due to dependency on protected lanes, this MP will grow first in heavily congested traffic areas. Due to its use in heavily congested traffic areas, more people will have access to this MP. People living in these traffic congested areas will have a motive to buy and use this MP. With the growing number of users the trend could also grow, increasing the market penetration.

12. Cooperative AHS in Dedicated Lanes

Target

The target for this market package (D.2.a) is to create an environment (dedicated lanes) where only fully automated vehicles can operate under full automation and driver is completely out of the driving loop. This is a necessary step to support platooning. Since the intra-platoon headways are small, manual control of the vehicle will not be possible. In this environment the driver will relinquish control to the system and will not be allowed to resume control until s/he is out of the dedicated lanes. This MP also calls for vehicles to be equipped with all the necessary gadgets required for full automation. Furthermore infrastructure should be able to provide necessary support for full automation. The target for this MP is reached when the vehicle owners have fully equipped vehicles and infrastructure is ready to support full automation with at least one dedicated lane setting.

Starting Conditions

Infrastructure support is available to support some guidance to drivers in the form of changeable message signs and highway advisory radio.

Some of the ITS services are in place in various parts of the country. DOTs are providing infrastructure to monitor traffic volumes. This traffic information is available via several outlets (Internet, Commercial radio and TV stations etc.). Similarly weather information is also available.

In some heavily congested areas toll roads are emerging which are being used by a good number of users. HOV lanes are also being used by a large number of users and the trend is growing.

Vehicles are showing up with more and more gadgets to ease the driving strain, ACC for example.

What Public Sector Must Do

For this to happen, the government at state and federal level must encourage private sector to help flourishing new business by either adding more toll lanes on existing freeways or build entire new toll freeways. At the same time the government should also encourage the intelligent vehicle users by subsidizing them in some way. The government should also help in setting up standards for design and communications. Also the government should provide funds for more research in the areas of freeway maintenance in general and traffic studies in particular. Government should also invest to set up more Traffic Management Centers (TMC) and field sensors to get freeway data from larger areas.

What Private Sector Must Do

Private sector must make investment in the following areas:

1) Research in coming up with different technologies that would help in implementation of low cost traffic automation.

2) Advertising that will help people understand the path towards freeway automation.

3) Trigger the bootstrap process, by coming up with gadgets that work in mixed traffic and on dedicated lanes as well, so that the public sector investment becomes justified.

4) Insurance companies should subsidize the AHS users in some way.

Technical Requirements

Vehicle should be able to sense and/or get the information from the other vehicle:

1) Range and range rate of the vehicle in front.

2) Center of the lane.

3) Capabilities of vehicle in front (Braking and acceleration).

4) Its position independently and with respect to other vehicles.

5) On-coming obstacles and hazards.

6) MP operated or manually driven vehicle.

7) Information of all the vehicle in immediate surrounding (velocity, immediate planned cooperative maneuvers, location etc.)

Vehicle should be able to communicate bi-directionally with

1) Each other

2) Infrastructure

Infrastructure should be able to provide the following information/services to the vehicles:

1) Downstream planned events

2) Downstream unplanned events (accidents etc.).

3) Traffic conditions downstream and on adjacent freeways.

4) Weather

5) Downstream surface conditions.

6) Gaps in the traffic stream on dedicated lanes.

7) Bi-directional, individually addressable voice channel, if bandwidth allows.

9) Immediate highway geometry.

VI Benefits Of Transition

Transitioning to this market package will completely relieve the driver from driving responsibility. Throughput will improve extensively because of close intra platoon headways. Safety will improve significantly as human intervention is removed from driving task. Furthermore energy consumption (air pollution) will reduce due to reduce aerodynamic drag resulting from close intra-platoon headway.

How Transition Furthers Overall Deployment

Being the goal of freeway automation, the next step will be to design full freeway automation that works in mixed traffic so that full automation can be achieved in the areas where a dedicated lane can not be built or a conversion of an existing lane is not possible. Street traffic automation could be another logical step. A more congenial traffic system will be created with the automation of street traffic.

How Market Package Grows

Due to dependency on dedicated lanes, this MP will grow first in heavily congested traffic areas. Due to its use in heavily congested traffic areas, more people will have access to this MP. People living in these traffic congested areas will have a motive to buy and use this MP. Efficient route guidance will cut the commute time considerably thus attraction to use this MP will increase thus increasing the market penetration.

13. Transition to Mixed Traffic

Target

Market Package D.1.a. There are at least some reasonably long roads on which fully automated operation is supported. These roads are multi-lane, with multiple entries and exits and are open to all vehicles that can operate on ordinary highways. These roads are cost-effective enough for the local transportation agency that they are built and maintained without additional subsidies or incentives beyond those available for a conventional road. Furthermore, there is a significant number of private citizens and fleet operators who have equipped their vehicles at their own expense and regularly use these roads.

Starting Conditions

The following are commercially available on private and fleet vehicles and in use on ordinary roads: forward collision avoidance of vehicles and obstacles using only brake and throttle; lane change collision avoidance, including overtaking vehicle and other motion of surrounding vehicles. There are some protected lanes that support vehicles with automatic lane keeping, adaptive cruise control and merge/demerge along with at least some manual vehicles.

What Public Sector Must Do

Local MPOs, State DOTs, and other road authorities: Gradually remove the restrictions on the protected lanes, both in terms of the lane itself and of the vehicles allowed to use it. This will happen when new roads are instrumented and as technological advances make the restrictions unnecessary. Each roadway operator must restrict road usage to only properly-equipped vehicles, and this must be maintained as roads and vehicles evolve. FHWA or other research-supporting organization: Support research into the remaining hard problems of full automation.

What Private Sector Must Do

The public must use the existing automated capabilities enough to (1) build public confidence in automation, (2) generate data to feed the ongoing research, and (3) demonstrate public interest in further automation. The public must buy or retrofit automated vehicles in increasing numbers, and with increasing capabilities. The vehicle/equipment industries must provide add-on capabilities

Technical Requirements

The combined vehicle/highway system must react safely to any condition that could reasonably be expected to occur on a highway that accepts all highway vehicles. At this point (before the transition) the AHS has developed an automated repertoire that covers all normal and most hazard situations. To complete the transition the system must be able to respond as well to the unusual and the challenging, on the assumption that the driver under full automation will not remain alert enough to do so himself. Most of this will be in situation assessment and response formulation, areas of tactical and strategic reasoning. This must be supported by ongoing analysis of accidents in existing automated systems. The research must be sufficient to convince the highway builders that it is safe to ease restrictions when the technology is mature enough.

Benefits Of Transition

The highway operators benefit since they can ease restriction on vehicles using their highways and eliminate the costs of protected lanes. The driving public benefits through highways usable by all, but with an option for stress-free, automated driving. The general public benefits through greater safety.

Alternate Paths

A. Alternate Path 1 [Ordinary Lanes]

The above discussed a path from protected lanes, but also assuming some market packages that do not depend on such lanes. This path does not assume any protected lanes.

1. Differences In Starting Conditions

Assume that there are no protected lanes.

2. Differences In Transition

The road authorities will not ease restrictions (there are none), but will add infrastructure capabilities as they become feasible. The highway operators benefit since the highways become increasingly safe and efficient. The drivers benefit since there is no more roles confusion from the semi-automated systems, and since they can drive fully automated and stress-free. The general public benefits through greater safety and mobility. The technical challenges involve integrating lateral and longitudinal control, lane change, merge and demerge, as well as those discussed above.

How Transition Furthers Overall Deployment

This is one ultimate vision, and as such is the culmination of the previous deployment. The next step might be to add platooning, for use where congestion is a problem and where dedicated lanes make sense. Beyond that would be automated surface streets.

How Market Package Grows

Additional vehicle owners will equip their vehicles for full automated operation on the initial roadways. This will start with commuters, long-haul trucks and fixed-route transit that can use these roadways. This will trigger the equipping or designation of additional miles of road, which in turn will motivate others to upgrade their vehicles. Eventually, all roads will support automated operation. The time it takes for this to happen will depend on how extensive the infrastructure modifications must be. If successful, automation will eventually become standard on all vehicles, leading to all vehicles being automated. Then all roads will be dedicated, which allows the next step of using coordination among vehicles for platooning or other efficiency measures.

14. Special Purpose

Target

This transition leads to several possible applications of AHS to specific, narrow situations. These situations are chosen as some that may warrant early deployments of AHS. Following are four possibilities.

Bus Maintenance Area

The transit group at the Stakeholder Forum found this very promising. Automation could be used to move the buses around in a relatively small, controlled, low-speed environment, similar to a car wash (but electronically linked). Maintenance people must walk as much as 20 miles a day.

Snowplows

This would allow the plows to sense the edge of the road and parked cars in heavy snow, and maintain a proper distance from them. The plows would be manually driven, but guided by signals fed from lane sensors and side vehicle detectors. Again, low speed, limited deployment. This is similar to lane departure warning, with the additional requirement that the sensors must operate through heavy snow.

Truck Convoy With A Lead Driver

This is a possible precursor to platooning systems, while maintaining an alert lead driver.

Safety Support To Fleets

The trucking stakeholders were interested in becoming the initial users of general purpose warning and safety systems. Such systems will be cost-effective for them before they are for the general public, due to the vastly greater number of miles driven and economic value of each shipment. This is not a distinct user service except in application to CVO only.

Starting Conditions

These are chosen as potential first deployments of the technologies. It is assumed that the underlying technologies, in particular lane detection with preview and adaptive cruise control, have been demonstrated and tested to the point that they are proven technologies.

What Public Sector Must Do

Bus Maintenance Area - A transit organization will automate their own maintenance area. Since this is still experimental, government will probably need to provide financial and technical support.

Snowplows - A community will instrument their own roads and plows to allow the plows to sense the lane edge and parked cars. A governmental organization probably will need to provide financial and technical support.

Truck Convoy With A Lead Driver - Public education about truck convoys and sharing the road with them. Changes to laws to allow drivers to drive longer hours (for example, by not counting hours when the driver is following in a truck convoy).

Safety Support To Fleets - Financial and technical support to fleet operators applying this experimental technology.

What Private Sector Must Do

Bus Maintenance Area - Bus and bus equipment manufacturers must equip the buses.

Snowplows - Private companies must equip the roads and plows (under contract)

Truck Convoy With A Lead Driver - A fleet operator must equip vehicles for convoy operation and train the drivers. The drivers and their union must accept convoy operation. The unions may need to change regulations to take into account "resting miles." (Note: It is assumed that driverless vehicles would not be acceptable). The public must accept sharing the road with convoys.

Safety Support To Fleets - A fleet operator must equip its vehicles with safety support systems. Vehicle and equipment managers must provide the equipment. If insurance companies lower rates for equipped vehicles, that would speed the transition, but may not be necessary.

Technical Requirements

Bus Maintenance Area - Very low speed lane following along a limited, fixed path with turns. Remote (external to the vehicle) start and stop at fixed points. Obstacle detect and stop.

Snowplows - Low speed lane following through heavy snow cover. Detection and position estimation of parked vehicles under heavy snow cover.

Truck Convoy With A Lead Driver - Very reliable vehicle following and coordinated braking and lane changing. Extremely reliable side-looking detection of adjacent lane from all vehicles and warnings to the lead driver if a convoy lane change is not safe.

Safety Support To Fleets - This includes a range of technologies, including those described in the transitions described in section 2, 9, 10, & 11 above. Early applications will be emergency braking and lane keeping resistance. These must operate in mixed traffic without roadside support, though they may use communications with the fleet operator.

Benefits Of Transition

For all, the government benefits by the early development and prolonged use of the technologies, leading to eventual broader deployment and resulting enhances safety and efficiency of the nation's highways.

Bus Maintenance Area - The transit authority saves time and labor, leading to savings, as well as good will as an AHS pioneer.

Snowplows - The community minimizes damage to plows, parked vehicles and surroundings.

Truck Convoy With A Lead Driver - The drivers can rest while making miles. The fleet operators can get greater use of their vehicles.

Safety Support To Fleets - The drivers will have greater safety. The fleet operators will save damage to vehicles and cargo, down time of vehicles and drivers, and possibly insurance costs.

How Transition Furthers Overall Deployment

Special applications of AHS capabilities often make sense economically long before they do for general application. Also, they often allow operation in a very restricted environment using trained drivers, a good starting point before deployment for the general public.

How Market Package Grows

Bus Maintenance Area - If the concept is successful, it will be implemented by other bus companies.

Snowplows - If the concept is successful, it will be implemented by other communities.

Truck Convoy With A Lead Driver - If the concept is successful, it will be implemented on more trucks, more drivers, more fleets.

Safety Support To Fleets - The equipment will be added to more trucks and more fleets. In parallel, additional capabilities will be added, growing to a highly automated vehicle.

10.3.6 Defining and Developing AHS Market Packages

Authors: Steve Mortensen and Evelyn Wagner, PB Farradyne Inc.

Introduction

As the direction of the NAHSC has turned towards safety, infrastructure based applications, and near term effects, efforts have increased to identify User Services and market packages based on user needs, keeping in mind a future 'big picture' of where AHS wants to be. This document provides guidance on what a market package is and how to develop market packages for AHS. This document was previously titled, "Discussion Note 3 – AHS Market Packages.

What is a Market package?

Market packages are groups of technologies that have been bundled together to provide a measurable service or benefit to the user of the system. Market packages describe how to provide one or more ITS User Services, and provide a physical or tangible means of satisfying user requirements. They are not a set of abstract functions, but concrete things that can or will be purchased in the market. User Services and market packages are closely related. User Services are the "what", market packages are the "how" in addressing problems and needs.

Market packages are technology dependent, but not technology specific. They are the building blocks of regional ITS frameworks or future big pictures. As such, they allow incremental deployment options that may apply to different scenarios and time frames and assist in the selection of technological solutions. They may also be used to describe and characterize existing and planned systems.

Market packages may also be used to illustrate the potential ITS solutions available in the market place today and in the future to non technical users. Users may include, but are not limited to, private car drivers, commercial vehicle operators (drivers, managers, dispatchers, shippers), transit operators (drivers, managers, dispatchers, riders), and traffic managers (traffic engineers, transportation planners, highway operations specialists).

History of market packages

National ITS Architecture Market Packages

The National ITS Architecture identifies a total of 53 market packages that address the current trend in the technology market. A complete listing of ITS market packages is found in Table 1 below. The National ITS Architecture has identified synergies and dependencies for its market packages.

Synergies

Synergies, in general, are the common elements among two or more market packages. The benefit of identifying these and developing them is that costs may be reduced, space requirements may be reduced, and operational efficiency may be improved. A common example of synergy among market packages is the means of communication. Often times several market packages can share the same medium.

Dependencies

Dependencies of market packages are the market packages which need to be implemented before another market package can be fully implemented. An example may be In Vehicle Signing. This requires some sort of sensors and processor to be in place before it can be used.

Table 1 - ITS Market Packages

Traffic Management

- Network Surveillance
- Probe Surveillance
- Surface Street Control
- Freeway Control
- HOV and Reversible Lane Management
- Traffic Information Dissemination
- Regional Traffic Control
- Incident Management System
- Traffic Network Performance Evaluation
- Dynamic Toll/Parking Fee Management
- Emissions and Environmental Hazards Sensing
- Virtual TMC and Smart Probe Data

Transit Management

- Transit Vehicle Tracking
- Transit Fixed-Route Operations
- Demand Response Transit Operations
- Transit Passenger and Fare Management
- Transit Security
- Transit Maintenance
- Multi-modal Coordination

Traveler Information

- Broadcast Traveler Information
- Interactive Traveler Information
- Autonomous Route Guidance
- Dynamic Route Guidance
- Information Service Provider (ISP) Based Route Guidance
- Integrated Transportation Management/Route Guidance
- Yellow Pages and Reservation
- Dynamic Ridesharing
- In Vehicle Signing

Advanced Vehicles

- Vehicle Safety Monitoring
- Driver Safety Monitoring
- Longitudinal Safety Warning
- Lateral Safety Warning
- Intersection Safety Warning
- Pre-Crash Restraint Deployment
- Driver Visibility Improvement
- Advanced Vehicle Longitudinal Control
- Advanced Vehicle Lateral Control
- Intersection Collision Avoidance
- Automated Highway System

Commercial Vehicles

- Fleet Administration
- Freight Administration
- Electronic Clearance
- Electronic Clearance Enrollment
- International Border Electronic Clearance
- Weigh-In-Motion
- Roadside CVO Safety
- On-board CVO Safety
- CVO Fleet Maintenance
- HAZMAT Management

Emergency Management

- Emergency Response
- Emergency Routing
- Mayday Support

ITS Planning

- ITS Planning

Example from the National ITS Architecture

As an aid to understanding the ITS Market Package concept, here is an example taken from the US National ITS Architecture Development Program. It describes a market package that provides highway network surveillance capabilities:

Network Surveillance

This basic market package provides fixed roadside surveillance elements utilizing wireline communication to transmit the surveillance data. It can be used in completely local mode such as loop detection connected with signal control or it can consist of CCTV cameras sending back data to the traffic management centers. This enables traffic managers to monitor road conditions, identify and verify incidents, analyze and reduce the collected data, and make it available to users and private information providers. It consists of road sensors, communication links between the sensors and the traffic management center, data reduction software, and utilizes the existing wireline links between the Traffic Management Center and the traveler information providers. Vehicle probes can be accommodated by including the Probe Surveillance market package.

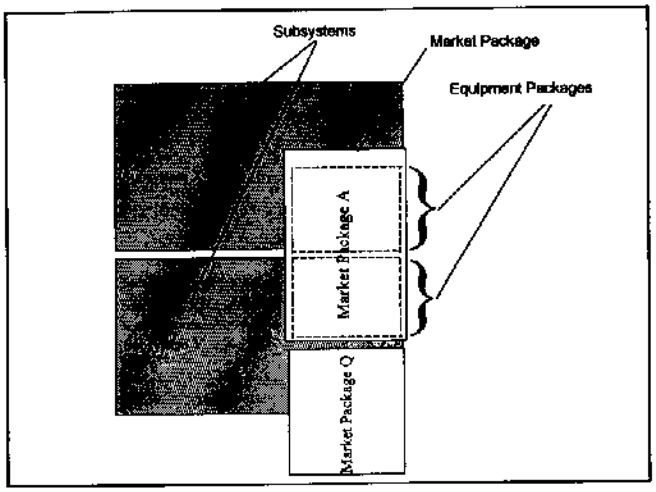
Defining and Developing Market Packages for AHS

It is important to note that market packages will change over time as technologies change and as new technologies are introduced into the market. Agencies and organizations may use the market packages identified in the National ITS Architecture, may create their own, or do both. The market packages identified in the National ITS Architecture provide a good model for development of new or modified market packages.

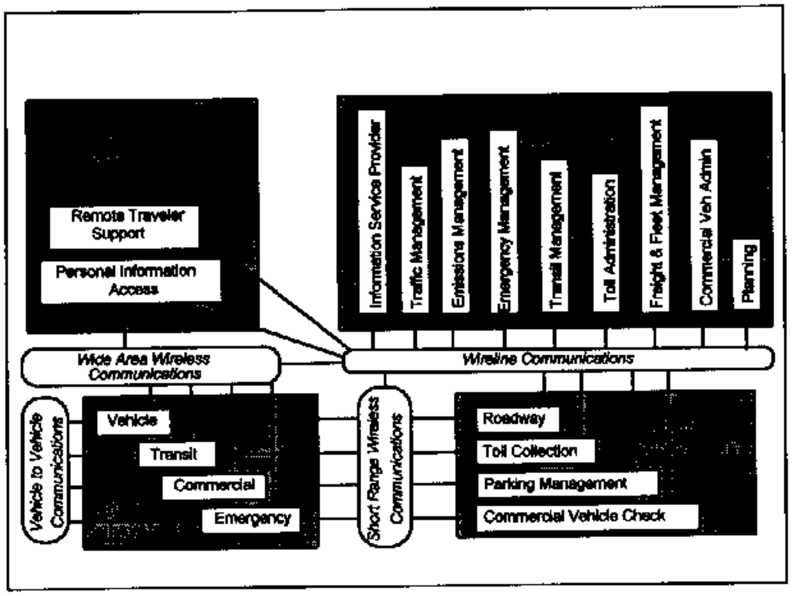
In the case of AHS, the National ITS Architecture has deliberately been vague on the market package definitions. Thus development of AHS market packages is needed. This may build upon the Advanced Vehicle Safety Systems (AVSS) market packages as well as those in other areas such as transit, commercial vehicles, and traffic management.

When defining a market package one must do the following:

1. **Identify equipment packages** -- This step identifies the necessary equipment packages required to provide the market package. An equipment package is a set of equipment that is likely to be purchased by users. They are the portion of the market package capabilities that are allocated to each subsystem (see step 2). The following figure shows the relationship between subsystems, market packages, and equipment packages.



2. **Identify subsystems** -- This step includes the identification of which subsystems the equipment packages reside in. The subsystems align closely with existing jurisdictional and physical boundaries that underscore the operation and maintenance of current transportation systems. The following figure illustrates all the subsystems associated with ITS.



3. **Identify data flows** -- This step involves the identification of the data which needs to be transmitted between subsystems to provide the market package. The media, upon which data is transmitted, are illustrated as ovals in the preceding figure.

4. **Develop operational descriptions** -- This involves the development of a description of how the market package will operate. This includes how it senses, what it

determines, the interface with the vehicle components or driver, etc. This description also contains information on how each of the user groups may perceive the market package as it relates to them.

5. **Identify measures of effectiveness** -- Measures of effectiveness or performance measures are identified in this step for that specific market package. For a market package to be considered for implementation, it will have to be evaluated to determine benefits.

6. **Develop illustration** -- A visual representation of the market package showing subsystems, equipment packages, and data flows.

The following statements may be used as a checklist to assist in definition of market packages and to ensure they fulfill their purpose. Each of them characterizes a different aspect of market packages.

- Market packages are a stakeholder and consumer tool to facilitate understanding of the technologies and the consequences
- Market packages describe HOW the solution is provided
- Market packages are groupings or bundles of technologies that address a defined need or provide a tangible benefit
- From a system planning perspective, market packages are the fundamental building blocks of regional ITS frameworks
- Market packages are technology dependent but not technology specific
- Market packages provide a meaningful description of technological capabilities to stakeholders
- Market packages are bundles of enabling technologies combined into tangible measurable units
- Market packages characterize future and presently available products and services
- Market packages may be used to characterize legacy systems
- Market packages enable implementation strategies to be developed
- Tangible benefits can be measured for market packages

Conclusion

Given this guidance, market packages may be developed which draw upon the user stated requirements and provide relevant information for the identification and development of market packages. The following template/worksheet should be used as a means of describing AHS market packages proposed and developed by stakeholders and the Progressive Deployment Team. A description of the AHS market package "Cooperative Adaptive Cruise Control" (C.2.a) is provided using this template/worksheet. As AHS market packages are developed, they will be placed in this format.

10.3.7 AHS Issues, Constraints, Guidelines, and Policies

Authors: Evelyn Wagner and Steve Mortensen, PB Farradyne Inc.; Progressive Deployment Team

INTRODUCTION

This document captures the various ground rules, assumptions, suggestions, and guidance for the development of Automated Highway Systems (AHS). It is a repository for useful ideas, and a tool for reflecting the current status of the development efforts in AHS User Services and market packages. The document is a living document and it will continuously be updated as the development of AHS User Services and market packages progresses.

OBJECTIVES

This document will serve as a repository of issues that are presented and lessons that are learned as we go through the process of defining AHS User Services and market packages. In particular, the document is to capture and provide advice and guidance to the NAHSC, specifically the Progressive Deployment Team, to support the invention, development, and design of specific market packages. As much of this guidance will vary in its weight, the document must indicate the importance to be attached to the various suggestions it contains. This is a document by and for the Progressive Deployment Team, but the User Needs Team and Critical Issues Team members will also be able to look at this document for ideas and guidance.

FRAMEWORK

The proposed approach to developing Automated Highway Systems is a user driven, needs focused process. The overall philosophy adopted in the approach is based on that adopted in the National ITS Architecture Program. The proposed approach is illustrated in Figure 1 and explained below.

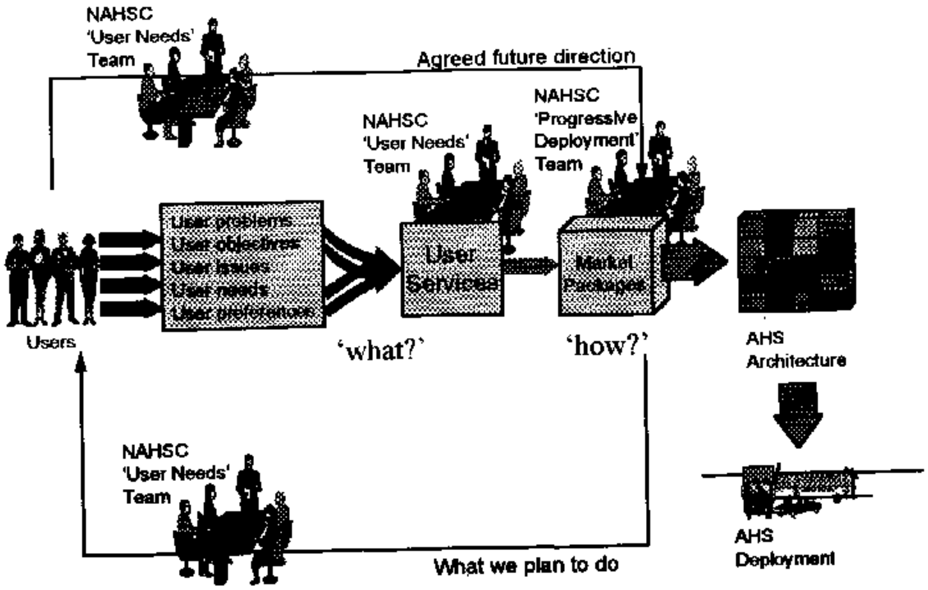


Figure 1. Approach to AHS Development

The approach represents an iterative process in which the user starts off with some preliminary conceptions of needs, but relatively limited knowledge of potential solutions and technology capabilities. The preliminary conceptions of needs are based on the following:

- **user problems** - what transportation problems do the users perceive as important, taking account of their lifestyles, interests, backgrounds and organizational affiliations?
- **user objectives** - what goals or objectives from both personal and organizational perspectives do the users want to have addressed by the ultimate AHS?
- **user issues** - what issues are associated with the satisfaction of stated needs and what factors may have to be taken into account when identifying and developing potential solutions?
- **user preferences** - what preferences do the users exhibit when they tell us what they want?

These preliminary needs are then revised, enhanced, and extended based on exposure to potential solutions and a growing understanding of what solutions are technically and economically feasible. The mechanism supports the situation in which one group of people, the users, have detailed knowledge of the problems, objectives, issues, and preferences, while another group of people, the developers, have detailed understanding of technology capabilities and potential solutions. This requires that the definition of 'what' the system has to do to be considered successful by the user, be kept separate and distinguished from 'how' the system proposes to address the needs.

This specialization is supported through the use of two tools, Automated Highway System User Services and Automated Highway System market packages, within the overall framework of a cooperative development approach.

AHS User Services

These are concise encapsulations of 'what' the users are asking for. They summarize 'what' the ultimate deployment will have to do, or provide, if the system is to be considered a success by the users. AHS User Services will fulfill the following roles:

- Provide the basic materials, describing user needs, problems, objectives and issues, to be used to guide the NAHSC technical analysts in the 'progressive deployment' team in identifying, defining and developing appropriate solutions
- Provide a simple tool to be utilized by the 'user needs' team in collaboration with users, to confirm that all user requirements have been discovered, understood and correctly interpreted
- Answer the question 'so what?' for the user

User Services are composed of User Service Requirements, or "shall" statements. User Services must be detailed enough to address all requirements and be concise enough to be useful in guiding an ITS framework and system development. User Service descriptions are composed of two components:

- A 'label' that identifies the User Service and gives an indication of its nature
- A 'description' that provides the material required to explain and confirm the User Service to the user and to the developer
- A series of shall statements that explain what the system is going to do

National ITS Architecture User Services

The User Service concept was first introduced in the National ITS Program Plan in 1995. Since then, the National ITS Architecture development teams have adopted and developed the National ITS Architecture around them. At present there are 30 User Services, which are listed in the Executive Summary document. These are shown in Table 1.

Table 1 - User Services

User Service Bundle	User Service
Travel and Transportation Management	En-Route Driver Information Route Guidance Traveler Services Information Traffic Control Incident Management Emissions Testing and Mitigation Highway - Rail Intersection
Travel Demand Management	Pre-Trip Travel Information Ride Matching and Reservation Demand Management and Operations
Public Transportation Operations	Public Transportation Management En-Route Transit Information Personalized Public Transit Public Travel Security
Electronic Payment Services Commercial Vehicle Operations	Electronic Payment Services Commercial Vehicle Electronic Clearance Automated Roadside Safety Inspection On-Board Safety Monitoring Commercial Vehicle Administrative Processes Hazardous Material Incident Response Commercial Fleet Management
Emergency Management	Emergency Notification and Personal Security Emergency Vehicle Management
Advanced Vehicle Control and Safety Systems	Longitudinal Collision Avoidance Lateral Collision Avoidance Intersection Collision Avoidance Vision Enhancement for Crash Avoidance Safety Readiness Pre-Crash Restraint Deployment Automated Highway Systems

Example from the National ITS Architecture

As an aid to understanding the User Service concept, here is an example taken from the National ITS Architecture development program. This is an excerpt of the description for the Route Guidance User Service from Appendix A of the Traceability document:

> **1.3** ROUTE GUIDANCE
>
> **1.3.0** IVHS shall include a Route Guidance (RG) function. Route Guidance will provide travelers with directions to selected destinations. Four functions are provided which are (1) Provide Directions, (2) Static Mode, (3) Real-Time Mode, and (4) User Interface.
>
> **1.3.1** RG shall include the capability to Provide Directions to travelers.

1.3.1.1 The Provide Directions function shall provide travelers with directions to their selected destination locations.

1.3.1.2 The Provide Directions function shall issue directions to travelers that is based on information about current conditions of transportation systems.

1.3.1.2.1 Current transportation system conditions upon which directions to travelers is based shall include, but not be limited to, the following:

1.3.1.2.1(a) Current traffic conditions.

1.3.1.2.1(b) Status of transit systems.

1.3.1.2.1(c) Schedules of transit systems.

1.3.1.2.1(d) Events taking place that influence travel routes.

1.3.1.2.1(d).1 Street closures.

1.3.1.2.1(d).2 Pedestrian events.

1.3.1.2.1(d).3 No pedestrian zones.

1.3.1.3 The Provide Direction function shall issue traveler directions that are simple and easy to understand in the form of arrow displays or voice messages providing turning instructions of which way to turn onto including, but not limited to, the following:

1.3.1.3(a) Particular streets.

1.3.1.3(b) Roads.

1.3.1.3(c) Walkways.

1.3.1.3(d) Transit facilities.

The "shall' statements, as illustrated above, identify the functions that need to be provided by market packages to satisfy the particular User Service.

AHS Market Packages

These are, from a system planning perspective, the basic building blocks of Intelligent Transportation Systems and AHS. They consist of groups or bundles of technologies that collectively address one or more User Service, providing tangible, measurable benefits for users. These building blocks can be assembled into system frameworks or architectures describing the 'big future picture' in simple terms. Market packages can also be sequenced over time and space as a way of explaining possible deployment paths from today's transportation context, to the final, future deployment. This will help to achieve the following:

- Characterize 'how' the AHS is going to meet user requirements
- List the products and features, and how each addresses a specific objective, need, or issue, or solves a specific problem
- Illustrate 'how' the AHS will provide tangible measurable benefits to the various users
- Explain possible incremental deployment sequences taking account of market influences, technology constraints, standards development, strategic investment, and other factors

Flexibility and interoperability are the keys to developing a successful architecture. There can be no single AHS design -- it must be a catalog or tool kit of compatible market packages. The selection of which market packages to implement are market driven, based on geographically-dependent user needs.

GUIDELINES

This section provides guidance on how to develop market packages for Automated Highway Systems. The guidelines include:

- Guidelines from the PMC
- Market Package Development and Structure Guidelines

Guidelines from the PMC

On May 14, 1997 a briefing was given to the PMC on the market package development work done to date. The objective was to judge the reaction and general sense of the PMC members to both the guidelines, which are being used to select and identify market packages, and to the preliminary lists of market packages themselves. The best way to approach this is to review the most important criteria that were used and the reaction of the PMC members to each.

- **Emphasize cooperative systems** -- This criteria suggests that we look at system approaches which try to utilize communications between vehicles and communications with the infrastructure. Obviously, communications with the infrastructure requires elements in the infrastructure which can provide useful information to the vehicles. This can range from very short term information (such as the existence of an obstacle on the immediate roadway) to long term information (such as congestion several miles away). Part of the rationale for this criteria is that most other AVCS activities are looking more at autonomous vehicle solutions than towards cooperative solutions, and that since this is an FHWA program, it should have a strong infrastructure focus. The PMC, in general, approved this relative emphasis, but would not want to exclude all work on non-cooperative systems.
- **Emphasize controlling systems, not just warning systems** -- Most other work going on, in particular the NHTSA work and much of the vehicle industry work, is focused on warning systems that work through the driver and do not attempt to take automated control of the vehicle, even in emergencies. However, the DOT, in their preliminary Intelligent Vehicle Initiative (IVI) plans, has included three levels of systems: level 1 for warning systems, level 2 for systems which intervene or take temporary control in emergencies, and level 3 for systems which automate normal driving actions, that is, which take full time control. Therefore the PMC, in general, approved this relative emphasis on three system levels, but again would not want to reduce the work on warning systems, especially that which was shown to be synergistic with development of controlling systems.
- **Complementary to, but not duplicative of, activities elsewhere** -- The two criteria above together suggest a third, that is, that the NAHSC plan to put their resources towards market packages which do not duplicate work going on elsewhere, especially with respect to work identified in NHTSA's current five year plan and in work known to be going on in industry. This certainly does not mean that the NAHSC work be seen as disconnected from the work of others. In fact, clear links between the two must be developed as part of the deployment plan. And further, work which clearly complements work by others is strongly advised. For instance, we should work on cooperative warning systems which would be integrated with the autonomous warning systems that are the focus of the NHTSA work.

- **Near term feasible** -- The program has been asked by the FHWA to have more of a near term focus. As we start to focus anyway on the prototypes we are going to build, and are selecting market packages which fit this bill, we will naturally start to think about things which fit one of the better definitions of near term, things for which we actually can build at least a feasibility prototype in the next 5 years. However, the PMC has, in general, no objection, and indeed a strong concern, that we keep a vision of AHS as we look at the near term.
- **Do we limit ourselves to systems that are applicable to freeways?** -- The core of these criteria is the question: Do we want to look at systems which are not applicable to freeways, but which have a significant safety payoff? The most obvious category is systems that attempt to deal with intersection collisions. The answer from the PMC is a cautious no. They recognize that this might open the floodgates to systems that do not lead to AHS, and they recognize that the Consortium's resources are limited. Never the less, they are not ready to rule out this type of system and want us to explore it a little. We should, in the next few months, familiarize ourselves with the scope of the NHTSA work in this area.

Market Package Development and Structure Guidelines

Market packages are groups of technologies that have been bundled together to provide a measurable service or benefit to the user of the system. Market packages describe how to provide one or more ITS User Service, and provide a physical or tangible means of satisfying user requirements. They are not a set of abstract functions, but concrete things that can or will be able to be purchased in the market. User Services and market packages are closely related. User Services are the "what", market packages are the "how" in addressing problems and needs.

Market packages may be used to illustrate the potential ITS solutions available in the market place today and in the future to non-technical users. Users may include, but are not limited to, those involved with consumers, transit, CVO (Commercial Vehicle Operations), infrastructure , and cross-cutting users.

National ITS Architecture Market Packages

The National ITS Architecture identifies a total of 56 market packages in the Implementation Strategy document that address the current trend in the technology market. A complete listing of these market packages is found in Table 2 below. The National ITS Architecture also identifies synergies and dependencies for the market packages.

Synergies

Synergies, in general, are the common elements among two or more market packages. The benefit of identifying these and developing them is that costs may be reduced, space requirements may be reduced, and operational efficiency may be improved. A common example of synergy among market packages is the means of communication. Oftentimes several market packages can share the same medium.

Dependencies

Dependencies of market packages are the market packages which need to be implemented before another market package can be fully implemented. An example may be In-vehicle Display. This requires some sort of sensors and processor to be in place before it can be used.

Table 2 - National ITS Architecture Market Packages

Traffic Management

- Network Surveillance
- Probe Surveillance
- Surface Street Control
- Freeway Control
- HOV and Reversible Lane Management
- Traffic Information Dissemination
- Regional Traffic Control
- Incident Management System
- Traffic Network Performance Evaluation
- Dynamic Toll/Parking Fee Management
- Emissions and Environmental Hazards Sensing
- Virtual TMC and Smart Probe Data
- Standard Railroad Grade Crossing
- Advanced Railroad Grade Crossing
- Railroad Operations Coordination

Transit Management

- Transit Vehicle Tracking
- Transit Fixed-Route Operations
- Demand Response Transit Operations
- Transit Passenger and Fare Management
- Transit Security
- Transit Maintenance
- Multi-modal Coordination

Traveler Information

- Broadcast Traveler Information
- Interactive Traveler Information
- Autonomous Route Guidance
- Dynamic Route Guidance
- Information Service Provider (ISP) Based Route Guidance
- Integrated Transportation Management/Route Guidance
- Yellow Pages and Reservation
- Dynamic Ridesharing
- In Vehicle Signing

Advanced Vehicle Safety Systems

- Vehicle Safety Monitoring
- Driver Safety Monitoring
- Longitudinal Safety Warning
- Lateral Safety Warning
- Intersection Safety Warning
- Pre-Crash Restraint Deployment
- Driver Visibility Improvement
- Advanced Vehicle Longitudinal Control
- Advanced Vehicle Lateral Control
- Intersection Collision Avoidance
- Automated Highway System

Commercial Vehicles

- Fleet Administration
- Freight Administration
- Electronic Clearance
- Electronic Clearance Enrollment
- International Border Electronic Clearance
- Weigh-In-Motion
- Roadside CVO Safety
- On-board CVO Safety
- CVO Fleet Maintenance
- HAZMAT Management

Emergency Management

- Emergency Response
- Emergency Routing
- Mayday Support

ITS Planning

- ITS Planning

Example from the National ITS Architecture

As an aid to understanding the ITS market package concept, an example taken from Appendix A in the Implementation Strategy document of the US National ITS Architecture Development Program is provided below. It describes a market package that provides highway network surveillance capabilities:

> **Network Surveillance**
>
> This basic market package, shown in Figure 2, provides the fixed roadside surveillance elements utilizing wireline communication to transmit the surveillance data. It can be used completely local such as loop detection connected with signal control or it can be CCTVs sending back data to the traffic management centers. This enables traffic managers to monitor road conditions, identify and verify incidents, analyze and reduce the collected data, and make it available to users and private information providers. It requires road sensors, communication links between the sensors and the traffic management system, data reduction software, and utilizes the existing wireline links between the Traffic Management Center and the traveler information providers.

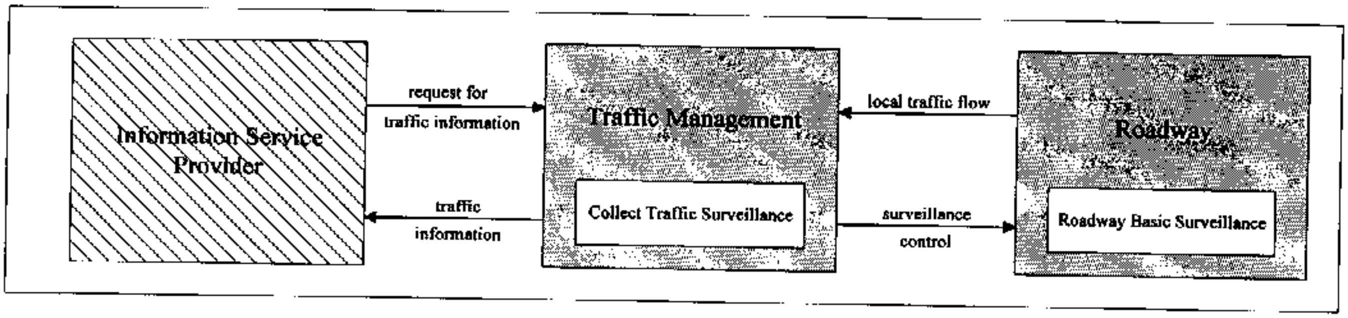


Figure 2. Graphical Representation of Network Surveillance Market Package

Defining and Developing Market Packages for AHS

A procedure for developing AHS market packages has been created by PB Farradyne Inc. in the AHS document titled *Defining and Developing AHS Market Packages*. Market package descriptions are composed of the following:

- A 'label' that identifies the market package and gives an indication of its nature
- The subsystems that contain the market package, and the data flows between the subsystems
- The measures of effectiveness for the market package
- A graphical illustration of the market package
- Societal and institutional issues surrounding the market package

It is important to note that market packages will change over time as technologies change and as new technologies are introduced into the market. Agencies and organizations may use the market packages identified in the National ITS Architecture, may create their own, or do both. The market packages identified in the National ITS Architecture provide a good model for development of new or modified market packages.

In the case of AHS, the National ITS Architecture has deliberately been vague on the market package definitions. Thus development of AHS market packages is needed. This may build upon the Advanced Vehicle Safety Systems (AVSS) market packages as well as those in other areas such as transit, commercial vehicles, and traffic management.

When defining a market package, one must do the following:

1. Identify subsystems -- This step includes the identification of the subsystems each market package resides in. The subsystems align closely with existing jurisdictional and physical boundaries that underscore the operation and maintenance of current transportation systems. The following figure from the Implementation Strategy document illustrates all of the subsystems associated with ITS as defined by the National ITS Architecture.

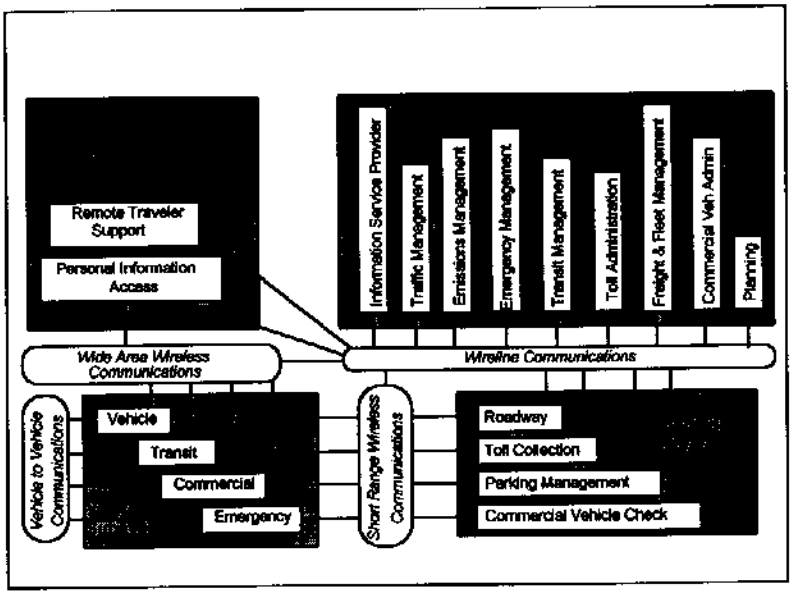


Figure 3. Identification of Subsystems

2. Identify data flows -- This step involves the identification of the data that needs to be transmitted between subsystems to provide the market package. The media upon which data is transmitted are illustrated as ovals in the preceding figure.

3. Develop operational descriptions -- This involves the development of a description of how the market package will operate. The description includes how it senses, what it determines, the interface with the vehicle components or driver, etc. It also contains information on how each of the user groups may perceive the market package as it relates to them.

4. Identify measures of effectiveness -- Measures of effectiveness, or performance measures, are identified for each specific market package. For a market package to be considered for implementation it will have to be evaluated to determine benefits.

5. Develop illustration -- A visual representation of the market package showing subsystems and data flows is developed.

The following statements may be used as a checklist to assist in definition of market packages and to ensure they fulfill their purpose. Each of them characterizes a different aspect of market packages.

- Market packages are a stakeholder and consumer tool to facilitate understanding of the technologies and the consequences
- Market packages describe HOW the solution is provided
- Market packages are groupings, or bundles, of technologies that address a defined need or provide a tangible benefit
- From a system planning perspective, market packages are the fundamental building block of regional ITS frameworks
- Market packages are technology dependent but not technology specific
- Market packages provide a meaningful description of technological capabilities to stakeholders
- Market packages are bundles of enabling technologies combined into tangible measurable units
- Market packages characterize future and presently available products and services
- Market packages may be used to characterize legacy systems
- Market packages enable implementation strategies to be developed
- Tangible benefits can be measured for market packages

Given this guidance, market packages may be developed which draw upon the user stated requirements.

EVALUATION CRITERIA

The evaluation criteria are suggested, descriptive criteria for evaluating the appropriateness and desirability of market packages. They should have a large subset of quantitative, objective measures that include a strict definition of the units of measurement. This will allow targets or baseline values for appropriate engineering-type evaluations.

Adhering to the idea of being user-driven and needs-driven, the evaluation criteria should be elicited from stakeholders. A first cut has been done by John Lathrop and Kan Chen for three user groups. Some of these Performance/Impact Measures (PIMs) may not pass everybody's definition of "quantitative, objective measures", but they are as close as possible, while still representing stakeholder values. In those cases where the PIMs do not seem satisfactory, expert panel subjective probabilities will have to be elicited to link those PIMs to whatever engineering measures do seem satisfactory.

Below are the evaluation criteria, or PIMs, that John Lathrop and Kan Chen elicited from three AHS stakeholder focus groups under C2. The stakeholder groups are 1) Private Direct User / Non-user, 2) Vehicle Industry, and 3) Government. Note that some of the PIMs are ranked (those preceded by a number) from most important to least important.

Private Direct User / Non-user
1. Safety
2. Travel time savings
3. Flexibility

4. System integrity
5. Travel time predictability
6. Change in vehicle operating cost
7. Access/egress
8. Change in vehicle capital cost
9. Aesthetics
10. Societal, environmental impacts
11. Override

Others:

- Hassle: checking in and out of the system
- Hassle: serviceability and certification
- Incrementalism
- Non-AHS user: changed congestion
- Non-AHS user: other disadvantages
- Privacy – "big brother" issue
- Privacy – proximity to strangers
- Remaining driving task
- Skills required
- Controlled, predictable environment
- Government mandates
- Learning curve, training time
- Reliability other than safety: security
- TechnoFear
- Reliability other than safety: vehicle operation
- Selectivity

Vehicle Industry

1. Liability
2. Customer objectives
3. Marketability
4. Image
5. Incrementability
6. Servicability
7. Producability
8. Spin-offs
9. Internal technical development

Government

1. Spin-off potential – safety
2. Change in capital cost
3. Incrementability
4. Upgrade/retrofit infrastructure
5. Institutional attractiveness
6. Operating burdens – liability

7. Operating burdens – maintenance
8. Spin-off – change existing tasks
9. Change in land use
10. Operating burdens – detour
11. Spin-off potential - information

IDEAS FOR DEVELOPING MARKET PACKAGES

This section, developed by Carol Jacoby, discusses several techniques to develop potential market packages. While we have an initial list of packages from the AVCS Compendium, we should attack the problem from other directions to be sure that it is complete and that we have considered the full range of ways to package capabilities.

Clearly, the preferred approach is to define market packages to supply the identified User Services. Yet these services will take some time to define, and we need to do as much of this as possible in parallel based on the user needs we already know. Also, User Services and market packages are not one-to-one, as can be seen in the ITS National Architecture (in just about any service but AVCS).

These approaches take advantage of work that was done previously by the team. While market packages are a new focus, there is much that has been done to date that supports their definition. It is expected that these various techniques will give many of the same answers. This is reasonable and enforces the appropriateness of the groupings that are defined.

There are a variety of techniques, or sources from previous work, that may be used for initial development of market packages. Ideas for market packages obtained from these sources, or using these techniques, should be collected, compared, and combined, if applicable, to form an initial list of AHS market packages. A "base" set of these initial AHS market packages should come from the AVSS market packages outlined in the National ITS Architecture. Once the AHS User Services are identified and materialized, it should be determined which initial market packages provide the identified User Services. Additional market packages will need to be developed for any User Service that is not satisfied by the initial list of market packages. Ultimately, unallocated market package ideas should be integrated with the initial market packages, lead to the development of new market packages that satisfy new or unallocated User Services, or be dropped.

Techniques, or sources from previous work that may be used for initial development of market packages include:

- **Use the AVCS Compendium** -- This has already been done. The 13 initial strawman market packages were defined from the Compendium by weeding out those that were not feasible or that were being developed elsewhere. The emphasis here is on various levels of control.
- **Use the AHS Stakeholder Forum** -- Additional input on User Services and market packages was obtained from stakeholders at the Stakeholder Forum. This input included new ideas and scenarios for Automated Highway Systems that may translate into new User Services and market packages.
- **Use the Functional Description of AHS** -- We have already defined the functionality of the AHS in data flow diagrams and in functional requirements. Ideally the market packages will provide an evolutionary path to the full AHS. This means that each of these functions should be provided by som market package. The technique here is to examine each function, determine what benefit it is supporting,

and what else needs to be included to provide the benefit.

- **Combine Decision Modules with Control Modules** -- Many of the functional requirements deal with making decisions. Each such decision involves sensing the environment, interpreting it, and defining a response. For example, obstacle avoidance needs a decision, with the following steps, (1) detect the obstacle, (2) determine whether it is a hazard, where it is and how likely it is that it will remain there, (3) decide whether to do nothing, brake, change lanes, or some combination.

  Such a decision or intelligence module could be added on top of the control base. This control base could be fully automated, fully manual, or something in between. The advantage of this approach is:

  - It applies to manual vehicles and hence has broad applicability
  - It allows us to develop some of the most difficult functions of the AHS – gathering definitive information about the driving environment for use in the decision process. Although it may appear that the decision process is the most difficult part of AHS, the decision process is greatly simplified if such definitive information about the driving environment is available. The decision process becomes difficult when there is large uncertainty in the information available about the driving environment.
  - We can test these packages safely as support to a fully alert manual driver.

  Any driving system includes control functions:
  - lane keeping
  - spacing keeping
  - speed keeping
  - lane changing
  - evasive maneuver
  - avoidance braking
  - entry
  - merge
  - exit

  and intelligence functions:
  - hazard recognition
  - hazard avoidance plan
  - navigation
  - traffic optimization
  - lane change planning
  - merge planning
  - safety optimization

  Each of these functions may be automated, semi-automated, manual, or precluded by the system design. For example, a vehicle with a navigation system, adaptive cruise control and haptic feedback for lane keeping, traveling on a single, dedicated, barriered and tightly controlled lane with one dedicated entry, would have semi-automated lane keeping, automated spacing and speed keeping, no lane changing, no merge, no hazards, automated navigation, and everything else would be manual.

  Of course, not all such combinations make sense. The "gap" is caused when automated control goes beyond automated intelligence. For example, automated lane, speed and spacing keeping (all of which are feasible now) in combination will cause the driver to lose vigilance, and so must be complemented by automated hazard response functions. This suggests that development of the intelligence functions . on the critical path to development of the full AHS.

The intelligence packages that are most promising for NAHSC are those that take advantage of infrastructure and/or vehicle cooperation to go significantly beyond what can be done by the vehicle alone. For example, merge support can track the gaps either by infrastructure detection or by communications from the mainline vehicles, and advise the vehicle (and possibly the ramp metering system) while the entering vehicle is still on the ramp. This makes for much safer, smoother and more reliable entries than a vehicle-based system that must try to fit into the traffic stream when it gets to the top of the ramp.

- **Add Cooperation to Vehicle-Centered Packages** -- NHTSA has already identified a wide range of safety-rated market packages. These should be specifically excluded from our work to avoid duplication of effort. However, each is designed to address a safety problem. If we ask how infrastructure and/or vehicle cooperation could help to solve the problem, it may suggest alternative market packages that are appropriate for NAHSC and that highlight the benefits of such cooperation. In general, the cooperative features are unique to NAHSC and should be leveraged wherever they provide advantage.
- **Start with the Hazards List and Accident Statistics from the Mixed Traffic Team** -- The Mixed Traffic Team has developed a list of 66 situations that the automated vehicle is expected to react to safely when operating in mixed traffic. These or combinations of these suggest safety-related market packages, such as lane change support or obstacle avoidance. Furthermore, the team has defined a matrix of accident causes based both on the initial cause (e.g., driver drowsiness) and the resulting geometry (e.g., single vehicle roadway departure). The reason the group chose a matrix was that accidents may be prevented by avoiding or reacting to either the initial cause (wake the driver or automation take-over), or the resulting geometry (sense the car going off the road and correct). This matrix then suggests little market packages to address each major accident cause. These may be grouped by rows or columns or by other groupings into meaningful packages.
- **Consider Applications For Each Combination Of The Key Attributes** -- The Concepts Team identified five key attributes that define various concepts. Following is a list of those attributes with expanded lists of alternatives for each. The additional alternatives are preliminary, and have been included to broaden the options for market packages beyond the original list that was designed for full AHS.
  - Dedicated lanes or mixed with manual?
    - ➢ Dedicated lanes
    - ➢ Protected lanes
    - ➢ Standard lanes
  - Distribution of intelligence
    - ➢ Autonomous
    - ➢ Low cooperation among vehicles
    - ➢ High cooperation among vehicles
    - ➢ Infrastructure supported (local broadcast) only
    - ➢ Infrastructure supported with low cooperation among vehicles

    - ➢ Infrastructure assisted (comm. with individual vehicles) with high cooperation among vehicles
- Grouped or separated?
    - ➢ Individual vehicles
    - ➢ Platoons
- Obstacle avoidance or exclusion?
    - ➢ Strict controls
    - ➢ Moderate controls
    - ➢ No controls
- Driver role
    - ➢ Fully manual (with warnings)
    - ➢ Automated control in emergency only
    - ➢ Haptic feedback
    - ➢ Automated resistance
    - ➢ Full automation with driver override
    - ➢ Full automation, no override

There are 648 combinations, but a large number of them are inconsistent and can be eliminated immediately. Each of the reasonable ones should be examined with an eye toward market packages that would work well in such an environment. This approach starts with a range of architectural constructs, and looks for suitable needs to apply them to. This activity should be based on the above needs-driven analyses.

HEURISTICS

This section details the heuristics that should be considered to provide direction during the process of defining AHS User Services and market packages. Relevant heuristics associated with AHS User Service and market package development includes:

- Heuristics for vehicle deployability, provided by Michelle Bayouth.
- Heuristics for infrastructure deployability, provided by Larry Graves, and based on work by Asfand Siddigui.
- Heuristics from systems architecting, to be provided.

Heuristics for Vehicle Deployability

- **Vehicle Line Manager Makes Choices, has Budget** -- The vehicle line manager is the one individual who decides what goes into the vehicle each year. He has a fixed budget, and must get the most into the vehicle within that budget. He knows his target consumer group well. Any component that goes into the vehicle must sell at a price the customer is willing to pay – requiring value identification and a good business case.
- **Tremendous Cost Pressures**
- **New technology** -- New technology that comes from the R&D side must pass stringent criteria for

durability, manufacturability, and cost.

- **R&D Money** -- A line manager can fund R&D for a particular capability that it wants to put on the vehicle. The products of this process are much easier to get onto the vehicle than those that come from exploratory money, which must be "sold" to the vehicle line manager.
- **Something Goes Out When Something Comes In** -- Cost pressures require that if a new capability gets put onto a vehicle, something else gets thrown out. This is cost equilibrium.
- **What Goes Down Gets Fancy** -- Depreciation in the component cost leads to fanciness rather than cost savings. For example, when radio cost goes down, more features are added so the cost stays the same.
- **Safety and Security Still Sell Seashells at the Seashore** -- Young people buying low end cars may prefer CDs, but, in general, safety still sells. The potential "safety" market has yet to be fully tapped.
- **New Reality: Volume Doesn't Help** -- Foreign competition has changed the standard 200,000 units/year to 20,000.
- **Legislation Does** -- It is easier to get new technologies onto the vehicle if the law requires it. No one wants to look like a lawbreaker to the public.
- **Small Chunks are More Appealing** -- The vehicle line manager knows his customers, and change comes slowly. You can't do too much at once because of cost and alienating the customer base.
- **Trucks are Technophobic – Will They Be?** -- There is good potential for introducing technology into the truck market (50 percent of business) although there may be opposition to doing so.
- **Leather Hugs You, Technology Doesn't** -- Consumers want comfort and convenience. Technology i not as big a seller.
- **Looking for Showstoppers, Not Winners** -- What customers do and what they say they will do are entirely different things. Do not look for what customers say they will buy. Look for what they are opposed to.
- **Consumers are Maxed Out** -- Most consumers are at the limit they are willing to pay for vehicles. Even those with more disposable income have a cap to what they are willing to spend.
- **It Has to Work as Well as the Customer Expects it to** -- It does not matter how it was supposed to work, or what the directions said. It matters what the general public's perception of the technology is. (i.e., Air bags are fluffy pillows, not something using solid rocket booster technology).
- **Customers Do Not Want Drastic Change** -- Vehicle line managers will be real hesitant to offend the customer base they cater to. Most customers want a few new things each purchase, not radical shifts in the way they drive or the things they use while driving.
- **Consider Your Own Buying Habits** -- Most people want as much value for their money as possible.
- **When the Going Gets Tough, High Tech is the First to Go** -- The economy can drastically change over the vehicle design cycle, and if times get lean, things get stripped out of the car to bring the cost down. Technology is the first to go.
- **2.5 to 3 Year Cycle for Plug and Play** -- Plug and play capabilities (e.g., leave a hole in the dash for the next cool thing) take 2.5 to 3 years to get into the vehicle and onto the showroom floor.

- **4 to 7 Year Cycle for New Stuff** -- Anything requiring vehicle modification takes four to seven years.
- **Positive Return on Investment within 2 Years** – A general rule of thumb from the trucking industry is that investments in equipment for trucks should have a positive return on investment within 2 years.
- **All Limited Intervention Systems Should Have Driver Override**

Heuristics for Infrastructure Deployability

- **Expensive** -- Infrastructure solutions are generally expensive due to their size and the type of work involved. Even for minor projects the amount goes into hundreds of thousands, if not millions, of dollars. Expense or "cost" of any solution must be weighed against the alternatives and benefits. Infrastructure solutions "generally" require a large investment that dictates a "governmental" solution, however we are seeing "private" toll roads become one way of financing these improvements.
- **Smaller Solutions Are Better in the Short Term** -- Smaller bundles of new technology are easier and less risky to implement. They are less complicated (easier to fit into present system) and, in general, cost less. Solutions that are smaller in size (in terms of time and money) are easier to sell. However, smaller solutions can lead to expensive maintenance and support problems later on, especially if non-compatible systems are implemented on the same roadway. This is a problem being addressed by the National ITS Architecture and other attempts at standardization.
- **Difficult To Maintain** -- With limited budgets and personnel, limited accessibility, and increasing usage of freeways, it is getting more difficult to maintain infrastructure. The movement toward standardized systems and life cycle costing of projects is attempting to address this problem and is very important in reviewing AHS infrastructure solutions.
- **No Simple Answer** -- There are no simple answers to solve infrastructure problems. Many times it seems that solutions to specific transportation problems are simple, but that is not the case. Each problem consists of unique variables pertaining to that location which must be considered before generating a solution.
- **Each Problem And Location Is Unique** -- Each location has it's own unique application problems. Solutions that work on one may not necessarily work at another similar location. Each problem is unique and requires a separate study before a solution is produced.
- **Solve Specific Problems** -- AHS solutions should be structured to provide solutions to specific problems such as increasing safety at a particular interchange, intersection, or curve. The way in which the solution is *applied* to a specific situation or problem may very well be unique. One example may be ramp metering infrastructure as a solution, but applying ramp metering parameters (traffic flow, time of day etc.) to specific situations will vary according to that location.
- **Project Oriented** -- Personnel working on design, development and implementation of infrastructure are project oriented. Infrastructure related AHS solutions should be in the form of projects (hierarchical, bottom-up deployment schemes).
- **Lower Risk Is Better** -- In general, solutions with lower risks are better. Risks may be physical, perceived, political, or economic.
- **Long Lead Time To Deploy / Implement** -- There is generally a correlation between the size of a

project and the time it takes to implement - the larger the project, the longer the required lead time.

- **Must Live With It A Long Time (Good or Bad)** -- Once a project is in place it is often very difficult to undo it.
- **Visual Changes Are More Important for Public Perception** -- Any change that looks good and provides better functionality creates a good public perception (i.e., filling potholes or adding a lane has higher visibility than signal synchronization).
- **Effective Enforcement is Difficult** -- Effective enforcement is difficult, as enforcement resources are limited.
- **Traffic Operations (Systems Influence) In Infancy** -- Controlling / influencing traffic with electronic systems for traffic management purposes is relatively new in the United States. There is still a lot of testing and experimentation that is needed to determine what works best.
- **Must Consider the Whole System** -- Transportation decisions have impacts well beyond highway right-of-way. Increases in throughput/capacity must be balanced with land use, environmental and local impact concerns. The extent to which ITS/AHS, including intermodal solutions, can support local, regional, and state goals and policies will determine the extent to which ITS/AHS will succeed.

Heuristics from System Architecting

Information will be added to this section at a later date.

CURRENT NEEDS / USER SERVICES / MARKET PACKAGES

This section contains current information on user needs and User Services obtained from AHS stakeholders, and current information on initial AHS market packages. The lists of user groups and user needs were initially developed from user needs research done by PATH. The list was later revised after receiving additional user input at the April 25, 1997 ITS Midwest meeting and the June 1997 Stakeholder Forum. The list is a compilation of all known needs, and was developed with a significant amount of input from users.

User Groups

Needs should be obtained from those who use or are affected by the transportation system. To facilitate the identification and categorization of needs, transportation users and providers have been categorized according to the following five groups:

- Consumers
- Transit
- Commercial Vehicle Operations (CVO)
- Infrastructure
- Cross-cutting

The Consumers category generally includes those who own and/or operate private vehicles. The category also includes the automotive and electronics industries. Specifically, consumers include:

- Private car commuters
- Local drivers
- Tourists
- Automotive suppliers
- Electronics vendors
- Rental car companies

The Transit category generally includes transit users and operators. Specifically, the Transit user group includes:

- Transit operators
- Taxi operators
- Private passenger fleet operators
- Transit riders
- Transit commuters
- Vanpools and carpools

The CVO user group includes commercial vehicle owners and operators, specifically:

- Common carriers
  - for hire
  - owner-operators
- Private carriers (operate a dedicated fleet as a secondary activity)

The Infrastructure category includes those affiliated with ownership, operation, and maintenance of transportation infrastructure. Examples include:

- Road infrastructure owners
- State DOTs
- Metropolitan Planning Organizations
- Toll and turnpike operators
- Traffic engineers
- Transportation planners
- Road maintenance and operations managers
- City, municipal, county

The Cross-cutting category includes those who could be included in any of the other categories, or other users associated with transportation system. The Cross-cutting user group includes:

- Environmental
- Insurance
- Vehicle manufacturers
- Electronics suppliers
- Enforcement
- Emergency services
- Other vested interests
- Regulatory bodies
- Standard setting bodies
- Non Users

Current List of AHS User Needs

Following is the current list of user needs. The user needs are presented in no specific order of importance.

Consumer Needs

- Reduce the stress of highway driving
- Reduce adverse environmental effects caused by vehicles
- Reduce congestion
- Reduce travel time
- Improve the safety of highway travel
- Be widely accessible and affordable
- Be convenient and easy to use
- Be reliable
- Ensure reliable travel time
- Avoid exacerbating transportation problems (e.g., urban sprawl)

Transit Needs

- Increase safety
- Support heavy vehicles as well as automobiles
- Support better adherence to published schedules
- Increase travel time reliability
- Increase customer satisfaction
- Increase throughput
- Reduce operations costs
- Decrease run time
- Provide parking information
- Improve bus docking precision
- Improve maintenance operations
- Improve maintenance labor productivity
- Increase flexibility to meet future demands
- Increase driver's availability for non-driving tasks
- Reduce driver stress
- Improve perceived security
- Approach rail-like disciplined operations
- Achieve fail safe rail approaches
- Improve support vehicle operations
- Improve inter-modal safety
- Provide fast emergency service

CVO Needs

- Increase safety
- Support heavy vehicles as well as automobiles
- Provide short term return on investment (less than 2 year payback)
- Increase journey time reliability
- Reduce journey times

- Increase throughput
- Reduce paperwork and administrative burden

Infrastructure Needs
- Reduce congestion
- Increase efficiency
- Improve safety
- Acceptable new construction costs
- Identifiable, acceptable, quantifiable risks
- 24 Hour all weather operation
- Competitive with conventional solutions
- Be incrementally or progressively deployable
- Check vehicle and system status
- Check and ensure driver readiness
- Check infrastructure
- Provide traffic surveillance
- Provide diagnostics to identify weather-related and other factors that affect traffic flow
- Provide information for current and predicted travel times
- Provide for Mayday capability
- Be designed for easy, affordable maintenance (acceptable cost)
- Manage/minimize liability exposure
- Improve incident detection and management
- Provide TMC or TMC-augmentation
- Provide way to acquire, protect, and use data
- Provide revenue-generating capability to offset costs
- Assure security of system
- Be capable of operation/management by infrastructure owners/institutions
- Increase accessibility
- Balance needs of infrastructure and adjacent land uses
- Support existing land uses, and land use and economic development plans
- Balance public equity in allocation of private vehicle and public costs
- Provide obstacle warning
- Provide for spot / critical location deployability
- Identify advisory speed in dangerous locations
- Control/govern speed in dangerous locations (CVO)

Cross-cutting Needs
- Highway safety
- Economical
- Return on investment
- Little or no environmental impact
- No introduction of unacceptable risks

Current List of AHS User Services

The current list of AHS User Services was derived from the following sources:

- April 25, 1997 ITS Midwest Conference - an ITS conference held in Chicago. IL. Attendees included transportation professionals involved in a variety of transportation areas of discipline, including, nut not limited to, AHS.
- AVCS Compendium - a document prepared by an NAHSC Committee to form a framework for NAHSC research efforts in Automated Vehicle Control (AVC) Services, and to provide common terminology and definitions.
- June 1997 AHS Stakeholder Forum - a two-day meeting for transportation professionals interested in AHS. The meeting was held in Washington D.C., following the ITS America conference.
- AHS System Specification - a working document prepared by the NAHSC to summarize the system requirements for an AHS.

The current list of AHS User Services provides a complete record of all input received from the source. Each of the below AHS User Services is addressed by (falls under) one of the high-level AHS User Service labels in Table 3. For detailed information on the current list of AHS User Services, refer to the NAHSC document, *Automated Highway System User Services, Parts 1 and 2*, authored by Jim Reynold and dated August 1997.

User Services Defined at the ITS Midwest Conference

Private Car Driver

- Request to Back Off
- Monitor and Diagnose Vehicle Condition
- Monitor and Diagnose Driver Condition
- Monitor and Diagnose Vehicle System
- Monitor and Diagnose Other Driver Behavior
- Monitor and Diagnose Other Vehicles
- Identify Risks
    - Other Driver
    - Context
    - Conditions
- Advise Appropriate Speed
- Advise Appropriate Actions
- Assist with Parking
    - On-street
    - Off-street
- Automate Appropriate Speed
- Automate Lane Keeping
- Automate Merging
- Automate Lane Changing
- Detect Obstacles

Commercial Vehicle Operators and Managers

- Increase Travel Time Predictability
- Automate Truck Driver Tasks
  - Record Keeping
  - Drive Truck
- Monitor and Diagnose Load Condition
- Monitor and Diagnose Security
- Detect Contraband
- Ensure Load Integrity
- Improve Mobile Communications
  - Truck to Center
  - Center to Truck
  - Truck to Truck
- Increase Driver Productivity

Transit Driver, Manager, and Rider

- Automate Bus Driver Tasks
  - Drive Bus
  - Collect Fares
  - Provide Traveler Information
  - Adhere to Schedule
- Maintain Spacing (with Other Buses)
- Monitor and Diagnose Vehicle Condition
- Monitor and Diagnose Driver, Road, and System
- Monitor and Diagnose Security

Traffic Manager

- Assist Parking – on street
- Manage Parking – off street

User Services Derived From the AVCS Compendium

Driver Aids, Situation Warning

- Warn of potential frontal collisions with vehicles
- Warn of potential frontal collisions with vehicles or obstacles
- Warn of vehicles in adjacent lanes
- Warn of over-taking vehicles
- Warn of lane departure
- Warn of coefficient of friction
- Obtain warning and advice from cooperative vehicles
- Obtain warning and advice from cooperative infrastructure
- Warn of driver drowsiness
- Monitor and warn of vehicle health

Driver Aids, Temporary Emergency Control

- Avoid skids
- Avoid frontal collisions with vehicles
- Avoid frontal collisions with obstacles and vehicles
- Avoid side collisions
- Avoid overtaking vehicle collisions
- Avoid lane departures
- Avoid frontal and side collisions
- Transmit control data to driver and system from cooperative vehicles
- Transmit control data to driver and system from cooperative infrastructure
- Mitigate drowsy drivers

Driver Aids, Driving Management in Mixed Traffic

- Provide adaptive cruise control
- Provide lane keeping
- Provide adaptive cruise control and lane keeping
- Provide background longitudinal warning
- Provide background lateral warning

Driver Aids, Driving Management with Temporary Emergency Control in Mixed Traffic

- Provide merge capability
- Automate control with driver override

Fully Automated Control in Mixed Traffic and Dedicated Lanes

- Automate control in mixed traffic
- Automate control in dedicated lanes

User Services Defined at the AHS Stakeholder Forum

Consumers

- Provide lane departure warning
- Provide lane keeping

Commercial Vehicle Operations

- Automatically keep a safe stopping distance

Infrastructure

- Optimize traffic flow
- Adjust and balance lanes
- Detect and respond to incidents
- Manage infrastructure maintenance

Cross-cutting

- Avoid frontal and side collisions

- Reduce accidents

User Service Input from the System Specification

- Control vehicle entry/exit
- Verify vehicle state
- Determine capacity and readiness of driver
- Control merging/lane changing
- Transfer control of vehicle
- Park Vehicle
- Determine Vehicle Position
- Provide lateral control
- Provide longitudinal control
- Maintain awareness of vehicle state and extent
- Detect and respond to anomalies
- Monitor and control traffic conditions
- Optimize traffic flow
- Determine vehicle's operational status
- Adjust vehicle parameters
- Adjust and balance lane usage
- Adjust and balance operating parameters
- Perform traffic diversion and rerouting
- Manage infrastructure maintenance operations
- Coordinate with non-AHS TMCs
- Reduce incident severity
- Provide baseline throughput
- Accommodate impeding maneuvers
- Monitor and control vehicle certification
- Monitor and control environmental impacts
- Detect and avoid obstacles
- Monitor and control system status
- Communicate with non-AHS vehicles
- Communicate with infrastructure
- Communicate with other AHS vehicles
- Detect intruder vehicles

Current List of AHS Market Packages

A list of market packages that have been defined to date as part of the AHS Progressive Deployment effort is provided below. This list is from the NAHSC document, *Automated Highway System Market Packages*, authored by Tom McKendree and dated September 24, 1997. This list was derived from AVSS market packages, other ITS market packages relevant to AHS, and unallocated market package ideas. It is recognized that the list may be too detailed to carry over to the National ITS Architecture as top-level market packages. Thus, these market packages may be grouped, with the current "market packages" being finer graduations of the final "market package" list. For detailed information on the current list of AHS market packages, refer to the *Automated Highway System Market Packages* document.

A. WARNING AND ADVICE MARKET PACKAGES

A.1 Autonomous Warning and Advice Market Packages

A.1.a Frontal Collision Warning without Communication
A.1.b Curve Overspeed Warning
A.1.c Blind Spot Warning
A.1.d Side Collision Warning
A.1.e Lane Change Collision Warning
A.1.f Lane Departure Warning
A.1.g Autonomous Road Surface Condition Warning
A.1.h Traffic Situation Awareness
A.1.i Unsafe Driving Situation Warning
A.1.j Merge Maneuver Advisor
A.1.k Lane Change Maneuver Advisor
A.1.l Traffic Negotiator
A.1.m Vehicle Condition Warning
A.1.n Driver Condition Warning

A.2 Cooperative Warning and Advice Market Packages

A.2.a Cooperative Frontal Collision Warning
A.2.b Cooperative Curve Overspeed Warning
A.2.c Cooperative Blind Spot Warning
A.2.d Cooperative Side Collision Warning
A.2.e Cooperative Lane Change Collision Warning
A.2.f Cooperative Lane Departure Warning
A.2.g Cooperative Road Condition Warning
A.2.h Cooperative Traffic Situation Awareness
A.2.i Cooperative Defensive Driving Advisory
A.2.j Cooperative Merge Maneuver Advisory
A.2.k Cooperative Lane Change Maneuver Advice
A.2.l Cooperative Traffic Negotiator
A.2.m Cooperative Vehicle Condition Warning

A.2.n Driver Condition Warning (with communications)

A.2.o Road Management Situation Warning (RMSW)

A.2.p Cooperative Intersection Warning

A.2.q Cooperative Railroad Crossing Warning

B. MARKET PACKAGES PROVIDING TEMPORARY EMERGENCY CONTROL

B.1 Autonomous Emergency Control Market Packages

B.1.a Frontal Collision Avoidance of Obstacles and Vehicles (brake only)

B.1.a' Frontal Collision Resistance of Obstacles and Vehicles (brake only)

B.1.b Curve Overspeed Avoidance

B.1.b' Curve Overspeed Resistance

B.1.c Blind Spot Collision Avoidance

B.1.c' Blind Spot Collision Resistance

B.1.d Side Collision Avoidance

B.1.d' Side Collision Resistance

B.1.e Lane Change Collision Avoidance

B.1.e' Lane Change Collision Resistance

B.1.f Lane Departure Avoidance

B.1.f' Lane Departure Resistance

B.1.g Autonomous Road Surface Condition Emergency Control

B.1.n Driver Condition Mitigation - Avoidance

B.1.n' Driver Condition Mitigation - Resistance

B.2 Cooperative Emergency Control Market Packages

B.2.a Cooperative Frontal Collision Avoidance of Obstacles and Vehicles (brake only)

B.2.a' Cooperative Frontal Collision Resistance of Obstacles and Vehicles (brake only)

B.2.b Cooperative Curve Overspeed Avoidance

B.2.b' Cooperative Curve Overspeed Resistance

B.2.c Cooperative Blind Spot Collision Avoidance

B.2.c' Cooperative Blind Spot Collision Resistance

B.2.d Cooperative Side Collision Avoidance

B.2.d' Cooperative Side Collision Resistance

B.2.e Cooperative Lane Change Collision Avoidance

- B.2.e' Cooperative Lane Change Collision Resistance
- B.2.f Cooperative Lane Departure Avoidance
- B.2.f' Cooperative Lane Departure Resistance
- B.2.g Cooperative Road Surface Condition Avoidance
- B.2.g' Cooperative Road Surface Condition Resistance
- B.2.j Cooperative Merge Maneuver Execution
- B.2.n Cooperative Driver Condition Mitigation
- B.2.o Road Management Situation Avoidance (RMSA)
- B.2.o' Road Management Situation Resistance (RMSA)
- B.2.p Cooperative Intersection Collision Avoidance
- B.2.p' Cooperative Intersection Collision Resistance
- B.2.q Cooperative Railroad Crossing Avoidance
- B.2.q' Cooperative Railroad Crossing Resistance

C. MARKET PACKAGES PROVIDING CONTROL OF NORMAL DRIVING ACTIONS

C.1 Autonomous Normal Driving Market Packages

- C.1.a Adaptive Cruise Control
- C.1.b (Advanced) Adaptive Cruise Control
- C.1.c Lane Keeping (proposed)
- C.1.d (A)ACC, FCA and SCA (Brake and Throttle Only)
- C.1.e (A)ACC, FCA, SCA (Brake and Throttle Only) and Driver Initiated Lane Changes
- C.1.f (A)ACC, FCA, SCA (Brake and Throttle Only) and Lane Keeping with Driver Alertness Monitoring
- C.1.g (A)ACC, FCA, SCA (Brake and Throttle Only), Lane Keeping with Driver Alertness Monitoring and Vehicle Initiated Lane Changes
- C.1.h (A)ACC, FCA, SCA (Brake and Throttle Only), Lane Keeping with Driver Alertness Monitoring, Vehicle Initiated Lane Changes and Automated Merge/Demerge

C.2 Cooperative Normal Driving Market Packages

- C.2.a Cooperative Adaptive Cruise Control
- C.2.b Cooperative (Advanced) Adaptive Cruise Control
- C.2.c Cooperative (Advanced) Adaptive Cruise Control and Frontal Collision Avoidance in Mixed Traffic on a Protected Lane
- C.2.d Cooperative (A) ACC, FCA, and Lane Keeping in Mixed Traffic on a Protected Lane

- C.2.e Cooperative (A) ACC, FCA, LK, and Merge/Demerge Capability in Mixed Traffic on a Protected Lane
- C.2.f Lane Keeping and (Advanced) Adaptive Cruise Control with Driver Alertness Monitoring

D. AUTOMATED HIGHWAY SYSTEMS

- D.1.a Autonomous AHS in Mixed Traffic
- D.2.a Cooperative AHS in Dedicated Lanes
- D.2.b Cooperative AHS in Mixed or Dedicated Lanes

SPECIALIZED APPLICATIONS

- Automated Bus Movement in the Maintenance Area
- Automated Snowplows
- Truck Convoy with Driver in Leading Truck
- Truck Safety System
- Bus Docking Aid
- Automated Container Movement (within terminal)
- Inter-terminal Passenger Shuttle
- Coordinated Startup (from a stop light)

AHS User Service / Market Package Relationship

The association between the currently identified AHS User Services and AHS market packages is presented in Table 3. Market packages that address a User Service are identified by the symbol, "X ". Market packages that may have some beneficial effect towards a User Service are identified by the symbol, "+". The table will be updated as AHS market packages and User Services continue to be developed. (Note: some of the User Service – market package relationships still need to be discussed and determined)

Table 3 – AHS Market Package to AHS User Service Relationship

AHS Market Package	**AHS User Service**						
	Avoid Longitudinal Collision	Avoid Lateral Collision	Avoid Intersection Collision	Enhance Vision for Crash Avoidance	Provide Safety Readiness	Deploy Pre-Crash Restraint	Automate Vehicle Operations
A. Warning and Advice Market Packages **A.1 Autonomous Warning and Advice Market Packages**							
A.1.a Frontal Collision Warning without Communication	X		+	X	+	+	
A.1.b Curve Overspeed Warning	+	X			+	+	
A.1.c Blind Spot Warning		X			+	+	
A.1.d Side Collision Warning		X	+		+	+	
A.1.e Lane Change Collision Warning	+	X			+	+	
A.1.f Lane Departure Warning		X			+	+	

AHS Market Package	**AHS User Service**						
	Avoid Longitudinal Collision	Avoid Lateral Collision	Avoid Intersection Collision	Enhance Vision for Crash Avoidance	Provide Safety Readiness	Deploy Pre-Crash Restraint	Automate Vehicle Operations
A.1.g Autonomous Road Surface Condition Warning	+	+	+	+	+		
A.1.h Traffic Situation Awareness	X	X	+	+	+	+	
A.1.i Unsafe Driving Situation Warning	X	X	+	+	+	+	
A.1.j Merge Maneuver Advisor	+	X			+	+	
A.1.k Lane Change Maneuver Advisor	+	X			+	+	
A.1.l Traffic Negotiator	+	+			+	+	
A.1.m Vehicle Condition Warning	+	+	+		X		
A.1.n Driver Condition Warning	+	+	+		X		

AHS Market Package	AHS User Service						
	Avoid Longitudinal Collision	Avoid Lateral Collision	Avoid Intersection Collision	Enhance Vision for Crash Avoidance	Provide Safety Readiness	Deploy Pre-Crash Restraint	Automate Vehicle Operations
A.2 Cooperative Warning and Advice Market Package							
A.2.a Cooperative Frontal Collision Warning	X		X	X	+	+	
A.2.b Cooperative Curve Overspeed Warning	+	X			+	+	
A.2.c Cooperative Blind Spot Warning		X			+	+	
A.2.d Cooperative Side Collision Warning		X	X		+	+	
A.2.e Cooperative Lane Change Collision Warning	+	X			+	+	
A.2.f Cooperative Lane Departure Warning		X			+	+	

AHS Market Package	**AHS User Service**						
	Avoid Longitudinal Collision	Avoid Lateral Collision	Avoid Intersection Collision	Enhance Vision for Crash Avoidance	Provide Safety Readiness	Deploy Pre-Crash Restraint	Automate Vehicle Operations
A.2.g Cooperative Road Condition Warning	+	+	+	+	+		
A.2.h Cooperative Traffic Situation Awareness	X	X	X	+	+	+	
A.2.i Cooperative Defensive Driving Advisory	X	X	X	+	+	+	
A.2.j Cooperative Merge Maneuver Advisory	+	X			+	+	
A.2.k Cooperative Lane Change Maneuver Advice	+	X			+	+	
A.2.l Cooperative Traffic Negotiator	+	+	+		+	+	

AHS Market Package	**AHS User Service**						
	Avoid Longitudinal Collision	Avoid Lateral Collision	Avoid Intersection Collision	Enhance Vision for Crash Avoidance	Provide Safety Readiness	Deploy Pre-Crash Restraint	Automate Vehicle Operations
A.2.m Cooperative Vehicle Condition Warning	+	+	+		X		
A.2.n Driver Condition Warning (with communications)	+	+	+		X		
A.2.o Road Management Situation Warning (RMSW)	X	+	+	+	+	+	
A.2.p Cooperative Intersection Warning **(TBD)**							
A.2.q Cooperative Railroad Crossing Warning **(TBD)**							
B Market Packages Providing Temporary Emergency Control (called Intervention or Avoidance)							
B.1 Autonomous Emergency Control Market Packages							

AHS Market Package	AHS User Service						
	Avoid Longitudinal Collision	Avoid Lateral Collision	Avoid Intersection Collision	Enhance Vision for Crash Avoidance	Provide Safety Readiness	Deploy Pre-Crash Restraint	Automate Vehicle Operations
B.1.a Frontal Collision Avoidance of Obstacles and Vehicles (brake only)	X		+	+	+	+	
B.1.a' Frontal Collision Resistance of Obstacles and Vehicles (brake only)	X			+	+	+	
B.1.b Curve Overspeed Avoidance	+	X			+	+	
B.1.b' Curve Overspeed Resistance	+	X			+	+	
B.1.c Blind Spot Collision Avoidance		X			+	+	
B.1.c' Blind Spot Collision Resistance		X			+	+	
B.1.d Side Collision Avoidance		X	+		+	+	

AHS Market Package	**AHS User Service**						
	Avoid Longitudinal Collision	Avoid Lateral Collision	Avoid Intersection Collision	Enhance Vision for Crash Avoidance	Provide Safety Readiness	Deploy Pre-Crash Restraint	Automate Vehicle Operations
B.1.d' Side Collision Resistance		X			+	+	
B.1.e Lane Change Collision Avoidance	+	X			+	+	
B.1.e' Lane Change Collision Resistance	+	X			+	+	
B.1.f Lane Departure Avoidance		X			+	+	
B.1.f' Lane Departure Resistance		X			+	+	
B.1.g Autonomous Road Surface Condition Emergency Control	+	+	+	+	+		
B.1.m Driver Condition Mitigation - Avoidance	+	+	+		X		

AHS Market Package	**AHS User Service**						
	Avoid Longitudinal Collision	Avoid Lateral Collision	Avoid Intersection Collision	Enhance Vision for Crash Avoidance	Provide Safety Readiness	Deploy Pre-Crash Restraint	Automate Vehicle Operations
B.1.m' Driver Condition Mitigation - Resistance	+	+	+		X		
B.2 Cooperative Emergency Control Market Packages							
B.2.a Cooperative Frontal Collision Avoidance of Obstacles and Vehicles (brake only)	X		X	+	+	+	
B.2.a' Cooperative Frontal Collision Resistance of Obstacles and Vehicles (brake only)	X		X	+	+	+	
B.2.b Cooperative Curve Overspeed Avoidance	+	X			+	+	
B.2.b' Cooperative Curve Overspeed Resistance	+	X			+	+	

AHS Market Package	**AHS User Service**						
	Avoid Longitudinal Collision	Avoid Lateral Collision	Avoid Intersection Collision	Enhance Vision for Crash Avoidance	Provide Safety Readiness	Deploy Pre-Crash Restraint	Automate Vehicle Operations
B.2.c Cooperative Blind Spot Collision Avoidance		X			+	+	
B.2.c' Cooperative Blind Spot Collision Resistance		X			+	+	
B.2.d Cooperative Side Collision Avoidance		X	X		+	+	
B.2.d' Cooperative Side Collision Resistance		X	X		+	+	
B.2.e Cooperative Lane Change Collision Avoidance	+	X			+	+	
B.2.e' Cooperative Lane Change Collision Resistance	+	X			+	+	

AHS Market Package	**AHS User Service**						
	Avoid Longitudinal Collision	Avoid Lateral Collision	Avoid Intersection Collision	Enhance Vision for Crash Avoidance	Provide Safety Readiness	Deploy Pre-Crash Restraint	Automate Vehicle Operations
B.2.f Cooperative Lane Departure Avoidance		X			+	+	
B.2.f' Cooperative Lane Departure Resistance		X			+	+	
B.2.g Cooperative Road Surface Condition Avoidance	+	+	+	+	+		
B.2.g' Cooperative Road Surface Condition Resistance	+	+	+	+	+		
B.2.j Cooperative Merge Maneuver Execution **(TBD)**							
B.2.n Cooperative Driver Condition Mitigation	+	+	+		X		

AHS Market Package	**AHS User Service**						
	Avoid Longitudinal Collision	Avoid Lateral Collision	Avoid Intersection Collision	Enhance Vision for Crash Avoidance	Provide Safety Readiness	Deploy Pre-Crash Restraint	Automate Vehicle Operations
B.2.o Road Management Situation Avoidance (RMSA)	X	+	+	+	+	+	
B.2.o' Road Management Situation Resistance (RMSR)	X	+	+	+	+	+	
B.2.p Cooperative Intersection Collision Avoidance **(TBD)**							
B.2.p' Cooperative Intersection Collision Resistance **(TBD)**							
B.2.q Cooperative Railroad Crossing Avoidance **(TBD)**							

AHS Market Package	AHS User Service						
	Avoid Longitudinal Collision	Avoid Lateral Collision	Avoid Intersection Collision	Enhance Vision for Crash Avoidance	Provide Safety Readiness	Deploy Pre-Crash Restraint	Automate Vehicle Operations
B.2.q' Cooperative Railroad Crossing Resistance **(TBD)**							
C Market Packages Providing Control of Normal Driving Actions							
C.1 Autonomous Normal Driving Market Packages							
C.1.a Adaptive Cruise Control	+				+	+	
C.1.b (Advanced) Adaptive Cruise Control	X		+		+	+	
C.1.c Lane Keeping **(TBD)**							
C.1.d (A) ACC, FCA and SCA (Brake and Throttle Only) **(TBD)**							

AHS Market Package	**AHS User Service**						
	Avoid Longitudinal Collision	Avoid Lateral Collision	Avoid Intersection Collision	Enhance Vision for Crash Avoidance	Provide Safety Readiness	Deploy Pre-Crash Restraint	Automate Vehicle Operations
C.1.c (A) ACC, FCA, SCA (Brake and Throttle Only) and Driver Initiated Lane Changes **(TBD)**							
C.1.f (A) ACC, FCA, SCA (Brake and Throttle Only) and Lane Keeping with Driver Alertness Monitoring **(TBD)**							
C.1.g (A) ACC, FCA, SCA (Brake and Throttle Only), Lane Keeping with Driver Alertness Monitoring and Vehicle Initiated Lane Changes **(TBD)**							

AHS Market Package	**AHS User Service**						
	Avoid Longitudinal Collision	Avoid Lateral Collision	Avoid Intersection Collision	Enhance Vision for Crash Avoidance	Provide Safety Readiness	Deploy Pre-Crash Restraint	Automate Vehicle Operations
C.1.h (A) ACC, FCA and SCA (Brake and Throttle Only), Lane Keeping with Driver Alertness Monitoring, Vehicle Initiated Lane Changes and Automated Merge/Diverge **(TBD)**							
C.2 Cooperative Normal Driving Market Packages							
C.2.a Cooperative Adaptive Cruise Control	+				+	+	
C.2.b Cooperative (Advanced) Adaptive Cruise Control	X		+		+	+	

AHS Market Package	**AHS User Service**						
	Avoid Longitudinal Collision	Avoid Lateral Collision	Avoid Intersection Collision	Enhance Vision for Crash Avoidance	Provide Safety Readiness	Deploy Pre-Crash Restraint	Automate Vehicle Operations
C.2.c Cooperative (Advanced) Adaptive Cruise Control and Frontal Collision Avoidance in Mixed Traffic on a Protected Lane	X	+			+	+	
C.2.d Cooperative (A) ACC, FCA, and Lane Keeping in Mixed Traffic on a Protected Lane	+	+			+	+	X
C.2.e Cooperative (A) ACC, FCA, LK, and Merge / Demerge Capability in Mixed Traffic on a Protected Lane	+	+			+	+	X

AHS Market Package	**AHS User Service**						
	Avoid Longitudinal Collision	Avoid Lateral Collision	Avoid Intersection Collision	Enhance Vision for Crash Avoidance	Provide Safety Readiness	Deploy Pre-Crash Restraint	Automate Vehicle Operations
C.2.f Lane Keeping and (Advanced) Adaptive Cruise Control with Driver Alertness Monitoring **(TBD)**							
D Automated Highway Systems							
D.1.a Autonomous AHS in Mixed Traffic	+	+			+	+	X
D.2.a Cooperative AHS in Dedicated Lanes	+	+			+	+	X
D.2.b Cooperative AHS in Mixed or Dedicated Lanes	+	+			+	+	X
Specialized Applications							

AHS Market Package	**AHS User Service**						
	Avoid Longitudinal Collision	Avoid Lateral Collision	Avoid Intersection Collision	Enhance Vision for Crash Avoidance	Provide Safety Readiness	Deploy Pre-Crash Restraint	Automate Vehicle Operations
Automated Bus Movement in the Maintenance Area	+	+			+		X
Automated Snowplows	+	X	+	X	+		
Truck Convoy with Driver in Leading Truck	+	+			+	+	X
Truck Safety Systems	X	X	X	X	X	X	
Bus Docking Aid	+	X		+	+		
Automated Container Movement (within terminal)					+		X
Inter-terminal Passenger Shuttle	+	+	+	+	+	+	X
Coordinated Startup (from a stop light)	+		X		+		

"X" = Market package addresses this User Service

"+" = Market package may have some beneficial effect towards this User Service

STATUS

Information will be added to this section at a later date.

PROCESS REVIEW

This section will consider changes that might be made to the process of defining AHS User Services and market packages. It will also consider how the work of the three teams, User Needs, Critical Issues, and Progressive Deployment, will be affected by the input to these documents. Information will added to this section at a later date.

10.3.8 Deployment Strategies

lead author Tom McKendree

1. Introduction

[Note, this document was developed by the Deployment Team in the first half of C3 Phase I, and has not been revised by the Progressive Deployment Team in the second half of C3 Phase I.]

1.1 Purpose

This document is intended to go through multiple revisions and ultimately become the NAHSC baseline plan for AHS Deployment. As a living document, earlier drafts such as this are deliberately rougher, less specific, and admit more options, than is expected of the final document.

1.2 Assumptions

This section will summarize briefly those assumptions being made for all deployment strategies. It is currently TBD. Assumptions are important to AHS deployment due to the long time until the end state is reached. They need to reflect imagination.

In the current draft, section 3.1 lists a large number of assumptions which are considered in specific deployment strategies. Section 3.2 provides a mapping between those assumptions and the deployment strategies.

2. What is AHS

2.1 Architecture

The Automated Highway System is a vehicle-highway system with AHS equipped vehicles that operate under automated control on dedicated highway lanes. The AHS equipped vehicles are also capable of automated operation on some specially equipped highway lanes inter-mixed with manually driven vehicles. The dedicated lanes are accessible by AHS equipped vehicles from roads and highways where manually driven vehicles operate. The dedicated lanes may or may not be adjacent to the manual highway lanes. An AHS-equipped vehicle may be any motor vehicle with four or more wheels. AHS equipped vehicles are divided into classes which include light-duty passenger vehicles and trucks, transit and intercity buses and single-unit and multiple-unit heavy trucks. The AHS-equipped vehicles are capable of being operated as manually driven vehicles when not operating on the specially equipped AHS lanes.

The AHS consists of three major subsystems:

- Vehicle Subsystem
- Roadway Subsystem
- AHS Traffic Management Subsystem

Vehicle Subsystem - The Vehicle Subsystem refers to vehicles that are specially equipped to operate under automated control while on AHS lanes. The Vehicle Subsystem will interact with the other AHS Subsystems, and in conjunction with information from the other AHS Subsystems, will: (1) validate that the vehicle is

AHS-capable, and assume control of the vehicle from the driver; (2) control the vehicle's movement when on AHS lanes; and (3) ensure that the driver is capable of regaining vehicle control, and return control to the driver.

The Vehicle Subsystem consists of a base vehicle and at least: brake, steering and drivetrain actuators, sensors, processors and software, communications equipment, and driver interface devices. AHS equipment will be mounted on the base vehicle and tested for proper integrated operation either at the factory or as an after-market retrofit.

Internal Vehicle Subsystem interactions include, at a minimum, control of the brakes, steering, throttle/engine; and perhaps vehicle equipment such as the ignition switch, door locks and lights. Interactions also include the sensing of various vehicle conditions such as fuel level, oil pressure, and tire pressure.

The Vehicle Subsystem is designed to operate in any of the following environments:

- Fully automated with only other fully automated vehicles on dedicated AHS lanes.
- Fully automated with manually driven vehicles, on specially equipped AHS lanes.
- Manually with optional driver aids, on specially equipped AHS lanes.
- Manually with optional driver aids, without specially equipped AHS lanes.

Roadway Subsystem - The Roadway Subsystem provides the roadway upon which the AHS-equipped vehicles operate, including entry and exit areas, and areas for temporarily storing disabled vehicles. This includes roadway surfaces, signs, markings and lane designs that are compatible with AHS operation; and physical interfaces with the manual lanes through which manually driven AHS-equipped vehicles will access and enter into AHS.

All AHS roadways are equipped to facilitate the movement of AHS equipped vehicles. This equipment may provide indications of lane location as well as communications capabilities which may be used to enable vehicle entry or rejection, transition from manual to automated operation, lane changing, safe vehicle movement and vehicle exit. The Roadway Subsystem may include sensors and processors to help alert the AHS Vehicle Subsystem and Traffic Management Subsystem of roadway configuration, road surface and traffic conditions, entry and exit ramp conditions, incidents, roadway maintenance activity, operational situations (e.g., sports event letting out ahead) and possibly operating parameters.

AHS Traffic Management Subsystem - The AHS Traffic Management Subsystem provides the means to operate and control the AHS. It contains the logic and algorithms to detect and manage all events that occur in the AHS, whether normal or abnormal, including all modes of operation. The AHS Traffic Management Subsystem is integrated with the traffic management capability that exists for manual traffic management. The AHS, to some degree, directly interacts with non-AHS systems that provide operations relevant information (e.g., weather).

2.1.1 Operational Modes

The AHS Operational Modes are the following:

- Normal traffic flow - non-congested

- Normal traffic flow - congested
- Restricted traffic flow - non-congested (e.g., weather)
- Restricted traffic flow - congested
- Special event (e.g., sports event letting out)
- Incident/emergency management - no lane shutdown, emergency response
- Incident/emergency management - lane shutdown, emergency response
- Incident/emergency management - system shutdown (e.g., earthquake, snowstorm or flood)

2.2 Potential Deployment Plan Components

Initial infrastructure deployment with simultaneous Fleet upgrades.

Block downgrades to AHS highway standards.

Wait for progress on mixed, and use when ready.

2.3 Overall Timeline

The purpose of this section is to present that portion of the timeline which is considered fixed.

2.3.1 Overview

NAHSC will continue it's program through conclusion, building a prototype, and releasing an AHS specification. That program will probably be followed by one or more Field Operational Tests (FOT) of AHS. Following demonstrated success of AHS it will become available for general deployment, and become used where appropriate. The market and foreign countries will continue their activities in parallel.

2.3.2 Strawman Timeline

Section 3.1 Discusses deployment uncertainties, and presents the results of an attempt to begin harmonizing these uncertainties within the consortium. Taking the nominal answer for the uncertainties yields the following Strawman timeline:

1997	First NAHSC Baseline Draft of Deployment plan.
2002	NAHSC finishes testing of its prototype, and completes final documentation.
	Machines are able to outperform humans on all individual driving tasks except sensing.
2003	AHS is technically feasible and deployed in some foreign country.
2008	Dedicated lane full AHS is technically feasible for (the more rigorous) requirements in the US.
	Automated vehicles are as capable as possible while still keeping drivers engaged in the driving task.
2018	Mixed traffic AHS is technically feasible for conditions in the US

2025	The annual increase in computer cost effectiveness first falls below 10% per year.
2028	Mixed operation AHS vehicles are first sold for operations on public highways (assumes prototype demonstration in 2018).
2035	Year AHS would occur purely from market pull (i.e., without NAHSC and special Federal efforts).

2.4 Implementation Roles

This section is to discuss the possible ranges of who does what, who pays, and what are the risks. Where possible, tie to the assumption packages or deployment strategies below, and be specific about who out of the range would be in the roles.

2.4.1 Vehicles

TBD

2.4.2 Roadway Infrastructure

TBD

2.4.3 Institutional

TBD

3. Potential Deployment Strategies

The principal part of the main document. This chapter is intended to evolve over future drafts into a describing of the preferred deployment strategy for AHS. At the moment it lists deployment strategies currently under consideration by NAHSC. That preferred deployment strategy will be identified by discarding rejected deployment strategies, merging similar deployment strategies, and possibly creating a decision tree in which currently separate deployment strategies would be different branches. Those strategies which remain viable in later drafts should discuss their implied Urban, Interurban, and Rural AHS deployments over time.

3.1 Major Uncertainties

Major uncertainties are defined here as issues considered, by at least some consortium members, to be important for AHS deployment, for which a clear answer is not available.

The major uncertainties have been formatted as questions. The certainty to which they can be answered is expressed as a range, with minimum, most likely and maximum answers identified. The intent is that minimum and maximum represent the full range of uncertainty which should be considered. While an attempt has been made to phrase the questions so that all answers are reduced to a clear, numeric scale, some questions are not that sharply defined. Text answers are illustrative.

These major uncertainties are starting to be organized so that similar issues are grouped together.

At the January 23-24 AHS Concept Interchange Meeting, the participants were all given a questionnaire regarding the following assumptions, and asked to make an estimate for at least 3 to 6 of the following major uncertainties. The participants were all Core members of NAHSC, working in some area of C3. These participants can be considered informed about the prospects for AHS. Nearly all of the C3 task leads and the site managers were in attendance. There was an 60% percent response rate. The lowest Minimum and the highest Maximum were selected.

Respondees were asked to self-identify those uncertainties for which they are "experts." The Expected column takes the median answer of all respondees, weighting self-described experts and the previous draft of this document (which itself had received prior review) as three respondees each.

Major Uncertainty	**Minimum (Low)**	**Expected (Most Likely)**	**Maximum (High)**
When will dedicated lane full AHS be technically feasible for conditions in the US?	Now	2008	2097
How long after dedicated lane AHS is technically feasible for conditions in the US will mixed traffic AHS be technically feasible for conditions in the US?	0 years	10 years	Never
How long before mixed traffic AHS is technically feasible for conditions in the US will it be technically feasible and deployed in some foreign country? (The difference is presumably due to non-technical factors.)	Feasible for conditions in the US 5 years before foreign deployment	5 years of foreign deployment before AHS is feasible for conditions in the US	15 years of foreign deployment before AHS is feasible for conditions in the US
What is the smallest dedicated lane AHS project which is sufficient as a first local deployment?	Any link or corridor, especially if it's dominated by the transit mode or by CVO's	10 miles	200 miles
What is the liability threshold at which Auto manufacturers will produce AHS vehicles?	$100 per vehicle	A liability cap or immunity from punitive damages for vehicles that pass a bright-line test	Immunity [very special cases, like DOD procured vehicles]
What level of prospective safe harbor legislation on AHS liability will be passed in the US?	None	Something analogous to air travel or nuclear power	Liability immunity for vehicles that pass a bright-line test

Major Uncertainty	**Minimum (Low)**	**Expected (Most Likely)**	**Maximum (High)**
Will the automotive companies be able to pass on the costs of their additional liability risk for AHS to the consumer?	No	Yes, but only after actuarial demonstration that total fleet liability exposure is reduced through AHS safety benefits.	Completely
How much will the Federal government spend over 2002-2017 on AHS (including any operational tests, but excluding money it would pay anyway for non-AHS Highway costs that AHS covers instead)?	$0	$1.5 billion [FY$96]	$5 billion [FY$96] per year for 15 years
How much per vehicle [FY$96] would early vehicle purchasers be willing to pay for AHS capability on an initial, dedicated lane system?	$0	$2000	$6000+ (Assuming a time savings of 25%)
How many vehicles/year would the AHS market have to be at start to interest the vehicle manufacturers?	100	10,000	100,000
When would AHS occur purely from market pull (i.e., without NAHSC and special Federal efforts)?	2010	2035	Never
How well will the partially automated services preceding fully automated AHS evolve into a reasonable sequence of steps leading to AHS?	Not at all	Very awkwardly and inefficiently	The partially automated services evolve smoothly into AHS
When AHS is first made operational, what percentage of new vehicle sales in the area will be vehicles designed to be "AHS-Compatible" (i.e., upgradeable to AHS)?	None. Vehicle manufacturers will only sell AHS as a new car option	5%	50%
What percentage of non-AHS personal vehicles on the road or sold after the first AHS system is operational in their area will be upgraded to AHS capability?	None. Vehicle manufacturers will not do it, and it will be too hard/ liability-risky for anyone else	Tiny (1-2%). Primarily expensive, custom retrofits to "classic cars"	100%

Major Uncertainty	**Minimum (Low)**	**Expected (Most Likely)**	**Maximum (High)**
What percentage of non-AHS heavy vehicles on the road or sold after the first AHS system is operational in their area will be upgraded to AHS capability?	None. Technical risk and liability will limit AHS capability to new vehicles.	Small (10-25%). Mostly moderately new vehicles which can neither be scrapped nor assigned to non-AHS lanes	100%
At what institutional level will the decision be made to dedicate a particular lane to AHS?	District	This will be a cooperative decision between State DOT's and local MPO's, etc., with extensive public hearings	Regional Transportation Authority
What percent of penetration for the initial AHS-ready fleet is required in a region at start or shortly after dedication for the successful introduction of a dedicated lane AHS facility?	None. AHS vehicles bought after lane opening will be sufficient.	1/number of parallel lanes in the congested corridor	50% of interstate users
Compared to the marginal cost of installing AHS capability as part of a new vehicle, how much will it cost to retrofit a non-AHS vehicle for AHS operations?	$200	3 times	Infeasible
To what extent will initial dedicated lanes be subsidized?	None	No more or less than other Federal highway projects (may be allocated differently with the project)	Completely, possibly even subsidized vehicles as well
How much help will State and local transportation agencies need in establishing an organization capable of operating and maintaining the AHS infrastructure-based system?	None	Significant, but fully affordable from private industry as part of budgets for AHS projects	Extensive. Will require additional federal effort.
What is the minimum, "Make or break" goal for AHS?	AHS is included in the reauthorization of ISTEA	Safety = 50% better; less congestion; user comfort (reduced stress)	70% of vehicles are AHS

Major Uncertainty	**Minimum (Low)**	**Expected (Most Likely)**	**Maximum (High)**
What is the maximum achievable real throughput on dedicated AHS lanes?	3000 vehicles/ lane/hour	5000 vehicles/ lane/hour	12,000 vehicles/ lane/hour
What is the maximum achievable real throughput on mixed AHS lanes?	Much lower than manual only	2000 vehicles/ lane/hour	7000 vehicles/ lane/hour
How long will it take in an area from initial introduction of pre-AHS vehicles into an area without dedicated lanes until there is 10 % market penetration of AHS, dedicated-lane capable vehicles?	6 months with government subsidies to retrofit	2 years after introduction of mixed traffic, non-specially equipped lane, AHS vehicles	Never
How long will it take in an area from initial AHS introduction to achieve 10% market penetration?	6 months	3 years	Never
What level of functionality must AHS perform for the non-human-in-the-loop driving?	All routine and most non-routine functions; able to drive 250,000 miles on average w/o a failure-to-properly-respond incident	Full automation	All functions physically feasible, including all safety useful, non-foreseen functions
To what extent may infrastructure modifications be made for AHS implementation which do not explicitly meet local needs for improving system performance?	None	Minor loses on cost or performance (5-10%) in order to satisfy national standards	Considerable, with subsidies
For the prototype in 2002, how much of the driving functions will machines be able to perform better than people?	20%	All but sensing	Coordinated merging; lane changing; infrastructure assisted obstacle detection
How much of the driving function will machines ultimately be able to perform better than people?	20%	Nearly all functions, except high-order inferencing from novel data	All functions

Major Uncertainty	**Minimum (Low)**	**Expected (Most Likely)**	**Maximum (High)**
How much intervehicle communications will be required on dedicated AHS lanes?	None	High intraplatoon; medium interplatoon (1 Mbps channel)	High Cooperative plus
How many years of pre-AHS driving, with drivers in charge but automation performing many functions, for drivers to get sufficiently used the system and for the collection of data on driving anomalies, before full-AHS could be deployed?	zero. (This is not on the critical path).	5 years	Not until robust obstacle detection proves itself in the field; many years if ever
How much will the typical new-vehicle purchaser who has not experienced driver disengagement pay for that feature?	$0	$500 (vis-a-vis partial automation)	$5000
How much will the typical new-vehicle purchaser who has experienced and become familiar with driver disengagement pay for that feature?	$0	$1000	Median pay (est. $15/hr) x median time spent highway driving (est. 200 hr./yr.) = $3000 yr. owned
Assuming no decrease in research and development effort, how long after automated vehicles are as capable as possible while keeping drivers engaged in the driving task until automated vehicles in mixed traffic are technically feasible for conditions in the US?	3 years	10 years	Never
If a dedicated-lane AHS system is deployed, what percentage of the useful life of that system will be made obsolete by full driver-disengaged, mixed traffic AHS arriving through the natural progress in technology?	None	0%	100%
How much harder to solve are the technical problems of automated driving in mixed traffic than the political and institutional problems of creating dedicated AHS lanes?	The political and institutional problems are vastly harder	The technical problems are harder	The technical problems are impossible

Major Uncertainty	**Minimum (Low)**	**Expected (Most Likely)**	**Maximum (High)**
When are difficulties in improving computers going to first result in the rate of progress in cost effectiveness falling below 10%/year?	2005	2025 (Should remain superexponential until then)	Maybe never
How long before or after AHS is deployed will stakeholders know what they want or the real requirements for AHS?	With effective techniques (e.g., information acceleration), stakeholder can now know their AHS requirements enough to be elicited	Stakeholders can know in very rough terms many years before; and in detail after learning in detail about actual fielded systems	They'll never know
How long after mixed operation AHS vehicles are demonstrated in a prototype until vehicle manufacturers can have them sold for operations on public highways?	3.5 years	10 years	Never
How significant are the benefits of V-V and V-R communications on lanes of non-automated traffic?	Essentially none	Small	Very significant

3.2 Mapping of Assumptions Into Deployment Strategies

The deployment strategies in this chapter map into the above assumptions in the following table. "L" means the low (minimum) is assumed, "M" means the most likely (expected) is assumed, and "H" means the high (maximum) is assumed. "LM" means somewhere between the low and most likely is expected, and "MH" means somewhere between the most likely and the high is expected. "-L" means the low (minimum) is assumed not to occur, and "-H" means the high (maximum) is assumed not to occur. A blank means that the deployment strategy is not sensitive to the assumption. A blank can also mean that the uncertainty has not been specified or considered for that deployment scenario. An answer in italics means that the answer may freely vary across the whole range for the viability of the deployment strategy, but the strategy would be better if the uncertainty were in the italicized range.

"LL" means that the answer must be below the minimum of the range, and "HH" means that the answer must be above the maximum of the range, but neither were used in this estimate. Either would say the deployment strategy is not compatible with feasible, and thus is not feasible.

Major Uncertainty	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
When will dedicated lane full AHS be technically feasible for conditions in the US?	*-H*	-L -H	-H	*-H*	-L	MH	*-H*	LM	LM	LM	*-H*	-H *M*
How long after dedicated lane AHS is technically feasible for conditions in the US will mixed traffic AHS be technically feasible for conditions in the US?	-H	*LM*	- LM	-H		*-H*	LM	- LM	- LM	-H		*M*
How long before mixed traffic AHS is technically feasible for conditions in the US will it be technically feasible and deployed in some foreign country? (The difference is presumably due to non-technical factors.)	*LM*	*LM*	*- MH*	*LM*	*LM*	*LM*		*LM*	*LM*	L	MH	*- MH*
What is the smallest dedicated lane AHS project which is sufficient as a first local deployment?	*-LM*	LM	LM	*-LM*	LM	-L	*-LM*	LM	MH	-H		*-L*
What is the liability threshold at which Auto manufacturers will produce AHS vehicles?	MH	LM	LM	LM	LM	LM	LM	LM	LM	LM	*MH*	LM
What level of prospective safe harbor legislation on AHS liability will be passed in the US?	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH	*L*	MH
Will the automotive companies be able to pass on the costs of their additional liability risk for AHS to the consumer?	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH	*LM*	MH
How much will the Federal government spend over 2002-2017 on AHS (including any operational tests, but excluding money it would pay anyway for non-AHS Highway costs that AHS covers instead)?	*-H*	MH	MH	*MH*	MH	*LM*	*LM*	MH	- LM	MH	*L*	-L *-H*
How much per vehicle [FY$96] would early vehicle purchasers be willing to pay for AHS capability on an initial, dedicated lane system?	*LM*	-L *M*	MH	*M*	-L *M*	*LM*	MH	-L	-L	-L		*M*
How many vehicles/year would the AHS market have to be at start to interest the vehicle manufacturers?	*LM*	*MH*	LM	*LM*	*M*	*MH*	*LM*	LM	-H	LM		*MH*

Major Uncertainty	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
When would AHS occur purely from market pull (i.e., without NAHSC and special Federal efforts)?	LM		-L	LM	-L	-H	LM	MH	MH	-L	*LM*	-L
How well will the partially automated services proceeding fully automated AHS evolve into a reasonable sequence of steps leading to AHS?	H	MH	*LM*	-LM	-LM	MH	-LM	LM	LM	*M*	*MH*	MH
When AHS is first made operational, what percentage of new vehicle sales in the area will be vehicles designed to be "AHS-Compatible" (i.e., upgradeable to AHS)?		*H*	*H*	*H*	*H*	*LM*	*LM*	*MH*	*MH*	*LM*	*L*	*MH*
What percentage of non-AHS personal vehicles on the road or sold after the first AHS system is operational in their area will be upgraded to AHS capability?		*-LM*	*-LM*	*-LM*	*-LM*	LM	*LM*	*MH*	*MH*	*LM*	*L*	*MH*
What percentage of non-AHS heavy vehicles on the road or sold after the first AHS system is operational in their area will be upgraded to AHS capability?		*MH*	*MH*	*MH*	*MH*	-MH		*MH*	*MH*	*LM*	*L*	*MH*
At what institutional level will the decision be made to dedicate a particular lane to AHS?												*MH*
What percent of penetration for the initial AHS-ready fleet is required in a region at start or shortly after dedication for the successful introduction of a dedicated lane AHS facility?	*MH*	*MH*	-MH	-L	LM *M*	MH	*MH*	LM	-L	*M*		*MH*
Compared to the marginal cost of installing AHS capability as part of a new vehicle, how much will it cost to retrofit an AHS vehicle for non-AHS operations?		*L*	*-MH*	*LM*	*-MH*	*MH*		*LM*	*-H*	*MH*		*L*
To what extent will initial dedicated lanes be subsidized?	*-H*	-L	MH	-H	MH	-H	LM	MH	MH	MH		MH
How much help will State and local transportation agencies need in establishing an organization capable of operating and maintaining the AHS infrastructure-based system?	L	*MH*	-L		*MH*		*H*	*LM*	*H*			*H*

Major Uncertainty	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
What is the minimum, "Make or break" goal for AHS?	*L*	*M*	*MH*		*M*	M	*L*	LM	LM	*MH*		*M*
What is the maximum achievable real throughput on dedicated AHS lanes?	*LM*		*MH*	*LM*	*MH*	-L	*L*	*MH*	*MH*	*MH*		*MH*
What is the maximum achievable real throughput on mixed AHS lanes?	*MH*	MH	*LM*	MH	MH	LM	MH	*LM*	*LM*	*H*		-L
How long will it take in an area from initial introduction of pre-AHS vehicles into an area without dedicated lanes until there is 10 % market penetration of AHS, dedicated-lane capable vehicles?	*MH*	-H	*MH*	-L	*MH*	-H	*MH*	*L*	MH	-H	*H*	*H*
How long will it take in an area from initial AHS introduction to achieve 10% market penetration?	-H	LM	LM	LM	-H	MH	LM	LM	LM	LM		*LM*
What level of functionality must AHS perform for non-human-in-the-loop driving?	*LM*	*MH*	*MH*	*LM*	*L*	MH	-H	*LM*	*LM*	*LM*	*H (in US)*	*L*
To what extent may infrastructure modifications be made for AHS implementation which do not explicitly meet local needs for improving system performance?	*LM*	MH	MH	*LM*	*M*	L	*L*	*MH*	*MH*	*MH*		*M*
For the prototype in 2002, how much of the driving functions will machines be able to perform better than people?	*H*	- *MH*	*MH*	*MH*	-H	-H		*MH*	*MH*		-L	LM
How much of the driving function will machines ultimately be able to perform better than people?	MH *H*	MH	-L	MH		*LM*	MH	-L	-L	MH	MH	MH
How much intervehicle communications will be required on dedicated AHS lanes?			*M*		*L*	-L	*MH*			*MH*		MH
How many years of pre-AHS driving, with drivers in charge, but automation performing many functions, for drivers to get sufficiently used the system and for the collection of data on driving anomalies, before full-AHS could be deployed?	*H*	-L *M*	L	*MH*	*-L*	*M*		L	L	- MH		*MH*

Major Uncertainty	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
How much will the typical new-vehicle purchaser who has not experienced driver disengagement pay for that feature?	-L	*LM*	-L	-L	*LM*	*LM*	MH	MH	MH	MH		*M*
How much will the typical new-vehicle purchaser who has experienced and become familiar with driver disengagement pay for that feature?	-L	*LM*	MH	-L	*M*	*LM*	-L	-L	-L	-L	-L	-L
Assuming no decrease in research and development effort, how long after automated vehicles are as capable as possible while keeping drivers engaged in the driving task until automated vehicles in mixed traffic are technically feasible for conditions in the US?	LM	M	- LM	-H	-H	- *MH*	LM	*-LM*	*H*	-H		-H
If a dedicated-lane AHS system is deployed, what percentage of the useful life of that system will be made obsolete by full driver-disengaged, mixed traffic AHS arriving through the natural progress in technology?	*-LM*	LM	LM	*-LM*	LM	LM	*-LM*	-H	-H	-H	*H*	LM
How much harder to solve are the technical problems of automated driving in mixed traffic than the political and institutional problems of creating dedicated AHS lanes?	- MH	MH *M*	MH	L	-L, - H	*MH*	LM	MH	MH	M		M
When are difficulties in improving computers going to first result in the rate of progress in cost effectiveness falling below 10%/year?	MH	*MH*	*L*	*MH*	*MH*		-L	*L*	*L*	*-L*	*-L*	*LM*
How long before or after AHS is deployed will stakeholders know what they want or the real requirements for AHS?		*L*	LM	*-LM*	*M*	*-H*		*LM*	*LM*	*LM*	*MH*	*MH*
How long after mixed operation AHS vehicles are demonstrated in a prototype until vehicle manufacturers can have them sold for operations on public highways?	LM *L*	*LM*	*MH*	*LM*			LM	*MH*	*MH*	LM		

Major Uncertainty	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
How significant are the benefits of V-V and V-R communications on lanes of non-automated traffic?	*L*	*ML*	*L*	*MH*	*-LM*	- LM		*LM*	*LM*	*M*		H

3.3 Merged Deployment Strategy Map

Reserved. [Note, The Deployment Map, Appendix 10.3.4, can be considered a fair approximation of the intent of this section.]

3.4 Smooth Evolution to Mixed Traffic AHS Deployment Strategy

3.4.1 Assumption Package

The primary assumption is that there is a continuum of progressively achievable automated vehicle systems, each of which works as a safe system and a more advanced, salable vehicle, and which leads eventually to a fully driver-disengaged, mixed traffic AHS vehicle. In particular, this assumption implies that there is no significant gap in the range of acceptable vehicle performance, in which an automated vehicle would be too capable to keep drivers sufficiently engaged in the driving task, but not sufficiently capable to fully deal with the various driving contingencies which arise.

It is not believed that this is possible if following the simple-minded approach of putting functions in vehicles when they become technically feasible. The problem with that approach is that automated lateral and longitudinal driving would be provided on vehicles which do not offer all necessary automated functions, such as robust obstacle detection. Many drivers of such a vehicle are expected to disengage from the driving task, leaving the entire vehicle-driver system without adequate vigilance against non-routine hazards. One alternative evolutionary path would leave drivers with the steering function, while increasingly sophisticated vehicles offer increasingly sophisticated driver warning features, until the point where the vehicle has all the necessary sensing and judgment capabilities to fully take over driving. This variant of the "Smooth Evolution to Mixed Traffic AHS Deployment Strategy" has not been shown infeasible.

A secondary assumption can be that full driver-disengaged, mixed traffic AHS will be achieved early enough in time so that if the US were to spend the time and investment to first develop a full dedicated-lane AHS capability, that capability would be overtaken by Mixed AHS. This assumption is not necessary for the Smooth Evolution to Mixed Traffic AHS Deployment Strategy to be feasible, but it makes this deployment strategy more desirable relative to other approaches.

3.4.2 Description of Strategy

Progressively refine and advance vehicles, adding increasingly technical capability. Advancing computers are used to off-load the more repetitive and boring driving tasks, progressively reducing the set of required driver functions. Many of these intermediate systems provide warning. New technologies enter as options on high-end vehicles, and flow down until they become standard features on all new vehicles. Note, the rate at which new options are offered on high-end vehicles might not be closely coordinated with the rate at which these options become standard on all vehicles.

3.4.3 Societal and Institutional Issues

Closely related to some of the technical challenges for this deployment strategy, there are very serious human factors challenges. Intermediate vehicle's on the deployment path may need to keep drivers engaged when it appears that such engagement is not necessary. The human factors for such systems must not only be effective, but also must do so while not annoying the driver. This path requires customers buying increasingly advanced products, and they will not do so if the products are sufficiently unfriendly.

3.5 Driver-Engaged AHS Data Collection Deployment Strategy

3.5.1 Assumption Package

Rationale: The driver must be kept in the loop until technology matures. Also a gradual handover of control from the driver allows a long intermediate phase in which drivers get used to the system and data is collected. According to stakeholders[i], being able to disengage is a very minor sales point for drivers.

3.5.2 Description of Strategy

3.5.2.1 Phase I – Development of driver aids

- Adaptive cruise control (brake and throttle) provided by auto industry as a customer option
- Lane departure warning will be provided by auto industry as a customer option.
- ITS services including two-way vehicle-roadside comm as customer, local option
- Lane keeping assistance (e.g., haptic feedback)

Phase I will be market driven and will require little if any subsidization by AHS. The driver is definitely in control (and liable) in this phase. The technology to respond safely to any hazard is not yet mature.

- AHS developers instrument equipped vehicles to collect data on driver override situations, to be used in the development of Phase III

Note: These vehicles will continue to operate on non-dedicated lanes throughout the deployment.

3.5.2.2 Phase II – Initial systems

- Dedicated lane prototype. Drivers are required to be engaged. May be in parallel with or even precede Phase I market development
- Initial dedicated lane open to the public. Requires the vehicles to have the Phase I capabilities. Driver still in control. Legal constructs in place to limit liability of roadway operators and vehicle manufacturers. Roadway fully ITS instrumented to sense traffic, slow-downs, obstacles, weather, etc. Sends speed and spacing commands to vehicle's ACC. Benefits to the driving public are safety, comfort and smooth flow. This may be a single-purpose lane, such as heavy trucks, buses or commuters.

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[i] Minutes of the November 5-6, 1996 AHS Stakeholder Focus Group, John Lathrop (in progress)

- Additional lanes or roadways dedicated

3.5.2.3 Phase III – AHS

- Add hazard recognition/avoidance to the vehicles. When it is prevalent enough require that capability to use the dedicated lanes.
- Add automated lane-keeping to the vehicles. Maintain legal constructs. Sell it as a driving aid and not as automated driving--the driver can take over and is expected to if needed. Eventually require this to use the dedicated lanes.
- Collect data from these automated vehicles, especially where drivers override
- Add legal construct for penalties for frivolous use of driver override
- Once the system has built a history of safe automated operation, preclude driver override except by a panic button that brings the vehicle and all those upstream to a stop.
- Use platoons in selected locations
- Continue to collect data from the vehicles (both Phase I in mixed traffic and Phase III on dedicated lanes) and to research and develop hazard recognition and avoidance technologies

3.5.2.4 Phase IV – Mixed traffic AHS

- Test the developing hazard recognition and avoidance capabilities in manual traffic, with alert drivers.
- Add these capabilities to Phase I vehicles (still without lane keeping).
- Collect data on these vehicles, especially driver override conditions

Note: These steps may happen in parallel with Phases II or III.

- When these technologies are sufficiently mature for safe operation in mixed traffic, add lane keeping, again sold as a driving aid.

3.6 "Policy-Driven" Deployment Strategy

This Deployment strategy was presented under this name at Workshop #3.

3.6.1 Assumption Package

This sequence is based on the assumption that the technical problems of automated driving in mixed traffic are more difficult to solve than the political and institutional problems of creating dedicated automated lanes. The incremental steps are taken in terms of the gradually increasing scale of development of the automated lanes.

3.6.2 Description of Strategy

1) Start with today's vehicles;
2) Current product development leads to adaptive cruise control on (on 10% of new vehicles sold) by 2004;

3) Add communications to provide vehicles position and speed information from other vehicles and the infrastructure (on 10% of new vehicles sold) by 2015;

4) Adding technology and dedicating a lane locally then provides automatic lane keeping and obstacle exclusion;

5) Market growth and policy decisions expand dedicated lanes to form networks; finally,

6) long term technology advances provide automated mixed-traffic operations.

3.7 "Market-Driven" Deployment Strategy

This Deployment strategy was presented under this name at Workshop #3.

3.7.1 Assumption Package

In contrast to the "Policy-Driven" sequence, this sequence is based on the assumption that the technical problems of automated driving in mixed traffic are easier to solve than the political and institutional problems of creating dedicated automated lanes. The incremental steps are taken in terms of the driving functions that are automated.

3.7.2 Description of Strategy

1) Start with today's vehicles;

2) Current product development leads to adaptive cruise control on (on 10% of new vehicles sold) by 2004;

3) Adding communications provides vehicle position and speed information from other vehicles and infrastructure (on 10% of new vehicles sold) by 2015;

4) In parallel, adding technology provides automatic forward obstacle detection and avoidance using braking (on 10% of new vehicles sold) by 2010-2015;

5) Adding technology then provides automatic lane keeping;

6) Adding technology then provides automatic lane-changing;

7) Market growth leads to many vehicles equipped, and widespread automated mixed traffic driving; finally,

8) Dedicating lanes provides for higher throughput operations.

3.8 "Bootstrapping" Deployment Strategy

This Deployment strategy was presented under this name at Workshop #3.

3.8.1 Assumption Package

Manufacturers will not take the risk of offering significantly automated vehicles, unless the vehicles are provided a very protected environment to operate in. The driver must be kept in the loop until technology matures.

3.8.2 Description of Strategy

1) Start with today's vehicles;

2) Current product development leads to adaptive cruise control on (on 10% of new vehicles sold) by 2004;
3) Adding communications provides vehicle position and speed information from other vehicles and infrastructure (on 10% of new vehicles sold) by 2015;
4) Dedicate a lane for AVCSS-only, and market growth, allows obstacle exclusion and enhanced speed and throughput;
5) Adding technology provides automatic lane keeping;
6) Adding technology provides automate entry, exit and lane changing, allowing the dedicated facilities to widen to multiple lanes; Finally,
7) Long term technology advances provide automated mixed-traffic operations.

3.9 Start With Driver Engaged Mixed Operations Deployment Strategy

3.9.1.1 Deployment Decision Tree

Due to the futuristic nature of AHS, there exist many uncertainties regarding its deployment. A decision-tree approach is necessary for developing deployment strategies. Once a decision tree is built, many possible deployment paths can be identified. A good way to build such a tree is to develop plausible deployment paths first and organize and refine them as a decision tree.

3.9.1.2 Axiomatic Approach to Developing Deployment Paths

One approach to developing such plausible deployment paths is the following "axiomatic approach." Since there are many deployment uncertainties or questions, one cannot afford to wait for definite answers. The axiomatic approach calls for (i) assuming likely answers to the questions, (ii) treating the assumed answers as something as true and not to be questioned (i.e., axioms), and then (iii) designing deployment paths accordingly.

3.9.1.3 Focus on Early Deployment

AHS deployment hinges on the end-state concept(s), which is still being studied and developed. Specific intermediate states toward the end-state concept depend on the end-state concept.

Rather than investing all the resources on speculating on the end states and designing deployment scenarios for them, it might be wise to give some thoughts to some steps that are likely to be NECESSARY for the deployment of most or ALL end-state concepts.

Initial market penetration tends to be more difficult than subsequent market expansion. There may NOT be many plausible early deployment scenarios. If so, one can take the few plausible early deployment scenarios as given and try to link them to the few possible end states.

3.9.2 Assumption Package

There are eight assumptions in this package.

Note:

- Assumptions made for all three major vehicle classes: auto, bus & truck
- "Initial" is used to refer to the period "prior to dedication of lanes"

Assumption 1: Major highway throughput improvement is needed and is the ultimate goal of AHS. [Throughput as ultimate goal]

Assumption 2: Major throughput improvement is achievable only through dedicating lanes for automated traffic. [Throughput by lane dedication]

Assumption 3: Lanes will not be dedicated to exclusive use by automated vehicles until sufficient number of vehicles can use them upon or shortly after the dedication. [Policy driven by popular demand.]

Assumption 4: Such sufficient market penetration requires years to develop, through (i) incremental research/development/deployment by the vehicle, highway and insurance suppliers and (ii) gradual demand by the driving public. [Incremental Market Penetration]

Assumption 5: No major infrastructure modification for AHS implementation can be expected unless such modification is explicitly made to meet local needs for improving system performance, e.g., system throughput and safety. [Infrastructure modification driven by local and system needs.]

Assumption 6: Driver intelligence is more difficult to replace than driver control of vehicle; only routine vehicle control chores can be safely automated at initial stages of AHS deployment. [Automating routine control chores first and then complicated decision-making]

Assumption 7: Machine can outperform the human driver in many driving chores. [Machine-human complementarily]

Assumption 8: Vehicle-to-vehicle communication has major safety benefits and is required for major throughput improvement on dedicated lanes.

3.9.2.1 Six Inferences

Inference 1: Assumptions 2, 3 and 4 imply that no dedicated lanes should be expected during early deployment stages of AHS technologies.

Inference 2: Assumptions 2 and 3 imply that early market penetration (i.e., market creation) should rely on providing driver comfort and safety, not travel time reduction or reliability.

Inference 3: Assumption 5, together with Assumptions 2, 3 and 4, imply that no major infrastructure modification and hence no major infrastructure component should be expected during initial deployment (i.e., prior to sufficient market penetration for lane dedication).

Inference 4: Assumption 6 implies that driver will be needed to make certain decisions, especially during non-nominal events, and hence be required to stay alert and attentive during initial deployment (i.e., driver-in-the-loop).

Inference 5: Assumption 6 and 7 imply that, although the vehicle may be invoked to perform some driving chores that it usually outperforms the driver, the driver holds the ultimate responsibility for driving during initial deployment. The driver can and should override all unsafe decisions made by the vehicle during initial deployment.

Inference 6: Assumptions 1 through 4 and 8 imply that the market for vehicle-to-vehicle communication capability needs to be built up and to mature prior to dedication of lanes.

3.9.3 Description of Strategy

3.9.3.1 Six Derived Requirements For Initial Deployment

Note:

- These are requirements for INITIAL deployment only
- "initial" refers to the period "prior to sufficient market penetration for lane dedication".

Requirement 1: Mixed traffic operation; no dedicated lanes

Requirement 2: market creation based on driver comfort and safety, not travel time reduction.

Requirement 3: no major infrastructure component.

Requirement 4: driver alertness and attentiveness required.

Requirement 5: full driver responsibility.

Requirement 6: creation of market for vehicle-to-vehicle communication.

3.9.3.2 Four Market Packages For Initial Deployment Of AHS Technologies (Building Blocks)

Note: - for all three major vehicle classes
- deployment on heavy vehicles BEFORE automobiles likely
- Requirement 1 (mixed traffic operation) satisfied by all market packages below
- again, "initial" refers to the period "prior to sufficient market penetration for lane dedication".

Market Package 1: (i) Adaptive Cruise Control, and
(ii) Vision-Based Automatic Lane-Keeping and
(iii) Driver Monitoring

Rationale: (i) and (ii) for Requirement 2.
(ii) for Requirement 3.
(iii) for Requirements 4 and 5.

Market Package 2: (i) Adaptive Cruise Control, or
(ii) Vision-Based Automatic Lane-Keeping,
But Not Simultaneously Invoked
(Partial Invocation; No Driver Monitoring)

Rationale: (i) or (ii) for Requirement 2.
(ii) for Requirement 3.
Partial Invocation for Requirements 4 and 5.

Market Package 3: (i) Adaptive Cruise Control, and
(ii) Vision-Based Automatic Lane-Keeping Simultaneously,

But Only at Low Speeds (in slow-moving traffic)
(Partial Invocation at Higher Speeds)
Rationale: (i) and (ii) for Requirement 2.
(ii) for Requirement 3.
Partial Invocation or Full Invocation at low speeds
for Requirements 4 and 5.
(assuming alertness and attentiveness more easily achievable
in slow-moving traffic and assuming lesser safety
consequences at low speeds without alertness or
attentiveness)

Market Package 4: Vehicle-to-vehicle communication for Braking Notification,
for signaling braking or for conveying deceleration rate.
(As add-on to the previous market packages)
Rationale: Primarily for Requirement 6.

3.10 Wait for Mixed Traffic AHS Deployment Strategy

3.10.1 Assumption Package

Mixed Traffic AHS will become feasible, given ongoing research and development of AHS.

A useful but not required assumption is that full driver-disengaged, mixed traffic AHS will be achieved early enough in time so that if the US were to spend the time and investment to first develop a full dedicated-lane AHS capability, that capability would be overtaken by Mixed AHS. This assumption is not necessary for the Market Mixed Traffic AHS Deployment Strategy to be feasible, but it makes this deployment strategy more desirable relative to other approaches.

3.10.2 Description of Strategy

1) Continue research and development of AHS;
2) Develop and promulgate appropriate legal structures to support a market-supplied AHS (e.g., legal guarantees for vehicle manufacturers regarding AHS, or maybe just general Tort reform);
3) Once technically, institutionally, and economically feasible, begin selling mixed traffic AHS capability as an option on high-cost vehicles. As production costs fall with volume, experience and advancing technology, offer mixed traffic AHS capability on an increasing percentage of new vehicles.

3.10.3 Preferred Operational Test

The design, manufacture, and subsidized provision to partnering fleet operators of a small number of expensive, professionally driven vehicles to operate under full automation on ordinary highways. The Operational Test vehicles would also carry substantial data gathering equipment to help support the test objectives.

3.10.4 Preferred Prototype

Development and construction of one or more prototype vehicles capable of performing some or all required functions for mixed AHS operations, with traceability for those functions that the vehicle cannot perform. (One approach for maintaining traceability while providing earlier technical feasibility is to use lower vehicle operating speeds under controlled test conditions.) The prototype(s) would be subjected to an expanding envelope of operating conditions, starting with a benign test track, moving through an increasingly challenging series of staged anomalies, and possibly concluding with substantial operations on ordinary highways in favorable and then unfavorable conditions.

3.11 Dedicated Lane Operational Test Showcase Deployment Strategy

3.11.1 Assumption Package

In contrast to the assumptions for "Lead With Driver Engaged Mixed Operations Deployment Strategy," this approach assumes that it will be possible, in at least one or a small number of locations, to deploy a dedicated lane AHS facility, probably funded by an organization enthusiastic about AHS deployment, so that this can be an "add a lane" rather than a "take a lane" infrastructure modification, and that this will be tolerable even with limited initial usage.

3.11.2 Description of Strategy

1) NAHSC develops a dedicated lane AHS prototype and design for an Operational test;
2) In one or a small number of locations, dedicated lane AHS Operational Test(s) are deployed;
3) These operational tests prove very successful, particularly in carrying capacity, reducing the regional congestion, user comfort and convenience and user travel-time savings, and these successes become well known to transportation planners and create consumer enthusiasm;
4) Building and expanding dedicated lane AHS facilities becomes a standard option to consider in Major Investment Studies (MIS's), and due to it's superior performance is often the selected alternative, leading to a growing, nation-wide installed base of AHS dedicated lane facilities, and AHS-capable vehicles.

Note, the operational test might be a Federally Funded project which widens an existing facility, adding the dedicated lanes without reducing the number of manual lanes available. It also might use HOV lanes as its physical starting point, providing an already dedicated and partly barriered lane. Early vehicles in the operational test would probably have their added costs for AHS capability subsidized. These could be based on transit, van-pool and other fleet vehicles, augmented by more general personal private passenger vehicles.

Also, mixed with manual AHS capabilities might be brought to market later by vehicle manufacturers as an additional capability, when that becomes technically and institutionally feasible. The success of dedicated lane AHS should increase the social acceptability of AHS, easing this follow-on step.

3.11.3 Timeline

The operational test would be developed immediately following the completion of the current NAHSC work program, beginning in 2002. Initial operation of the Field Operational Test (FOT) could be in the 2005-6 time frame, and assuming success in that FOT, development of the subsequent systems could be in the 2010 time frame.

3.11.4 Societal and Institutional Issues

In the operational test, and in initial ordinary deployment of AHS lanes in areas, special actions might be taken to increase "first day" usage of the AHS facility. Examples would be special encouragement's to fleet operators, such metropolitan transportation districts and local truck operators, to buy dedicated lane AHS vehicles in time to have them ready for AHS use when the facility first opens.

3.12 Dedicated Lane Operational Test Seedlings Deployment Strategy

3.12.1 Assumption Package

This approach assumes that initial deployment of a dedicated AHS facility in a region sufficient to justify the cost is very difficult, but that extensions of existing AHS dedicated lane facilities can be in small steps and quite worthwhile. Nonetheless, it also assumes that it will be possible, in at least one or a small number of locations, to deploy a dedicated lane AHS facility as a subsidized operational test. These assumptions imply that the minimum dedicated lane AHS facility sufficient to be worthwhile is probably quite large.

3.12.2 Description of Strategy

1) NAHSC develops a dedicated lane AHS prototype and design for an Operational test;
2) In one or a small number of locations, dedicated lane AHS Operational Test(s) are deployed, relying on significant Federal subsidies to in order to be palatable to local transportation organizations;
3) These operational tests prove successful, creating a large installed base of AHS vehicles in their immediate areas;
4) Expansions of an existing dedicated lane AHS facilities become a standard option to consider in Major Investment Studies (MIS's), and due to this options superior performance in locations where many vehicles are AHS-capable, it is often the selected alternative, causing the initial operational tests to grow geographically over time from their initial operational test "seeds";
5) Eventually, this leads to extensive deployment of dedicated lane AHS facilities around the country.

Note, it would be a very good idea to place one of the operational tests in the Boston-Washington Corridor, and other operational tests in major extended regions of high traffic, maybe the industrial Midwest, maybe California, maybe other areas. Since each operational test will act as a "nucleation point" for the expansion of AHS lanes, it is important to place operational tests on both sides of any geographic "gap" that lack sufficient density to justify dedicated lane AHS facilities.

Also, mixed with manual AHS capabilities might be brought to market later by vehicle manufacturers as an additional capability, when that becomes technically and institutionally feasible. The success of dedicated lane AHS would be expected to increase the social acceptability of AHS, easing this follow-on step.

3.12.3 Societal and Institutional Issues

In the operational test, and in initial ordinary deployment of AHS lanes in areas, special actions might be taken to increase "first day" usage of the AHS facility. Examples would be special encouragement's to fleet operators, such metropolitan transportation districts and local truck operators, to buy dedicated lane AHS vehicles in time to have them ready for AHS use when the facility first opens.

3.13 Dedicated as a Stepping Stone to Dual-Capable Deployment Strategy

3.13.1 Assumption Package

This approach also assumes that it will be possible, in at least one or a small number of locations, to deploy a dedicated lane AHS facility. It assumes that the preferred AHS is capable of full Mixed-Traffic operations. It does not require, but fits, the assumption that in a significant number of locations, high-throughput dedicated-lane AHS operations will be affordable and desirable.

3.13.2 Description of Strategy

1) NAHSC recognizes the need for mixed operations capability and the earlier viability of dedicated lane AHS, designs a dual capable AHS, and develops a dedicated lane AHS prototype and the design for an Operational test that creates an upward compatible path towards the dual capable AHS;
2) In one or a small number of locations, dedicated lane AHS Operational Test(s) are deployed;
3) These operational tests prove successful, creating a large installed base of AHS vehicles in their immediate areas;
4) Once these operational tests show success, previously proposed AHS standardization laws may be passed, requiring compliance with an overall AHS specification for all AHS vehicles sold in the US;
5) Expansions of an existing dedicated lane AHS facility becomes a standard option to consider in Major Investment Studies (MIS's), and due to this options performance in locations where many vehicles are AHS-capable, it is sometimes selected alternative, causing the initial operational tests to grow geographically over time from their initial operational test "seeds," and increasing the potential market for AHS vehicles;
6) Spurred by these successes, the growing market for AHS vehicles, the additional research this engenders and supports, the vision of dual-capable automation, and the compatible specification for dual capable AHS, it eventually becomes technically, institutionally, and economically feasible to provide dual-capable (dedicated lane and mixed traffic) AHS vehicles;
7) No longer hindered by a need for special and expensive facilities to support AHS operations, the installed base of AHS vehicles quickly spreads across the US, and continually deepens;
8) Building and expanding dedicated lane AHS facilities becomes a standard option to consider in all Major Investment Studies (MIS's), and due to its superior performance in certain geographic environments, is sometimes is the selected

alternative. This is even true in dense traffic regions which do not have an initial dedicated lane AHS facility, due to the installed base of local AHS-capable vehicles that were purchased for their mixed-traffic capabilities.

3.14 Foreign Leadership Through Risk Taking Deployment Strategy

3.14.1 Assumption Package

The level of safety acceptable for AHS in some developed or rapidly developing foreign country is significantly lower than the level of safety acceptable for AHS in the United States. This might be due to social differences, for example, a foreign country taking a collective approach to safety, and accepting a lower aggregate level of fatalities than today, with the US only accepting a level of fatalities that is lower, per person, than the highway driving risks currently incurred by very good drivers. It might be because greater liability risks in the US require much higher confidence in the same level of AHS safety before it can be deployed. It might be because US laws and regulations impose a significantly longer approval process before AHS operations can be authorized in the US. It might be a combination of these and maybe other factors.

3.14.2 Description of Strategy

1) Research continues in the US and Foreign Countries on AHS;
2) Increasingly advanced partial automation is brought to market;
3) Eventually, AHS technology reaches a level of maturity where it can acceptably be deployed in one or more Foreign countries;
4) Sales of AHS vehicles, and the building of special AHS lanes (if necessary), occurs in these countries, building up the knowledge base and advancing the technology for those involved;
5) This increase in capabilities and knowledge eventually leads to sufficient safety and confidence in AHS to deploy it in the United States.

3.14.3 Societal and Institutional Issues

Vehicle and component manufacturers are located in a variety of countries. It would be advantageous for any company to begin selling an advanced product, like AHS, in accepting markets as soon as that is acceptable in that local market. This builds market share, and company knowledge about the product, its technology, manufacturing, and other characteristics. Accepting the fact of companies selling products overseas which are not allowed in the US is a Social and Institutional challenge, particularly if the reason is US concerns about safety, and particularly if the company is American.

Will US institutions (Government and legal) accept and recognize foreign experience and learning about AHS? For comparison, the Food and Drug Administration allegedly does not accept the results of safety and efficacy tests performed on people prescribed a drug in foreign countries.

If the organizations learning from these earlier Foreign deployments of AHS are not American, will the US provide sufficient support in research and development for US organizations to keep up with the advancing global understanding and technology in AHS?

3.15 *Communications Policy Driven Approach on Mixed Dedicated Lanes*

3.15.1 *Assumption Package*

This strategy assumes benefits (TMC related) for early v-v and v-r data communications, independent of control automation capability. It would also provide infra-based hazard detection and communication capability at earliest possible stage, at least by 'hands-off' stage. The key aspect of this strategy is that automated control capabilities are a goal, not a requirement. The communications requirements (for safety and efficiency reasons) coupled with dedicated lanes encourage automated control implementation (for additional safety and convenience benefits) encourage AVC implementation.. AVC users will receive additional benefits at each stage.

Another assumption is that high throughput (+3000 vplph) is not a key (or at least not an early-to-intermediate) requirement. As in the "mixed dedicated lane" strategy, this approach would allow mixed levels of automation (in the early to intermediate stages, at least).

Comm requirements allow check-in options on dedicated lanes at the earliest stage.

3.15.2 *Description of Strategy*

3.15.2.1 *Encourage Communications Equipage on Special lanes*

Similar to first step of previous mixed traffic dedicated lane strategy. Allow onto existing HOV lanes and/or create new special lanes for any v-v equipped car.

Equip HOV vehicles for free or at reduced cost.

Need not require AVC capabilities at this stage, but could be required in first stage if market warrants.

Minimum comm capabilities should include:

- short range "ID" transponder (to assist TMC and AVC equipped vehicles
- receiver for targeted TMC instructions

3.15.2.2 *Encourage AVC*

AVC need not be required at this stage. Require vehicle transmission of dynamic and certain actuator states.

The comm requirements at this stage provide the baseline for "manual" vehicles in all future stages (until high throughput is required). Minimum comm capabilities should include (above, plus):

- braking capability
- brake actuation
- speed
- lane change intentions
- [other . . . emergency or malfunction conditions?]

3.15.2.3 Encourage 'Hands-Off' Driving

Need acceptable level of obstacle management. Provide appropriate lane markings for lateral control systems.

Could be single lane, no non-emergency automated maneuvers

Minimum AVC capability:

- integrated lat./long; (integrated CAS?); driver condition monitor (for "check out"); navigation system

3.15.2.4 Encourage Full AHS

Provide infra-based support for automated merge, demerge, and lane change maneuvers.

3.15.2.5 Encourage Higher Safety and/or Throughput

Exclude non-AVC vehicles; add AVC requirements as appropriate (ACC to full AHS). Unlike in "mixed dedicated lane" strategy above, some of the benefits (comfort/convenience) of full AHS will now exist on the dedicated lanes; "clunker" cars will be excluded as market and/or system benefits warrant.

Note: the safety/throughput benefits of low-end vehicle exclusion may be marginal until all vehicles are equipped with "high-end" control capabilities (e.g., 'complex maneuver' capable; possibly full AHS only) which is a goal but not a requirement of the early stages of this strategy.

3.16 Highway Requirements Block Downgrades

3.16.1 Assumption Package

This strategy assumes that initial dedicated lane deployment is feasible.

It does not require, but benefits, from the assumptions that Mixed will not develop quickly or on its own.

3.16.2 Description of Strategy

Initial deployment of dedicated lane operational test, using expensive, highly restrictive lanes. Then, over time, progressively release Block downgrades to allowable AHS highway standards. Type I would be the initial, highly restrictive and presumably expensive Operational Test Highway. A Type III vehicle would be able to operate on a Type I, II or III highway. A vision would be that eventually Type N would correspond to automated operations on standard highways with no special equipment beyond some sign or marker designating permission for automated operations.

3.17 Prototype Drive Off in 2007

Suggested, but not defined.

4. Deployment Plan Issues

In the 7 year plan, NAHSC ultimately must convincingly describe how AHS is deployed. This description must resolve stakeholder issues, (e.g. "chicken and egg" issue between infrastructure and in-vehicle equipment, how AHS off-loads onto local street network).

To approach defining the issues, the relationship between AHS and the ITS National Architecture, and the Transportation Planning Process

4.1 Relationship to ITS National Architecture

The AHS is planned to be an evolutionary extension of the emerging intelligent transportation system, (ITS). AHS operation is envisioned to be operational beginning in year 2012 realizing improvements in safety and urban and inter-urban congestion.

Current trends in Federal transportation policy indicate that the ITS approach to transportation is becoming part of the long term transportation program nationally. Federal support for the program has survived three administrations, and new user services are being added. Current efforts are concentrating on building an intelligent transportation infrastructure, (ITI), and integrating ITS alternatives into the mainstream transportation planning process.

Public support for developing an AHS may hinge on the ability of the program to demonstrate its compatibility with the National ITS. From a stakeholder perspective, the AHS must be mutually supportive with the parent ITS for the program to be credible. Examples of this support could be:

- Regional TMC's monitoring or controlling AHS
- Instrumented HOV lanes becoming the dedicated AHS lanes
- ITI communications infrastructure supporting AHS operation
- AHS vehicles as probes supporting TMC operation
- AHS providing congestion relief for overall system benefit
- AHS providing a source of data for Advanced Traveler Information Systems

4.2 Relationship to the Transportation Planning Process

Aspects of the current transportation planning policy under the Intermodal Surface Transportation Efficiency Act of 1991, (ISTEA) affecting AHS are:

- Emphasis on broadening participation in transportation planning to include key stakeholders including the business community, the public, community groups and other governmental agencies.
- Understanding constraints imposed upon further expansion of the highway network, particularly in metropolitan areas, and that the maximization of system efficiency becomes a priority.
- Unprecedented linkages to achievement of the air quality objectives embodied in the Clean Air Act Amendments of 1990 and in state air quality plans.

A few key elements of the ISTEA planning process include:

- Major investment studies as part of plan development to address significant transportation problems in a corridor or subarea that might involve the use of Federal funds. Alternatives such as adding lanes to a freeway, building a light rail line, *or building an AHS corridor,* would undergo a comparative analysis <u>only once</u> at this point in the project development process.

- Congestion management systems are recommended to include an ongoing effort to provide information on the performance of the transportation system and on alternative strategies to alleviate congestion and enhance mobility.
- Federal operation and management funding is newly permitted for the first two years of a new system operation.

New legislation is being drafted to renew the 1991 ISTEA. It is likely that these trends will continue with a strengthening reliance on ITS and technology approach to transportation needs.

It can be concluded that AHS must therefore be cost effective from the government investment standpoint in order to become a transportation alternative recommended over other alternatives. AHS must also be supported by operational funding to sustain its operation by governmental entities.

technology development, and market forces. Market forces dominate the process, as evidenced by the many technical advances that are not yet brought to market, (e.g. in vehicle navigation).

4.3 Relationship to the Vehicle Development Process

The vehicle development process is driven by five major forces;

- Technology development
- Market forces (i.e., customer acceptance and competition)
- Government regulation
- Requirements of corporate citizenship
- Liability and litigation

The latter four tend to inhibit the introduction of new technology. Two good counter-examples of that tendency, however, are the catalytic converter and GM's commercial electric vehicle, the EV-1.

For AHS, there is a sixth force: the deployment of infrastructure technology, which must happen in parallel with development of automotive technology. This differs from typical vehicle development, which occurs assuming only existing infrastructure.

Central to all planning for new automotive technology introduction is cost. There must be a clear business case for the new idea, which means that the product must be priced so that enough customers will purchase it to provide payback in 2-4 years. Regulations aside, the only exception to this rule is very special cases where products are introduced as good corporation citizenship. It's not clear that there is a business case for the EV-1. There will be little government or public pressure, however, for vehicle manufacturers to take the lead in deploying AHS.

The effect of foreign competition is blurred with the globalization effect of the vehicle developers making this less of a factor. The same features are available on both domestic and foreign production cars.

The effect of government is also a significant influence on vehicle development through the following activities:

- providing roadway infrastructure
- setting environmental policy

- setting technical standards
- setting safety standards

The role of the vehicle developers will therefore interface with the public and commercial customer base, technology developers, and government. These interface relationships must be mutually supportive in order to achieve a cost feasible migration toward an AHS:

- Infrastructure
- Customer base
- Vehicle supply

Vehicle developers are also in the unique position of possibly inducing a market for AHS vehicles through their traditional role of setting trends through vehicle development, prototyping, marketing and sales strategies. I don't think that vehicle developers can or should do this alone. The real implication of this paragraph is that not only must technology development be coordinated with others, but also must promotion and public education be similarly coordinated.

AUTOMATED VEHICLE CONTROL (AVC) SERVICES COMPENDIUM

3 April 1997

This draft document was prepared by a committee formed by the National Automated Highway System Consortium (NAHSC). Committee members include Kevin Dopart of Mitretek Systems, Carol Jacoby of Hughes, Steve Shladover of PATH, and Bill Stevens of the NAHSC Program Office. It is intended that these materials will provide common terminology and definitions of Automated Vehicle Control (AVC) services, and will form a framework for NAHSC research efforts in both partially and fully automated AVC services.

The material is being made available to NAHSC Core and Associate Participants as well as other selected organizations for review and comment.

NAHSC
National Automated Highway System Consortium

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A. INTRODUCTION

An Automated Highway System (AHS) is a system where fully automated vehicles operate on specially instrumented "AHS lanes"; those lanes may be dedicated to fully automated vehicles ("dedicated lanes"); or they may be lanes where manually driven vehicles operate and the fully automated vehicles operate inter-mixed with the manually driven vehicles ("mixed traffic"), either on specially-equipped, protected lanes or on regular highways.

An AHS is closely related to partial automated vehicle control (AVC) services:

- Some partial AVC services are likely to precede AHS implementation, and will serve as stepping stones for AHS implementation
- The individual automobile manufacturers may offer AHS-equipped vehicles that provide drivers with partial AVC services when the vehicle is not operating in a fully automated mode; for example, the vehicle may provide some partial AVC support when operating in traffic lanes with manually operated vehicles.

The purpose of this compendium is to (1) identify all AVC services; and (2) propose a set of common terminology and definitions for them. None of the services have been analyzed for either feasibility or desirability. The analysis defines nine categories of AVC with close to 60 AVC services within the categories.

These services can be combined, in some cases, to come up with new combined services; for example, *Coefficient of Friction Warning* could be combined with *Frontal Warning for Vehicles*. Basic combinations such as that are not included in this analysis. However, combining some services implies a level of integration and complexity beyond the basic combination; for example, *Frontal Collision Avoidance* and *Side-Looking Collision Avoidance* would need to be integrated so that the collision avoidance sensing is integrated and the control responses as well as user interfaces are integrated. Several, but not all, of these "integrated" services have been included as separate services.

The categories and services within each category are imperfect since the degrees of sensing that can be accomplished or are needed are, in fact, continuums rather than incremental steps as implied by the defined services. Similarly, the ranges and degrees of control that can be accomplished and/or are needed are also continuums. The services described herein are data-points on the continuums. Also, it could be argued that some of the services are not separate services but are, instead, variations of other services.

The service categories are defined using these parameters:

- Driver involvement--"Partially automated" services assist the driver but the driver is able to regain control at any time and is fully responsible for the vehicle's control. The "Fully Automated" services provide complete control, and grant the driver control only when it is deemed safe. In these services, the system is responsible for vehicle control when it activated.
- Level of control service--The range for level of control is "Warning" (no control); "Temporary Emergency Control"; "Driving Management"; "Fully Automated in Mixed Traffic" (complete control in mixed traffic); and "Dedicated Lanes". Dedicated lane services differ from mixed traffic services in quality of service (safety, throughput, user comfort), overall traffic control, types of sensors required, levels of control needed, and involvement of the state agencies in development. For these reasons these services are identified in a separate category.

B. SERVICE CATEGORIES

The nine service categories and the AVC service variants within each category are listed below. A description of each variant is given in the next section. The *Miscellaneous Services*, category 9, are listed but not described in this Compendium.

1. Situation Warning in Mixed Traffic

1.1 Frontal Warning for Vehicles
1.2 Frontal Warning for Obstacles and Vehicles
1.3 Side-looking Warning for Vehicles
1.4 Over-Taking Vehicle Warning
1.5 Lane Departure Warning
1.6 Coefficient of Friction Warning
1.7 Warnings and Advice from Cooperative Vehicles
1.8 Warnings and Advice from Cooperative Infrastructure
1.9 Driver Drowsiness Warning
1.10 Vehicle Health Monitoring Warning

2. Temporary Emergency Control in Mixed Traffic

2.1 Skid Avoidance (individual brake actuation to maintain directional control)
2.2 Frontal Collision Avoidance of Vehicles (braking and power train control only)
2.3 Frontal Collision Avoidance of Obstacles and Vehicles (brake & power train only)
2.4 Side Collision Avoidance
2.5 Overtaking Vehicle Collision Avoidance
2.6 Lane Departure Avoidance
2.7 Integrated Frontal and Side Collision Avoidance (integrated braking, power train and steering control actuation to avoid collisions)
2.8 Control Data to Driver and System from Cooperative Vehicles (control data may relate to avoidance of skid, frontal collision, side collision and/or lane departure)

- 2.9 Control Data to Driver and System from Cooperative Infrastructure (may relate to avoidance of skid, frontal collision, side collision and/or lane departure)
- 2.10 Drowsy Driver Mitigation

3. Continuous Partial Control in Mixed Traffic

- 3.1 Adaptive Cruise Control (ACC)
- 3.2 Lane Keeping (LK)
- 3.3 Integrated ACC and LK

4. Integrated Emergency Control and Continuous Partial Control in Mixed Traffic

- 4.1 Integrated ACC and LK with frontal and side ("full") CA
- 4.2 Integrated ACC and LK with full CA with Cooperative Vehicles
- 4.3 Integrated ACC and LK with full CA with Cooperative Infrastructure
- 4.4 Merge Capability for Integrated ACC, LK
- 4.5 Fully Automated with Driver Override

5. Fully Automated Control in Mixed Traffic

- 5.1 Fully Automated with Mixed Traffic on Protected Lane
- 5.2 Fully Automated in Mixed Traffic
- 5.3 Fully Automated in Mixed Traffic with Cooperative Vehicles
- 5.4 Fully Automated in Mixed Traffic with Cooperative Infrastructure

6. Background Warning and Control in Mixed Traffic

- 6.1 Background Longitudinal Warning
- 6.2 Background Lateral Warning
- 6.3 Integrated background Longitudinal and Lateral Warning
- 6.4 Integrated Background Longitudinal and Lateral Warning with Temporary Emergency Control
- 6.5 Fully Automated Background Control with Cooperative Vehicles
- 6.6 Fully Automated Background Control with Cooperative Infrastructure

7. Continuous Partially Automated Control on Dedicated Lanes

- 7.1 ACC Only
- 7.2 Integrated ACC and Lane Keeping
- 7.3 Integrated ACC and LK with Frontal CA with Cooperative Vehicles
- 7.4 Integrated ACC and LK, Frontal CA with Cooperative Infrastructure
- 7.5 Integrated ACC, LK and Frontal CA Capable of Operating Mixed with Fully Automated on a Dedicated Lane
- 7.6 Merge Capability (Part-time) for ACC, LK and Frontal CA Vehicles Capable of Operating Mixed with Fully Automated on a Dedicated Lane

8. Fully Automated Control on Dedicated Lanes

- 8.1 Fully Automated on Dedicated Lanes, No Vehicle or Infrastructure Cooperation
- 8.2 Fully Automated on Dedicated Lanes with Cooperative Vehicles
- 8.3 Fully Automated on Dedicated Lanes with Cooperative Infrastructure

8.4 Fully Automated on Dedicated Lanes with Cooperative Vehicles and Infrastructure, Capable of Platooning
8.5 Fully Automated Capable of Mixed Traffic Operations

9. Miscellaneous Services

These are services that use forms of AVC but are not discussed in this analysis; they are listed here for sake of completeness. Even though the technologies applied may be similar to AHS, the functions they provide do not necessarily directly relate to the evolution of an AHS; that is, AHS can evolve without the development of any of these services. However, AHS technologies may be applicable to some of these services. The driverless vehicle services, while closest to AHS in functionality, are not addressed in this analysis since they have not been a focus of the AHS program.

9.1 Backing Collision Warning
9.2 Backing Collision Avoidance
9.3 Intersection Collision Warning
9.4 Intersection Collision Avoidance
9.5 Parking Assistance, Warning
9.6 Parking Assistance, Control
9.7 Vehicle Over-turn Warning (trucks)
9.8 Vehicle Over-turn Avoidance (trucks)
9.9 Congestion Movement Control, Longitudinal--throttle and brake control only
9.10 Congestion Movement Control, Longitudinal and Lateral--throttle, brake and steering control
9.11 Driverless Vehicle Control in Closed (Non-Public) Systems (airport shuttles, warehouse freight movement, etc.)
9.12 Driverless Vehicle Control on Dedicated Public Lanes (driverless vehicles that are shuttled from one location to another; for example, return of rental vehicles to the rental parking lot or specialized freight containers, or driverless public transit shuttles)
9.13 Driverless Following Vehicle (first vehicle has a driver, but following vehicles are electronically linked to the first vehicle and are driverless; these could be on automated or non-automated roadways)
9.14 Event Recorder--records both automated and manual actions for crash reconstruction

C. SERVICE DESCRIPTIONS

Services in each of the first eight service categories are described below; services in category 9, *Miscellaneous Services*, are not described in this compendium.

The sensing and control for each of the services is summarized in tables 1 through 16, as referenced in the text below. In the sensing tables, a large "X" indicates that the full sensing capability must be present; a small "x" indicates that some level of sensing may be necessary but not to the full extent. The absence of any mark indicates that no sensing is necessary. In the control tables, the extent of vehicle control is indicated as "FT" for full time and "PT" for part time; "haptic" indicates that the vehicle may assert control only as a haptic feedback to the driver. Merge/pass and Driver Override capabilities are indicated as "yes" or "no". The extent of check-in is explained with notes such as "system verify" or "sv", "coop." meaning cooperation with other vehicles or the infrastructure. Other lane control capabilities are indicated as "yes", "no" , or "maybe" with some explanatory notes in a few cases. Blanks indicate that no control is required in that category.

C.1. Situation Warning in Mixed Traffic Services

These are services in which the system warns the driver of a sensed potential incident; the driver chooses to respond. The driver is always in control and is fully responsible. All of these warning services can be combined with other warning services or with other control services. When combined with a control service, the warning can be transmitted to the on-board system as well as, or in place of, the driver. **(Tables 1 and 2)**

1.1 <u>Frontal Warning for Vehicles</u> - This service detects when a vehicle is in close proximity to the subject vehicle and warns the driver. The service judges the closing rate on the vehicle in front and may give increasingly urgent warnings to the driver as the possibility of collision increases. At any time, the driver would be able to turn the service on or off as desired. The service must be able to distinguish vehicles in the lane of travel from vehicles in other lanes or roadside objects such as retaining walls or barriers. A high rate of false alarms would cause drivers to deactivate the service rather than use it.

1.2 <u>Frontal Warning for Obstacles and Vehicles</u> - This service is significantly more sophisticated than service 1.1, *Frontal Warning for Vehicles.* The driver would be warned when there were either vehicles or obstacles in close proximity in the lane ahead. Given today's technology, the sensor suite needed to accomplish dependable obstacle detection would be far more difficult to develop and would probably be far more expensive to produce than one that detects only vehicles. However, sensors can be developed to detect some obstacles. In the near term, the vehicle manufacturer would need to be careful in marketing the service to not over-promise.

1.3 <u>Side-looking Warning for Vehicles</u> - Sensors on the side of the vehicle would detect the presence of a vehicle in the adjacent lane; when the driver indicates intent to change lanes, the service would warn the driver. The sensor could also detect a vehicle two lanes over and gauge its motion so that if it appeared to also be moving into the passing lane, the system could give a warning. Again, a high rate of false alarms would cause drivers to deactivate the service rather than use it. False warnings would seem to be easier to design out than for the frontal warning systems because of the relatively close proximity of the vehicles.

1.4 <u>Over-Taking Vehicle Warning</u> - This is an enhancement to service 1.3, *Side-Looking Warning.* Besides warning the driver if there is a vehicle in the next lane, it would also warn the driver if a vehicle in the next lane was approaching fast from the rear. Added sensors and logic would be needed to sense overtaking vehicles.

1.5 Lane Departure Warning - Sensors would detect the position of the vehicle relative to the lane boundaries and/or roadway shoulders. The driver would be warned when the vehicle approached and/or exceeded the lane boundaries. Warnings could be graduated so that they increase in intensity as the lane edge is breached.

SITUATION WARNING IN MIXED TRAFFIC SERVICES

TABLE 1: SENSING FOR SITUATION WARNING IN MIXED TRAFFIC SERVICES

	ON-VEHICLE SENSING						EQUIPPED LANE SENSING				
SERVICE NAME	**frontal - veh. sep.**	**frontal-obstacles**	**side for vehicles**	**lane boundry**	**coeff. of friction**	**driver condit.**	**road condtion**	**obstacles**	**vehicle location**	**entry veh. (&destin?)**	**monitor if exit avail.**
1.1 Frontal warning, vehicle	X			x							
1.2 Frontal warning, obstac.	X	x(some)		x							
1.3 Side looking warning			X								
1.4 Over-taking veh. warn.				x							
1.5 Lane departure warning			(some?)	X							
1.6 Coeffic. of frict. warn.					X						
1.7 Coop vehicl. warnings											
1.8 Coop. infra. warning	x	x	x								
1.9 Drowsy driver warn.						X	x				
1.10 Veh. health mon. warn.											

TABLE 2: CONTROL FOR SITUATION WARNING IN MIXED TRAFFIC SERVICES

	VEHICLE CONTROL					CONTROL FROM LANE				
SERVICE NAME	drive train	brakes	steering	merge/ pass	Driver Override?	check-in of system	operating parameters	merge and pass	checkout to driver	Dedicated lane?
1.1 Frontal warning, vehicle	haptic?				yes	sv (self-ver)				
1.2 Frontal warning, obstac.	haptic?				yes	sv				
1.3 Side looking warning			haptic?		yes	sv				
1.4 Over-taking veh. warn.			haptic?		yes	sv				
1.5 Lane departure warning			haptic?		yes	sv				
1.6 Coeffic. of frict. warn.						sv				
1.7 Coop vehicl. warnings						sv				
1.8 Coop. infra. warning						sv				
1.9 Drowsy driver warn.						sv				
1.10 Veh. health mon. warn						sv				

1.6 Coefficient of Friction Warning - Sensors on-board the vehicle would detect when the tire-to-road surface coefficient of friction is reduced due to water, ice or road surface condition. The driver would be warned of reduced traction; this warning could increase as the severity of the loss of friction increases. The capability of this service could vary substantially from a simple warning light of possible traction loss (as some vehicles have today) to an indication of the percent of traction loss; this could be needed with systems that control the vehicle response to the traction loss.

1.7 Warning and Advice from Cooperative Vehicles - Other vehicles on the road could detect possible safety hazards including detected incidents, obstacles, stopped vehicles, poor driving conditions, or conditions on-board the transmitting vehicle such as hard braking. The information could also consist of advice; for example, "exit 33 is congested; take an alternate route". These conditions would be communicated to drivers of other vehicles, perhaps through in-vehicle signing. The warning vehicles could precede the warned vehicle in its lane of travel, or be in a lane with traffic approaching the warned vehicle. Equipped vehicles would both transmit warnings to other vehicles when appropriate conditions are sensed, as well as receive warning messages from other vehicles.

1.8 Warning and Advice from Cooperative Infrastructure - Beacons on the infrastructure could warn passing equipped vehicles of hazards or conditions, either through roadside signing or in-vehicle signing. The information transmitted by these beacons could come from a regional traffic management center (e.g., repair crew at mile marker 23), from roadside sensors (e.g., icy bridge ahead), or as a relay from other vehicles (e.g., a vehicle from the other direction passed an "icy road" message to the roadside beacon, which in turn transmits the message to all approaching vehicles). This implies that the infrastructure owner/operator must invest in roadside equipment that is compatible with equipped vehicles.

1.9 Driver Drowsiness Warning - Driver condition is monitored on-board the vehicle; if the driver is detected as drowsy or otherwise incapacitated, warnings would be given to the driver to slow down or stop until the drowsy condition was overcome or the system was turned off.

1.10 Vehicle Health Monitoring Warning - Today's vehicles have some form of vehicle condition monitoring such as oil pressure and coolant temperature. This service would go a step further and monitor the vehicle's safety-related functions. Examples of conditions monitored could include tire pressure, sensor failure, or communications failure. The warnings would be given to the driver, or for those cases involving some form of automated control, the warnings/notices would be given to the system.

C.2. Temporary Emergency Control In Mixed Traffic Services

With these services, the system assumes control only when it perceives that conditions are unsafe or that a crash is imminent. The driver can override the control at any time; the driver is fully responsible for the driving--the control is driver-assist only. However, drivers will expect the vehicle to detect and avoid most potential crashes; and the driver will expect infrequent false warning of crashes. Most if not all of these temporary control services can be "combined" with warning services and/or with other temporary control services. For example, service 2.2, *Frontal Collision Avoidance,* would logically be coupled with service 1.1, *Frontal Collision Warning,* so that if the driver did not heed the warning, the temporary control would be assumed to avoid the crash. However, combining some of these services will require that the services be integrated so that sensing, driver interfaces, and vehicle responses are integrated. This would add a level of complexity beyond the simple addition of two services to the same vehicle. **(Tables 3 and 4)**

2.1 Skid Avoidance--This service would build upon the sensing of the vehicle's coefficient of friction as it travels along the roadway. In addition to warning the driver, the service maintains stability when the driver applies the brakes through individual brake actuation to maintain directional control; in addition, the service might adjust the forward-looking sensor range.

2.2 Frontal Collision Avoidance of Vehicles - This service is a step beyond the *Frontal Vehicle Warning* service in that it will detect when the closing rate on the vehicle in front is high enough that a collision will occur if there is not additional braking, and will actuate the power train and/or brakes to avoid the collision or reduce its severity. An advanced form of this service would also use the vehicle's steering to avoid a crash; this requires integration with a more sophisticated set of sensors (e.g., side-looking and perhaps back-looking) and a more sophisticated integrated processing logic. For purposes of this analysis, this added capability to steer to avoid a crash is assumed to be a part of service 2.7, *Integrated Frontal Vehicle Collision Avoidance, Side Collision Avoidance*. At any time, the driver would be able to turn the service on or off (even when the service is exercising control).

2.3 Frontal Collision Avoidance of Obstacles or Vehicles - This service is very similar to service 2.2, *Frontal Collision Avoidance of Vehicles*; it differs only in that collisions with either vehicles or detected obstacles are avoided, or severity minimized, through actuation of the power train and/or brakes. Even though the sensing would be more challenging, once an obstacle is detected, the response may not be different from the response to a slowed or stopped vehicle.

TEMPORARY EMERGENCY CONTROL IN MIXED TRAFFIC SERVICES

TABLE 3: SENSING FOR TEMPORARY EMERGENCY CONTROL IN MIXED TRAFFIC SERVICES

	ON-VEHICLE SENSING						EQUIPPED LANE SENSING				
SERVICE NAME	frontal - veh. sep.	frontal - obstacles	side for vehicles	lane boundry	coeff. of friction	driver condtion	road condition	obstacles	vehicle location	entry veh. (&destin?)	monitor if exit avail.
2.1 Skid avoidance					X						
2.2 Frontal veh collis. avoid.	X			x (some)							
2.3 Frontal obstacle avoid.	X	x(some)		x							
2.4 Side coll. avoid. (CA)			X								
2.5 Overtaking vehic. CA			X+overtk	x							
2.6 Lane depart. avoidance			x (some)	X							
2.7 Integ. front & side CA	X	x (some)	X								
2.8 Data from coop. vehicle	x (comm.)	x (comm.)			x (comm.)						
2.9 Data from coop. infra.							x (comm)	x			
2.10 Drowsy driver mitigate						X					

TABLE 4: CONTROL FOR TEMPORARY EMERGENCY CONTROL IN MIXED TRAFFIC SERVICES

	VEHICLE CONTROL					CONTROL FROM LANE				
SERVICE NAME	drive train	brakes	steering	merge/ pass	Driver Override?	check-in of system	operating parameters	merge and pass	checkout to driver	Dedicated lane?
2.1 Skid avoidance	PT (when needed)	PT (indiv.)				sv (self-ver)				
2.2 Front. veh collis. avoid.	PT	PT			yes	sv				
2.3 Frontal obstacle avoid.	PT	PT			yes	sv				
2.4 Side coll. avoid. (CA)	PT		PT		yes	sv				
2.5 Overtaking vehic. CA	PT		PT		yes	sv				
2.6 Lane depart. avoidance	PT		PT		yes	sv				
2.7 Integ. front & side CA	PT	PT	PT		yes	sv				
2.8 Data from coop. vehicle	input	input			yes					
2.9 Data from coop. infra.	input	input			yes					
2.10 Drowsy driver mitigate	PT	PT	PT		yes	sv			some?	

2.4 Side Collision Avoidance - Sensors on the side of the vehicle would detect the presence of a vehicle in the adjacent lane; when the driver indicates intent to change lanes, the service would warn the driver and discourage the driver from moving into the other vehicle; this could be done through haptic cues and/or steering actuation to prevent the lane change and avoid the collision. The driver would be able to override the system and assume control at any time.

2.5 Overtaking Vehicle Collision Avoidance - Sensors would detect if a vehicle is approaching fast from the rear in the lane into which the subject vehicle is attempting to move. The service would prevent the driver from moving into the other vehicle. The driver would be able to override the system and assume control at any time.

2.6 Lane Departure Avoidance - Sensors would detect the position of the vehicle relative to the lane barriers and/or the shoulders of the roadway. The driver would be warned, perhaps through haptic cues, when the vehicle closely approached the lane boundaries. If the vehicle were to continue toward and/or cross the lane boundaries, the vehicle's steering and possibly braking would be actuated to return the vehicle to the center of the lane and prevent a run-off-the-road occurrence.

2.7 Integrated Frontal and Side Collision Avoidance - This service will detect when the vehicle's operation is such that a crash will occur unless there is a coordinated vehicle maneuver to avoid the crash. The service will control the power train, brakes and/or steering to avoid the collision or reduce its severity. For this service to be effective, the on-board sensing must be integrated so that the processor has a more complete perspective of the situation (e.g., can the vehicle swerve into the next lane or is there another vehicle there?). The vehicle control must also be coordinated so that the vehicle's path is chosen to maximize the likelihood of either avoiding the crash or minimizing its severity. This combination raises the sophistication of this service several levels; it can be argued that the sophistication is beyond service 8.1, *Fully Automated on Dedicated Lanes*, because it must operate safely in mixed traffic. The driver can choose to turn the service off at any time, even in a dangerous situation. An issue is how does the vehicle return control to the driver once the crash has been avoided? For example, the problem may have been caused by the driver falling asleep; once the system assumes control is it responsible? Another issue concerns how to optimize the system response--for the individual or for society? For example, if there is a trade-off between avoiding an impact with a large truck on one side or two motorcyclists on the other side, which path is best?

2.8 Control Data to Driver and System from Cooperative Vehicles - This service is similar to service 1.7, *Warning from Cooperative Vehicles* service in that other vehicles on the road may detect possible safety hazards and communicate the conditions to other vehicles; however, the information transmitted would include specific operating parameter information such as "vehicle ahead is stopping" or "icy--reduce speed to 50 km/h". The specific advisories could be used by the on-board control services to slow the vehicle or change its trajectory; they could also be used to advise the driver to take action. The service would also transmit similar advisories to other vehicles if the on-vehicle sensors detected dangerous conditions such as icy roadway.

2.9 Control Data to Driver and System from Cooperative Infrastructure - Like service 2.8, control parameter advisories would be given to vehicles; however, the information would come from roadside beacons. The source of the information could be from other passing vehicles, local sensors or a regional traffic management center.

2.10 Drowsy Driver Mitigation - If the monitoring of the driver's condition indicates drowsiness or other incapacitation, then this service would respond to reduce possible incident occurrence. The vehicle response would depend on the vehicle's control sophistication; at the least, the system would attempt to waken the driver while simultaneously slowing the vehicle and activating its warning lights. An advanced form of this service is service 6.5, *Fully Automated Background Control in Mixed Traffic*; that service would maintain full control and attempt to park the vehicle until the driver was determined to be alert, or the driver turned the service off. This latter service would require the capability to provide fully automated operation in mixed traffic.

C.3. Continuous Partial Control in Mixed Traffic Services

These are "driver-in-the-loop" services that provide continuous assistance to the driver in normal driving functions. Adaptive Cruise Control (ACC) and Lane Keeping (LK) provide continuous control of selected vehicle functions when the driver turns the services on. The driver is fully responsible for all driving functions at all times; when the system is controlling, the driver is able to override it; the driver can turn the service on or off at any time. Advisories could be received by these services from either other vehicles or from the infrastructure. Existing systems such as ABS are not included in the list. **(Tables 5 and 6)**

3.1 Adaptive Cruise Control (ACC) - This service incorporates forward-looking sensors to enhance the cruise control service so that the vehicle is continuously kept at a safe following distance from the vehicle in front. This distance would vary with vehicle velocity; and the driver may be able to adjust the distance to better fit his or her driving habits. Automatic power train control actuation is used to increase and decrease speed; in addition, some gentle actuation of the brakes may occur.

3.2 Lane Keeping (LK) - When this service is on, the vehicle senses the center of the lane and continually actuates the steering to keep the vehicle in the center of its lane. For the service to dependably detect the lane boundaries, some infrastructure cooperation is required such as accurately painted lane marker stripes, embedded magnetic nails, or radar-reflective stripes. For greatest safety, the lane markers must be conscientiously maintained; when the lane markers cannot be detected by the service (e.g., snow, construction or switch to a different class of roadway), the

CONTINUOUS PARTIAL CONTROL IN MIXED TRAFFIC SERVICES

TABLE 5: SENSING FOR CONTINUOUS PARTIAL CONTROL IN MIXED TRAFFIC SERVICES

	ON-VEHICLE SENSING						EQUIPPED LANE SENSING				
SERVICE NAME	frontal - veh. sep.	frontal - obstacles	side for vehicles	lane boundry	coeff. of friction	driver condtion	road condtion	obstacles	vehicle location	entry veh. (&destin?)	monitor if exit avail.
3.1 Adaptive cruise (ACC)	X	x (some)									
3.2 Lane keeping (LK)				X							
3.3 Integrated ACC and LK	X	x (some)		X							

TABLE 6: CONTROL FOR CONTINUOUS PARTIAL CONTROL IN MIXED TRAFFIC SERVICES

	VEHICLE CONTROL					CONTROL FROM LANE				
SERVICE NAME	drive train	brakes	steering	merge/ pass	Driver Override?	check-in of system	operating parameters	merge and pass	checkout to driver	Dedicated lane?
3.1 Adaptive cruise (ACC)	full time (FT)	some?			yes	sv (self-ver)				
3.2 Lane keeping (LK)			FT		yes	sv				
3.3 Integrated ACC & LK	FT	some?	FT		yes	sv				

driver must be adequately warned to resume manual control. The driver can assume control at any time. If the driver attempts to turn the service when adequate lane markers are not present, the service will not activate.

3.3 Integrated ACC and LK - This service would assume both the longitudinal and lateral control of the vehicle so that the vehicle would keep a safe distance from the vehicle in front, and would stay in its lane of travel. Because it is an integrated service, it has a level of complexity above the individual ACC and LK services. Collision avoidance is not part of this service. The driver can turn this integrated service on or off at any time. The driver would need to maintain full awareness of the driving task at all times to ensure that the lane keeping is working, to detect obstacles, and to avoid potential crashes if the vehicles ahead stops suddenly. There is significant concern that on long stretches of road—for example, an inter-city Interstate highway—a driver might become distracted from the driving task if both longitudinal and lateral control are handled automatically. Once the system assumes control, does it share responsibility? Would the system need to ensure that the driver is capable of resuming control before returning it through alertness monitoring? Services 1.9 and 2.10, *Driver Drowsiness Warning and Mitigation,* might need to be a part of this service.

C.4. Integrated Emergency Control and Continuous Partial Control in Mixed Traffic Services

These services represent the integration of *Temporary Emergency Control* services with *Continuous Partial Vehicle Control in Mixed Traffic* services. They are separately identified because (1) the level of sophistication that must be achieved in integrating the services is significantly higher than for the stand-alone services; and (2) the degree of protection afforded by these integrated services is significantly higher than with the stand-alone services. There are potentially several combinations that are possible when integrating the services. The simpler combinations, such as *Lane Keeping* service integrated with *Side Collision Avoidance* service, are not included. The services that are included are the more complex and difficult-to-achieve services. **(Tables 7 and 8)**

4.1 Integrated ACC and LK with Frontal and Side ("full") CA - When the driver turns this service on, the vehicle will provide both automatic longitudinal and lateral control as well as longitudinal and lateral collision warning and avoidance. The driver could take both hands off the steering wheel and both feet off the pedals; however, this would need to be done very cautiously since the vehicle is operating intermixed with manually driven vehicles, and the driver is fully responsible for the driving task. With the added safety of collision avoidance, the temptation toward driver distraction would be a very serious problem for this integrated service. The driver would be able to turn the service on or off as desired. When the service is on, the driver would need to be constantly aware of, and be ready to respond to, obstacles, unclear lane markings that disrupt the lane keeping function, and nearby erratic drivers.

INTEGRATED EMERGENCY CONTROL AND CONTINUOUS PARTIAL CONTROL IN MIXED TRAFFIC SERVICES

TABLE 7: SENSING FOR INTEGRATED EMERGENCY CONTROL AND CONTINUOUS PARTIAL CONTROL IN MIXED TRAFFIC SERVICES

	ON-VEHICLE SENSING						EQUIPPED LANE SENSING				
SERVICE NAME	frontal - veh. sep.	frontal - obstacles	side for vehicles	lane boundry	coeff. of friction	driver condtion	road condtion	obstacles	vehicle location	entry veh. (&destin?)	monitor if exit avail.
4.1 Integrated ACC and LK with frontal and side CA	X	x (some)	X	X							
4.2 Integr. ACC, LK, CA, ctrl data from coop. veh.	X	x (some more)	X	X	x (some)						
4.3 Integr. ACC, LK, CA, ctrl data from coop. infr.	X	x (some more)	X	X	x (some)		X	x (some)			
4.4 Merge capability for integrated ACC and LK	X	x (some)	X	X	x (some)		X	x (some)	X	X	maybe
4.5 Full auto., drvr override	X	X	X	X	X	X	X*	X*	X*	X	maybe

* Assumes cooperative vehicles and infrastructure.

TABLE 8: CONTROL FOR INTEGRATEDEMERGENCY CONTROL AND CONTINUOUS PARTIAL CONTROL IN MIXED TRAFFIC SERVICES

	VEHICLE CONTROL					CONTROL FROM LANE				
SERVICE NAME	drive train	brakes	steering	merge/ pass	Driver Override?	check-in of system	operating parameters	merge and pass	checkout to driver	Dedicated lane?
4.1 Integrated ACC and LK with frontal & side CA	FT	FT	FT		yes	self-verify (sv)				maybe
4.2 Integr. ACC, LK, CA, ctrl data from coop. veh.	FT	FT	FT		yes	coop. sys. verify?	Of other vehicles			maybe
4.3 Integr. ACC, LK, CA, ctrl data from coop. infr.	FT	FT	FT		yes	coop. sys. verify?	Of the infrastruc.			maybe
4.4 Merge capability for integrated ACC and LK	FT	FT	FT	yes		yes	yes	maybe	maybe	maybe
4.5 Full auto., drvr override	FT	FT	FT	yes	yes	yes*	yes*	yes*		maybe

* Assumes cooperative vehicles and infrastructure.

An issue is how the system would return control to the driver once it had been assumed. If the collision avoidance were good enough to detect virtually all potential incidents and avoid them, then this service would, in effect, be service 5.2, *Fully Automated in Mixed Traffic* where the vehicle is enhanced with additional sensors and logic so that the vehicle is prepared to respond to the erratic actions of the manually driven vehicles (see service 4.6, *Fully Automated Control with Driver Override*, described below).

4.2 Integrated ACC and LK with Full CA with Cooperative Vehicles This would be similar to the service described above only the vehicle's logic would also be able to use information received from other vehicles as part of its decision-tree process. This would enhance the vehicle's safety and efficiency; for example, if the subject vehicle can communicate with the vehicle in front of it, that vehicle's velocity, acceleration and braking capabilities could all be received. This would allow the subject vehicle to safely move closer since any changes in the leading vehicle's travel vector would immediately be known and adjusted for. The driver would be able to override the system at any time, so the closeness of travel of the following vehicle would need to be tempered by that possible occurrence.

4.3 Integrated ACC and LK with Full CA with Cooperative Infrastructure - This service would be similar to the service described above only the vehicle's logic would also be able to use information received from the infrastructure as part of its decision process. The driver would be able to override the system at any time.

4.4 Merge Capability for Integrated ACC, LK - This service would supplement service 4.1, *Integrated ACC And LK with Full CA,* by responding to the driver's request and providing the ability to change lanes and/or merge with other traffic. It would depend on (1) Side-Looking Warning and Collision Avoidance; (2) Approaching Vehicle Warning and Collision Avoidance; (3) Frontal Collision Warning and Avoidance; and (4) communications with cooperative vehicles, and possibly communications with a cooperative infrastructure as well.

4.5 Fully Automated Control with Driver Override - This service is service 5.2, *Fully Automated in Mixed Traffic,* with the exception that the driver would be able to override the service. The vehicle would need the same level of automated control capability as service 5.2; it is included as a driver aid only because the driver is able to resume control at any time, even in dangerous situations. If the system makes the judgment that the situation is too dangerous to return control to the driver, and prevents the driver from taking over, then the service is service 5.2, *Fully Automated in Mixed Traffic.*

C.5. Fully Automated Control in Mixed Traffic Services

These are "driver-out-of-the-loop" services. The services provide continuous full control of the vehicle. the driver requests the system to take control; if safe, appropriate, and if the system is operable, the system assumes control from the driver. The driver can request control; the system grants control to the driver when conditions are safe and/or appropriate. When the system is on, the system has primary responsibility for the vehicle control.

These fully automated systems are several levels of complexity beyond integrated collision avoidance systems, which merely supplement the driver's capabilities; that is, if a service *supplements* the driver, then the driver has responsibility and the system assumes that the driver will assume control in those instances where the system is not capable. With fully automated, the driver is not required to remain in control and is no longer responsible for the driving task; the system must replace the driver's senses and logic while operating in mixed traffic. The system must have the added sensing acuity that will allow it to detect abnormal as well as normal highway events including the erratic actions of nearby drivers. And the system must have a level of logic and judgment at least equivalent to that of today's driver so that the vehicle can robustly and safely react to the events. **(Tables 9 and 10)**

5.1 Fully Automated with Mixed Traffic on Protected Lane - This service assumes that the fully automated vehicle can only interact with mixed traffic when on a protected lane of some sort; for example, an HOV lane could allow manually-operated buses and car pools as well as fully-automated vehicles. The protected lane could allow some obstacle exclusion and provide protection against incidences in the parallel manual-only lanes from intruding on the automated operation. This would mean that the sensors and logic of the fully automated vehicles could be substantially less than if the vehicle were to operate where there is no protection. The system, not the driver, would have responsibility for safe vehicle operation.

5.2 Fully Automated in Mixed Traffic - This service would be able to provide fully automated vehicle control in mixed traffic. In turning on the service, the driver requests that the service assume control. The system would assume full control if it was operational, if operating conditions were safe, and if conditions were appropriate; for example, if any infrastructure support were needed, the system would accept control only if the support were available. The driver could request to take control of the vehicle, but the system would decide when it was safe to transfer control back to the driver. The underlying assumption for this service is that the vehicle is capable of handling all occurrences it might encounter while driving among manually driven vehicles, including likely attempts by the manual drivers to deliberately disrupt the automated vehicle. The system, not the driver, would have responsibility for safe vehicle operation.

FULLY AUTOMATED CONTROL IN MIXED TRAFFIC SERVICES

TABLE 9: SENSING FOR FULLY AUTOMATED CONTROL IN MIXED TRAFFIC SERVICES

	ON-VEHICLE SENSING						EQUIPPED LANE SENSING				
SERVICE NAME	frontal - veh. sep.	frontal - obstacles	side for vehicles	lane boundry	coeff. of friction	driver condtion	road condtion	obstacles	vehicle location	entry veh. (&destin?)	monitor if exit avail.
5.1 Fully automated with mixed on protected lane	X	X (for protected lane)	X	X	X	X	maybe	maybe		maybe	maybe
5.2 Fully automated in mixed with no coop. data	X	XX (for mixed)	X	X	X	X					
5.3 Fully auto. in mixed with data from coop. vehicle	X	XX (for mixed)	X	X	X	X	x (some)	x (some)		X - entering veh.	
5.4 Fully auto. in mixed with data from coop. infrastructure	X	XX (for mixed)	X	X	X	X	X	x (some)	X	X	X

TABLE 10: CONTROL FOR FULLY AUTOMATED CONTROL IN MIXED TRAFFIC SERVICES

	VEHICLE CONTROL					CONTROL FROM LANE				
SERVICE NAME	drive train	brakes	steering	merge/ pass	Driver Override?	check-in of system	operating parameters	merge and pass	checkout to driver	Dedicated lane?
5.1 Fully automated with mixed on protected lane	FT	FT	FT	maybe	requests	maybe	maybe	maybe	yes	
5.2 Fully automated in mixed with no coop. data	FT	FT	FT	FT	requests	self verify			yes, on veh; park veh	maybe
5.3 Fully auto. in mixed with data from coop. vehicle	FT	FT	FT	FT	requests	coop. with other veh?	from coop. vehicles		yes, on veh; park veh	maybe
5.4 Fully auto. in mixed with data from coop. infrastructure	FT	FT	FT	FT	requests	yes	yes	yes	yes; park veh.	maybe

5.3 Fully Automated in Mixed Traffic with Cooperative Vehicles - This is the service described above only the vehicle's logic would be able to use information received from other vehicles as part of its decision process. For example, if the vehicle immediately were also automated with communications capability, then the preceding vehicle's braking capability and movement information could be transmitted allowing the following vehicle to operate with closer tolerances. The system, not the driver, would have responsibility for safe vehicle operation.

5.4 Fully Automated in Mixed Traffic with Cooperative Infrastructure - This service is the same as the service described above only the vehicle's logic would also be able to receive control data from the roadside as part of its decision process. For example, if there were repairs on the roadside ahead, the vehicle's operating logic could be instructed to slow to 40 km/h with a 10 meter spacing from the vehicle in front, and merge into the left lane. The system, not the driver, would have responsibility for safe vehicle operation.

C.6. Background Warning and Control in Mixed Traffic Services

These are services that expect the driver to control the vehicle, and exert influence only when a potentially dangerous or abnormal event is detected. For the first four services, the driver is fully responsible for all driving functions at all times; when the system provides haptic warning and/or control, the driver is able to override it. The driver can turn the service on or off at any time. Advisories could be received by these services from either other vehicles or from the infrastructure.

With the two fully automated services, the driver perceives that he or she is in control; but in fact the system is allowing the driver to operate within certain safe boundaries; as soon as the driver exceeds any one of these boundaries, the system gradually assumes the control and returns the vehicle's operation to a safe condition. The system will then either seek to return control to the driver in some manner, or maintain full control until the driver requests that control be returned; the system would return control when it is safe and appropriate. **(Tables 11 and 12)**

6.1 Background Longitudinal Warning - This service detects when a vehicle in front is in close proximity to the subject vehicle and warns the driver. This is a variation of Service 1.1, *Frontal Warning for Vehicles,* where the warning is in the form of haptic cues that apply a bias to the driver's control inputs. The service judges the closing rate on the vehicle or obstacle in front and gives increasing haptic cues to the driver through gas pedal resistance as the possibility of collision increases. At any time, the driver can override the pedal resistance and is able to turn the service off.

BACKGROUND WARNING AND CONTROL IN MIXED TRAFFIC SERVICES

TABLE 11: SENSING FOR BACKGROUND WARNING AND CONTROL IN MIXED TRAFFIC SERVICES

	ON-VEHICLE SENSING						EQUIPPED LANE SENSING				
SERVICE NAME	frontal - veh. sep.	frontal - obstacles	side for vehicles	lane boundary	coeff. of friction	driver condtion	road condtion	obstacles	vehicle location	entry veh. (&destin?)	monitor if exit avail.
6.1 Background long. warn.	X	x (some)		x							
6.2 Background later. warn.				X							
6.3 Integrated background long. and lateral warning	X	x (some)		X							
6.4 Integ. bckgrnd. long. and lat. ctrl + collis. avoid	X	X	X	X							
6.5 Fully auto. backgrnd. in mixed, coop. veh. data	X	X (for mixed)	X	X	X	X	x (some)			yes-entering veh.	
6.6 Fully auto. backgrnd. in mixed, coop. infra. data	X	X (for mixed)	X	X	X	X	X	X	X	X	X

TABLE 12: CONTROL FOR BACKGROUND WARNING AND CONTROL IN MIXED TRAFFIC SERVICES

	VEHICLE CONTROL					CONTROL FROM LANE				
SERVICE NAME	drive train	brakes	steering	merge/ pass	Driver Override?	check-in of system	operating parameters	merge and pass	checkout to driver	Dedicated lane?
6.1 Background long. warn.	PT as needed	some?			yes	sv				
6.2 Backgrnd lateral warn.	x (some?)		FT		yes	sv				
6.3 Integrated background long. and lateral warning	PT as needed	some?	PT as needed		yes	sv				
6.4 Integ. bckgrnd. long. and lat. ctrl + collis. avoid	PT as needed	PT	PT		yes	sv				
6.5 Fully auto. backgrnd. in mixed, coop. veh. data	PT (when needed)	PT	PT		rqst after ctrl. taken	coop. with other veh	from coop. vehicles	with coop. vehicles	yes, after ctrl. taken	
6.6 Fully auto. backgrnd. in mixed, coop. infra. data	PT	PT	PT		rqst. after ctrl. taken	yes	yes	yes	yes, after ctrl. taken	

6.2 Background Lateral Warning - Sensors on the vehicle would detect the lane boundaries; when the driver approached the lane boundaries, the driver would receive a warning in the form of haptic cues that apply a bias to the driver's control inputs (i.e., pressure on the steering wheel); these warnings would encourage the driver to return to the lane center. If the driver is not actively engaged in steering the vehicle (e.g., his or her hands are not on the steering wheel) the service will not operate the vehicle. At any time, the driver can turn the service on or off. If the infrastructure did not have adequate lane markers, the service would simply not work.

6.3 Integrated Background Longitudinal and Lateral Warning - This service would operate in the background until it senses that the vehicle's operation is abnormal, such as drift out of the lane or rapid approach to the vehicle in front. The system would warn the driver in the form of haptic cues that apply a bias to the driver's control inputs. These warnings could increasingly warn the driver to take action as the event's seriousness increased, perhaps through firmer haptic feedback. The service would not work unless the driver was actively engaged in controlling the vehicle; and the service would not control the vehicle to prevent a crash. The driver can choose to turn the service off at any time.

6.4 Integrated Background Longitudinal and Lateral Warning with Temporary Emergency Control - This service would operate in the background until it determined that the vehicle's operation would lead to an incident (e.g., lane departure or running into the vehicle in front) unless there was a coordinated vehicle maneuver to bring the vehicle back into normal operating range. The system would use haptic cues initially, but gradually assume control of the vehicle as if giving guidance to the driver. The service would actuate the power train, brakes and/or steering to return to normal operating ranges. Additionally, if the situation developed to the point that a crash was likely, the system would temporarily assume control of the vehicle's steering, braking and power train and maneuver the vehicle to either avoid the crash or mitigate its seriousness. The driver would choose to turn the service off at any time, even during emergency maneuvers. One concern: if the driver falls asleep, would the system assume full control or continue to "herd" the vehicle along the lane? And once the system assumes control, how would the system return control to the driver?

6.5 Fully Automated Background Control in Mixed Traffic with Cooperative Vehicles - The level of AVC in this service is the same as in service 5.2, *Fully Automated in Mixed Traffic* service; however, the driver perceives that he/she is in control; the system intervenes to ensure that the driver does not make mistakes. The service would maintain full vigilance around the vehicle to prevent any possible incidents or crashes, and would monitor the driver and the vehicle's operation so that if errors are made or an incident seems to be developing, the vehicle would assume full control. Additional control data would be provided from cooperative nearby vehicles. If the system perceives that the driver is not controlling the vehicle (e.g., the driver is asleep), the system would continue operating the vehicle until such time as the driver could prove that he or she is capable of resuming control; alternatively, the service could park the vehicle at the roadside and signal for help. The system, not the driver, has responsibility for system operation. The driver could request that the system be turned off; the system would turn off when it determines that it is safe.

6.6 Fully Automated Background Control in Mixed Traffic with Cooperative Infrastructure - This service is the service described above, only the service would also receive control data from the infrastructure.

C.7. Continuous Partially Automated Control on Dedicated Lanes Services

The first five of these services are "driver-in-the-loop" services that provide continuous control of selected vehicle functions when the driver turns the services on; the driver can turn the services off at any time. With these five services, the driver moves the vehicle to the dedicated lane entrance; if accepted the driver steers onto the dedicated lane and turns on the services; the driver is encouraged to not turn the services off while on the dedicated lane. Vehicles equipped with background warning and/or control can operate on dedicated lanes; however, for purposes of this analysis, it is assumed that while on the dedicated lanes, the drivers would want to enjoy the full-time control of ACC and LK; so background warning and control services are not separately listed.

The service next service is an enhancement to the driver-in-the-loop services; as the driver is granted entry to the dedicated lane, the system temporarily assumes control of the vehicle's power train, brake and steering and, through communications with other vehicles or the infrastructure, moves the vehicle to an opening in the traffic flow on the dedicated lane. Since the service requires control of all vehicle functions plus communications, it would be a logical extension of services 7.3 or 7.4, *Integrated ACC and LK with Full CA with Information from Cooperative Vehicles and/or Infrastructure.*
(Tables 13 and 14)

7.1 ACC Only - This service is identical to ACC in mixed traffic. The driver would be able to turn the service on or off as desired; however, while on the dedicated lane, the driver would be strongly encouraged to leave the ACC on. Consequently, the vehicles in the lane would mostly be under ACC control except at entry and exit points where drivers would be directed to turn the service on (upon entry) or off (upon exit). In congested conditions, this would cause disruption in the traffic flow. The dedicated lane would significantly increase the safety of the vehicle's operation since the driver would not be concerned with manual drivers impinging from the side lanes; and it would increase the efficiency of the vehicle's operation since most of the other traffic on the lane is also automated, the traffic flow would be smoother and free from human-induced disruption. The speed of the traffic flow would be determined by the slowest driver in the lane. Enforcement of a policy to keep ACC on in the dedicated lane could be difficult without external indictors of the ACC status.

CONTINUOUS PARTIALLY AUTOMATED CONTROL ON DEDICATED LANES SERVICES

TABLE 13: SENSING FOR CONTINUOUS PARTIALLY AUTOMATED CONTROL ON DEDICATED LANES SERVICES

	ON-VEHICLE SENSING						EQUIPPED LANE SENSING					
SERVICE NAME	frontal - veh. sep.	frontal - obstacles	side for vehicles	lane boundary	coeff. of friction	driver condtion	road conition	obstacles	vehicle location	entry veh. (&destin?)	monitor if exit avail.
7.1 ACC only	X	x (some)		x							
7.2 Integrated ACC and LK	X	x (some)		X							
7.3 Integrated ACC, LK and frontal CA with coop. vehicle data	X (front veh brake data sent)	x (some-- brake data sent)		X							
7.4 Integrated ACC, LK and frontal CA with coop. infrastr. data	X	x (some)		X			maybe	x (added data sent)			
7.5 Integrated ACC, LK and frontal CA with coop.veh. data capable of oper. with fully auto.	X (tell others of operating status)	x (some)		X			X	X			
7.6 Merge capab. for integ. ACC, LK, CA, able to operate with fully auto.	X (comm. operating status)	X (for dedicated lane opn.)		X	X		X	X	X	X (maybe destin.)	maybe

CONTINUOUS PARTIALLY AUTOMATED CONTROL ON DEDICATED LANES SERVICES (CONTINUED)

TABLE 14: CONTROL FOR CONTINUOUS PARTIALLY AUTOMATED CONTROL ON DEDICATED LANES SERVICES

	VEHICLE CONTROL					CONTROL FROM LANE				
SERVICE NAME	**drive train**	**brakes**	**steering**	**merge/ pass**	**Driver Override?**	**check-in of system**	**operating parameters**	**merge and pass**	**checkout to driver**	**Dedicated lane?**
7.1 ACC only	**FT**	**some?**			**yes**	**self verify**				**yes**
7.2 Integrated ACC and LK	**FT**	**some?**	**FT**		**yes**	**sv**				**yes**
7.3 Integrated ACC, LK and frontal CA with coop. vehicle data	**FT**	**FT**	**FT**		**yes**	**yes (with other veh.)**	**yes (with other veh.)**			**yes**
7.4 Integrated ACC, LK and frontal CA with coop. infrastr. data	**FT**	**FT**	**FT**		**yes**	**yes (with infrastr.)**	**yes**			**yes**
7.5 Integrated ACC, LK and frontal CA with coop.veh. data capable of oper. with fully auto.	**FT**	**FT**	**FT**		**yes**	**yes (tell other vehicles of operation)**	**yes, with other vehic.**			**yes**
7.6 Merge capab. for integ. ACC, LK, CA, able to operate with fully auto.	**FT**	**FT**	**FT**	**yes**	**not during merge**	**yes (with infrastr.)**	**yes**	**yes**	**yes, after merge**	**yes**

7.2 Integrated ACC and LK - This would be the same as the combined ACC and LK service in mixed traffic, but on a lane dedicated to vehicles capable of partially and/or fully automated operation. The dedicated lane would significantly increase the safety of the vehicle's operation since the driver would not be concerned with manual drivers impinging from the side lanes; and it would increase the efficiency of the vehicle's operation since most of the other traffic on the lane is also automated, the traffic flow would be smoother and free from human-induced disruption. The enforceability of requiring drivers to conform to the "rules of the lane" by not switching into manual control is unknown; however, there would be manually operated vehicles at each entry and exit point--they would disrupt the smooth flow of the traffic. The driver would need to remain fully aware of the vehicle control and be prepared to respond to obstacles and/or other problems affecting traffic flow.

7.3 Integrated ACC and LK with Frontal CA with Cooperative Vehicles - In this service, vehicles with ACC, frontal collision avoidance and lane keeping would be allowed to operate on a highway lane dedicated to those vehicles. The collision avoidance capability would add an extra level of safety to the operation. The vehicles would have the ability to communicate among themselves to allow closer spacing and more efficient operation. The drivers would be advised, possibly through signing, of the recommended speed and spacing. The driver would be able to turn the integrated service on or off as desired, but would be encouraged not to do so; there would be manually operated vehicles at each entry and exit point. The driver would need to remain fully aware of the vehicle control and be prepared to respond to obstacles and/or other problems affecting traffic flow that the collision avoidance feature might not be able to respond to.

7.4 Integrated ACC and LK, Frontal CA with Cooperative Infrastructure - This service would add the ability to communicate with roadside beacons that would advise the drivers of recommended basic operating parameters such as safe speed and spacing, or potential problems ahead. This service would allow the operating parameters from the roadside to set values in the longitudinal control circuitry of the ACC in the vehicles; that is, the driver would choose to turn control over to the system, but when he/she does, the system would control speed and spacing until the system is turned off.

7.5 Integrated ACC, LK and Frontal CA Capable of Operating Mixed with Fully Automated on a Dedicated Lane - This service may add a capability over and above service 7.4, *Integrated ACC and LK with Full CA with Control Data from Cooperative Infrastructure*. The vehicle would be able to operate more effectively on a dedicated lane inter-mixed with fully automated vehicles. This added capability may be the ability to communicate to the nearby fully automated vehicles that (1) it is not fully automated so it has limited capabilities; and (2) it is in automatic or manual control mode.

7.6 Merge Capability for ACC, LK and Frontal CA Vehicles Capable of Operating Mixed with Fully Automated on a Dedicated Lane - This service is an enhancement to the service 7.5, *Integrated ACC, LK and Full CA Vehicles Capable of Operating Mixed with Fully Automated on a Dedicated Lane.* It would control the vehicle's steering, braking and power train during the critical stage of merging with the main flow of traffic on the dedicated traffic lane. It assumes that the dedicated lane is carrying vehicles whose longitudinal control logic receives control data from the roadside, and this could be used to open a slot for entering vehicles that would be under control of this service. This service would eliminate the manually operated vehicles near the entry and exit points that some of the services above would have. The combination of these services essentially constitutes a fully automated system in which the driver is able to turn the services on or off as desired; it is presumed that the driver would be highly discouraged from doing that, particularly in merge or in emergency situations.

C.8. Fully Automated Control on Dedicated Lanes

These services are driver-out-of-the-loop fully automated services on lanes dedicated to fully automated operation. The driver approaches the dedicated lane and, if the service is not already on (that is, if the vehicle has not already been operating as a fully automated vehicle in mixed traffic), requests the system to assume control and operate on the dedicated lane. The system fully operates the vehicle's merge and travel until the driver's destination is reached; at that point, the system moves the vehicle to an exit lane where control is returned to the driver after the driver has indicated an ability to assume control and when it is safe; alternatively, the system may continue operating the vehicle as fully automated in mixed traffic (either full time or background) if it has that capability. **(Tables 15 and 16)**

8.1 Fully Automated on Dedicated Lanes, No Vehicle or Infrastructure Cooperation - The system assumes control of the vehicle after the driver has indicated a desire to enter the system and the vehicle and driver are accepted by the system. Once the system has assumed control, the system will move the vehicle into the dedicated lane and will retain control until the vehicle reaches the driver's desired exit. The system will then move the vehicle into an exit area and verify that the driver is ready to assume control again; only then will the driver be allowed to resume control. With a few, infrequent exceptions (e.g., determined system intruder, or a total vehicle control failure where all vehicles are brought to a full stop), all vehicles on AHS will be automatically controlled at all times. because

8.2 Fully Automated on Dedicated Lanes with Cooperative Vehicles - The communications among the vehicles will allow the vehicles to operate more efficiently and more safely. The communications may also enable both automated merge and lane change maneuvers. The system has full operational responsibility.

FULLY AUTOMATED VEHICLE CONTROL ON DEDICATED LANES SERVICES

TABLE 15: SENSING FOR FULLY AUTOMATED VEHICLE CONTROL ON DEDICATED LANES SERVICES

	ON-VEHICLE SENSING						EQUIPPED LANE SENSING				
SERVICE NAME	frontal - veh. sep.	frontal - obstacles	side for vehicles	lane boundry	coeff. of friction	driver condtion	road conition	obstacles	vehicle location	entry veh. (&destin?)	monitor if exit avail.
8.1 Fully auto. with ctrl. data from coop. veh.	X	X (for ded. lane)	X	X	X	X					
8.2 Fully auto. with ctrl. data from coop. infrast.	X	X (for ded. lane)		X	X	X	X	X	X	X	X
8.3 Fully auto. with ctrl data capable of platooning	X	X (for ded. lane)		X	X	X	X	X	X	X	X
8.4 Fully auto. on ded. lane also capability of fully auto. in mixed traffic	X	XX (for mixed traf. opn	X	X	X	X	X	not neeeded	X	X	maybe

TABLE 16: CONTROL FOR FULLY AUTOMATED VEHICLE CONTROL ON DEDICATED LANES SERVICES

	VEHICLE CONTROL					CONTROL FROM LANE				
SERVICE NAME	drive train	brakes	steering	merge/ pass	Driver Override?	check-in of system	operating parameters	merge and pass	checkout to driver	Dedicated lane?
8.1 Fully auto. with ctrl. data from coop. veh.	FT	FT	FT	yes	requests	yes (with other veh.)	yes (with other veh.)	yes	yes (on vehicle)	yes
8.2 Fully auto. with ctrl. data from coop. infrast.	FT	FT	FT	yes	requests	yes	yes	yes	yes	yes
8.3 Fully auto. with ctrl data capable of platooning	FT	FT	FT	yes	requests	yes	yes	yes	yes	yes
8.4 Fully auto. on ded. lane also capability of fully auto. in mixed traffic	FT	FT	FT	yes	requests	yes	yes	yes	yes	yes, or in mixed

8.3 Fully Automated on Dedicated Lanes with Cooperative Infrastructure - This would be the same as service 8.1, *Fully Automated on Dedicated Lanes with Control Data from Cooperative Vehicles*, but with the added capability for the vehicles to communicate with the roadside for control information derived from roadside sensors and/or overall traffic conditions. The roadside communications could ensure safer operation and enable merge and lane change maneuvers.

8.4 Fully Automated on Dedicated Lanes with Cooperative Vehicles and Infrastructure, Capable of Platooning - In a congested situation, this service would allow groups of vehicles on the AHS lane to move closely together into platoons. In the platoon, the inter-vehicle spacing would be very close and the platoon would function as an operating unit. The spacing between the platoons would be large enough to ensure safe operation. This mode of operation would result in more efficient operation; in the case of an emergency stop, platooning would ensure safe, low-velocity collisions among the stopping vehicles. This is an operating variation on either of the two "fully automated on dedicated lane" services above. It is not assumed to be a variation of a service where the driver can resume control at any time; in a platoon operation, where operating tolerances are very close, the driver cannot be allowed to assume control.

8.5 Fully Automated Capable of Mixed Traffic Operation - These vehicles would operate as other fully automated vehicles while on the dedicated lane, but it will differ in the check-in and check-out precedures. When approaching the dedicated lane, the on-board vehicle controller would interact with the dedicated lane check-in process to ensure that the highway is capable of accepting the vehicle and that the vehicle and roadway systems are properly interacting. One of these vehicles could be rejected as well as accepted. When accepted, the vehicle's mode of operation would switch to dedicated lane operation from mixed mode operation. As one of these fully automated vehicle leaves the dedicated lane, the vehicle would revert to service 5.2, *Fully Automated in Mixed Traffic*. This switching from one mode of operation to the other would occur automatically. Similarly, as the vehicle approaches the dedicated AHS lane, the switch to dedicated lane operation would also be automatic and not require driver intervention.

D. EVALUATION OF THE AVC SERVICES

This section contains the initial strawman evaluations of the Automated Vehicle Control (AVC) services. There are six evaluation tables corresponding to the six AVC categories:

- **Table 17: Evaluation of Situation Warning in Mixed Traffic**
- **Table 18: Evaluation of Temporary Emergency Control in Mixed Traffic**
- **Table 19: Evaluation of Continuous Partial Control in Mixed Traffic**
- **Table 20: Evaluation of Integrated Emergency Control and Continuous Partial Control in Mixed Traffic**
- **Table 21: Evaluation of Fully Automated Control in Mixed Traffic**
- **Table 22: Evaluation of Background Warning and Control in Mixed Traffic**
- **Table 23: Evaluation of Continuous Partially Automated Control on Dedicated Lanes**
- **Table 24: Evaluation of Fully Automated Control on Dedicated Lanes**

Within the tables there are two major sets of evaluation factors--**Technical Feasibility** and **Benefits**. The evaluation factors were selected to provide a basis for making relative comparisons among the AVC services. **Costs** were not included at this time because of the difficulty of estimating relative service costs. The factors are described below.

1. Technical Feasibility

This evaluation category provides a relative assessment of the technical feasibility of each service. The metrics for this assessment are as follows:

- **Prototype** - What is the estimated time frame in which the service could be prototyped; that is, when can the primary technical elements of the service be designed and incorporated into a few, specially prepared vehicles and roadway for live demonstration of the major technical aspects of the service?
- **Operational Test** - What is the estimated time frame in which the service could first be offered in an operational field test environment to the public? This system would need to have all of the necessary safety elements included; however, its robustness, efficiency and cost may not be at the level needed for a fully operational, marketed system.

2. Benefits

The relative value of the services are compared using the categories described below. The metrics applied are subjective at this point. In each category, the relative benefit can be assessed on a scale of -5 to +5, where -5 is very bad, and +5 is the best that an AVC service can offer. The scale is relative to today's vehicle-highway system as well as to the other AVC services.

- **Safety** - This refers to the safety of an operational, equipped production line vehicle rather than the safety of the entire highway system since that is very dependent on penetration of the service into the driving environment. In all cases, it is assumed that if the service is offered, it would have an acceptable level of safety. Nevertheless, it is assumed that operation on a highway intermixed with manually driven vehicles is not as safe as operation on a dedicated (and protected) lane because of the unpredictability of the manual driving environment.
- **Throughput** - This refers to the effect that the vehicle's operation in automated mode will have on the highway system upon which it is operating. For example, fully automated operation in mixed traffic may actually slow overall throughput when penetration is low because of the cautious, safe nature of the automated operation--only when penetration becomes substantial would throughput increase if the vehicles can communicate. Thus, a range is shown. Similarly, it is assumed that communications among similarly equipped vehicles will allow more efficient operation.
- **Travel Time** - This refers to the speed that the AVC vehicle can travel relative to the non-automated vehicles. It does not account for the possible delays and congestion that might be encountered by drivers that attempt to access dedicated lanes since that is a locally-determined phenomenon and is, hence, unpredictable.
- **User Comfort** - This attempts to measure the driver's comfort and convenience in having the service. Full-time services such as ACC and Lane Keeping are viewed as having value to the driver; part-time emergency services such as frontal collision avoidance, while providing increased safety, are judged as not increasing user comfort.
- **Reduced Emissions and Fuel Consumption** - This assesses the relative likelihood that an AVC service will help reduce emissions and fuel consumption because of its operational characteristics. For example, studies have shown that continued operation of cruise control can reduce fuel consumption because of the smooth, jerk-free operation; and tests have shown that platooning can significantly reduce emissions and fuel consumption.
- **Relative Value to the Driver** - This is a judgment of the overall value to driver; it is estimated by combining safety, travel time and user comfort.
- **Relative Value to State DOTs** - This is a judgment of the overall value to the state agencies that must own and operate the highways. It is estimated by combining throughput primarily, but also safety and reduced emissions.
- **Relative Value to Society** - This is a judgment of the overall value to society. It is a combination of safety, reduced emissions and fuel consumption, and to a lesser degree, throughput.

TABLE 17: EVALUATION OF SITUATION WARNING IN MIXED TRAFFIC SERVICES

	Tech. Feasibility		Benefits							
SERVICE NAME	Prototype	Operation. test	Safety	Throughput	Travel time	User comfort	Reduced Emiss, fuel	Rel. Value, Driver	Rel. value, DOTs	Rel. value, Societal
Frontal warning, vehicle	1995	1996	+1	-	-	-	-	+1	-	+1
Frontal warning, obstac.	2000-2010	2010	+2	-	-	-	-	+1	-	+1
Side looking warning	1996-2000	2005	+1	-	-	-	-	+1	-	+1
Over-taking veh. warn.	2005	2010	+1	-	-	-	-	+1	-	+1
Lane departure warning	1996-2000	2005	+1	-	-	-	-	+1	-	+1
Coeffic. of frict. warn.	2000-2005	2005	+1	-	-	-	-	+1	-	+1
Coop vehicl. warnings	2000	2005	+1	-	-	-	-	+1	-	+1
Coop. infra. warning	1996-2005	2005	+1	-	-	-	-	+1	-	+1
Drowsy driver warn.	1997-2000	2005	+1	-	-	-	-	+1	-	+1
Veh. health mon. warn.	1996-2000	2005	-	-	-	-	-	+1	-	-

TABLE 18: EVALUATION OF TEMPORARY EMERGENCY CONTROL IN MIXED TRAFFIC SERVICES

	Tech. Feasibility		Benefits							
SERVICE NAME	Prototype	Operation test	Safety	Throughpt	Travel time	User comfort	Reduced Emiss, fuel	Rel. Value, Driver	Rel. value, DOTs	Rel. value, Societal
Skid avoidance	1993	1994	+1	-	-	-	-	+1	-	+1
Front veh CA-brake only	2000		+2	-	-	-	-	+2	-	+2
Front obs. avoid., brake	2010		+3	-	-	-	-	+3	-	+3
Side CA, blind spot	2010		+2	-	-	-	-	+2	-	+2
Overtaking vehic. CA	2015		+1	-	-	-	-	+1	-	+1
Lane depart. avoidance	2005		+2	-	-	-	-	+2	-	+2
Integ. front & side CA	2015		+3	-	-	-	-	+3	-	+3
Data from coop. vehicle	2000		+1	-	-	-	-	+1	-	+1
Data from coop. infra.	2000		+1	-	-	-	-	+1	-	+1
Drowsy driver mitigate	2020		+2	-	-	-	-	+2	-	+2

TABLE 19: EVALUATION OF CONTINUOUS PARTIAL CONTROL IN MIXED TRAFFIC SERVICES

	Tech. Feasibility		Benefits							
SERVICE NAME	Prototype	Operation. test	Safety	Throughpt	Travel time	User comfort	Reduced Emiss, fuel	Rel. Value, Driver	Rel. value, DOTs	Rel. value, Societal
Adaptive cruise (ACC)	today	1997	-	-	-	+1	-	+1	-	+1
Lane keeping (LK)	1997		+1	-	-	+1	-	+1	-	+1
Integrated ACC and LK	2000		+2	-	-	+2	-	+2	-	+2

TABLE 20: EVALUATION OF INTEGRATED EMERGENCY CONTROL AND CONTINUOUS PARTIAL CONTROL IN MIXED TRAFFIC SERVICES

	Tech. Feasibility		Benefits							
SERVICE NAME	Prototype	Operation test	Safety	Throughpt	Travel time	User comfort	Reduced Emiss, fuel	Rel. Value, Driver	Rel. value, DOTs	Rel. value, Societal
Integrated ACC and LK with frontal and side CA	2015-2020		+3	-	-	+1	-	+2	-	+1
Integr. ACC, LK, CA, ctrl data from coop. veh.	2015-2020		+3	-	-	+1	-	+2	-	+1
Integr. ACC, LK, CA, ctrl data from coop. infr.	2015-2020		+3	-	-	+1	-	+2	-	+1
Merge capab. for integrated ACC and LK	2020-2030		+1	-	-	+1	-	+1	-	+1
Full auto., drvr override	2020-2040		+3 to +4	-2 to +1	-2 to +1	+5	-	+2 to +3	-	+2

TABLE 21: EVALUATION OF FULLY AUTOMATED CONTROL IN MIXED TRAFFIC SERVICES

	Tech. Feasibility		Benefits							
SERVICE NAME	Prototype	Operation test	Safety	Throughpt	Travel time	User comfort	Reduced Emiss, fuel	Rel. Value, Driver	Rel. value, DOTs	Rel. value, Societal
Fully automated in mixed on protected cooper. lane	2000		+3	0 to +1	0 to +1	+3	+1	+3	+2	+2
Fully automated in mixed with no coop. data	2020-2040*		+3	-1 to 0	-2	+3	-	+1	-	+1
Fully auto. in mixed with data from coop. vehicle	2020-2040*		+4	-1 to +1	-1	+4	-	+3	-	+2
Fully auto. in mixed with data from coop. infrastr.	2020-2040*		+5	-1 to +1	0	+5	-	+4	-	+3

* Not determined at this point, but no sooner than 2020.

TABLE 22: EVALUATION OF BACKGROUND WARNING AND CONTROL IN MIXED TRAFFIC SERVICES

	Tech. Feasibility		Benefits							
SERVICE NAME	Prototype	Operation test	Safety	Throughpt	Travel time	User comfort	Reduced Emiss, fuel	Rel. Value, Driver	Rel. value, DOTs	Rel. value, Societal
Background long. warn.	1996	1997	+1	-	-	-	-	-	-	+1
Background later. warn.	1996	1997	+1	-	-	-	-	-	-	+1
Integrated background long. and lateral warn.	1998-2000		+2	-	-	-	-	+1	-	+2
Integrated background long. and lat. ctrl + CA	2020		+4	-	-	-	-	+2	-	+3
Fully auto. backgrnd. in mixed, coop. veh. data	2020-2040*		+5	-1 to +1	-1	+5	-	+2	-	+3
Fully auto. backgrnd. in mixed, coop. infra. data	2020-2040*		+5	-1 to +1	0	+5	-	+2	-	+3

TABLE 23: EVALUATION OF CONTINUOUS PARTIAL CONTROL ON DEDICATED LANES SERVICES

	Tech. Feasibility		Benefits							
SERVICE NAME	**Prototype**	**Operation test**	**Safety**	**Throughpt**	**Travel time**	**User comfort**	**Reduced Emiss, fuel**	**Rel. Value, Driver**	**Rel. value, DOTs**	**Rel. value, Societal**
ACC only	**today**	**1997**	**+1**	**-**	**-**	**+1**	**+2**	**+1**	**-2 to +1 (evolution)**	**-1 (Lexus lane)**
Integrated ACC and LK	**1997**		**+2**	**-**	**-**	**+2**	**+2**	**+2**	**-2 to +1**	**-1**
Integrated ACC, LK and frontal CA with coop. vehicle data	**2000**		**+4**	**+1**	**+1**	**+2**	**+2**	**+2**	**-2 to +1**	**+2**
Integrated ACC, LK and frontal CA with coop. infrastr. data	**2000**		**+4**	**+1**	**+1**	**+2**	**+2**	**+2**	**-2 to +1**	**+2**
Integrated ACC, LK and frontal CA with coop.veh. data capable of oper. with fully auto.	**2000**		**+4**	**+1**	**+1**	**+2**	**+2**	**+2**	**-2 to +1**	**+2**
Merge capab. for integ. ACC, LK, CA, able to operate with fully auto.	**2000**		**+4**	**+2**	**+2**	**+3**	**+1**	**+3**	**-1 to +1**	**+3**

NOTE: Evaluation Is only for operation while on dedicated lane with obstacle exclusion.

TABLE 24: EVALUATION OF FULLY AUTOMATED CONTROL ON DEDICATED LANES SERVICES

	Tech. Feasibility		Benefits							
SERVICE NAME	**Prototype**	**Operation test**	**Safety**	**Throughpt**	**Travel time**	**User comfort**	**Reduced Emiss, fuel**	**Rel. Value, Driver**	**Rel. value, DOTs**	**Rel. value, Societal**
Fully auto. on dedicated, no veh or infra. coop.	**2000**		+3	-	-	+5	+1	+3	+2	+2
Fully auto. with ctrl. data from coop. veh.	**2000**		+5	+3	+2 to +4	+5	+3	+5	+4	+4
Fully auto. with ctrl. data from coop. infrast.	**2000**		+5	+3 to +4	+2 to +4	+5	+3	+5	+4	+4
Fully auto. with ctrl data capable of platooning	**2000**		+5	+5	+2 to +5	+4	+5	+5	+5	+5
Fully auto. on ded. lane also capable of fully auto. in mixed traffic	**2020-2040**		+5	+3 to +4	+2 to +4	+5	+3	+5	+4	+4

NOTE: Evaluation Is only for operation while on dedicated lane with obstacle exclusion.

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Functional Evolution of an Automated Highway System for Incremental Deployment

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ABSTRACT

A combination of market forces, cost constraints, and other factors necessitate incremental evolution of a fully automated highway system (AHS) rather than instantaneous deployment. Thus, an understanding of the interdependencies among required AHS functional capabilities is essential for planning. This paper proposes a set of three AHS functional evolution reference models that include essential as well as supplemental functions. The reference models include lateral motion handling, longitudinal motion handling, obstacle handling, and selected infrastructure support functions. This family of three models is used to present the needs of baseline autonomous tactical vehicle operation, the benefits of adding inter-vehicle communications, and the benefits of adding infrastructure support. The reference models reveal a critical need for vehicle motion prediction capability, and suggest that both communications and infrastructure support are beneficial but not mandatory for achieving an AHS. Furthermore, there appear to be a number of safety and efficiency benefits that can be realized with only partial automation and in some cases no automation. These results could help set priorities and guide strategies for incremental introduction of AHS technology into vehicles and roadways.

Keywords: AHS functional evolution; incremental deployment

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INTRODUCTION

For many years, scientists and engineers have envisioned building an automated highway system (AHS) to increase both the safety and efficiency of the nation's highways. In such a system, the vehicles become driving robots, capable of sensing and reacting to the surrounding environment while the driver is free to do other tasks. Automating the vehicle has significant potential advantages: it can reduce accidents caused by driver error and can potentially increase traffic-carrying capacity and fuel economy by eliminating human driver inefficiencies. Automating the vehicle also presents difficulties: shifts in legal liability, issues of technical feasibility, and questions of political and social acceptance make the design of an AHS highly constrained, and often subject to heated debate.

There is not yet consensus on exactly what policies and configurations will be used in the operation of a fully deployed AHS. However, it is clear that an automated system will require a number of common functions such as the ability to stay in a traffic lane and to avoid collisions. Furthermore, a number of cost, technical, social, and customer constraints make it seem likely that any deployment of AHS will need to be an incremental one, as opposed to a fielding of a completely automated system from the beginning (*National Automated Highway System Consortium Stakeholder Workshop #3*, Minneapolis Minnesota, September 18-20, 1996, unpublished).

This paper addresses the technical evolution of the AHS by asking the following questions: what common functions are all automated vehicles required to have? and what are the evolutionary dependencies among these functions? The answers to these questions form a proposed family of three reference models for AHS evolutionary development. In this context, the reference models illustrate a reasonably straightforward way to implement the incremental introduction of technology into the vehicle-highway system. It is not necessarily the only possible way, but rather a general representation that encompasses essential issues. These reference models may be useful for both planning and for providing common ground for detailed discussions about technological dependencies and tradeoffs. These models do not include control policies (*e.g.*, whether vehicles follow each other at short distances in "platoons"), but rather focus on the common underlying technical functions (such as maintaining safe headway spacing among a group of vehicles).

PREVIOUS WORK

In order to deploy AHS capabilities, the uncertainties in the research and development of new technology must be managed well. Additionally, it is impractical to introduce fully automated vehicles on all highways instantaneously. Incremental deployment, then, is a significant issue, and several alternative strategies have been proposed. One strategy advocates the deployment of fully automated vehicles on dedicated lanes, but restricts the deployment to heavily used roadway segments equipped with special-purpose AHS guidance infrastructure.(*1*) Another strategy is to introduce AHS capabilities onto mass transit vehicles for use on existing High Occupancy Vehicle (HOV) lanes, subject to the supervision of a safety driver.(*2*) A third general strategy involves gradually increasing the degree of automation of new and refitted vehicles over time, with both AHS vehicles and manually driven vehicles sharing essentially all interstate highways.(*3*)(*4*)

This paper does not assume that any one of the above deployment strategies will be implemented. Rather, it presents the set of functions and sequencing constraints that are likely to be involved in deploying an AHS. Whichever deployment strategy is used, the system will need to contain some subset of the reference models' functionality to be considered a partial AHS. And, no matter the deployment strategy selected, substantially all of the functions will need to be implemented to achieve a complete AHS.

This paper begins by presenting the baseline functional evolution reference model of an autonomous robotic vehicle, assuming that inter-vehicle communications are not universally available. An expanded reference model is then presented that includes the use of inter-vehicle communications, and is used to illustrate functions that are enhanced or enabled for the first time. Finally, a fully elaborated reference model is presented that adds communications with roadside intelligence (highway infrastructure support), enhancing and enabling even more functions. These three reference models illustrate important technical dependencies, highlight the effects of communication and infrastructure support on the deployment of autonomous vehicle systems, and can be used as a roadmap for tracing the development and potential usage of the functions inherent to an AHS.

FUNCTIONAL EVOLUTION

The evolution of the AHS is broken into three diagrammatic reference models: vehicle automation, the addition of inter-vehicle communications, and the addition of infrastructure support. This is done to delineate the evolutionary linkages among functions beginning with the vehicle itself and then adding system-wide applications. This delineation does not suggest that complete vehicle automation must come before communications or infrastructure-based systems, but rather is used to separate development issues and clearly define how the addition of system-wide functions eases (and does not ease) the development of core vehicle systems.

Each of these reference models is further segregated by three functional categories: lateral motional handling, longitudinal motion handling, and obstacle handling. The last reference model adds a fourth category, infrastructure support, in which roadside-based assistance systems are presented. Note that these categories are deliberately chosen to separate technically relevant deployment functions. Lateral and longitudinal motion consider vehicle automation in each of these domains while also handling the effects of surrounding vehicles. Obstacle handling is separated from the core of the vehicle maneuvering functions because of the unique technical issues surrounding obstacle detection and vehicle response. Infrastructure assistance provides unique capabilities that are separate from the basic automation of the vehicle itself.

The three diagrammatic reference models also depict two important relationships: functional dependencies, and functional beneficiaries. In each of these diagrams, the presence of a solid arrow from one function to the next indicates a functional dependency, where the first function must be technically viable for the next function to be. (This is not to say that the first function must be marketable; this is a separate issue.) For example, lane departure warning cannot be achieved without first being able to detect the lane boundaries. A solid arrow therefore links the two functions.

A dashed arrow indicates a functional beneficiary, where the technical development of the first function provides some benefit to that of the second, however the viability of the first is not required for the second to work. For example, the technologies developed for vehicle and vehicle motion detection will likely speed the development of obstacle detection and relevance determination; the unique issues associated with obstacle handling require a separate development effort however, that is not directly linked to vehicle detection.

What is important to note is how these arrows change from one diagram to the next: the addition of communications and infrastructure-based systems alleviates the technical development of vehicle-based systems in some cases yet in others provides little benefit. This provides useful insight into where the larger AHS system can make the in-vehicle technology simpler, but more importantly delineates where it does not do so. This is an important point in the use of these diagrams as a decision-making tool for directing the development efforts of AHS-like systems.

Each of these diagrammatic reference models is presented with cognizance of time-to-market issues. Within the best judgment of the authors, those functions displayed further to the right on the diagrams are likely to be available after those depicted on the left. This is true both within each category and across categories.

Baseline Reference Model: Vehicle Automation

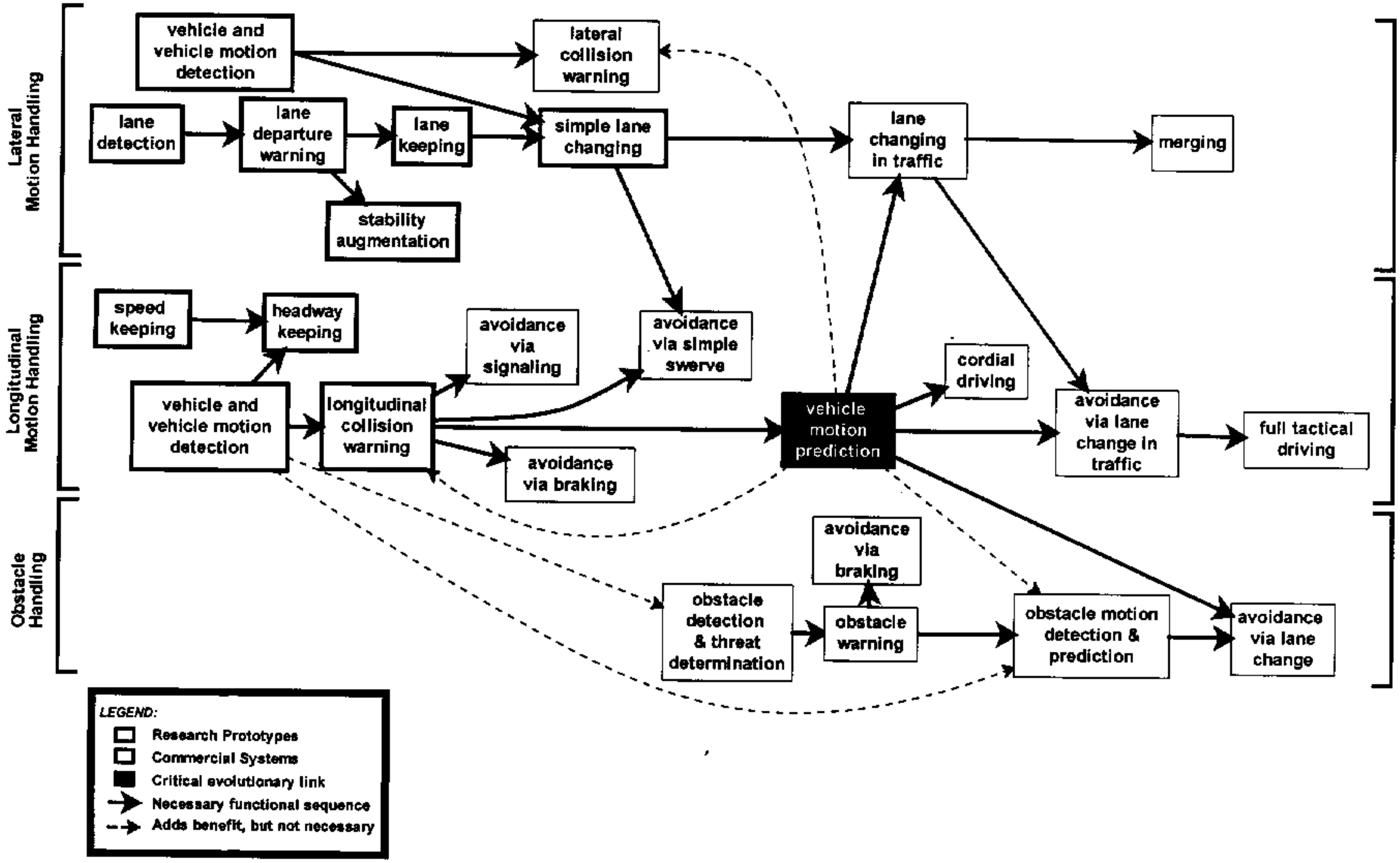
The baseline reference model presents the evolution of vehicle automation capabilities in terms of lateral motion handling, longitudinal motion handling, and obstacle handling. Within each of these categories, Figure 1 shows the key technical functions of an AHS and their dependencies. This diagram presents the core in-vehicle functions that rely neither on inter-vehicle communication nor on the infrastructure for any support in autonomous operations.

While there are clear sequences of functions within each category, there are also cross-functional dependencies that increase in complexity with proximity to the end-state of full tactical driving capability (*i.e.*, fully autonomous operation). The various functional capabilities and their relationships are discussed below.

Lateral Motion Handling

The lateral (side-to-side) motion of the vehicle has a number of different functions, from vehicle-centric maneuvers such as lane keeping to those involving merging in heavy traffic. First, if the vehicle is to stay within the lane, it needs to know where the lane boundaries are. **Lane detection** is currently achieved through

Figure 1: Baseline Autonomous Reference Model



a number of different technologies, including a vision system(*5*), magnetic nails buried in the roadway which are then sensed by the vehicle(*6*), or a radar-reflective stripe (unpublished work at Ohio State University). Regardless of the technology chosen, this basic function is required for the vehicle to begin automatic steering and lane changing.

With the advent of lane detection capability, the system can then detect where it is within the lane, leading to **lane departure warnings** when a vehicle strays out of the lane unintentionally. This is an attractive function to have available for incremental deployment as 31% of all highway fatalities are a result of single-vehicle, run-off-road accidents.(*7*) Marketable systems might be in the form of warnings which alert the driver when a lane change is attempted without prior activation of a turn signal, or might involve a driver-based model that adapts to the characteristic driving patterns of the driver.

Once a vehicle knows the lane boundaries and is able to determine its own position within the lane, **lane keeping** also becomes possible. Lane keeping is the ability of the vehicle to drive down the center of the lane, taking into account upcoming curves and the required pre-steering used to maneuver into them gracefully. A vision system(*5*) uses a preview area of the lane image for this purpose. Magnetic markers and radar reflective strips could encode upcoming curve information in the roadway, or rely on navigational position information and an electronic map in order to alter the vehicles' trajectories appropriately.

Simple lane changing is the ability of the vehicle to move smoothly out of one lane and into another in light traffic conditions. The technical requirements for such a system include side-looking sensors that detect a gap, and the ability to cross between adjacent lanes and begin lane keeping in the new lane. Such a system could be considered "simple" if it changes lanes only in the absence of nearby vehicles, thus being assured of no risk of collision during the lane changing operation. Simple lane changing requires elementary, side-looking vehicle detection. (**Vehicle and vehicle motion detection**, a precursor functional dependency, is discussed at length in the following section.)

Lane changing in traffic is a more complicated task. The vehicle must not only sense whether a suitable gap exists in traffic, but reason as to whether the gap will continue to exist throughout the maneuver execution. (This requires the use of vehicle motion prediction, a function discussed in the following section.) The vehicle will have to employ rear- and side-looking sensors to accurately detect and track vehicles in adjacent lanes, and tracking/prediction models to determine whether those vehicles have a closing rate that might reduce the gap space unacceptably or otherwise make the maneuver less safe. The vehicle must also be concerned with traffic two lanes over, as a vehicle from the far lane might also merge into the same gap while the vehicle is executing the maneuver, creating a risk of lateral collision.

Merging is a special case of lane changing in traffic in that the lane change must be executed within a fixed space. By the time the lane ends, the vehicle must successfully merge or come to a stop and wait for traffic to clear. This function requires the ability to change lanes in heavy traffic as well as satisfy the constraint of changing lanes within a fixed distance.

Other lateral motion handling functions that do not reside on this direct dependency path include lateral collision warning and stability augmentation. **Lateral collision warning** provides a way to warn of adjacent vehicles encroaching on lateral safety buffer space (for example, an adjacent vehicle that is attempting an inappropriate lane change, or has lost lane keeping ability). Lateral collision warning differs from lane departure warning: the former is concerned with other vehicles encroaching upon the automated vehicle's safety buffer space, while the latter is concerned with the vehicle departing from its own lane unexpectedly.

Stability augmentation is a function wherein the vehicle gently resists changing lanes when a turn signal is not used. The steering wheel resists the motion of the driver, making it feel as if the vehicle is driving with its wheels in ruts, helping keep the vehicle in its lane. This type of function might also prove useful in high crosswind situations, where the vehicle assists the driver in stabilizing a position within the center of the lane.

Longitudinal Motion Handling

The longitudinal (front-to-back) motion of the vehicle also has a variety of functions which range from simplistic in-vehicle handling to tactical driving within a congested traffic scene. **Speed keeping** is the most elementary function within this category, involving the maintenance of a constant travel speed. It is widely deployed in the form of "cruise control." **Headway keeping**, also known as adaptive cruise control, is a function which adapts the speed of the vehicle to match that of a lead vehicle while maintaining a safe distance. Headway keeping is currently being deployed on a limited scale in foreign markets.

Headway keeping, like all of the advanced functions in this category, depends upon reliable **vehicle detection & vehicle motion detection**. This is the ability to ascertain fundamental information about surrounding vehicles and their behavior. This capability will likely evolve from simple look-ahead functions to include look-behind and look-to-the-side as well. The term "look" is used loosely in this context, and refers to an ability to obtain information about surrounding areas in a particular direction. It does not mean to imply that vision-based systems must necessarily be used; indeed radar, ladar, and sonar systems may prove far more useful than vision systems, especially in reduced visibility situations such as rain and fog.

Given the ability to detect vehicle and vehicle motion, **longitudinal collision warning** becomes possible. This function will probably have two distinct sub-functions: forward- and rearward-looking warning. In the forward-looking case, the system warns the driver if the vehicle is closing too fast on a lead vehicle. In the rearward-looking case, it is concerned with whether a following vehicle is closing too fast. These warning functions, in and of themselves, rely on the driver to respond to the hazard. As technology develops, this capability can lead to several safety enhancements: avoidance via signaling, avoidance via hard braking, and avoidance via simple swerve. These three functions are not integral to the main deployment path, however they provide interim benefits until the time when more advanced automation functions are enabled. **Avoidance via hard braking** is where the vehicle brakes to avoid an accident with a lead vehicle or obstacle; **avoidance via simple swerve** is where the vehicle swerves into the shoulder or into a clear, adjacent lane; **avoidance via signaling** is where the vehicle sends a warning signal to a following vehicle. Avoidance via signaling may use rapidly flashing brake lights to gain the attention of the rear vehicle, or may employ communications as will be discussed later.

Vehicle motion prediction is the heart of advanced in-vehicle intelligence. This function, which is critical to the development of all high-level fully automated systems, predicts the traffic scene forward in time and will likely employ driver models, vehicle capability models, probabilistic analyses, and a fundamental understanding of driving "rules." Vehicle motion prediction enables the vehicle to determine the safest maneuver amongst the numerous available possibilities, and has the potential to predict an unsafe situation before it unfolds and can be sensed.

Notice that vehicle motion prediction is the only function which provides retroactive functionality to already-deployed capabilities. Both lateral and longitudinal collision warning can be significantly enhanced with additional in-vehicle intelligence. It is also clear that all higher-order fully automated systems depend on this capability in order to function. For this reason, vehicle motion prediction is identified as a critical link in the deployment of AHS and is shown in black in order to highlight its importance.

Cordial driving, the next step in maneuvering, is best described as driving which accommodates the desires of other vehicles in a friendly way. For example, if a vehicle is in a merge lane with its turn signal activated, manual drivers tend to (but do not always) give way so that vehicle can merge. Cordial driving by an automated or semi-automated vehicle can be enabled once the vehicle can discern the intentions of surrounding vehicles. In Figure 1, the assumption is that communications are not universally and dependably available; therefore, the vehicle must infer intention by vehicle location, vehicle motion, and vehicle signaling. (Signaling could be augmented with, for example, a radio transmission but such signaling is not assumed to be universally available.) This type of inference is, therefore, a large part of vehicle motion prediction.

Avoidance via lane change in traffic is a capability that enables the vehicle to change lanes given a hazardous situation, such as the sudden and unexpected slowdown of a preceding vehicle. This capability is a reasonable and attractive alternative to hard braking, as it may avoid secondary and tertiary accidents that could ensue when braking is used. In order to perform this function safely in traffic, the vehicle system must be acutely aware of the operating environment, and predict the behavior of surrounding vehicles with enough accuracy that the lane change can be done safely and efficiently. Note that lane changing in traffic, a lateral motion handling capability, must be supported in order for this function to be available.

Finally, **full tactical driving** is introduced. Tactical driving is the ultimate form of full automation within an individual vehicle. At this stage in the deployment process, the vehicle not only tracks and reacts to other vehicles, but also proactively plans out series of maneuvers which are executed to achieve a goal or goals. For example, if the vehicle (or the driver) desires to increase speed and the vehicle is "boxed in," the tactical capability of the vehicle will enable it to plan a way out of the box in order to achieve its goal with a combination of speed changes (including perhaps temporarily slowing down) and lane changes.

Obstacle Handling

Obstacle avoidance capabilities reduce or eliminate safety hazards caused by obstacles on the automated highway roadway. This includes rocks, vegetation, dropped vehicle parts, disabled vehicles, and animals such as deer.

One way to reduce the need for obstacle avoidance is to implement obstacle exclusion. To a limited degree this is already deployed with fencing and highway department maintenance of the interstate highway system. Obstacle exclusion can significantly reduce the frequency of obstacles on the roadway, but it seems implausible that any exclusion method can be 100% effective. Thus, more sophisticated forms of obstacle handling will be needed in most foreseeable end-state AHS implementations. Note that obstacle exclusion, as an infrastructure-based system, it is depicted on a later diagram that introduces infrastructure functionality.

Obstacle detection and threat determination is a much more difficult task than vehicle detection due to the technical difficulties of sensing obstacles and identifying whether those obstacles present a threat. A mylar toy balloon, for example, is easy to sense but would preferably not trigger a severe braking maneuver that could risk minor injury to vehicle occupants. On the other hand, deer present a much greater threat but are more difficult to sense and track. It seems likely that obstacle detection and threat determination will be available well after vehicle detection and collision avoidance functions are fielded. Notice that a dotted arrow links the two functions as there may be value to the research done for the detection of vehicles in the development of obstacle detection capability.

Given that obstacles can be detected and properly categorized, **simple obstacle warning** may be possible, whereby the driver is warned of hazards in and around the roadway. This function can provide obstacle information for the driver to use, or it could be coupled with the **avoidance via braking** capability. In that avoidance via braking was fielded previously as a longitudinal motion handling function, it is likely that it could be marketed as an obstacle avoidance function as soon as reliable warning systems are available. For this reason, the avoidance via braking box appears directly above the obstacle warning function box on Figure 1.

Obstacle motion detection & prediction may be a particularly difficult capability to develop. Unlike vehicles, which are physically constrained in realizable maneuvers, obstacles may not behave in readily predictable ways. Deer may run into the road and stop abruptly. Loose tires can bounce randomly, depending on road surface, tire wear, and angle of incidence. Mylar balloons, plastic bags, and tarps are at the whim of the wind and thermal pressures created by hot roadways. None of these are easy to quantify, and as such, create very difficult detection and prediction problems. Notice that vehicle motion detection and vehicle motion prediction might provide benefit to the development of this capability.

Assuming that obstacle motion prediction can be achieved, the vehicle can achieve **avoidance via lane change.** This becomes a unique capability that depends heavily on good prediction, not only of the motion of the obstacle, but also of how other vehicles will react to that obstacle.

Baseline Reference Model: Discussion

Figure 1 presents several important items. First, it delineates the evolution of functions within an automated vehicle system, beginning with warning functions and evolving into full vehicle control. The functional dependencies, denoted by solid arrows, identify the critical linkages between functions and clearly define which systems must be mature in order for further capability to be technically feasible.

A major finding in the process of identifying these linkages is the importance of vehicle motion prediction. This capability is critical to the successful implementation of all higher-order full automation functions including lateral, longitudinal, and obstacle handling tasks. It has the added distinction of providing recursive benefits to several already-deployed systems, notable in that no other function does this. The criticality of this link has not been previously appreciated in the development of AHS subsystems, with efforts generally concentrated in the development of sensors and actuators that manage the lower-level automation functions. This reference model serves to identify and highlight this function's importance.

Communications Reference Model

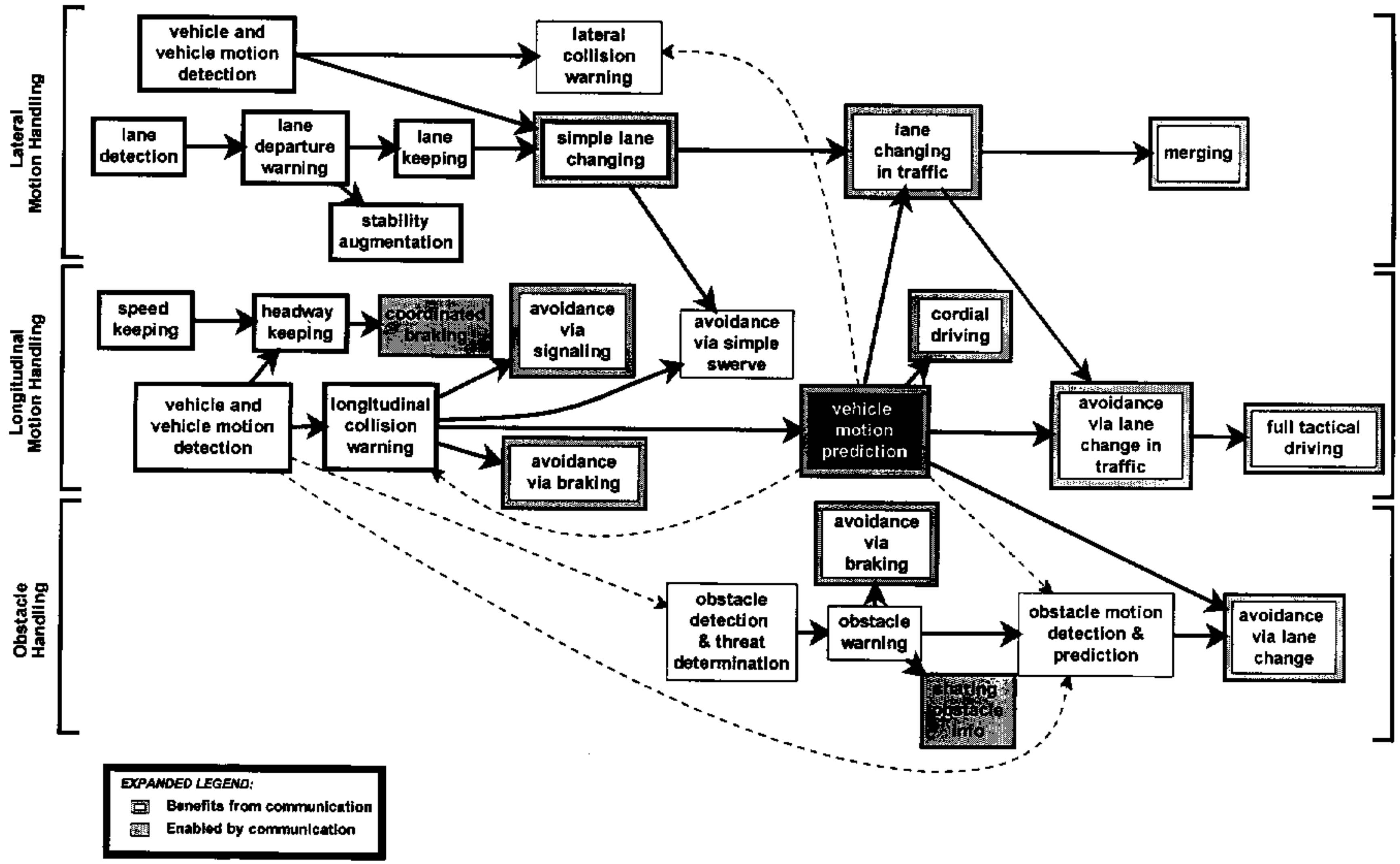
Figure 2 identifies changes to the functional evolution depicted in Figure 1 when inter-vehicle communication links are introduced. Perhaps the most striking thing about Figure 2 is that there are only two additional functions introduced, indicating that communications are not a necessary element to achieve fully automated tactical driving capabilities. On the other hand, there are many functions highlighted to indicate that they may significantly benefit from reliable inter-vehicle communications.

First, consider those existing functions from Figure 1 that benefit from communications being introduced. Numerous functions gain from having "pre-maneuver announcement information," which provides greater insight into the future motion of surrounding vehicles, and "inter-vehicle negotiations," which allow vehicles to gain assurances from surrounding vehicles. These existing functions are highlighted in Figure 2, and each of these will be discussed in turn.

Consider a **simple lane-changing** maneuver. With the addition of communications, a vehicle may "negotiate" with surrounding vehicles to gain assurances that the gap it senses will remain available throughout the maneuver. This may allow simple lane changing to occur in a heavy traffic situation where two adjacent lanes are moving at about the same speed, a significant increase in capability over lane changing in the absence of surrounding vehicles. Even in the case where vehicle-to-vehicle negotiations are not employed, knowing that a local vehicle is moving into a gap near to your vehicle provides additional information about the ever-changing traffic scene, and enables a vehicle to begin readjusting its headway in anticipation of the new situation.

Lane changing in traffic may also benefit from pre-maneuver announcements. If traffic in adjacent lanes is moving at significantly different speeds, communications enhance maneuver safety by providing intent

Figure 2: Baseline Autonomous Reference Model with Inter-vehicle Communication



information before the maneuver can be sensed, and are particularly useful when a maneuver may not be anticipated by the vehicle motion prediction models. So too, **merging** benefits from knowing a vehicle's exact intention, as opposed to presuming intention. Vehicles that communicate can send assurances that a gap will be maintained, or even created, so that other vehicles can merge into the mainline traffic stream.

A number of longitudinal motion functions also benefit from the introduction of communications. If following vehicles can respond based on the knowledge that a lead vehicle is about to respond to an incident, safety margins are increased over the situation where the vehicle must first sense the incident before responding to it. **Avoidance via hard braking, avoidance via lane change,** and **avoidance via shoulder swerve** can improve system safety by announcing maneuvers before executing them, providing a small but possibly significant amount of additional time for the surrounding vehicles to proactively respond. Additionally, swerving and lane changing information enables surrounding vehicles to respond proactively and create a gap, as opposed to reactively, in a variety of situations. In the **avoidance via signaling** case, a trailing vehicle may be provided with information that the closing rate is too high, or a vehicle that wants to pass might signal its desire for a leading vehicle move out of the lane.

Communications can also provide more detailed and timely information to the **vehicle motion prediction** algorithm. The less that this function has to extract intention, the more appropriate and faster the responses can be. If intent of other vehicles is well known, **cordial driving**, **avoidance via lane change in traffic,** and **full tactical driving** are all simplified.

In addition to existing functions benefiting from the addition of communication, two new functions emerge. Prior to this point, the sharing of braking information has been promoted as a way to provide faster reaction times in emergency situations. **Coordinated braking** might use communications to provide smoother headway keeping in non-emergency situations, such as stop-and-go or slow-and-go traffic. In some AHS alternatives, coordinated braking could be used to permit reduced headway and thus denser traffic; but such uses would require an extremely reliable communications system to avoid collisions in emergency situations.

Shared obstacle information might also provide tangible safety benefits, even to manually driven vehicles. A lead vehicle that detects an obstacle might accurately pinpoint its position and transmit that information to the following vehicles. Without communications, a following vehicle might not have time to detect and respond to the obstacle, given that the lead vehicle may be blocking the line-of-site until it swerves out of the way.

Communication Reference Model: Discussion

As shown in Figure 2, the addition of inter-vehicle communications enhances a number of core, in-vehicle functions and enables several new functions. These enhancements and additions, over time, will provide increasingly greater system-wide effects as more vehicles acquire communications capabilities and are able to share information. Two factors influence this reality: the evolutionary nature of these technology-based systems, and the long life span of automobiles. In that a mixture of automation and communication capabilities will be found on any given roadway due to a mixed-aged vehicle fleet, all vehicles must be built to handle all other vehicle types and ages. This is why none of the dependency arrows in Figure 2 change from those presented in Figure 1. The addition of vehicle-to-vehicle communications enables refined estimations of the upcoming traffic situation, however the expected presence of non-communicating vehicles in traffic precludes using communication to alleviate the core in-vehicle requirements.

In addition to the effects and requirements of an evolutionary deployment scheme, there is an additional and important caution about considering an AHS that relies upon communications. The obvious communications medium is radio, but radio has a number of potential reliability problems including correct and timely frequency allocation among multiple proximate vehicles; interference from other sources such as commercial radio transmitters, illegally boosted citizen band radio transmitters, military transmitters or malicious jamming; and interference from natural sources such as lightning strikes. Because of these issues it would not be prudent to rely upon radio communications in a safety-critical role unless reliability is demonstrated across a wide range of environmental conditions or a cost-effective alternative to radio communications can be found. Instead, communications should be treated as information to optimize performance of an AHS, not as a part of safety-critical control loops.

Even if inter-vehicle communications are deemed to be not wide-spread or reliable enough for safety-critical functions, the use of communications when available has the potential to increase both individual and global system safety by providing an additional source of detailed information.

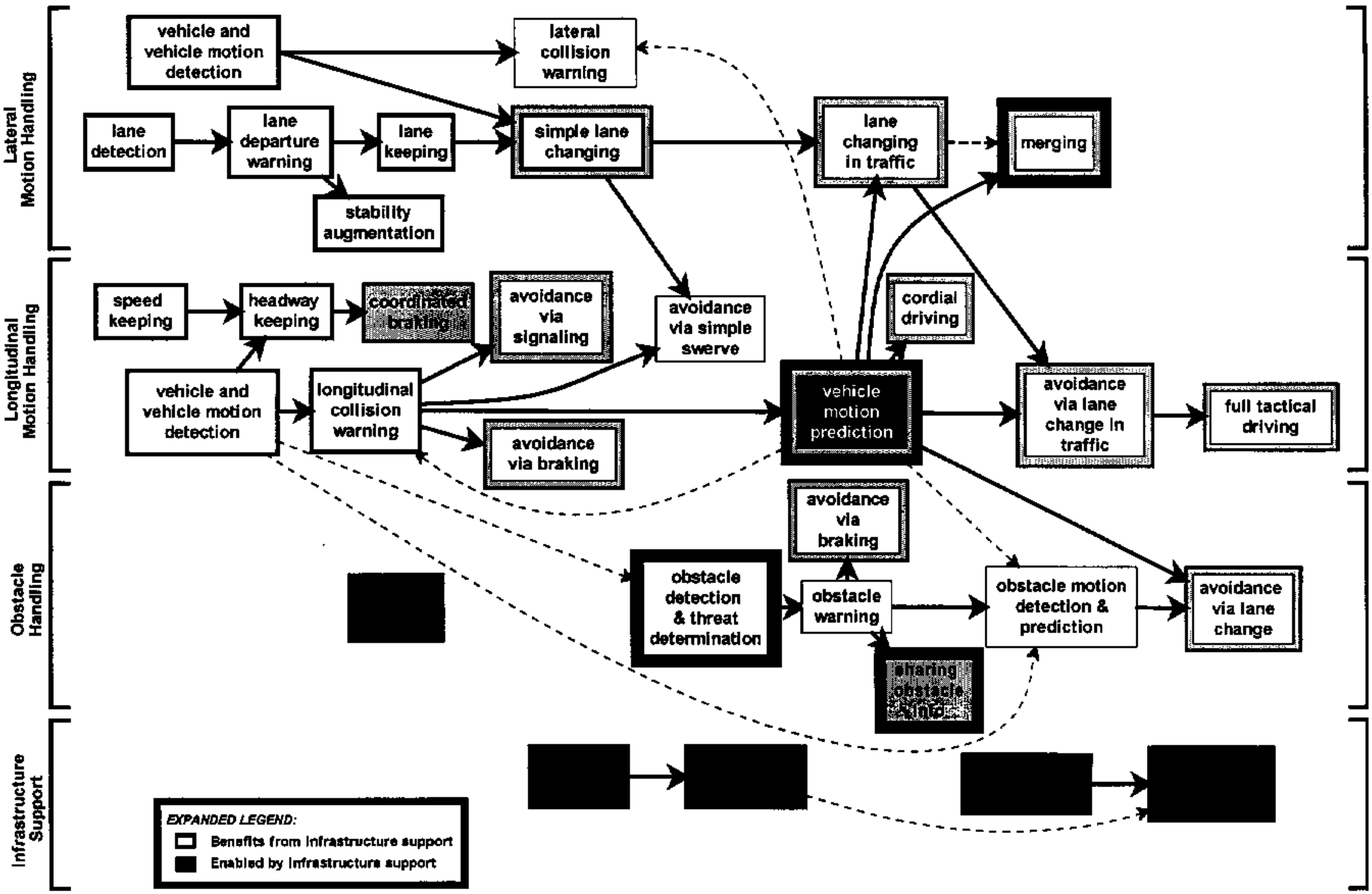
Infrastructure Assistance Reference Model

Figure 3 identifies how infrastructure-based capabilities might affect the vehicle evolution. Five new functional boxes are added, and four existing functional boxes from Figure 2 are highlighted to indicate that they either benefit from infrastructure support or could be used in a roadside-based application.

The four existing functions which can benefit by or be adapted for use in the infrastructure are merging, vehicle motion prediction, obstacle detection and relevance determination, and shared obstacle information. The **merging** function may benefit from having infrastructure sensors providing gap information, especially on blind merges where the vehicle's own sensors may be limited. Although current highway designs avoid blind merges, many older highways have extremely difficult merge points that are the cause of both congestion and safety problems. Infrastructure-based merge assistance will require infrastructure-based **vehicle motion prediction** capability in order to provide appropriate gap information to equipped vehicles. This will not obviate the need for vehicle-based vehicle motion prediction, but will use the developed capability in an additional capacity.

Obstacle detection and relevance determination, as an infrastructure-based system, can either complement or completely replace vehicle-based systems. Reasonable arguments can be made for either

Figure 3: Baseline Autonomous Reference Model with Infrastructure Support



alternative: infrastructure-based systems can be upgraded more readily as new technology becomes available; vehicle-based systems are applicable and improve safety on all roadways. It is likely that obstacle detection will have a place in both infrastructure- and vehicle-based systems, given the safety benefits to be gained by its implementation.

Sharing obstacle information can also have widespread benefit by sending obstacle information to the infrastructure and maintenance personnel in addition to surrounding vehicles. With this capability, every equipped vehicle becomes a scout, providing information about hazardous situations and relaying that information to the infrastructure for quick removal and to surrounding vehicles for early warning. This capability also improves safety in light density traffic, where vehicle-to-vehicle communication may not occur because of large gaps in the traffic stream.

Five new functions also are enabled by the addition of infrastructure-based intelligence. As mentioned previously, **obstacle exclusion** may obviate the need for obstacle avoidance capability within the vehicle by preventing obstacles from being on the roadway in the first place. For a policy of exclusion to be effective, all vehicles would need to be inspected for loose loads and vehicle parts and made reliable enough that they would not suffer failure. As this seems improbable to an effective enough level of safety, obstacle exclusion is posed as a measure to reduce the occurrence of obstacles that is coupled with additional obstacle handling functions.

Real-time **traffic advisories**, which are communicated to the vehicles by the roadside, can aid the vehicle and driver in determining an appropriate route given existing and historical traffic data. In this system, the driver and/or the vehicle decides the route given the information presented. **Route optimization** involves a more organized effort, where the driver provides his origin, destination, and desired arrival time to the infrastructure, which in turn provides the optimal route to the driver and vehicle.

Lane use optimization is a fourth infrastructure-based system. This allows the infrastructure to determine the fastest moving lane, aggregated over many miles, and dynamically assign vehicles to move into that lane to even out traffic flow. Even more intricate is **system-wide traffic flow optimization**, which dynamically assigns routes and lane choices in an effort to maximize the system throughput given the current system-wide demand.

Infrastructure Support Reference Model: Discussion

The introduction of infrastructure support provides a number of system-wide benefits that cannot be achieved with in-vehicle intelligence alone. Most notably flow and route optimization can only be handled with coordination between vehicles and the infrastructure. Additionally, merging, obstacle detection, and the sharing of obstacle information can be improved with the addition of infrastructure-based systems.

Notice that the introduction of infrastructure-based systems changes the dependency arrows into the merging function. Merging becomes a beneficiary to lane changing in traffic without being dependent upon it for implementation; the arrow between the two functions is changed to a dashed arrow to reflect this. A new dependency arrow is drawn from vehicle motion prediction, as an infrastructure-based system, to the merging function. In that automated merging may actually become available sooner with infrastructure support than would have been possible with vehicle-based systems alone, this function is moved leftward on Figure 3 relative to Figures 1 and 2.

DISCUSSION

These three-staged reference models are oriented toward evolving in-vehicle systems from warning to vehicle control with an appreciation for the effects of inter-vehicle communication and infrastructure-based assistance. There is a risk in presenting these systems with the "ultimate end-state" of full automation on highways presumed: the real goal of this work is roadway safety and efficiency. While these models provide insight into the elements of evolutionary deployment of AHS, there appear to be additional potential for safety and efficiency gains without the use of automation.

Note in Figure 3 that all of the route and system optimization functions are independent of vehicle automation. It is possible that the existing highway system might be improved with the development of infrastructure-exclusive systems coupled with a simplistic infrastructure-to-vehicle communication system and a willing driver. Merging assistance, for example, could be provided to the driver with advice on when to accelerate into traffic at difficult entrance points with limited visibility.

Likewise, inter-vehicle communication is a mechanism that has not been considered without being coupled to vehicle automation functions. Maneuver signaling information, shared between vehicles, could be presented in a head-up display format for drivers with limited peripheral vision. A non-freeway application might employ an infrastructure-to-vehicle communication link that presents real-time stoplight information in an easily visible location for these impaired yet licensed drivers.

CONCLUSIONS

Three successively more comprehensive reference models have been presented to depict how an AHS might evolve using incremental introduction of functionality. These models indicate precedence constraints on the introduction of capabilities and depict how the introduction of inter-vehicle communication and infrastructure support can increase the efficacy of an AHS. The models also demonstrate that addition of additional capabilities in most cases does not supplant previously introduced in-vehicle functionality.

A significant result of developing these reference models is the discovery that vehicle motion prediction capability is critical to the development and implementation of all higher-order automation functions. Most AHS analyses to date have emphasized a need to improve sensors and actuators; the results presented here suggest that effort must also be applied to the development of prediction algorithms for use in both vehicles and infrastructure support functions.

The first reference model suggests that full tactical driving capability requires neither inter-vehicle communication nor roadside-to-vehicle communication. However, if robust communication mechanisms can be provided, communications might be used to significantly improve the quality of maneuvering and collision avoidance capabilities.

With the exception of merging, adding communication capabilities does not obviate the need for any vehicle-based functions when these vehicles are incrementally introduced onto an existing roadway system. The presence of non-AHS-equipped and older-but-equipped vehicles in an incremental deployment scheme necessitates the development of in-vehicle systems that can function effectively without relying on communication.

Even though an end-state of full automation is desirable, the reality is that an incremental deployment will be necessary. As shown by the reference models, there appear to be a number of obtainable safety and efficiency benefits at intermediate deployment points utilizing partial automation and in some cases no automation. Using these models as a roadmap may help plan evolutionary approaches to creating an AHS that satisfy both technical constraints and a need to provide value before fully automated operation is achieved.

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This paper has been accepted for publication in an ITS Special Edition Journal on AHS Risk Management (publication in early 1998). It is included here as a report to the sponsors of this research.

10.3.11 Orthogonal Capability Building Blocks for Flexible AHS Deployment

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ABSTRACT

Once a baseline level of full automation is possible for an Automated Highway System, there are numerous choices to be made in deploying enhanced capabilities to improve safety, throughput, and travel time. Identifying a set of orthogonal capabilities enables describing multiple deployment paths within a common framework. Sixteen AHS configurations can be formed from a proposed set of orthogonal capabilities including: number of vehicles grouped into an entity (free agent vs. platoon), number of automated lanes (single or multiple), obstacle strategy (exclusion or detection), and system vigilance (trusting or vigilant). Given these capabilities, this systematic approach reveals a maximally enhanced end-state configuration: a platooned, multi-lane, obstacle detecting, vigilant AHS that could be attained using any of 24 incremental deployment paths. A mapping technique is presented that can assist in risk management by depicting alternative deployment paths and constraints within a single framework.

KEY WORDS

incremental AHS deployment, orthogonal building blocks

INTRODUCTION

Reaping the full benefits of an Automated Highway System (AHS) involves a carefully orchestrated deployment of various features to achieve improvements in safety, travel time, and highway throughput. Organizing potential feature upgrades into distinct building blocks (*capabilities*) may aid in understanding and planning the possible alternative deployment paths. This paper proposes four such capability building blocks: the number of vehicles grouped into an entity (free agent vs. platoon), number of automated lanes (single or multiple), obstacle strategy (exclusion or detection), and system vigilance (trusting or vigilant). A mapping technique depicts deployment paths involving these four capabilities.

The issues discussed here involve deploying key capability enhancements starting with a minimal but fully-automated highway system. An early definition for an Automated Highway System (AHS) was a user service that provides fully automated vehicle control on dedicated highway lanes in a manner that is compatible with and evolvable from the present highway system. [Stevens *et al.*, 1996, pg. 44] The "fully automated" portion of this definition refers to so-called "hands-off, feet-off" operation of a vehicle, meaning that the vehicle itself controls the throttle, brake, and steering. More recently, the National Automated Highway System Consortium (NAHSC) has expanded this vision of an AHS to also consider lanes that serve both automated and manually operated vehicles. [NAHSC, 1996, chapter 7] Partially automated systems (*e.g.*, lateral-only or longitudinal-only automated control) seem to be likely stepping stones to an eventual fully automated AHS configuration. [Stevens, 1997a] This paper, however, is concerned with AHS deployment at and beyond the crucial stage in which vehicle occupants are freed from the driving task.

A *baseline* level of automation is defined for current purposes as the ability to perform lateral control (*i.e.*, lane-keeping within a particular travel lane), perform longitudinal control (*i.e.*, maintaining a safe operating speed and avoiding crashes into preceding vehicles), and provide a way to minimize encounters with hazards such as roadway obstacles. Single vehicle lane-keeping has been demonstrated on existing conventional highways in a variety of roadway and environmental conditions, [Pomerleau *et al.*, 1996] as well as on highways modified to provide infrastructure assistance. [Shladover, 1992] Speed-keeping applications have long been available in the form of cruise control, and will serve as the foundation for more advanced systems that regulate vehicle separation distance. Although technical challenges remain in developing these baseline functions, the risks associated with providing baseline automation seem small within the development framework of an entire AHS.

There are several opportunities for deploying enhancements beyond baseline AHS functionality. Vehicles could coordinate maneuvers and spacing in order to facilitate lane changing, merging, and optimizing traffic throughput. Additionally, vehicles could automatically react to hazardous conditions such as obstacles on the roadway or unexpected behavior from nearby manually driven vehicles. But, there is no clear consensus on a deployment path for these advanced AHS functions.

Planning for deploying enhanced AHS capabilities involves accounting for uncertainties in the research and development of new technology. Furthermore, it is impractical to instantaneously introduce full automation into all vehicles operating on all highways. In response to these difficulties, several alternative strategies have been proposed for the incremental deployment of an AHS. One strategy is initially to deploy fully automated vehicles on dedicated lanes, but only on certain heavily-used roadway segments equipped with special-purpose AHS guidance infrastructure. [Shladover, 1991] Another strategy introduces AHS capabilities onto mass transit vehicles for use on existing High Occupancy Vehicle (HOV) lanes, at least initially subject to the supervision of a safety driver. [Tsao, 1995a] A third general strategy involves gradually increasing the degree of automation of new and refitted vehicles over time, with both AHS vehicles and manually driven vehicles sharing essentially all interstate highways. [Bayouth *et al.*, 1996][Ward, 1997]

Each strategy for incremental deployment has both strengths and weaknesses that should be discussed in terms of a common framework. This paper presents such a common framework based on four key AHS capabilities. The following sections discuss previous work, describe the four capabilities, and present a mapping tool for representing deployment paths. Additionally, examples are provided for using the deployment map to describe alternative deployment strategies, depict deployment constraints, and illustrate a deployment contingency option.

PREVIOUS WORK

The NAHSC is sponsoring ongoing technical and architectural development of an AHS. The first phase of the current effort examined a number of potential end-state AHS architectures and identified the strengths and weaknesses of each. [NAHSC, 1996] As a result, two main conceptual candidates emerged from many possible end-state AHS configurations considered:

"Dedicated Lanes," in which platoons of closely-spaced vehicles operate in AHS-only lanes that have strictly controlled admittance so as to exclude manual vehicles as well as potential obstacles. This concept could provide high throughput and reduced control system complexity by operating in a well-regulated roadway environment. However, there are unresolved issues with respect to achieving a viable critical mass of deployed roadway and vehicle upgrades [Ward 1997], technology and human factors in deploying platoons [Shladover, 1997], and the practicability of excluding all obstacles as well as manually driven vehicles from AHS roadways.

"Mixed Traffic," in which autonomous vehicles commingle with manually operated vehicles on largely unmodified existing roadways. This concept has the advantage of being applicable to most existing roadways. However, there are concerns about the difficulty of creating an automated system that can cope with potential roadway obstacles as well as manually operated vehicles driven in an aggressive or erratic manner.

In order to better understand underlying issues, the NAHSC selected several "concept attributes" grouped into five categories for further study [NAHSC, 1996]: complete automation only in dedicated lanes or mixed with manual traffic; driver roles; distribution of intelligence and separation policy; obstacle management; and deployment sequence. While useful for managing the study of various issues, these categories were not completely orthogonal (*e.g.*, dedicated lanes presumed high density traffic, which significantly limited possible driver roles). The sixteen activity areas for the AHS Precursor Systems Analyses [Stevens *et al.*, 1996] also provided a breakdown of AHS concerns, but were not entirely suitable for use as deployment building blocks for similar reasons.

Tsao describes a single evolutionary deployment path in detail, including both technical and non-technical factors. [Tsao, 1995b] The framework presented here fulfills a different role, identifying twenty-four alternative deployment paths based on differing sequences of capability enhancement introductions, with sixteen distinct end-state AHS possibilities. Furthermore, it provides a way to manage risk by illustrating alternatives available when scheduled capability enhancements are delayed or available sooner than anticipated. Thus, once a particular end-state and deployment sequence is chosen, it is possible to represent and study contingency strategies in advance. This may help reduce AHS deployment risk if there is a delay in the development of technology for implementing some key capability.

ORTHOGONAL CAPABILITIES

Four key AHS capabilities have been specifically selected for orthogonality. A set of capabilities is considered *orthogonal* if either the baseline or enhanced capability can be deployed regardless of whether other capabilities have been enhanced. This use of orthogonality is not to say that blends of capability enhancements may not occur; indeed, they can and likely will as phased introduction of cost-optimized vehicles supports elements of different enhancements. What is crucial is that each could be deployed independently if desired, and that such deployment does not create a technical necessity for enhancing other capabilities.

The proposed orthogonal capabilities are:

The **entity size:** either autonomous "free agents", or multi-vehicle "platoons"

The **number of automated lanes** which automated traffic can exploit using lane change maneuvers: either a single lane, or multiple lanes

Obstacle strategy: either obstacle exclusion, or obstacle avoidance

The amount of **system vigilance** required for unexpected vehicle actions: either none, or complete

The baseline AHS capabilities are: free agents, single automated lane, obstacle exclusion, and no vigilance. This selection was made because, as will be discussed, these are subsets of enhanced capabilities. "Enhanced" capabilities are platooning, multiple adjacent lanes, obstacle avoidance in addition to obstacle exclusion, and complete vigilance. While a binary approach (either "baseline" or "enhanced") is used in describing these capabilities, it is likely that real deployment situations will not be as clear-cut. Nonetheless, there is significant benefit in presenting clearly defined cases to permit concise comparisons of alternatives.

The approach used can be extended to encompass additional orthogonal key capabilities as they may be identified and understood by the research community (*e.g.*, approaches to improving reliability, approaches to stabilize traffic flow for optimum efficiency). While there are other important design issues to be considered in developing an AHS (*e.g.*, safely engaging and disengaging automated control, reacting to weather conditions), those issues do not seem to be orthogonal to other issues, and instead have approaches that depend at least in part by the four key capabilities discussed herein. The following sections detail the baseline and enhanced states of each capability.

Entity Size

A *free agent* is a single vehicle that maintains relatively large inter-vehicle spacing (perhaps 20 meters at highway speed). Because of the large spacing, a free agent need not have tight coupling of control algorithms with other vehicles. Electronic communication among free agents is not required to avoid collisions, although it might be used to increase efficiency. [Ren *et al.*, 1994]

In contrast, a *platoon* is a set of two or more vehicles having small inter-vehicle spacing (on the order of a meter), [Shladover, 1995] , and much larger inter-platoon spacing (perhaps 60 meters at highway speed [Varaiya, 1993]). Platoons may permit increased vehicle density in order to increase system throughput. [Kanaris *et al.*, 1997] Because of exacting control and inter-vehicle communication requirements, platoons will probably be composed entirely of automated vehicles. (The term platoon has in the past been used to encompass a free agent [Varaiya *et al.*, 1991], but that usage assumed even single vehicles would be platoon-capable, which need not be the case.)

A vehicular *entity* is defined as a grouping of vehicles of size one or larger that acts together as a coherent unit. The concept of an entity encompasses both a free agent and a platoon, and is applicable whenever the number of vehicles acting in tight concert is unimportant. (The term "entity" is introduced by [Kanaris *et al.*, 1997], and helps distinguish when entity size is important from when it is not.) Upon examination, it is apparent that in any given driving situation a platoon taken as a whole entity must have at least as much functionality as a free-agent entity. In particular:

Free agents, as an entity of size one, must be able to perform baseline AHS functionality including avoiding collisions with preceding entities.

Platoons, as entities of size two or greater, must be able (as a group) to provide baseline AHS functionality, but in addition must perform coordination to avoid collisions among vehicles within the platoon.

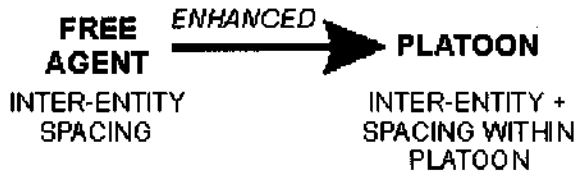


Figure 1. Platoons can only be implemented once Free Agents are possible, because a whole Platoon must encompass Free Agent functionally.

Thus, as shown in Figure 1, a platoon capability is an enhancement of a baseline free agent capability. Because it is simpler, free agent capability must necessarily precede, or be available simultaneously, with the enhancement of platoon capability. (Consider that even platoon-capable vehicles must be able to operate as a single-vehicle entity when they are on an otherwise empty roadway; commercial vehicles that are specifically dedicated to trailing other vehicles may be an exception.) Technical developments required to progress from free agent capability to platoon capability include precise automated longitudinal control, robust inter-vehicle communication, coordination algorithms to deal with joining and splitting vehicles, and coordinated emergency behavior. [Ioannou, 1997]

Number of Automated Lanes

A *dedicated* lane is one in which manually driven vehicles are excluded via mechanisms such as admission gates, barriers, and law enforcement sanctions. This is in contrast to *mixed traffic*, in which both manual and automatic vehicles must be able to coexist within the same lanes. It may be more difficult to design an automated system for mixed traffic than for dedicated lanes because of the complexities of performing lane changes in the presence of potentially uncooperative manual drivers. However, a more useful distinction for the purposes of defining orthogonal capabilities is not whether the lanes are dedicated to automated vehicles only, but rather whether an entity operates on a *single lane* only, or whether it can change among *multiple lanes*. (The issue of manual driver behavior is not presented as a separate capability building block, but rather is considered when defining this and other capabilities.)

Consider a *single* lane, in which vehicles enter automated operation either at a single entry gate or by being "turned on" by the driver once positioned in a particular lane. While more than one lane may be present, an automated vehicle does not change lanes. In this situation, it is sufficient for any particular entity operating on that single lane to simply lane-keep, maintain speed, and avoid colliding with the preceding entity (obstacle handling is orthogonal to single lane capabilities). Whether or not the entity in front of an automated entity is manually or automatically operated does not change the base functionality required, because even a preceding automated entity might need to perform a sudden stop, decelerate quickly as the result of a collision, or suffer breakdown. Lateral inter-vehicle collisions are impossible if lane barriers are provided. (If barriers are not used, collisions may occur if an automated vehicle experiences a failure or a human driver makes a mistake. But, in the worst case, the presence of manual drivers may increase, rather than solely determine, the chance of longitudinal collision.)

Now consider *multiple* lanes, in which automated vehicles are permitted to change among a set of adjacent lanes. Longitudinal spacing and speed control must be provided as in the single lane case. Additionally, the possibility of lane change maneuvers requires lateral sensing and possibly coordination (*e.g.*, via turn signals or electronic communication) to avoid lateral collisions and "cutting off" other vehicles. Dangerous lane changes or even collisions may take place due to equipment failures, environmental factors such as strong lateral wind gusts over an icy patch, inappropriate obstacle avoidance reactions, or manual driver aggressiveness. Similar to the single lane case, the presence of manual drivers might increase, but does not solely determine, the probability of a collision.

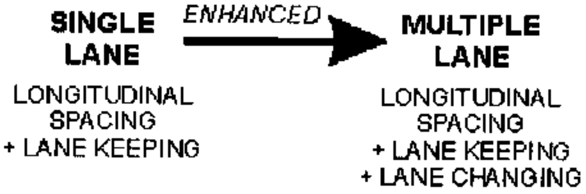


Figure 2. Multiple Lane capabilities can only be implemented once Single Lane capability is possible, because Multiple Lane capability adds lane changing onto Single Lane capability.

Figure 2 illustrates that baseline Single Lane operating capability is a subset of Multiple Lane capability, and must necessarily precede, or be provided simultaneously with, Multiple Lane capability in any deployment path. The presence of manual drivers is not a discriminator in terms of requiring a capability to safely perform lane changing operations and avoid lateral collisions; it changes the probability of an incident (and perhaps whether a particular system configuration is safe enough to be viable for deployment), but not whether an incident can occur. Technology development required to implement multiple lanes might include side- and rear-looking sensors as well as lane-changing algorithms that can anticipate and react to concurrent acceleration by multiple vehicles.

Obstacle Strategy

In order to achieve autonomous operation, entities must not collide with potential obstacles, including objects and disabled vehicles on the roadway. This goal can be achieved by either eliminating the possibility of obstacles being on the roadway, or avoiding collisions when obstacles are detected.

An *obstacle exclusion* capability attempts to eliminate all ways in which obstacles can gain access to or be deposited on the roadway. Ways of potentially performing exclusion include: use of physical barriers, inspection of vehicles for loose loads, requiring vehicles to be so reliable that they essentially never break down on the roadway, performing frequent debris removal, and stringent law enforcement activity. [NAHSC, 1996] While it is clear that no obstacle exclusion system can be perfect, the intent is to make incidents and accidents due to obstacles so rare as to be an acceptably low safety risk; whether that can be accomplished effectively enough to be viable remains uncertain. Civil infrastructure such as encaged roadways may exclude many obstacles and is straightforward to implement, if perhaps expensive. Eliminating hazards such as dropped vehicle components, animals that gain entry at vehicle access points, and sabotage may prove challenging.

In an *obstacle detection* strategy, the AHS detects obstacles so that entities may perform obstacle-avoidance maneuvers consisting of either braking, lane changing, or both. Examples of obstacles that may need to be detected include not only disabled vehicles and fallen rock, but also people, animals, fallen cargo, pavement buckles, sink holes, large potholes, blown-down highway signs, and possibly even washed-out bridges. Creating obstacle detection sophisticated enough to permit evading or removing animals and difficult-to-sense but dangerous objects while minimizing false alarms could prove difficult.

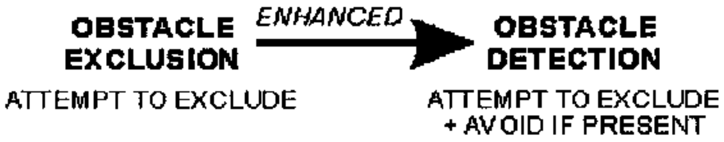


Figure 3. Some degree of obstacle exclusion is required in any system in order to achieve efficiency. An enhanced capability of obstacle detection augments obstacle exclusion.

Exclusion is designated as the baseline capability in Figure 3 for two reasons: it is already in place on limited access highways in a limited form (involving varying combinations of access restrictions, fencing, and state vehicle safety inspections), and it is necessary to minimize lane blockages and other traffic disruptions even with obstacle detection. Obstacle detection is an enhanced capability that may be necessary for a viable AHS if exclusion cannot yield a required level of safety at a low enough cost.

System Vigilance

The preceding discussion has argued that the only difference between mixed traffic and AHS-only traffic is that the rate of human driver errors is (presumably) more frequent than the rate of control failures for an affordable automated system. This higher error frequency could mean that potentially hazardous events would happen more often in a mixed traffic situation, but does not seem to fundamentally change the types of hazardous events that can occur and lead to collisions.

Inter-entity collisions can be avoided by either a policy of *trust* or *vigilance*. In a baseline *trusting* system, an entity must keep from running into the preceding entity. Trailing entities are trusted to do the same. Additionally, each entity must stay within its lane, and entities changing lanes within a multiple lane system are responsible for yielding to entities staying within a lane. This trust may be violated by equipment failure, environmental conditions, or human error. While a trusting system might well be at least as safe as current manual driving, it must be recognized that no system will be 100% dependable, nor will it be guaranteed free from abnormal environmental conditions. Therefore, no AHS can be 100% trustworthy in terms of freedom from aberrant vehicle behavior. However, some AHS configurations might be trustworthy enough to be considered acceptably safe.

In a *vigilant* system, an entity must not only attempt to prevent forward impacts, but is enhanced to take corrective action for potential rear impacts, because it does not trust the trailing entities. Similarly, it must attempt to evade lateral impacts because it does not trust neighboring entities in the absence of lane barriers.

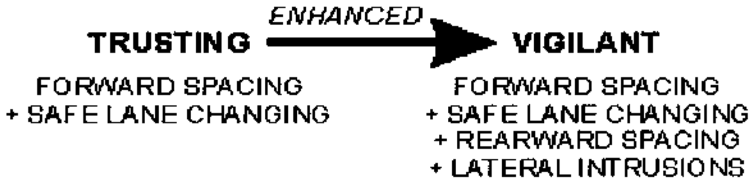


Figure 4. Vigilant capabilities can only be implemented once Trusting capabilities are in place.

As Figure 4 shows, vigilant systems must not only have the baseline capability of trusting systems to avoid colliding with other entities, but enhancements to evade being hit as well. Thus the problem of dealing with potentially erratic or aggressive manual driving errors is not whether manual vehicles are included in the system *per se*, but whether or not any particular entity can trust other entities with respect to unsafe behavior. (This distinction is important, because failed vehicle controls or environmental abnormalities can lead to a breach of trust, and would not be addressed if this area of concern were simply limited to the presence of manual drivers.) It is likely that an AHS will experience failure or environmental extremes on occasion, so the issue of whether a trusted system is safe enough must be based on the acceptable frequency of accidents from all sources, both man and machine. A vigilant system requires information about trailing as well as preceding entities, and control algorithms that detect and react to breaches of trust.

DEPLOYMENT MAP

Given that it is not currently possible to forecast when any given capability enhancement will be ready for deployment, it seems unlikely that all enhancements will be ready to deploy simultaneously. The first fully automated deployed system might be the baseline set of capabilities, which could be the simplest compared to a system requiring enhanced capabilities. But, an initial deployment might instead require a certain minimum set of capability enhancements to attain viability in the face of safety, social, and other constraints. Thereafter, other capability enhancements can be added as they become feasible, desirable, and cost-effective. The following discussion presents a map that concisely represents all incremental deployment paths involving the four capabilities discussed.

The actual AHS deployment sequence and desired end-state will be significantly influenced by political, market, environmental, legal, and economic factors. [Stevens, 1997b][Underwood, 1990] The deployment sequence framework presented here can be used to illustrate the limitations imposed by these non-technical constraints, and thus to represent both technical and non-technical constraints to deployment in a single graphical framework.

A Map for Enhanced Capability Deployment

In order to construct a deployment map, each capability is assigned a binary value, with a zero indicating that that element is in the simpler, baseline state, and a value of one indicating that the element is in the enhanced capability state. (The possibility of blended or partial technology availability is recognized, but binary representations are used herein for the sake of simplicity to facilitate understanding.)

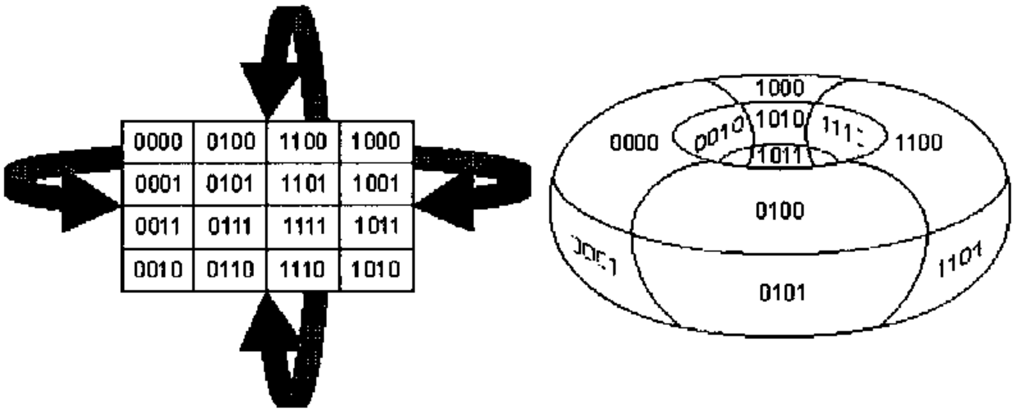
	0-BASELINE	1-ENHANCED
ENTITY SIZE	FREE AGENT	PLATOON
NUMBER OF AUTOMATED LANES	SINGLE LANE	MULTIPLE LANE
OBSTACLE STRATEGY	OBSTACLE EXCLUSION	OBSTACLE DETECTION
SYSTEM VIGILANCE	TRUSTING	VIGILANT

Figure 5. Capabilities can have two discrete values: a zero bit represents a baseline capability, while a one bit represents an enhanced capability.

		NUMBER OF	OBSTACLE	
0000	FREE AGENT	SINGLE LANE	EXCLUSION	TRUSTING
0001	FREE AGENT	SINGLE LANE	EXCLUSION	VIGILANT
0010	FREE AGENT	SINGLE LANE	DETECTION	TRUSTING
0011	FREE AGENT	SINGLE LANE	DETECTION	VIGILANT
0100	FREE AGENT	MULTIPLE	EXCLUSION	TRUSTING
0101	FREE AGENT	MULTIPLE	EXCLUSION	VIGILANT
0110	FREE AGENT	MULTIPLE	DETECTION	TRUSTING
0111	FREE AGENT	MULTIPLE	DETECTION	VIGILANT
1000	PLATOON	SINGLE LANE	EXCLUSION	TRUSTING
1001	PLATOON	SINGLE LANE	EXCLUSION	VIGILANT
1010	PLATOON	SINGLE LANE	DETECTION	TRUSTING
1011	PLATOON	SINGLE LANE	DETECTION	VIGILANT
1100	PLATOON	MULTIPLE	EXCLUSION	TRUSTING
1101	PLATOON	MULTIPLE	EXCLUSION	VIGILANT
1110	PLATOON	MULTIPLE	DETECTION	TRUSTING
1111	PLATOON	MULTIPLE	DETECTION	VIGILANT

Table I. A binary number can be assigned to any combination of capability enhancements. A "0" represents a baseline capability, while a "1" indicates an enhanced capability.

Figure 5 shows the value assignments for the orthogonal categories discussed in the preceding sections. Given that binary values are assigned to each capability, then various deployment stages can be represented by multi-bit binary numbers, wherein each bit represents whether a particular capability has been enhanced. For the four-element technology set used, this results in a 4-bit binary number representation of all possible major deployment states (Table I). As an example to interpreting Table I, the value 0110 has the leading "0" indicating "Free Agent", the first 1 (the second bit) indicating "Multiple Lanes", the second 1 (the third bit) indicating "Obstacle Detection", and the second 0 (the fourth bit) indicating "Trusting".



0000	0100	1100	1000
0001	0101	1101	1001
0011	0111	1111	1011
0010	0110	1110	1010

Figure 6. The squares in a K-map are a two-dimensional representation of a torus, in which the top wraps around to meet the bottom, and the sides wrap around to meet each other. Each square in a K-map has four neighbors that differ in value by exactly one bit.

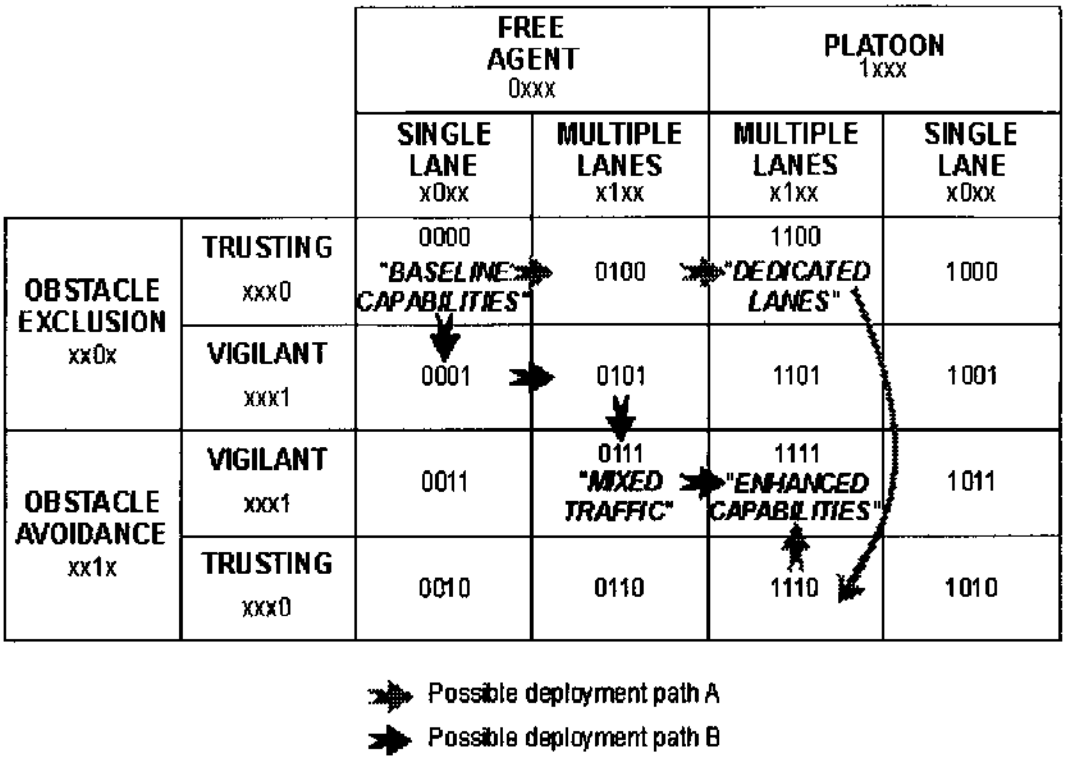
Using the binary numbers of Table I, all sixteen different AHS configurations can be represented in a single picture. The left half of Figure 6 shows a special arrangement of these configurations in the format used for Karnaugh maps (K-maps). [Fletcher, 1980] K-maps are a digital logic design optimization tool; however here the format of the K-map is all that is being used, not the logic optimization methodology.

A special property of a K-map arrangement is that all squares which are horizontally or vertically adjacent differ by exactly one bit in value. In order to accomplish this, edge square adjacency is considered to "wrap around" the map either horizontally or vertically as appropriate. In actuality, a K-map is a two-dimensional representation of a torus, as shown in the right half of Figure 6. As an example of this adjacency property on the two-dimensional map, square 0000 is above square 0001, to the left of square 0100, to the "right" of square 1000, and "below" square 0010.

Use of the Deployment Map

The use of this map in the context of designing an AHS is to plot deployment paths as sequences of introduction for orthogonal capability enhancements. Square 0000 on the map represents baseline automated functionality, with no capability enhancements deployed. A baseline AHS starts, therefore, in square 0000 and evolves by incrementally introducing technologies, represented here by changing one bit from "0" to "1" at each technology introduction. Each bit change corresponds to a one-square move, either horizontally or vertically, on the deployment map. After all four technology components have been introduced, the AHS is in square 1111, a maximally enhanced capability configuration.

It might be that not all four capability enhancements will be desired (or feasible) for an end-state AHS. Similarly, it might be that a baseline AHS is not acceptably safe to merit deployment. However, it is instructive to assume for the purposes of discussion that state 1111 is the desired end-state, and state 0000 the beginning state. (Thus, this discussion does not encompass how to get to a baseline AHS, but rather how to evolve from baseline automated operation to a more comprehensive AHS system.)



		FREE AGENT 0xxx		PLATOON 1xxx	
		SINGLE LANE x0xx	MULTIPLE LANES x1xx	MULTIPLE LANES x1xx	SINGLE LANE x0xx
OBSTACLE EXCLUSION xx0x	TRUSTING xxx0	0000 *"BASELINE CAPABILITIES"*	0100	1100 *"DEDICATED LANES"*	1000
	VIGILANT xxx1	0001	0101	1101	1001
OBSTACLE AVOIDANCE xx1x	VIGILANT xxx1	0011	0111 *"MIXED TRAFFIC"*	1111 *"ENHANCED CAPABILITIES"*	1011
	TRUSTING xxx0	0010	0110	1110	1010

Figure 7. A K-map represents potential AHS states, and two possible deployment paths from the baseline capability configuration (0000) to the maximally enhanced configuration (1111).

Using the K-map in Figure 7, an AHS could be deployed using any sequence of introduction of enhancements, traversing the grid from 0000 to 1111 in four steps. At each step, which capability is enhanced next determines the direction of a move along the map. Two example deployment paths are shown for illustrative purposes. Because Figure 7 depicts a two-dimensional flattening of the three-dimensional torus, one arrow appears longer than others, but this is solely an artifact of the order in which different technologies have been labeled on the map.

> Deployment sequence A: This sequence assumes that Multiple Lane capability will occur first, followed by Platooning, Obstacle Avoidance, and finally

Vigilance. This is an extension of the dedicated lane evolutionary deployment described in [Tsao, 1995b].

Deployment sequence **B**: This deployment sequence envisions Vigilance occurring first, followed by Multiple Lane capability, followed by Obstacle Avoidance, followed by Platooning.

These sample sequences represent two possible deployment paths. What is most notable is that both the Dedicated Lane concept and the Mixed Traffic concept being considered by NAHSC stop short of enhancing all four capabilities; thus, there are more capable system configurations possible than those alternatives currently being considered.

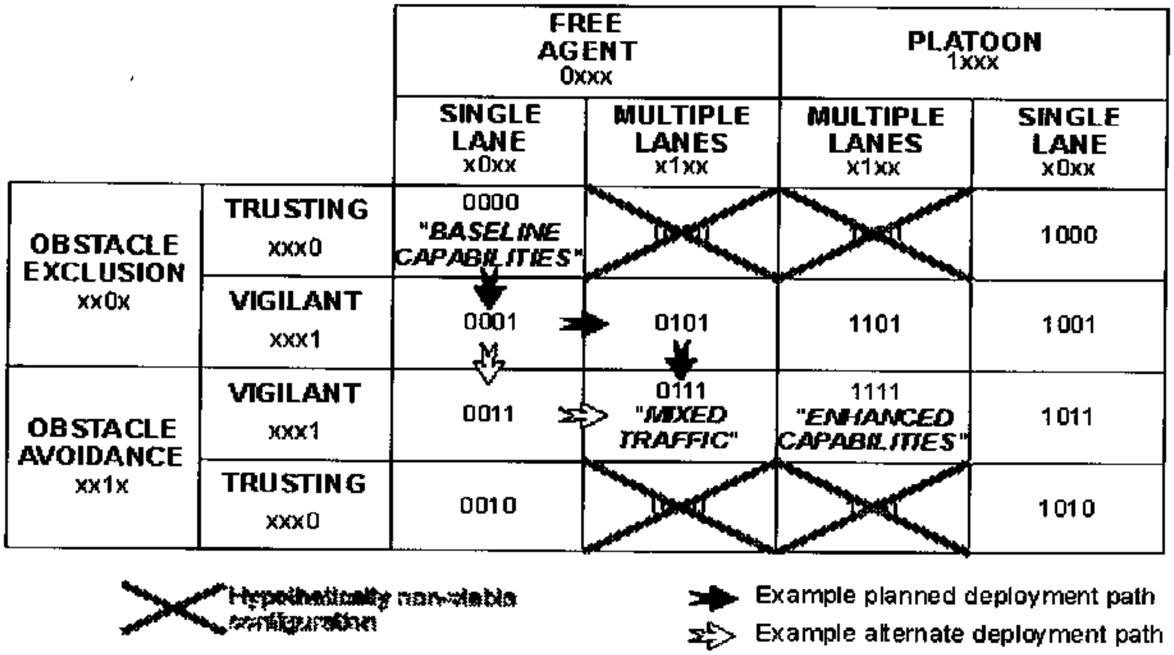


Figure 8. Alternate deployment paths may be represented as different transition sequences on the deployment map. Some squares may be considered non-viable, such as deploying a Trusting, Multiple Lane system represented by the X marks in this example.

In addition to representing alternate deployment strategies, a deployment map may be used to represent contingency plans. For example, Figure 8 assumes a particular planned deployment path for the Mixed Traffic concept. However, an alternate deployment path is shown for the contingency that multiple lane technology (0001 to 0101) proves more difficult than expected, and obstacle avoidance capabilities are instead fielded first (0001 to 0011).

Because there are four capabilities, there are 4 factorial, or 24, possible deployment sequences that move from the most simplistic to the most technically comprehensive AHS, assuming that no capabilities are removed after being introduced. The K-map representation permits graphically representation all 24 possible paths.

In addition to graphically representing potential technology deployment sequences, the map in Figures 7 and 8 can also be used as a basis for setting deployment constraints. Rows, columns, and individual boxes can be declared off-limits due to liability constraints, economic constraints, market factors, and socio-political factors. This constraining of deployment paths designates those regions where concurrent multi-technology deployments might required to "jump over" a forbidden region, or a different sequence might be required to avoid a proscribed square.

Figure 8 depicts a hypothetical example constraint that Trusting Multiple Lane systems might be undesirable because of concerns about lateral collisions (requiring enhancement of Vigilance in Multiple Lane configurations), blocking out squares 0100, 0110, 1100, and 1110 from consideration. The K-map approach, therefore, enables the AHS developers to represent and potentially minimize programmatic risk by blocking off paths that are infeasible due to technical and non-technical reasons, and then to explore and develop those paths that are left.

CONCLUSIONS

A taxonomy of potential AHS configurations can be defined, and exploration of potential deployment paths can be accomplished by defining a set of orthogonal capabilities such as: entity size, number of automated lanes, obstacle strategy, and system vigilance. By defining baseline and enhanced levels of development for each capability a binary representation of each possible deployment combination can be created and depicted on a K-map. A significant finding is that enhanced system configurations exist beyond what has been envisioned to date by NAHSC: both the Dedicated Lane concept and the Mixed Traffic concept stop short of a concept that combines the capabilities of both.

The AHS decomposition presented here is a representative way to approach, bound, and manage the problem of AHS deployment. In addition to the actual decomposition into four capability building blocks presented, this paper introduces a methodology and visualization tool for reasoning about deployment sequences that can be used for other orthogonal capability sets that might be proposed in the future. It not only depicts a comprehensive yet small set of deployment paths, but also can be used to depict both technical and non-technical constraints on selecting viable deployment paths and contingency plans. Additionally, the combination of an orthogonal decomposition with a deployment map provides a framework within which critical capabilities can be clearly distinguished and emphasized for systematic development.

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A Hybrid Human-Computer Autonomous Vehicle Architecture

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Abstract

The principled design of robot architecture is crucial for the development of low-cost and reliable robotics. Recent advances in the study of robot architecture indicate that *layered* architectures are becoming the standard model throughout the robotics community. In this paper, we describe architecture development for the design of automated highway vehicles. These robots are unique in that they combine the fundamental robot challenges of autonomy and reliability with the less traditional issues of human-computer interaction and division of control. We propose a robot architecture, derived from the standard layered model, that enables a system-wide view of the human-machine autonomous system. We then discuss the hybrid nature of the human-computer interaction scheme, describing several possible human-machine hybrid vehicle controllers.

1 Introduction

The study of *robot architecture* plays an important role in the development of a new generation of autonomous robots that are required to meet real-time constraints and exceed particular safety minima. A principled approach to design, called *architecting*, is being applied to robot projects in a wide array of domains, from autonomous spacecraft [5] to distributed software robots [3].

This paper is concerned with an autonomous roadway vehicle, an application domain that introduces additional challenges: the system must interface deliberately with the human element, it must accommodate a variety of incremental deployment options, and it must interact with surrounding autonomous and manually-driven vehicles.

Figure 1 pictures Navlabs 6 through 10, four of several vehicles that are being designed to autonomously navigate the roadway system [6]. These vehicles can demonstrate lane-following, speed-keeping, headway-keeping, and obstacle avoidance.

Figure 1: The Navlab 6 through Navlab 10 vehicles

The fundamental challenge of architecting for Navlab is much the same as any complex, real-time robot system. The system must effect sensor fusion to interpret its inputs, and it must control actuators in a temporally continuous and durative manner. All this is done with two constraints in mind: real-time response and long-term goal achievement. Of course, in the case of automated highway vehicles, safety issues are paramount, as the *raison d'être* for an autonomous roadway vehicle is that it can achieve a higher level of safety than a human driver.

Widely accepted robot architectures and development environments such as RAPS and 3T

[4,1] provide a means for architecting solutions to the challenges Navlab faces. We began with the 3T architecture as a starting point. However, a number of challenges unique to the automated roadway vehicle problem required further architectural development.

The radical point of departure for automated vehicle systems is that humans will be present in the vehicles, and their relationship (or non-relationship) to vehicle autonomy must be clearly defined. The control system and the system architecture therefore must represent a *hybrid human-machine system*.

Furthermore, this hybrid architecture does not define a static relationship between human and machine. Speed-of-acceptance and long-term deployment demand that the roadway vehicle only gradually transfer autonomy from human to machine. Even in a more temporally fine-grained sense, the everyday user of an autonomous vehicle will see a continuously shifting boundary between human and machine control. Especially at the beginning of the deployment cycle, there are certain to be vehicles that relieve the human of control responsibilities only in some driving regimes, raising crucial issues regarding transfer of control.

In short, the problem of roadway vehicle autonomy brings together the standard problems of robot architecture design—real-time control, goal-based rationality—and less frequent challenges—human-computer interaction, hybrid human-machine control, incremental deployment, and large-scale robot cooperation.

In this paper, we propose an architecture for an autonomous roadway vehicle. The architecture is striking both because of shared characteristics with standard robotic architectures and because the architectural components are designed and interfaced in order to enable either human or computer authority at every level of control. We describe the architecture and its components in Section 2, then discuss a variety of hybrid deployment scenarios in Section 3. Finally, Section 4 offers some conclusions and describes future work.

2 Architecture Description

The high-level objectives for vehicle automation are to increase safety and mobility. These objectives lead to four specific requirements for autonomous vehicle operation. *Reactive safety* demands that a vehicle respond in real time to hazards in the environment [2]. *Proactive safety*, or defensive driving, requires the vehicle to choose actions that minimize future danger. *Roadway-oriented deliberation* requires the vehicle to make rational trajectory choices at the roadway level. Finally, *route-oriented deliberation* demands that the vehicle make rational route-level choices to lead from the point of origin to the destination.

These individual requirements lead to a wide variety of sensor, actuator and intelligence needs. Obviously, satisfying all of the requirements with a one-time market introduction that is low-cost, user-friendly and fully-autonomous is not realistic. Issues of technical design are perhaps even superseded by deployment issues concerning the introduction of automation to the public and by liability concerns. As a result, highway autonomy can only proceed via an incremental deployment of the automation.

Figure 2 is a schematic of the architecture we propose to meet these challenges. This architecture is an instance of a *layered architecture*, in which system control is divided between multiple modules, or layers, based upon representational resolution, both geometric and temporal [1].

A layered architecture is useful in this situation for several reasons. At development-time, layers provide natural boundaries for incremental implementation and testing. Functions which must meet similar reactivity and robustness criteria will naturally define a layer, and so careful testing of that single layer will be straightforward, given that the layer's connections to its neighbors are well defined in the architecture specification.

More importantly, layering enables well-defined, mixed human-machine control. The notion of being able to insert a human into an architectural layer has profound implications for the evolutionary deployment of automation. The layers chosen must have clean interfaces which can connect either to a human or to another automated layer. A low-level layer must be capable of safely operating when severed from higher-level layers due to faults or failures. Note that this requirement applies, not simply to the automated component of an architecture, but to the entire human-machine system: if part of the automation is compromised, the *entire system*, which may or may not include the driver, should be functionally capable of continuing operation of the vehicle at a most basic level of safety.

A hybrid human-machine architecture is thus one in which the functions and interfaces of each architectural layer are clearly defined such that either a human or a machine can operate at each level, and one in which safety-related functions are embedded at low levels of control. The 3T architecture is particularly amenable to this functional delineation, and the three layers we propose bear some resemblance to 3T.

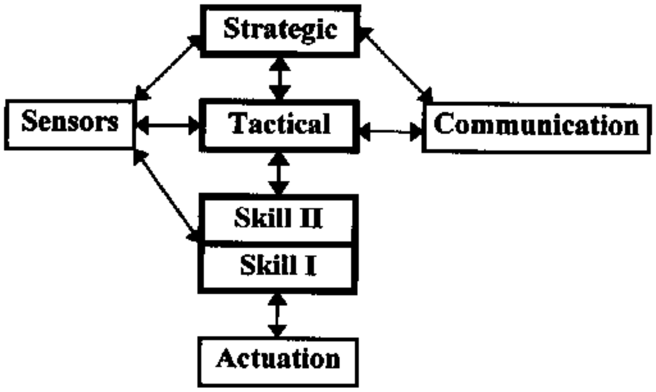

Figure 2: The automated vehicle architecture

We characterize each of these three layers in terms of *function* and *purview*. By *function*, we mean the particular system goals that a layer satisfies through combinations of control techniques. By *purview*, we mean those divisions in spatial and temporal interest that are required in order to satisfy the layer's functional goals.

This functional definition allows us to avoid a common trap in architecture design. Robot architectures commonly make premature representational decisions, frequently imposing an explicit and symbolic form of *knowledge* at the higher layers and an implicit, *reactive* encoding at lower layers. As has been demonstrated by Rosenschein & Kaelbling [8], functional intelligence can be achieved through either implicit or explicit, symbolic or non-symbolic techniques, and so these decisions are premature.

2.1 *Skill Layer*

The Skill Layer is responsible for both *reactive safety* and the robot's lowest level of control. The Skill Layer has the following competencies: maintenance of lateral control within a lane, maintenance of headway, speed control, acceleration, deceleration, braking, changing lanes, and informing the driver when a situation beyond its capabilities arises. These competencies, although cognitively limited, form the basis from which the vehicle can react to obstacles and other vehicles in the roadway

In regard to purview, this layer is concerned temporally with actions and reactions on a fine-grained and short time horizon (e.g. within the next three seconds). Spatially, the Skill Layer is interested in the acute location and the activities of vehicles and obstacles in its immediate surroundings (approximately 100 meters to the front and back, and 7 meters to each side).

The Skill Layer does *not* reason about series of actions. Rather, it considers single maneuvers as reactions to hazards in the roadway. Similarly, the Skill Layer does not install or modify goals, such as desired speed or headway distances. Such goals are determined at a higher level of control, be that the Tactical Layer or the highway infrastructure, or by default values originating from the system designers.

A quality of this architecture is that The Skill Layer, being ultimately responsible for the safety of the system, is the only layer capable of generating actuator commands. Indeed, the interfaces to higher levels of control may be viewed simply as channels of *advice*; the Skill Layer is a final arbiter and cannot be subsumed by other layers' goals.

We further subdivide the Skill Layer into two sublayers: Skill I and Skill II. Skill I is responsible for basic longitudinal and lateral control (e.g. acceleration, deceleration, headway control, lane-following). Skill I represents a set of competencies that have been engineered and are available currently on vehicles such as Navlab 9. Skill II adds an extra dimension of lateral control: lane changing and merging. These are technically more challenging functionalities that are currently in development, naturally falling in a different category from the more technically mature functions of Skill I.

2.2 *Tactical Layer*

The Tactical Layer is responsible for *proactive safety* and *roadway-oriented deliberation.* The Tactical Layer can project the traffic scene forward in time, predicting the motions and future positions of surrounding vehicles. Furthermore, the Tactical Layer may, via vehicle-to-vehicle and infrastructure-to-vehicle communication, receive information concerning the intentions and future positions of other vehicles on the roadway.

In our prototype implementation, this layer will generate probabilistic descriptions of future world states, allowing it to maximize the likelihood of goal achievement while meeting probabilistic safety constraints. For example, the Tactical Layer can control recommend vehicle speeds and headway separations that maximize the number of extreme swerve options available to the vehicle in the event of an emergency.

Roadway-oriented deliberative planning uses these same tactical reasoning abilities to choose between various paths in order to achieve system goals. For example, if the autonomous vehicle is trailing a slow-moving truck in the right lane, the Tactical Layer can plan a series of maneuvers (*change-lanes-left, accelerate, change-lanes-right*) in order to achieve the desired speed. Of course, if the vehicle's exit is near, the Tactical Layer will remain in the right lane because the lane change may decrease its probability of success below an acceptable value.

The Tactical Layer's ability to take advantage of communication is *opportunistic*. In that surrounding vehicles may or may not have communication links, this capability is not relied upon but rather utilized when available. Negotiations between vehicles enable additional efficiencies and safety guarantees which ar particularly useful. For example, when merging into mainline traffic from an entrance ramp, knowledge that a gap will be maintained because of negotiated assurances from other automated vehicles increases the safety of the entire system, and may enable a merge to occur into a smaller gap (and thereby afford greater vehicle throughput).

With respect to purview, the Tactical Layer is concerned temporally with *sequences* and *conditional sets* of actions and reactions within the next tens of seconds. Spatially, it is concerned with the vehicles within several hundred meters meters front and back, and several lanes to each side.

2.3 *Strategic Layer*

The Strategic Layer is responsible for the high-level functions of route planning and guidance. It makes use of information from sources in the infrastructure to determine the route which mos efficiently satisfies the vehicle's given goals. Indeed, precursors to such technology are already being deployed in several overseas markets. Note that the Strategic Layer's functionality exceeds that of a simple, interactive map. It evaluates the position of the vehicle on the existing roadways on an ongoing basis, informing the Tactical Layer when subgoals must be specified. Furthermore, the Strategic Layer can reason about the global efficiency of alternative, strategic plans, choosing new plans and modifying old plans at run-time in order to achieve greater success as roadway conditions change.

The purview of the Strategic Layer extends throughout the roadway system relevant to the task at hand. By the same token, the Strategic Layer uses a more granular form of representation. For instance, specifics such as the local traffic scene surrounding the vehicle will not be represented at the strategic level of detail.

2.4 *Interfaces*

In order for this hybrid human-machine architecture to be successful, the layers should be as independent as possible. The complexities of the system should reside within the layers themselves, and the interfaces should be well-defined and simple [7]. The following discussion provides a framework for the kinds of information that pass between the layers shown in Figure 2.

An important global view concerning the interfaces is that they are meant to communicate *information* as well as subgoals. The interfaces we describe are not just slaved control interfaces; rather, they serve as a means for neighboring layers to *inform* one-another, providing information gain and thereby aiding in the decision-making process at each layer.

For instance, the Tactical Layer not only presents the Skill Layer with basic goals, such as desired speed and headway distance; it can also inform the Skill Layer about a neighboring vehicle's intention to change lanes, thus modifying the forward projection of that neighboring vehicle, as constructed by the Skill Layer.

Furthermore, the Tactical Layer can achieve its higher-level goals by issuing recommendations to the Skill Layer that cause long-term changes in the vehicle's local scene—changes that cause the vehicle to better match its goals. For instance, using a sequence of granular actions such as *accelerate*, *change lanes left*, *change lanes right*, the Tactical Layer may cause the vehicle to pull ahead of a slow-moving vehicle and thus achieve the desired roadway speed more successfully. By the same token, information can flow from the Skill Layers back up to the Tactical Layer, indicating failures of high-level recommendations as well as reasons for those failures.

The relationship between the Strategic Layer and Tactical Layer is similar, with the difference being primarily one of granularity. The Strategic Layer informs the Tactical Layer with subgoals that allow the long term goals to be achieved. The Tactical Layer, in turn, responds to the Strategic Layer, either communicating success or identifying failures in the achievement of those subgoals.

We will leave further detail concerning the representational and translation issues involved with inter-layer communication for a longer publication. Instead, we turn our attention to the most fascinating aspect of this architecture: the hybrid human-machine nature of the automated vehicle.

3 Hybrid Human-Machine Scenarios

Autonomous vehicle systems are unique in robot architectures in that the human is formally part of the autonomous system. Because of both technical and non-technical (social, psychological, legal) issues, it is difficult to predict which layers will be machine-controlled first. At the technical level, of course, a highest level strategic system is already in operation on many vehicles. A lowest level Skill layer, at the Skill I level, has been successfully tested [6].

Nevertheless, the non-technical issues as well as the unsolved engineering challenges lying in wait at the Skill II and Tactical Layer demand that the system architecture be capable of incorporating human control at *any* architectural layer. Furthermore, devising an architecture that is amenable to varying levels of human control enables the system designers to implement automation at the level dictated by the design circumstance, leaving the vehicle open to evolution as those circumstances change.

Refer to Table 1, which summarizes a number of viable control schemes with varying degrees of human control. The options shown are surprisingly diverse, proposing human control in the middle layers (scenarios 5 & 6) as well as the opposite (scenario 7).

Table 1: Deployment options indicating human control (h) and machine control (m) at various layers.

Layer	1	2	3	4	5	6	7
Strategic	h	h	h	m	m	m	h
Tactical	h	h	m	h	h	h	m
Skill II	h	m	m	h	h	m	h
Skill I	m	m	m	h	m	m	h

Consider scenario 2, in which the Skill Layer, both Skill I and Skill II, is operated under machine control and the human serves at both the Tactical and Strategic Layers. If the driver desires to pass a slow vehicle, he indicates this to the Skill Layer by specifying a subgoal to change lanes left. In turn, the Skill Layer does so when it is safe to execute the maneuver. If no vehicles are in the new lane, the Skill Layer will accelerate to the desired speed as set by the Tactical Layer, and continue to operate in this state until the driver issues a change-lanes-right goal. Thus, the driver is responsible for staying cognizant of the trip plan, and for maneuvering this "push button" vehicle through traffic. This implementation could conceivably improve system safety by executing maneuvers under machine control that meet or exceed specified safety standards.

Next, consider scenario 7, an unusual implementation in which the Tactical Layer is machine-controlled and the Skill and Strategic Layers are human-controlled. In this case, the Tactical Layer would provide the human with information to facilitate vehicle control. For instance, when merging on a freeway, a head-up display could indicate the optimal gap to the driver based on projections for gap openings and formal negotiations with nearby vehicles.

A more traditional approach is captured by scenario 4, in which the machine is responsible for Strategic-level planning. Given a high-level goal specification by the driver, the machine ascertains the trip origin and destination, desired time of departure and arrival, and preferred routes. Using a communication link with the infrastructure, it determines the current traffic conditions and the historic traffic trends for the potential routes, and selects an optimal route and departure time. The Strategic Layer gives road-by-road instructions to the driver, providing congestion-specific instructions such as *begin merging right* in order to ensure that the driver reaches appropriate exits.

The few examples we have provided only begin to shed light on the various operational modes that are possible when the human-machine vehicle is viewed as a single autonomous system. The important lesson is that the architecture must consider the human-machine interface carefully to enable seamless and safe human-machine control.

4 Conclusions and Future Directions

We have identified a version of the standard layered architecture that is amenable to the problem of automated vehicle systems. We are fortunate enough to have real-world vehicles on-hand that achieve Skill I and partial Skill II levels of automation. In coming months, we will demonstrate the "push-button car" of scenario 2, then go on to implement basic machine control at the Tactical Layer.

An important issue that will arise is that, initially, the vehicle will only be capable of automatic control at the Tactical Layer in light traffic. Therefore, the issue of run-time transfer of control between human and computer will play an important role in our implementation. A hopeful note is that, in this case, passage of control will only take place at a relatively high level: the Tactical Layer, leaving seamless and continuous low-level control to the machine at the Skill Layer. This facilitates transfer of control immensely by removing hard real-time demands from the transfer process.

Automated vehicle design is a unique problem not only because of the human-computer interaction element but also because safety guarantees are of paramount importance. A formal robot architecture, and in particular a layered architecture with its well-defined control hierarchy between layers, facilitates the process of formally evaluating system safety.

Of course, these issues span further than only automated vehicles. We hope that this paper summarizes the basic problem of architecting automated vehicles clearly so that a productive discourse on this subject can take place in the greater robotics community.

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C3 Interim Report

10.4 Feasibility Analysis

Includes:

10.4.1 ANALYSIS OF AHS PIPELINE CAPACITY

Author, Bret Michael

10.4.1.1 Introduction

The analyses conducted as part of Task C2 yielded characterizations of the relationships between pipeline capacity and the parameters of the vehicle-following models for each pairing of the levels of vehicle cooperation with the vehicle spacing policies (i.e., uniform versus non-uniform). A key finding from these analyses was that pipeline capacity is sensitive to changes in the properties (e.g., the lower bound, mean and standard deviation) of the distribution of the maximum braking rates of light-duty passenger vehicles in the U.S.

During Task C2, a small sample of maximum braking rate data was used to create a discrete probability distribution. The braking rates ranged from 0.495 to 0.98 g. The shape of the distribution is that of a Gaussian distribution. The sample consisted of nineteen models of light-duty passenger vehicles and three months of domestic unit production data corresponding to each of the nineteen models, for a total of 862,892 vehicles, of which it was not known how many of these vehicles were produced for domestic sales versus export.

These limitations of the representation of the braking performance of the population of light-duty passenger vehicles traveling on U.S. highways led to questions about the robustness of the conclusions drawn about pipeline capacity using that distribution. In order to provide confirming evidence for the conclusions made during Task C2, during Phase I of Task C3 a data collection effort was undertaken, resulting in the construction of a distribution covering a much wider spectrum of the population of light-duty passenger vehicles. The new distribution contains two years of domestic unit sales, 1994-95, with data on maximum braking rates covering approximately 85.5 percent of the 29,870,481 vehicles sold in the U.S. during those two years.

In addition to the data on maximum braking rates for dry pavement, data was also collected about the braking rates of light-duty passenger vehicles on wet pavement. The braking-rate data covers approximately 83.2 percent of the light-duty passenger vehicles sold in the U.S. during 1994-95.

Equipped with the two new distributions, a pipeline capacity analysis was performed during Phase I of Task C3. The following is a summary of the results of the Phase I of Task C3 pipeline capacity analysis:

- For vehicle operations on dry pavement, the relationships between pipeline capacity and the independent variables of the vehicle-following models are consistent with those obtained in Task C2.

- For all levels of cooperation among vehicles and over the nominal range of operating speeds (i.e., 10 and 40 m/s), the distribution of braking rates used in Phase I of Task C3 produces higher pipeline capacities than those derived from the braking-rate distribution used in Task C2.
- There is a difference in the shape of the distribution of maximum braking rates for dry and wet pavement: the former takes the shape of the Gaussian distribution while the latter can be approximated with a gamma-type distribution. Moreover, both the lower and upper bounds of the wet-pavement-braking-rate distribution are lower than the corresponding bounds on the dry-pavement-braking-rate distribution. In addition, the standard deviation of the distribution representing braking on wet pavement is higher than that for dry pavement.
- The shape of the relative frequency distributions of braking rates is correlated with both the type of tires installed on the vehicle and whether the vehicle is equipped with an antilock braking system.
- At the nominal operating speed (i.e., 30 m/s), cooperative non-uniform spacing policies produce smaller percentage differences between the pipeline capacity for dry and wet pavement than do uniform spacing policies.
- For each level of cooperation with uniform spacing, AHS pipeline capacity for operation on wet pavement is lower than that for dry pavement, although the magnitude of the absolute difference in pipeline capacity is not constant as a function of speed, *ceteris paribus*.
- For both dry and wet pavement, pipeline capacity for cooperative non-uniform spacing with a 0.5 s minimum headway is much higher than that of non-uniform spacing with a 1 s minimum headway. For speeds between approximately 25 and 40 m/s, pipeline capacity for cooperative non-uniform spacing with a 0.5 s minimum headway is greater than that for operation of autonomous individual vehicles, low-cooperative individual vehicles, and high-cooperative individual vehicles. Given a 1 s minimum headway for non-uniform spacing and speeds between 10 and 30 m/s, co-operative non-uniform spacing produces a lower pipeline capacity than that of uniform spacing of autonomous individual vehicles.
- For both dry and wet pavement, platoon operation results in the highest level of pipeline capacity within the nominal range of operating speeds.
- Low-cooperative non-uniform spacing with a minimum headway of 0.5 s results in higher pipeline capacities than high-cooperative uniform spacing at speeds of between 26 and 40 m/s for dry pavement and between 17.5 and 40 m/s for wet pavement.
- Pipeline capacity, as a function of speed, is continuous and increasing over the nominal range of operating speeds for the following: platoon operation on dry pavement, cooperative non-uniform spacing with a 1 s minimum headway, and cooperative non-uniform spacing with a 0.5 s minimum headway and the following vehicle knowing its own maximum braking capability and that of the preceding vehicle. For all other pairing of levels of cooperation and spacing policies, the graphs of the continuous functions which approximate the relationship between pipeline capacity and speed are concave downward, with each of the inflection points representing the absolute extrema. The maximum pipeline capacities for operation of

autonomous individual vehicles, low-cooperative vehicles, and high-cooperative vehicles occur at approximately 16 and 12 m/s for dry and wet pavement, respectively. The maximum pipeline capacities occur at speeds in excess of 30 m/s for platoon operation on wet pavement and non-uniform spacing given a minimum headway of 0.5 s on dry pavement with the following vehicle knowing its own braking capability. The maximum pipeline capacity for non-uniform spacing given a minimum headway of 0.5 s on wet pavement with the following vehicle knowing its own braking capability is at 28.5 m/s.

- For operation of autonomous individual vehicles, low-cooperative vehicles, and high-cooperative vehicles, the percentage decrease from the maximum pipeline capacity to the pipeline capacity at 30 m/s is higher for wet pavement than for dry pavement. The percentage decrease from the maximum pipeline capacity to the pipeline capacity at 30 m/s is much lower for cooperative non-uniform spacing on wet pavement with a 0.5 s minimum headway. Such comparisons are not applicable for the other pairings of levels of cooperation and spacing policies because the maximum value of the pipeline capacity is reached at a speed in excess of 30 m/s.
- The rate of increase in pipeline capacity per unit increase of the lower bound on the maximum braking rate diminishes above 0.76 and 0.61 g for the operation of AHS vehicles using uniform spacing on dry and wet pavement, respectively.

The remainder of this document consists of the following: a description of the procedure for conducting the pipeline capacity analysis, a detailed description each step of the procedure and the results from carrying out the step, and conclusions.

10.4.1.2 Procedure

The procedure used for determining the relationships between pipeline capacity and the independent variables of the vehicle-following models is as follows:

1. Develop a statistical summary of the braking-rate and vehicle-sales data. The summary is a characterization of how well the sample represents the entire population of vehicles sold during the years 1994-95. It is known *a priori* that gaps exist in the braking-rate data, that is, there exist some models of light-duty passenger vehicles for which Consumer's Union did not conduct testing of braking performance.

2. For each model of light-duty passenger vehicle sold during the years 1994-95, map the maximum braking performance for test track results on dry and wet pavement, as reported in *Consumer Reports*, to the number of the vehicles sold in the United States, as reported in *Automotive News Market Data Book*. The outputs of this step are two relative frequency distributions, one for dry and the other for wet pavement.

3. Select the nominal values and the range of values for each of the parameters of the vehicle-following models.

4. For each level of cooperation between individual vehicles, compute the inter-vehicle spacing versus speed that meets the *hard braking safety criterion*, which requires that if a vehicle applies maximum braking until it comes to a stop, the following vehicle should be able to stop without colliding with the preceding vehicle.

5. For platoon operation, compute the intra-platoon spacing versus speed required to meet the *low-relative velocity safety criterion*, which requires that if a vehicle applies maximum braking and the following vehicle collides with it, the relative velocity at impact between the two vehicles should be small. Next compute the inter-platoon spacing versus speed that meets the *hard braking safety criterion*.

6. For all levels of cooperation, use the inter-vehicle and inter-platoon spacing values to compute pipeline capacity.

7. Assess the sensitivity of pipeline capacity to changes in speed, the lower bound on the maximum braking rate, the percentage of the vehicle population excluded from the AHS pipeline, and a check-in policy with lower bounds on braking rates for both dry and wet pavement.

10.4.1.3 Statistical Analysis of Vehicle Sales and Maximum Braking Rate Data

The population of light-duty passenger vehicles includes cars and light trucks, and is partitioned into fifteen classes. The nine classes corresponding to cars are budget, small, lower mid-range, mid-range, upper mid-range, near luxury, luxury, sporty, and specialty. The six light-truck classes are minivan, full-size van, compact sport utility vehicle, full-size sport utility vehicle, compact pickup, and full-size pickup. These classes, along with the unit sales volume for the period January 1994 through December 1995, are shown in Table 10.4.1.1. Small cars, mid-range cars, compact sport utility vehicles, and full size pickup trucks account for fifty percent of the unit sales. Specialty vehicles comprise the smallest market share. The sales figures are based on market data provided in the *Automotive News Market Data Book*, 1995 and 1996 editions.

Table 10.4.1.1. Light car and truck market class as a percentage of unit sales, January 1994 through December 1995

Market Class	Unit Sales, 1/94-12/95	Percent of Light Vehicles
Budget	1,492,151	5.0
Small	3,484,384	11.7
Lower mid-range	2,266,967	7.6
Mid-range	5,207,518	17.4
Upper mid-range	1,645,097	5.5
Near luxury	954,761	3.2
Luxury	1,231,669	4.1
Sporty	1,184,896	4.0
Specialty	129,901	0.4
Minivan	2,511,982	8.4
Full-size van	804,951	2.7
Compact sport utility	2,846,877	9.5
Full-size sport utility	507,598	1.7
Compact pickup	2,209,079	7.4
Full-size pickup	3,392,650	11.4
Total	29,870,481	100.0

Brake stopping distances for domestic and foreign cars and light trucks are published monthly in *Consumer Reports*. The braking stopping distance is the distance traveled by a car or truck from the start of a brake application to the point at which the vehicle comes to rest. The vehicle-braking tests are performed on a test track under both dry and wet pavement conditions.

The vehicles are purchased from dealers and driven for 3,000 miles under normal driving conditions prior to being subjected to testing. The testing is performed at a test facility located in East Haddam, Connecticut. The tests of braking performance are conducted from an initial velocity of 60 mph. Each vehicle is equipped with a sensor that measures velocity, distance traveled, and time. The brakes are applied such that the vehicle follows a straight trajectory until it comes to a full stop; that is, the vehicle does not swerve and the driver—in concert with the antilock braking system—do not permit the wheels to lock. Ten consecutive trials are run. The purpose for running these trials one right after the other is to assess the effect of fade on the vehicle's braking performance due to overheating of the brake system components.

For the purpose of building distributions of car and light truck braking rates corresponding to dry and wet pavement conditions, the brake-stopping distances are paired with the corresponding market class and unit sales data. In this report, all stopping distances are converted to rates of deceleration using the formula $b = ((v_0 \cdot 1.47)/2d)/32.2$ where b is the rate of deceleration g (i.e., the acceleration of gravity), v_0 is the velocity at of vehicle at the instant when braking commences if ft/s, d is the brake stopping distance in feet, and 32.2 is the conversion factor from ft/s^2 to g.

The summary statistics of braking rates for all models are shown in Table 10.4.1.2. The dry and wet pavement braking rates for each model of car and light-truck are given at the end of this appendix. The sample size refers to the number of cars and light trucks for which data on their brake stopping distances is reported in *Consumer Reports*. Dry or wet brake stopping distance data was not available for some models: approximately 13.3 percent for dry pavement braking rates. Data coverage statistics are shown in Tables 10.4.1.3 and 10.4.1.4 for dry pavement. The symbols σ and σ^2 are used to denote standard deviation and variance, respectively. No brake stopping distances are reported for full-size vans and specialty vehicles. These two classes account for a total of 3.1 percent of the two-year unit sales of cars and light trucks.

There extreme ends of the spectrum of braking represent a very small percentage of the entire population of light-duty passenger vehicles. The lowest braking rate, 0.495 g, corresponds to the test-track results for an Eagle Summit on wet pavement. The Eagle Summit is in the budget market class. Within that class, all of the other models for which brake stopping distance data is available have braking rates on wet pavement in excess of 0.62 g. The highest braking rate, 1.025 g, corresponds to the test-track results for a Pontiac Firebird on dry pavement.

Table 10.4.1.2. Comparison of braking rates for dry and wet pavement

	Dry Pavement	Wet Pavement	Difference (percent)
Sample size (no. of vehicles)	25,528,814	24,849,457	3.8
Lowest braking rate (g)	0.707	0.495	29.6
Highest braking rate (g)	1.025	0.889	13.3
Braking rate range (g)	0.318	0.394	NA
Difference, low-to-high (percent)	31.0	44.3	NA
Average braking rate (g)	0.867	0.751	13.4
Braking rate mode (g)	0.845	0.780	NA
Braking rate variance	0.004	0.004	NA
Braking rate standard deviation	0.059	0.066	NA

Table 10.4.1.3 Light-duty passenger vehicles by market classification, dry pavement measurements

Market Classification	Number of Vehicles for which both Braking Rate Data and Unit Sales are Known	Coverage of Market Class (percent)	Braking Rate (g)			
			Average	Mode	σ^2	σ
Budget	1,261,200	84.5	0.827	0.864	0.003	0.053
Small	3,374,408	96.8	0.865	0.896	0.002	0.041
Lower Mid-Range	1,996,073	88.1	0.857	0.851	0.002	0.044
Mid-Range	5,126,240	98.4	0.879	0.882	0.001	0.035
Upper Mid-Range	1,644,351	99.9	0.863	0.909	0.007	0.085
Near Luxury	664,355	69.6	0.917	0.909	0.0005	0.022
Luxury	560,071	45.5	0.921	0.882	0.002	0.040
Sporty	986,929	83.3	0.939	0.916	0.002	0.041
Specialty	0	0	NA	NA	NA	NA

Table 10.4.1.4. Light trucks by market classification, dry pavement measurements

Market Classification	Number of Vehicles for which both Braking Rate Data and Unit Sales are Known	Coverage of Market Class (percent)	Braking Rate (g)			
			Average	Mode	σ^2	σ
Minivan	2,468,430	98.3	0.829	0.840	0.002	0.045
Full-size van	0	NA	NA	NA	NA	NA
Compact sport utility	2,433,111	85.5	0.827	0.775	0.002	0.042
Full-size sport utility	202,082	39.8	0.816	0.765	0.004	0.062
Compact pickup	1,901,321	86.1	0.810	0.857	0.003	0.051
Full-sized pickup	3,324,733	98.0	0.806	0.811	0.0001	0.011

The intervals corresponding to one and two standard deviations from the mean (μ_{dry} = 0.867, μ_{wet} = 0.751, σ_{dry} – 0.059, σ_{wet} = 0.066) are shown in Table 10.4.1.5.

Table 10.4.1.5. Measurement intervals

	Range of Dry Pavement Measurements (g)	Range of Wet Pavement Measurements (g)
$\mu\pm\sigma$	[0.808, 0.926]	[0.685, 0.817]
$\mu\pm2\sigma$	[0.749, 0.985]	[0.619, 0.883]
Entire	[0.707, 1.025]	[0.495, 0.889]

10.4.1.4 Development of Relative Frequency Histograms

Figures 10.4.1.1 and 10.4.1.2 show the dispersion of the braking rates across the dry and wet pavement measurement ranges. In order to characterize the shape of the distributions for dry and wet pavement brake stopping distance measurements, the braking-rate range for each type of measurement is partitioned into the intervals shown in Tables 10.4.1.6 and 10.4.1.7. The relative frequency distribution for dry pavement braking rates has the shape of a Gaussian distribution. In contrast, the relative frequency histogram for wet pavement braking rates has the shape of a gamma-type density function.

Table 10.4.1.6. Partition of dry pavement measurements into eleven intervals

Braking Rate Interval (g)	Number of Vehicles in the Interval	Percentage of Total Vehicles for which Dry Pavement Braking Data is Available
(0.70, 0.73)	82,737	0.324
[0.73, 0.76)	39,314	2.896
[0.76, 0.79)	2,113,252	8.278
[0.79, 0.82)	4,998,540	19.580
[0.82, 0.85)	4,337,794	16.992
[0.85, 0.88)	5,418,365	21.225
[0.88, 0.91)	5,080,291	19.900
[0.91, 0.94)	1,758,588	6.889
[0.94, 0.97)	810,769	3.176
[0.97, 1.0)	90,078	0.353
[1.0, 1.03)	99,086	0.388

Table 10.4.1.7. Partition of wet pavement measurements into ten intervals

Braking Rate Interval (g)	Number of Vehicles in the Interval	Percentage of Total Vehicles for which Wet Pavement Braking Data is Available
(0.49, 0.53)	20,464	0.082
[0.53, 0.57)	55,281	0.222
[0.57, 0.61)	554,123	2.230
[0.61, 0.65)	2,150,720	8.655
[0.65, 0.69)	3,500,387	14.086
[0.69, 0.73)	5,372,288	21.619
[0.73, 0.77)	5,053,678	20.337
[0.77, 0.81)	6,316,930	25.421
[0.81, 0.85)	1,585,915	6.382
[0.85, 0.89)	239,671	0.964

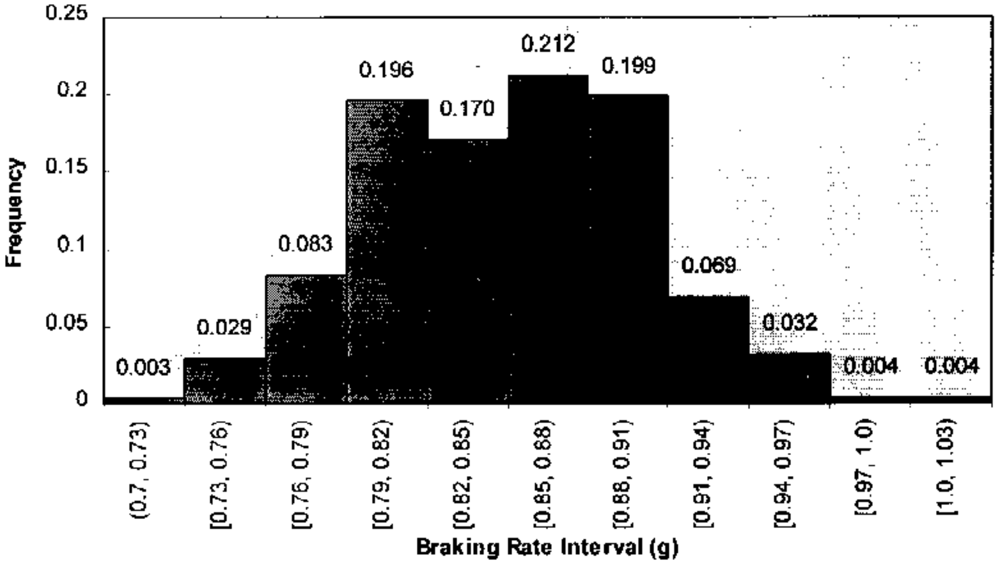


Figure 10.4.1.1.Relative frequency distribution of dry pavement braking rates partitioned into eleven intervals (cars and light trucks)

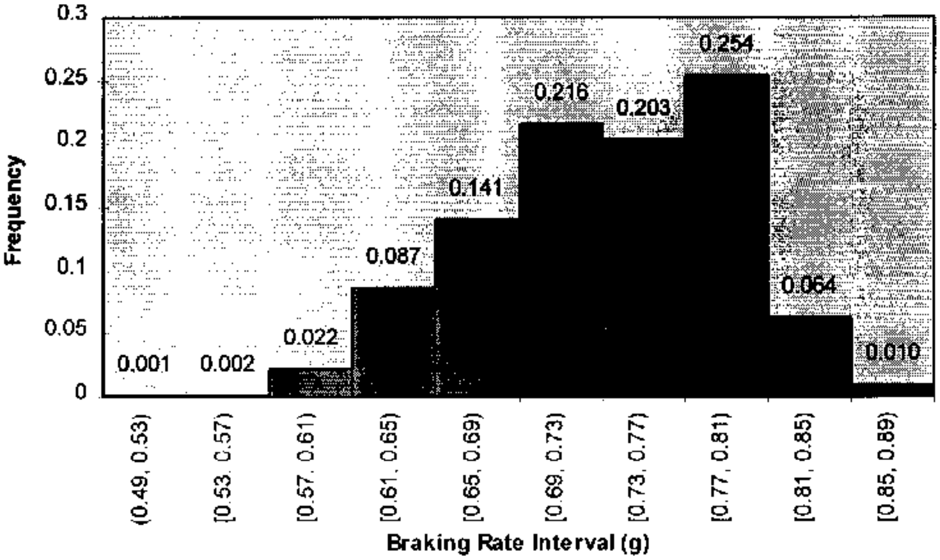


Figure 10.4.1.2.Relative frequency distribution of wet pavement braking rates partitioned into eleven intervals, cars and light trucks

The shape of these distributions and the range of braking rates are affected by both the type of tires the light-duty passenger vehicles are equipped with at the time of testing and whether the vehicle is equipped with an antilock braking system (ABS). For example, tests were conducted using eleven different makes of performance tires to determine how well a Pontiac Bonneville brakes with each set of tires. (Consumer's Union also tested different makes of all-season tires.) In this particular set of tests, braking commenced from an initial speed of 40 mph on wet pavement, as opposed to 60 mph on dry pavement.

The tests, reported in *Consumer Reports*, showed that with ABS and dry pavement, the braking distances ranged from 132.9 to 149.3 ft, corresponding to Dunlop D60 A2 and Michelin XGT H4 tires, respectively. On wet pavement, the braking distance for Dunlop D60 A2 tires in combination with antilock braking was 61.4 ft. (*N.B.*: The braking distances for dry and wet pavement cannot be compared against each other in this case because the initial velocity when braking began differs for the two test conditions.) This distance increased by 26 ft when the ABS was disabled (for testing purposes). The Goodyear Eagle tires in combination with ABS and wet pavement resulted in the Pontiac Bonneville stopping at 70 ft. With the ABS disabled and the pavement wet, the stopping distances for Yokohoma Avid MD-H4 and Michelin MXV4 Green X were 85.5 and 95 ft, respectively.

Therefore, the shape of the relative frequency distributions of braking rates is correlated with both the type of tires and whether the vehicle is equipped with an antilock braking system.

10.4.1.5 Selection of Parameter Values

The following tables show the parameters, nominal values, and range of values that were used in this analysis. For an explanation of the choice of these parameters and values, except for the braking rates, please refer to Appendix G of the *Automated Highway System (AHS) Milestone 2 Report*, National Automated Highway System Consortium, June 1997. This information also can be found in Michael *et al.* (1997).

Table 10.4.1.8. Parameters and their range of values

Parameter Name	Nominal Value	Range
Vehicle speed	30 m/s	[10, 40] m/s
Vehicle length	5 m	NA
Intra-platoon spacing	2 m	NA
Platoon size	10 vehicles	NA
Lower bound on braking rate, dry pavement	0.76 g	[0.707, 1.025] g
Lower bound on braking rate, wet pavement	0.61 g	[0.495, 0.889] g
Minimum headway, non-uniform spacing	0.5 s	[0.5, 1] s

Table 10.4.1.9. Nominal values for overlapped lags

Level of Cooperation and Spacing Policy	Overlapped lumped lag (ms)
Autonomous individual vehicle	300
Low-cooperative individual vehicle, uniform spacing	70
High-cooperative individual vehicle, uniform spacing	40
Platoon leader, uniform spacing	70
Platoon follower, uniform spacing	40
Low-cooperative individual vehicle, non-uniform spacing	70

10.4.1.6 Computation of Vehicle Spacing and Pipeline Capacity

The results of computing the pipeline capacities at the nominal speed (i.e., 30 m/s) for the four levels of cooperation among vehicles are summarized in tables 10.4.1.10 and 10.4.1.11. Tables 10.4.1.12 through 10.4.1.15 give the spacing required by the hard braking safety criterion for operation of vehicles on dry pavement, while tables 10.4.1.16 through 10.4.1.19 provide spacing for vehicle operation on wet pavement. The spacing values were computed for every 0.05 m/s increment within the nominal range of speeds, but only the spacing values for 10, 20, 30, and 40 m/s are shown in the tables. In the remainder of Section 10.4, polynomial functions were fit to the data.

Pipeline capacity, given in vehicles per lane per hour (veh/ln/hr), for operation of individual vehicles and platoons is computed as shown in Equations 10.4.1 and 10.4.2, respectively.

$$I = (3600 \cdot v)/(l + f)$$

Eq. 10.4.1

$$P = (3600 \cdot v)/[(n + (r \cdot l) + (q \cdot (r - 1)))/r]$$

Eq. 10.4.2

where v is the steady-state velocity of the vehicles on AHS pipeline, l is the vehicle length, m is the inter-vehicle spacing, n is the inter-platoon spacing, q is the intra-platoon spacing, and r is the platoon length.

Table 10.4.1.10. Summary of pipeline capacities at 30 m/s for dry pavement

		Pipeline Capacity (veh/ln/hr)			
Lower Bound on Maximum Braking Rate (g)	Percent of Distribution Truncated	Autonomous Individual Vehicles	Low-Cooperative Individual Vehicles	High-Cooperative Individual Vehicles	Platoons
0.707	0	3404	3680	4026	9875
0.73	0.324	3627	3947	4349	10116
0.76	3.220	3939	4327	4817	10425
0.79	11.498	4278	4749	5348	10727
0.82	31.078	4648	5220	5955	11023
0.85	48.070	5052	5748	6656	11312
0.88	69.295	5496	6345	7473	11595
0.91	89.125	5985	7025	8439	11872
0.94	96.084	6527	7805	9596	12144
0.97	99.260	7131	8711	11010	12409
1.00	99.613	7806	9774	12775	12669

Table 10.4.1.11. Summary of pipeline capacities at 30 m/s for wet pavement

		Pipeline Capacity (veh/ln/hr)			
Lower Bound on Maximum Braking Rate (g)	Percent of Distribution Truncated	Autonomous Individual Vehicles	Low-Cooperative Individual Vehicles	High-Cooperative Individual Vehicles	Platoons
0.495	0	2079	2163	2262	7790
0.53	0.082	2349	2460	2590	8259
0.57	0.304	2694	2847	3023	8783
0.61	2.534	3086	3296	3536	9295
0.65	11.189	3537	3823	4153	9794
0.69	25.275	4058	4452	4908	10282
0.73	46.894	4668	5212	5852	10759
0.77	67.231	5391	6152	7068	11224
0.81	92.652	6262	7341	8691	11678
0.85	99.034	7329	8892	10966	12122

Table 10.4.1.12. Vehicle spacing for autonomous individual vehicles on dry pavement, for nominal values of parameters

	Inter-Vehicle Spacing (m)					Pipeline Capacity (veh/ln/hr)
Braking Rate Interval (g)	speed of 10 m/s	speed of 20 m/s	speed of 30 m/s	speed of 40 m/s	Percent of Distribution Truncated	speed of 30 m/s
Entire	4.1301	13.0448	26.7287	45.1819	0	3404
[0.73, 1.025]	3.9335	12.1983	24.7782	41.6730	0.324	3627
[0.75, 1.025]	3.7735	11.5070	23.1830	38.8018	3.220	3832
[0.76, 1.025]	3.6971	11.1757	22.4182	37.4245	3.220	3939
μ±2σ	3.5853	10.7569	21.4974	35.8069	3.608	4076
[0.77, 1.025]	3.6229	10.8537	21.6741	36.0841	4.125	4049
[0.78, 1.025]	3.5508	10.5404	20.9498	34.7792	9.337	4162
[0.79, 1.025]	3.4808	10.2356	20.2447	33.5083	11.498	4278
μ±σ	2.8441	7.6440	14.3793	23.0501	24.792	5573
[0.82, 1.025]	3.2826	9.3687	18.2371	29.8880	31.078	4648
[0.85, 1.025]	3.1004	8.5673	16.3778	26.5319	48.070	5052
[0.88, 1.025]	2.9326	7.8246	14.6514	23.4130	69.295	5496
[0.91, 1.025]	2.7777	7.1348	13.0448	20.5078	89.125	5985
[0.94, 1.025]	2.6345	6.4928	11.5465	17.7956	96.084	6527
[0.97, 1.025]	2.5017	5.8940	10.1462	15.2584	99.260	7131
[1.0, 1.025]	2.3786	5.3345	8.8351	12.8805	99.613	7806

Table 10.4.1.13. Vehicle spacing for low-cooperative individual vehicles on dry pavement, for nominal values of parameters

	Inter-Vehicle Spacing (m)					Pipeline Capacity (veh/ln/hr)
Braking Rate Interval (g)	speed of 10 m/s	speed of 20 m/s	speed of 30 m/s	speed of 40 m/s	Percent of Distribution Truncated	speed of 30 m/s
Entire	3.3432	11.4609	24.3479	42.0042	0	3680
[0.73, 1.025]	3.1352	10.5911	22.3620	38.4479	0.324	3947
[0.75, 1.025]	2.9655	9.8798	20.7366	35.5362	3.220	4196
[0.76, 1.025]	2.8843	9.5387	19.9569	34.1389	3.220	4327
μ±2σ	2.7779	9.1307	19.0525	32.5433	3.608	4490
[0.77, 1.025]	2.8054	9.2069	19.1980	32.7787	4.125	4463
[0.78, 1.025]	2.7287	8.8840	18.4591	31.4541	9.337	4604
[0.79, 1.025]	2.6541	8.5695	17.7394	30.1638	11.498	4749
μ±σ	2.0091	5.9609	11.8482	19.6709	24.792	6410
[0.82, 1.025]	2.4422	7.6744	15.6890	26.4859	31.078	5220
[0.85, 1.025]	2.2468	6.8455	13.7878	23.0737	48.070	5748
[0.88, 1.025]	2.0661	6.0759	12.0206	19.9000	69.295	6345
[0.91, 1.025]	1.8986	5.3599	10.3741	16.9411	89.125	7025
[0.94, 1.025]	1.7431	4.6922	8.8367	14.1766	96.084	7805
[0.97, 1.025]	1.5985	4.0684	7.3983	11.5882	99.260	8711
[1.0, 1.025]	1.4637	3.4844	6.0499	9.1601	99.613	9774

Table 10.4.1.14. Vehicle spacing for high-cooperative individual vehicles on dry pavement, for nominal values of parameters

	Inter-Vehicle Spacing (m)					Pipeline Capacity (veh/ln/hr)
Braking Rate Interval (g)	speed of 10 m/s	speed of 20 m/s	speed of 30 m/s	speed of 40 m/s	Percent of Distribution Truncated	speed of 30 m/s
Entire	2.5080	9.7813	21.8239	38.6358	0	4026
[0.73, 1.025]	2.2979	8.9072	19.8315	35.0708	0.324	4349
[0.75, 1.025]	2.1264	8.1922	18.2006	32.1516	3.220	4655
[0.76, 1.025]	2.0443	7.8493	17.4182	30.7508	3.220	4817
μ±2σ	1.9642	7.4950	16.5947	29.2633	3.608	5001
[0.77, 1.025]	1.9645	7.5158	16.6566	29.3870	4.125	4987
[0.78, 1.025]	1.8870	7.1911	15.9150	28.0589	9.337	5164
[0.79, 1.025]	1.8115	6.8749	15.1928	26.7651	11.498	5348
μ±σ	1.4035	4.7503	10.0297	17.2443	24.792	7186
[0.82, 1.025]	1.5972	5.9748	13.1347	23.0769	31.078	5955
[0.85, 1.025]	1.3994	5.1410	11.2261	19.6549	48.070	6656
[0.88, 1.025]	1.2163	4.3667	9.4518	16.4716	69.295	7473
[0.91, 1.025]	1.0463	3.6461	7.7984	13.5036	89.125	8439
[0.94, 1.025]	0.8881	2.9740	6.2544	10.7301	96.084	9596
[0.97, 1.025]	0.7401	2.3456	4.8095	8.1331	99.260	11010
[1.0, 1.025]	0.6006	1.7561	3.4543	5.6965	99.613	12775

Table 10.4.1.15. Vehicle spacing for platoons on dry pavement, for nominal values of parameters

	Inter-Platoon Spacing (m) (intra-platoon spacing is 2 m)					Pipeline Capacity (veh/ln/hr)
Braking Rate Interval (g)	speed of 10 m/s	speed of 20 m/s	speed of 30 m/s	speed of 40 m/s	Percent of Distribution Truncated	speed of 30 m/s
Entire	4.6989	18.4875	41.3709	73.3490	0	9875
[0.73, 1.025]	4.4195	17.3385	38.7617	68.6890	0.324	10116
[0.75, 1.025]	4.1912	16.3980	36.6249	64.8719	3.220	10323
[0.76, 1.025]	4.0818	15.9468	35.5994	63.0396	3.220	10425
μ±2σ	4.0318	15.7118	35.0436	62.0273	3.608	10481
[0.77, 1.025]	3.9754	15.5076	34.6010	61.2555	4.125	10526
[0.78, 1.025]	3.8718	15.0800	33.6286	59.5178	9.337	10627
[0.79, 1.025]	3.7711	14.6635	32.6813	57.8246	11.498	10727
μ±σ	3.1434	12.0052	26.5872	46.8894	24.792	11418
[0.82, 1.025]	3.4843	13.4766	29.9806	52.9964	31.078	11023
[0.85, 1.025]	3.2190	12.3759	27.4742	48.5140	48.070	11312
[0.88, 1.025]	2.9729	11.3526	25.1423	44.3418	69.295	11595
[0.91, 1.025]	2.7441	10.3991	22.9675	40.4493	89.125	11872
[0.94, 1.025]	2.5309	9.5085	20.9347	36.8096	96.084	12144
[0.97, 1.025]	2.3319	8.6751	19.0308	33.3992	99.260	12409
[1.0, 1.025]	2.1458	7.8938	17.2442	30.1975	99.613	12669

Table 10.4.1.16. Vehicle spacing for autonomous individual vehicles on wet pavement, for nominal values of parameters

	Inter-Vehicle Spacing (m)					Pipeline Capacity (veh/ln/hr)
Braking Rate Interval (g)	speed of 10 m/s	speed of 20 m/s	speed of 30 m/s	speed of 40 m/s	Percent of Distribution Truncated	speed of 30 m/s
Entire	6.1742	21.8237	46.9414	81.5274	0	2079
[0.53, 0.889]	5.5481	19.2128	40.9857	70.8670	0.082	2349
[0.57, 0.889]	4.9330	16.6342	35.0940	60.3124	0.304	2694
[0.60, 0.889]	4.5295	14.9342	31.2032	53.3367	0.434	2983
[0.61, 0.889]	4.4046	14.4062	29.9936	51.1670	2.534	3086
$\mu \pm 2\sigma$	4.2581	13.7950	28.5992	48.6707	2.666	3214
[0.63, 0.889]	4.1677	13.4026	27.6929	47.0387	3.198	3303
[0.64, 0.889]	4.0553	12.9254	26.5981	45.0734	5.225	3418
[0.65, 0.889]	3.9467	12.4636	25.5380	43.1700	11.189	3537
[0.66, 0.889]	3.8417	12.0164	24.5111	41.3257	13.757	3660
[0.69, 0.889]	3.5468	10.7566	21.6147	36.1212	25.275	4058
$\mu \pm \sigma$	3.1038	8.9976	17.6673	29.1128	26.683	4765
[0.73, 0.889]	3.1954	9.2461	18.1357	29.8642	46.894	4668
[0.77, 0.889]	2.8848	7.9015	15.0316	24.2753	67.231	5391
[0.81, 0.889]	2.6088	6.6978	12.2466	19.2551	92.652	6262
[0.85, 0.889]	2.3624	5.6151	9.7353	14.7231	99.034	7329

Table 10.4.1.17. Vehicle spacing for low-cooperative individual vehicles on wet pavement, for nominal values of parameters

	Inter-Vehicle Spacing (m)					Pipeline Capacity (veh/ln/hr)
Braking Rate Interval (g)	speed of 10 m/s	speed of 20 m/s	speed of 30 m/s	speed of 40 m/s	Percent of Distribution Truncated	speed of 30 m/s
Entire	5.5060	20.4825	44.9273	78.8404	0	2163
[0.53, 0.889]	4.8583	17.8276	38.9053	68.0912	0.082	2460
[0.57, 0.889]	4.2196	15.2009	32.9409	57.4394	0.304	2847
[0.60, 0.889]	3.7991	13.4661	28.9976	50.3935	0.434	3177
[0.61, 0.889]	3.6686	12.9267	27.7708	48.2008	2.534	3296
$\mu \pm 2\sigma$	3.5171	12.3054	26.3611	45.6841	2.666	3444
[0.63, 0.889]	3.4207	11.9008	25.4363	44.0273	3.198	3548
[0.64, 0.889]	3.3029	11.4126	24.3249	42.0397	5.225	3683
[0.65, 0.889]	3.1890	10.9399	23.2483	40.1143	11.189	3823
[0.66, 0.889]	3.0788	10.4819	22.2050	38.2481	13.757	3970
[0.69, 0.889]	2.7685	9.1903	19.2606	32.9792	25.275	4452
$\mu \pm \sigma$	2.3279	7.4366	15.3211	25.9814	26.683	5315
[0.73, 0.889]	2.3971	7.6389	15.7195	26.6391	46.894	5212
[0.77, 0.889]	2.0674	6.2547	12.5555	20.9699	67.231	6152
[0.81, 0.889]	1.7729	5.0129	9.7126	15.8721	92.652	7341
[0.85, 0.889]	1.5088	3.8933	7.1453	11.2649	99.034	8892

Table 10.4.1.18. Vehicle spacing for high-cooperative individual vehicles on wet pavement, for nominal values of parameters

	Inter-Vehicle Spacing (m)					Pipeline Capacity (veh/ln/hr)
Braking Rate Interval (g)	speed of 10 m/s	speed of 20 m/s	speed of 30 m/s	speed of 40 m/s	Percent of Distribution Truncated	speed of 30 m/s
Entire	4.7804	19.0256	42.7390	75.9207	0	2262
[0.53, 0.889]	4.1284	16.3620	36.7038	65.1504	0.082	2590
[0.57, 0.889]	3.4850	13.7258	30.7252	54.4832	0.304	3023
[0.60, 0.889]	3.0612	11.9842	26.7717	47.4237	0.434	3399
[0.61, 0.889]	2.9296	11.4427	25.5417	45.2266	2.534	3536
μ±2σ	2.7811	10.8272	24.1408	42.7217	2.666	3706
[0.63, 0.889]	2.6796	10.4125	23.2008	41.0445	3.198	3830
[0.64, 0.889]	2.5608	9.9222	22.0862	39.0527	5.225	3987
[0.65, 0.889]	2.4459	9.4474	21.0065	37.1231	11.189	4153
[0.66, 0.889]	2.3347	8.9874	19.9601	35.2528	13.757	4327
[0.69, 0.889]	2.0214	7.6898	17.0067	29.9719	25.275	4908
μ±σ	1.6275	6.0305	13.2094	23.1640	26.683	5931
[0.73, 0.889]	1.6464	6.1308	13.4542	23.6164	46.894	5852
[0.77, 0.889]	1.3130	4.7394	10.2793	17.9327	67.231	7068
[0.81, 0.889]	1.0148	3.4907	7.4260	12.8210	92.652	8691
[0.85, 0.889]	0.7458	2.3643	4.8488	8.2005	99.034	10966

Table 10.4.1.19. Vehicle spacing for platoons following on wet pavement, for nominal values of parameters

	Inter-Platoon Spacing (m) (intra-platoon spacing is 2 m)					Pipeline Capacity (veh/ln/hr)
Braking Rate Interval (g)	speed of 10 m/s	speed of 20 m/s	speed of 30 m/s	speed of 40 m/s	Percent of Distribution Truncated	speed of 30 m/s
Entire	7.9053	31.4531	70.6470	125.4872	0	7790
[0.53, 0.889]	7.0484	27.9715	62.7730	111.4527	0.082	8259
[0.57, 0.889]	6.2013	24.5229	54.9683	97.5373	0.304	8783
[0.60, 0.889]	5.6423	22.2427	49.8043	88.3272	0.434	9168
[0.61, 0.889]	5.4686	21.5332	48.1971	85.4602	2.534	9295
μ±2σ	5.2832	20.7713	46.4671	82.3706	2.666	9435
[0.63, 0.889]	5.1383	20.1831	45.1375	80.0014	3.198	9546
[0.64, 0.889]	4.9811	19.5403	43.6803	77.4012	5.225	9670
[0.65, 0.889]	4.8290	18.9176	42.2685	74.8817	11.189	9794
[0.66, 0.889]	4.6817	18.3141	40.9000	72.4392	13.757	9917
[0.69, 0.889]	4.2664	16.6109	37.0357	65.5411	25.275	10282
μ±σ	3.8889	15.0167	33.3848	58.9930	26.683	10652
[0.73, 0.889]	3.7681	14.5622	32.3844	57.2347	46.894	10759
[0.77, 0.889]	3.3239	12.7313	28.2237	49.8012	67.231	11224
[0.81, 0.889]	2.9259	11.0858	24.4809	43.1112	92.652	11678
[0.85, 0.889]	2.5674	9.5996	21.0970	37.0596	99.034	12122

10.4.1.7 Sensitivity Analyses

10.4.1.7.1 Pipeline Capacity versus Speed

10.4.1.7.1.1 Assessment of Pipeline Capacity for Uniform Spacing of Vehicles

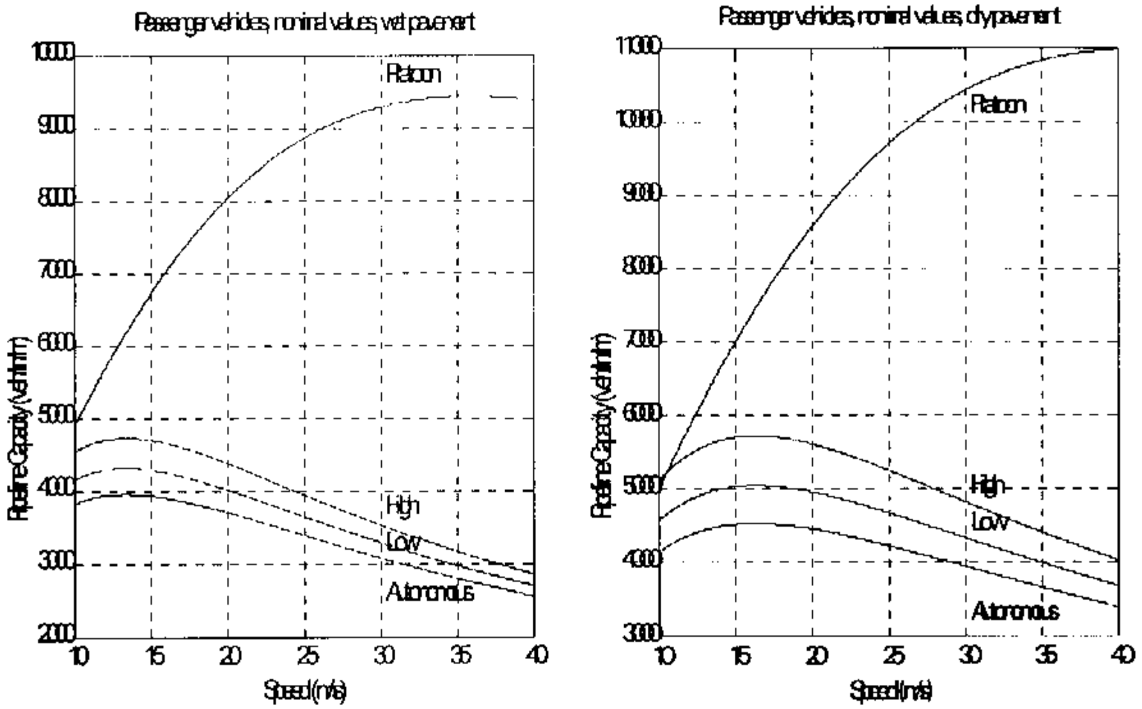
Pipeline capacity versus speed is shown in Figure 10.4.1.3. For vehicle operations on dry pavement, the relationships between pipeline capacity and the independent variables of the vehicle-following models are consistent with those obtained in Task C2. On the closed interval [10, 40] m/s, for all levels of cooperation except platoon operation, pipeline capacity increases until it reaches an absolute maximum value and then begins to decrease. In the case of platoon operation on dry pavement, pipeline capacity is an increasing function on the closed interval and therefore has no absolute extrema, although the capacities appear to be asymptotically approaching a peak above 40 m/s for dry pavement. In the case of platoon operation on wet pavement, the right-most part of the curve in Figure 4.10.1.3(b) appears to peak due to the residual error in fitting a polynomial function to the data. For both dry and wet pavement, platoon operation results in the highest level of pipeline capacity within the nominal operating speeds.

The absolute maximum values for each level of cooperation are shown in Table 10.4.1.20. The absolute maximum pipeline capacities for dry pavement conditions occur between 16.2 and 16.35 m/s, whereas the absolute maximum pipeline capacities for wet pavement conditions occur between 12.1 and 12.2 m/s. The reason for the difference in the range of speeds over which the absolute maximum pipeline capacity for dry and wet pavement conditions is that the lower and upper bounds of the corresponding braking rate distributions differ.

For all levels of cooperation at the nominal speed of 30 m/s, the pipeline capacity on dry pavement is greater than that for wet pavement conditions. In addition, each level of cooperation with uniform spacing, AHS pipeline capacity for operation on wet pavement is lower than that for dry pavement, although the magnitude of the absolute difference in pipeline capacity is not constant as a function of speed, *ceteris paribus*.

Table 10.4.1.20. Maximum pipeline capacity for uniform spacing on dry and wet pavement

	Dry Pavement		Wet Pavement	
Level of Cooperation	Maximum Pipeline Capacity (veh/ln/hr)	Speed at Maximum Pipeline Capacity (m/s)	Maximum Pipeline Capacity (veh/ln/hr)	Speed at Maximum Pipeline Capacity (m/s)
Autonomous individual vehicle	4524	[16.2, 16.35]	3682	[12.1, 12.2]
Low-cooperative vehicle	5042	[16.2, 16.35]	3973	[12.15, 12.2]
High-cooperative vehicle	5718	[16.2, 16.35]	4324	12.15
Platoon operation	NA	NA	NA	NA



(a) (b)

Figure 10.4.1.3. Pipeline capacity versus lower bound on the maximum braking rate: (a) wet pavement and (b) dry pavement

10.4.1.7.1.2 Comparison of the Results of Uniform and Non-Uniform Spacing

With uniform spacing, all vehicles follow each other at the same distance. In the case of non-uniform spacing, each vehicle modifies its following distance to the preceding vehicle based on its knowledge of its own braking capability and possibly knowledge of the preceding vehicle's braking capability. The results for low-cooperative non-uniform spacing are shown in Figures 10.4.1.4 and 10.4.1.5. Table 10.4.1.21 shows the pipeline capacities at 30 m/s for low-cooperative vehicles with non-uniform spacing.

At the nominal operating speed, low-cooperative non-uniform spacing policies produce smaller percentage differences between the pipeline capacity for dry and wet pavement than do uniform spacing policies. In addition, for both dry and wet pavement, pipeline capacity for low-cooperative non-uniform spacing with a 0.5 s minimum headway is much higher than that of non-uniform spacing with a 1 s minimum headway. For speeds between approximately 25 and 40 m/s, pipeline capacity for low-cooperative non-uniform spacing with a 0.5 s minimum headway is greater than that for operation of autonomous individual vehicles, low-cooperative individual vehicles, and high-cooperative individual vehicles with uniform spacing. Given a 1 s minimum headway and speeds between 10 and 30 m/s, low-cooperative non-uniform spacing produces a lower pipeline capacity than that for operation of autonomous individual vehicles with uniform spacing. Low-cooperative non-uniform spacing with a minimum headway of 0.5 s results in higher pipeline capacities than that for high-cooperative vehicles at speeds of between 26 and 40 m/s for dry pavement and between 17.5 and 40 m/s for wet pavement.

Note that the minimum headway of 0.5 s is an artificial limit. All of the vehicles will try to attain this minimum headway and some vehicles could, if not constrained by the limit, follow at a closer inter-vehicle spacing. This is the reason that there appears to be very little increase in pipeline capacity between having a knowledge of one's own braking capability versus having knowledge of both vehicles' braking capabilities.

Table 10.4.1.21. Pipeline capacity for low-cooperative vehicles at the nominal speed of 30 m/s, with the lower bound on the dry braking rate of 0.76 g, and the lower bound on the wet braking rate of 0.61 g

Type of Non-Uniform Spacing Policy	Pipeline Capacity, Dry Pavement (veh/ln/hr)	Pipeline Capacity, Wet Pavement (veh/ln/hr)	Difference (percentage)
Knowledge of own vehicle's braking capability, 0.5 s headway	5351	4997	6.6
Knowledge of own vehicle's braking capability, 1 s headway	3086	3084	0.06
Knowledge of both vehicles' braking capability, 0.5 s headway	5399	5329	1.3
Knowledge of both vehicles' braking capability, 1 s headway	3086	3086	0

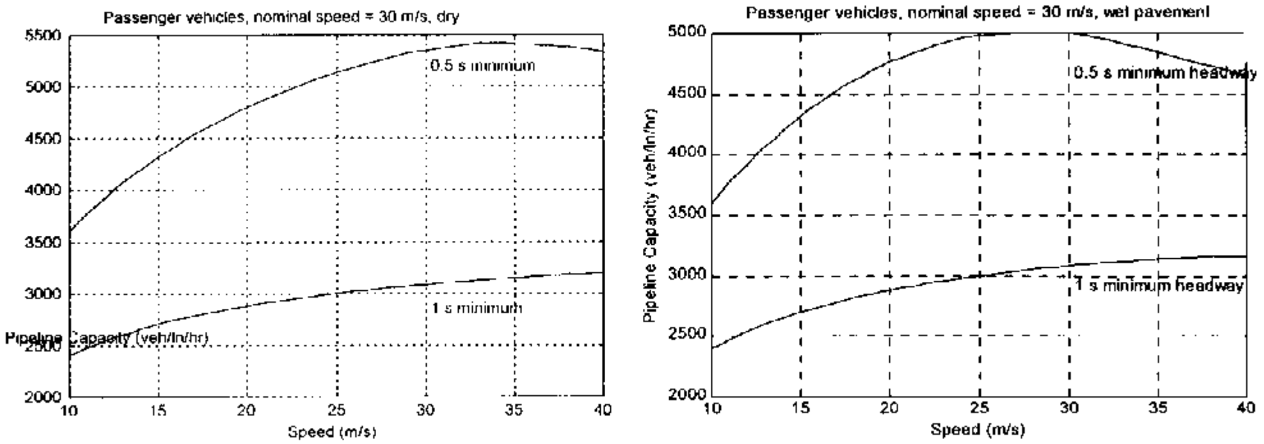


Figure 10.4.1.4. Pipeline capacity versus speed for low-cooperative individual vehicles with non-uniform spacing and the following vehicle only having knowledge of its own braking capability

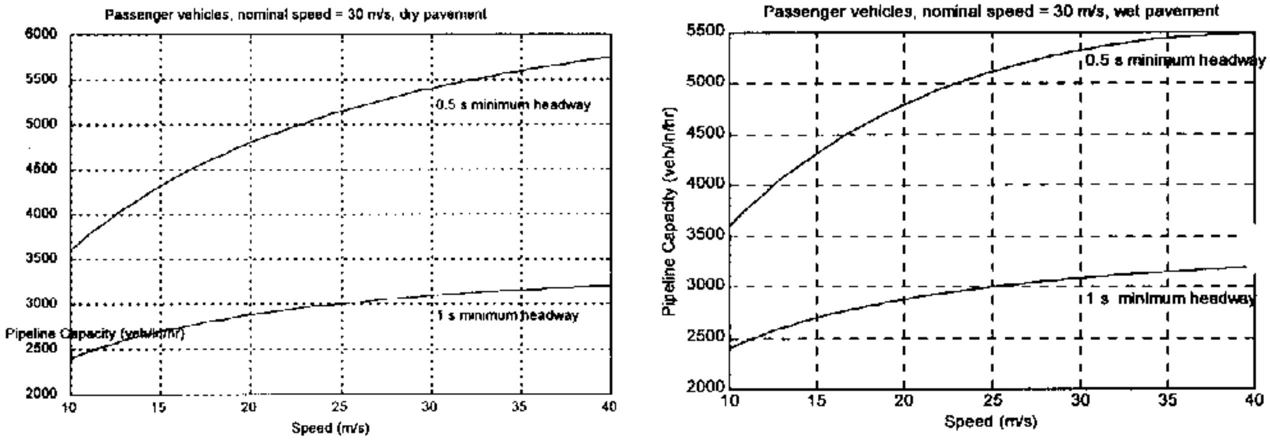


Figure 10.4.1.5. Pipeline capacity versus speed for low-cooperative individual vehicles with non-uniform spacing and the following vehicle having knowledge of its own braking capability and that of the preceding vehicle

Table 10.4.1.22 shows the maximum value of pipeline capacity for each level of cooperation among vehicles and type of spacing policy. Pipeline capacity, as a function of speed, is continuous and increasing over the nominal range of operating speeds for the following: platoon operation on dry pavement, cooperative non-uniform spacing with a 1 s minimum headway, and low-cooperative non-uniform spacing with a 0.5 s minimum headway and the following vehicle knowing its own maximum braking capability and that of the preceding vehicle. For all other pairing of levels of cooperation and spacing policies, the graphs of the continuous functions which approximate the relationship between pipeline capacity and speed are concave downward, with each of the inflection points representing the absolute extrema.

The maximum pipeline capacities for operation of autonomous individual vehicles, low-cooperative vehicles, and high-cooperative vehicles occur at approximately 16 and 12 m/s for dry and wet pavement, respectively. The maximum pipeline capacities occur at speeds in excess of 30 m/s for platoon operation on wet pavement and non-uniform spacing given a minimum headway of 0.5 s on dry pavement with the following vehicle knowing its own braking capability. The maximum pipeline capacity for low-cooperative non-uniform spacing given a minimum headway of 0.5 s on wet pavement with the following vehicle knowing its own braking capability is at 28.5 m/s.

For operation of autonomous individual vehicles, low-cooperative vehicles, and high-cooperative vehicles, the percentage decrease from the maximum pipeline capacity to the pipeline capacity at 30 m/s is higher for wet pavement than for dry pavement. The percentage decrease from the maximum pipeline capacity to the pipeline capacity at 30 m/s is much lower for cooperative non-uniform spacing on wet pavement with a 0.5 s minimum headway. Such comparisons are not applicable for the other pairings of levels of cooperation and spacing policies because the maximum value of the pipeline capacity is reached at a speed in excess of 30 m/s.

10.4.1.7.2 Sensitivity of Pipeline Capacity to the Lower Bound on Maximum Braking Rate

For dry and wet pavement and over the nominal range of braking rates, autonomous, low-cooperative, and high-cooperative individual vehicle operation results in a continuous increase in pipeline capacity as the lower bound on the maximum braking rate is raised. In addition, the graphs in figures 10.4.1.6 and 10.4.1.7 show the divergence of the curves representing pipeline capacity as the lower bound on the maximum braking rate increases.

For both dry and wet pavement, the pipeline capacities for high-cooperative individual vehicle and platoon operation converge as the lower bound on the maximum braking rate is raised. The convergence of the curves is due to the fact that the rate of increase in pipeline capacity for high-cooperative individual vehicle operation (i.e., the slope of the curve) is much greater than that for platoon operation.

The rate of increase in pipeline capacity per unit increase of the lower bound on the maximum braking rate diminishes above 0.76 and 0.61 g for the operation of AHS vehicles using uniform spacing on dry and wet pavement, respectively. The percentage difference in pipeline capacity between dry and wet pavement at 0.76 and 0.61 g, respectively, increases as the level of cooperation among vehicles is raised, as shown in Table 10.4.1.23. However, for platoon operation, the percentage difference between pipeline capacity for dry and wet pavement is approximately half of that of individual vehicles.

Table 10.4.1.22. Maximum values of pipeline capacity for each of the levels of cooperation and the pairing of low-cooperative individual vehicle operation with non-uniform spacing

	Dry Pavement			Wet Pavement		
Level of Cooperation or Spacing Policy	Maximum Value for Speeds less than 30 m/s	Pipeline Capacity (veh/ln/hr) at 30 m/s	Change (percent)	Maximum Value for Speeds less than 30 m/s	Pipeline Capacity (veh/ln/hr) at 30 m/s	Change (percent)
Low-cooperative, non-uniform, self, 1 s minimum headway	NA(a)	3086	NA	NA(a)	3084	NA
Low-cooperative, non-uniform, both, 1 s minimum headway	NA(a)	3086	NA	NA(a)	3086	NA
Autonomous	4524	3939	-12.9	3682	3086	-16.2
Low-cooperative	5042	4327	-14.2	3973	3296	-17.0
High-cooperative	5718	4817	-15.8	4324	3536	-18.2
Low-cooperative, non-uniform, self, 0.5 s headway	NA(b)	5351	NA	5000(c)	4997	-0.06
Low-cooperative, non-uniform, both, 0.5 s minimum headway	NA(a)	5399	NA	NA(a)	5329	NA
Platoon	NA(a)	10425	NA	NA(d)	9295	NA

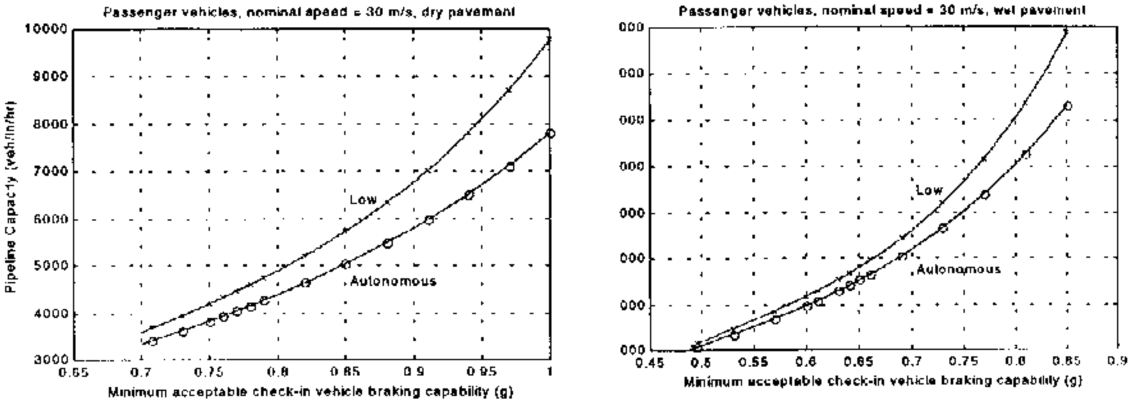
Notes: (a) No inflection point. (b) Maximum pipeline capacity of 5422 veh/ln/hr occurs at 33 m/s. (c) Maximum pipeline capacity occurs at 28.5 m/s. (d) Maximum pipeline capacity of 9441 veh/ln/hr occurs at 35.8 m/s.

Table 10.4.1.23. Pipeline capacity at the nominal speed of 30 m/s, with the lower bound on dry braking rate of 0.76 g, lower bound on wet braking rate of 0.61 g

Level of Cooperation	Pipeline Capacity, Dry Pavement (veh/ln/hr)	Pipeline Capacity, Wet Pavement (veh/ln/hr)	Difference (percentage)
Autonomous individual vehicle	3939	3086	21.7
Low-cooperative vehicle	4327	3296	23.8
High-cooperative vehicle	4817	3536	26.6
Platoon operation	10425	9295	10.8

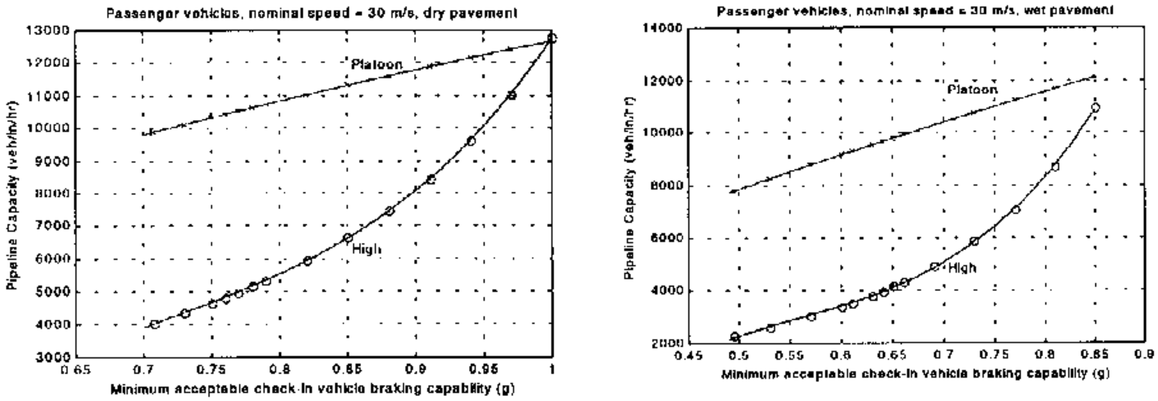
10.4.1.7.3 Sensitivity of Pipeline Capacity to the Percentage of Vehicles Excluded from AHS

Pipeline capacity is sensitive to changes in the percentage of the vehicle population denied access to the AHS. For example, figure 10.4.1.8(a) shows this relationship for the operation of autonomous individual vehicles on dry pavement. As the percentage of vehicles disallowed from entering the AHS lane increases from 0 to 3.22, there is a very rapid increase in the pipeline capacity. Pipeline capacity continues to increase as the percentage of vehicles disallowed entry increases from 3.22 to 89.125, but at a much slower rate than over the initial interval. For percentages in excess of 89.125, pipeline capacity once again increases rapidly. The same trend in changes in the rate of increase in pipeline capacity occurs in the operation of autonomous individual vehicles on wet pavement, as shown in figure 10.4.1.8(b). However, the lower and upper bounds of the three intervals are different, as shown in Table 10.4.1.24.



(a) (b)

Figure 10.4.1.6. Pipeline capacity versus the lower bound on the maximum braking rate: (a) dry pavement and (b) wet pavement



(a) (b)

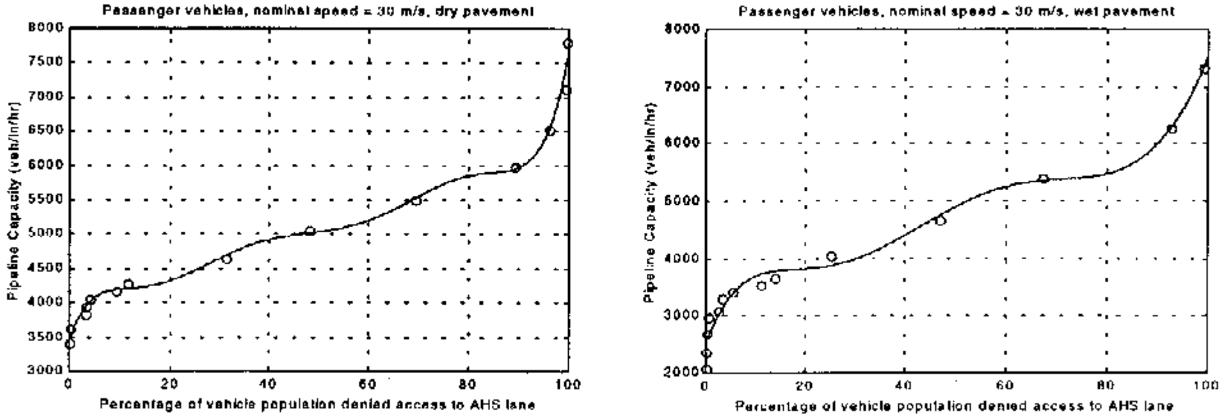
Figure 10.4.1.7. Pipeline capacity versus the lower bound on the maximum braking rate: (a) dry pavement and (b) wet pavement

The same trends occur within these regions for the operation of low-cooperative individual vehicles, high-cooperative individual vehicles, and platoons on both dry and wet pavement. Let $\bar{b}_r$ represent the arithmetic mean of the percentage changes of maximum braking rates in region r, that is $\bar{b}_r = \left(\sum_{i=1}^{n} b_{r_i} \right) \Big/ n$ where n is one model of vehicle less than the total number models in r. The reason for the rapid increase in pipeline capacity when $r = 1$ is that $\bar{b}_r$ is approximately equal to 1.2 and 3.8 percent for dry and wet pavement, respectively. In contrast, if

$r = 2$ then $\overline{b}_r$ is approximately equal to 0.16 and 0.26 percent for dry and wet pavement, respectively. If $r = 3$ then $\overline{b}_r$ is approximately equal to 0.4 and 2.1 percent for dry and wet pavement, respectively.

Table 10.4.1.24. Partitioning of the entire braking-rate intervals into three regions.

	Region I	Region II	Region III
Pavement Condition	Interval (percent)	Interval (percent)	Interval (percent)
Dry	[0, 3.22]	(3.22, 89.125)	[89.125, 99.613]
Wet	[0, 2.534]	(2.534, 92.625)	[92.625, 99.034]



(a) (b)

Figure 10.4.1.8. Pipeline capacity versus percentage of autonomous individual vehicles disallowed from entry onto the AHS lane

In order to highlight the differences in the rate of change of pipeline capacity among the regions, the percentage change and slope for each region are given in tables 10.4.1.25 and 10.4.1.26. Let Δc_r and m_r be the percentage change and slope of region *r*, respectively. In this analysis Δc_r and m_r are approximated by using the values of lower and upper bounds of the region. The equations are $c_r = \left(c_{r_u} - c_{r_l}\right) / \left(c_{r_u}\right)$ and $m_r = \left(c_{r_u} - c_{r_l}\right) / \left(t_{r_u} - t_{r_l}\right)$ where *t* is the percentage of the population of vehicles disallowed from entering the AHS lane, and *l* and *u* denote the lower and upper bounds of the region, respectively. For all the levels of cooperation except platoon operation of an AHS, given dry pavement, $m_3 > m_1 >> m_2$; the relationships for platoon operation are $m_1 >> m_3 >> m_2$. For wet pavement the relationships $m_1 >> m_3 >> m_2$ hold for all levels of cooperation. These relationships differ for dry and wet pavement because of the differences between the properties of the dry and wet braking-rate distributions.

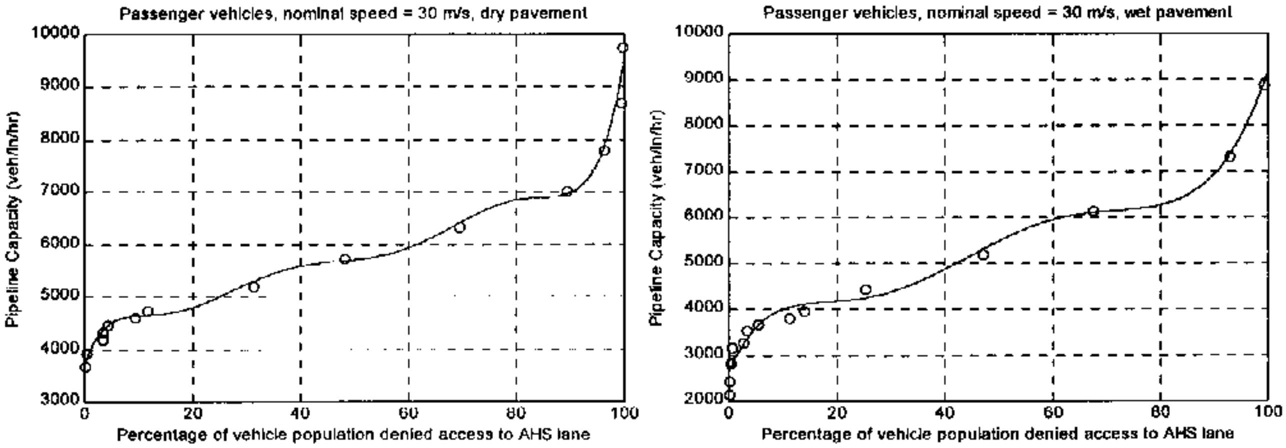
Figures 10.4.1.9 through 10.4.1.11 show the relationship between *c* and *t* for low-cooperative individual vehicles, high-cooperative individual vehicles, and platoons.

Table 10.4.1.25. Percentage change in pipeline capacity and slope, dry pavement

	$r = 1$		$r = 2$		$r = 3$	
Level of Cooperation	c	m	c	m	c	m
Autonomous individual vehicles	13.6	166.1	34.2	23.8	23.3	173.6
Low-cooperative vehicles	15.0	200.9	38.4	31.4	28.1	262.1
High-cooperative vehicles	16.4	245.7	42.9	42.2	33.9	413.4
Platoons	5.3	170.8	12.2	16.8	6.3	76.0

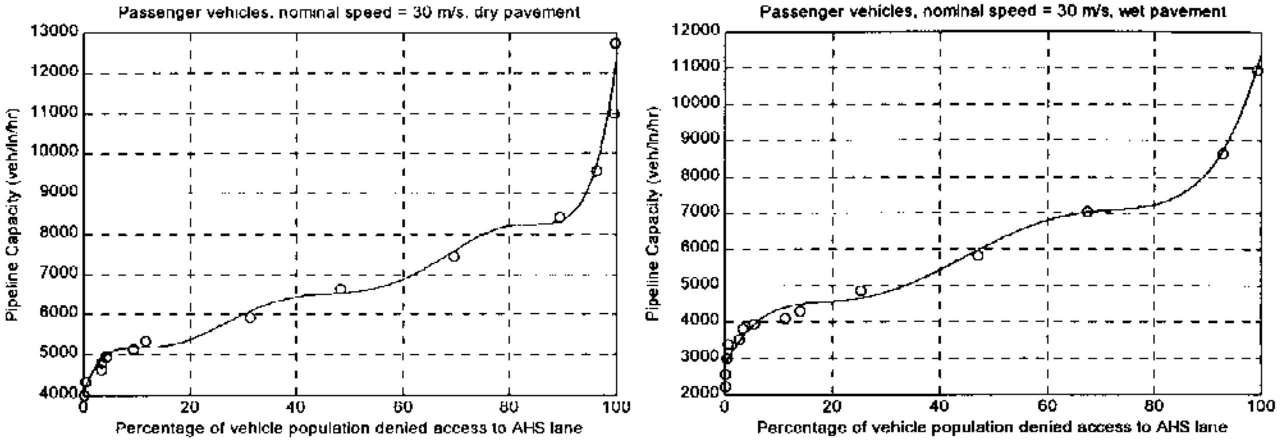
Table 10.4.1.26. Percentage change in pipeline capacity and slope, wet pavement

	$r = 1$		$r = 2$		$r = 3$	
Level of Cooperation	c	m	c	m	c	m
Autonomous individual vehicles	32.6	397.4	50.7	35.2	14.6	167.2
Low-cooperative vehicles	34.4	447.0	55.1	44.9	17.4	243.0
High-cooperative vehicles	36.0	502.8	59.3	57.2	20.7	356.5
Platoons	16.2	591.8	20.4	26.4	3.7	69.6



(a) (b)

Figure 10.4.1.9. Pipeline capacity versus percentage of low-cooperative individual vehicles disallowed from entry onto the AHS lane



(a) (b)

Figure 10.4.1.10. Pipeline capacity versus percentage of high-cooperative individual vehicles disallowed from entry onto the AHS lane

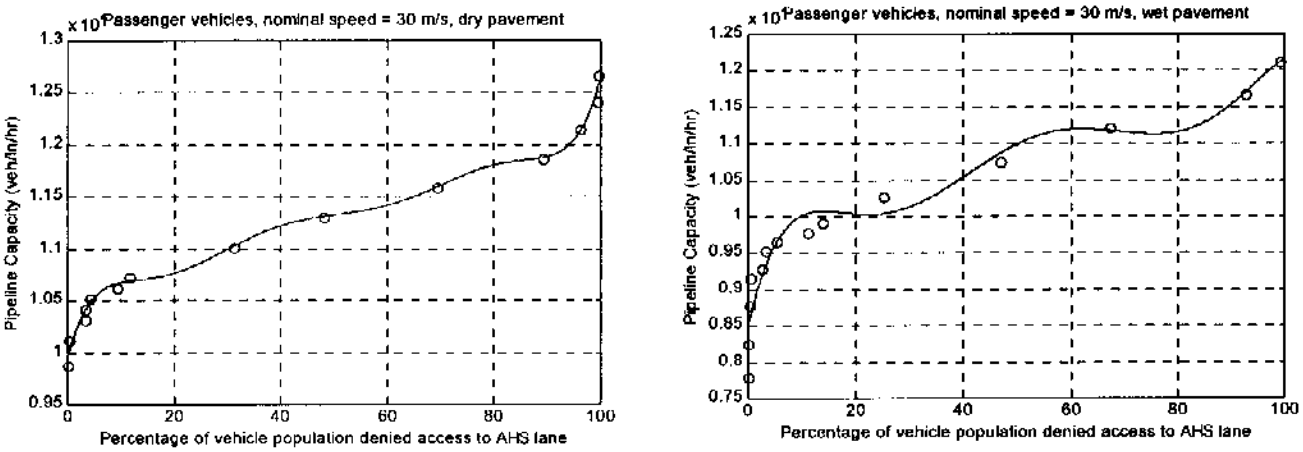


Figure 10.4.1.11 Pipeline capacity versus percentage of platoon-equipped vehicles disallowed from entry onto the AHS lane

10.4.1.7.4 Assessment of Candidate Lower Bounds on Acceptable Braking Rates

For the purpose of optimizing pipeline capacity on an AHS lane, a policy must be enforced at the point of entry to the AHS lane regarding the minimum braking performance a vehicle must exhibit. Since the occurrence of precipitation is outside the control of the AHS, the vehicle check-in policy must take into consideration the braking performance of each vehicle for both dry and wet pavement conditions. For instance, if a vehicle brakes well on dry pavement but performs poorly on wet pavement, it may be in the best interest of the AHS lane users as a whole to disallow entry of that vehicle into the flow of traffic on the AHS lane.

Therefore, a check-in policy regarding braking performance is a conditional rule consisting of two conjuncts. The general form of the rule is

> If and only if the vehicle meets or exceeds both the minimum thresholds on the maximum braking rate on dry pavement *and* the maximum braking rate on wet pavement, then the vehicle may enter the AHS lane. Otherwise, the vehicle is rejected from entry to the AHS.

In Section 10.4.1.7.2 it was noted that the rate of increase in pipeline capacity per unit increase of the lower bound on the maximum braking rate diminishes above 0.76 and 0.61 g for the operation of AHS vehicles using uniform spacing on dry and wet pavement, respectively. Suppose one were to set the lower bound on the maximum rate of deceleration on dry pavement to 0.76 g. What should be the corresponding lower bound on wet pavement? To answer this question, consider the summary statistics for the lower twenty-two percent of the sample of the vehicle population in terms of maximum braking rates shown in Table 10.4.1.27. Note that the first five rows of the table contain braking rates for dry pavement that are below 0.76 g. The next four rows contain braking rates on wet pavement that are less than 0.61 g.

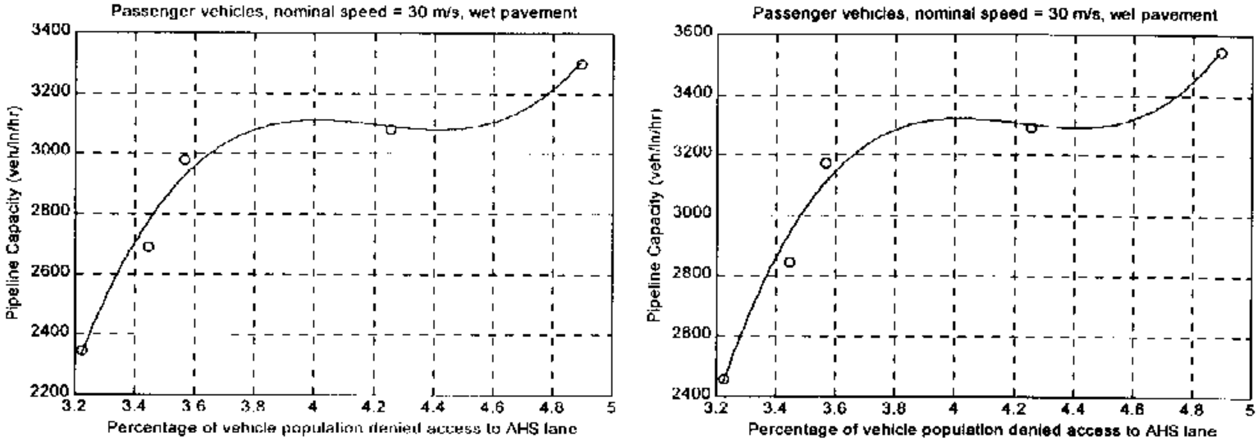
Table 10.4.1.27. Summary statistics for the lower twenty-two percent of the sample of the vehicle population in terms of maximum braking rates

Model	Dry (g)	Wet (g)	Total Unit Sales (veh) 1994-95
Eagle Summit	0.707	0.495	20464
Buick Roadmaster	0.724	No data	62273
Ford Aerostar	0.733	No data	255710
Oldsmobile Eighty-Eight	0.742	No data	135920
Toyota pickup (Tacoma LX)	0.742	0.604	347684
Subaru Impreza	0.828	0.550	55281
Land Rover (Discovery)	0.845	0.598	32071
Honda Passport (EX)	0.857	0.604	53739
Isuzu Rodeo	0.857	0.604	120629
Toyota Tercel	0.775	0.620	164916
Dodge Ram pickups (1500)	0.811	0.633	503593
Chevrolet Tahoe	0.765	0.646	105368
GMC Yukon	0.765	0.646	39352
GMC Safari	0.765	0.657	86238
Buick LeSabre	0.780	0.657	300910
Chevrolet Astro	0.785	0.657	250724
Ford Escort	0.822	0.668	622537
Ford Windstar	0.896	0.675	346071
GMC Sonoma (SLE)	0.775	0.679	111850
Toyota Camary	0.882	0.687	650581
Chevrolet C/K pickups (C1500)	0.811	0.691	1117346
GMC Sierra pickup	0.811	0.691	366303

Table 10.4.1.28 shows the percentage of the vehicle population excluded from AHS pipeline given progressively stricter lower bounds on the maximum braking rates on dry and wet pavement, denoted b_d and b_w, respectively. Holding b_d constant and increasing the value of b_w results initially in a very small increase—less than a third of a percent—in the percentage of the vehicle population excluded from the AHS pipeline. From 0.61 g onward, 0.01 g increases in b_w result in much greater incremental increases in the exclusion of the vehicle population. Figures 10.4.1.12 through 10.4.1.13 show the corresponding increases in pipeline capacity for the braking rate requirements given in Table 10.4.1.28. The slope of the functions shown in those graphs is high initially, and then tapers off between 0.61 and 0.63 g.

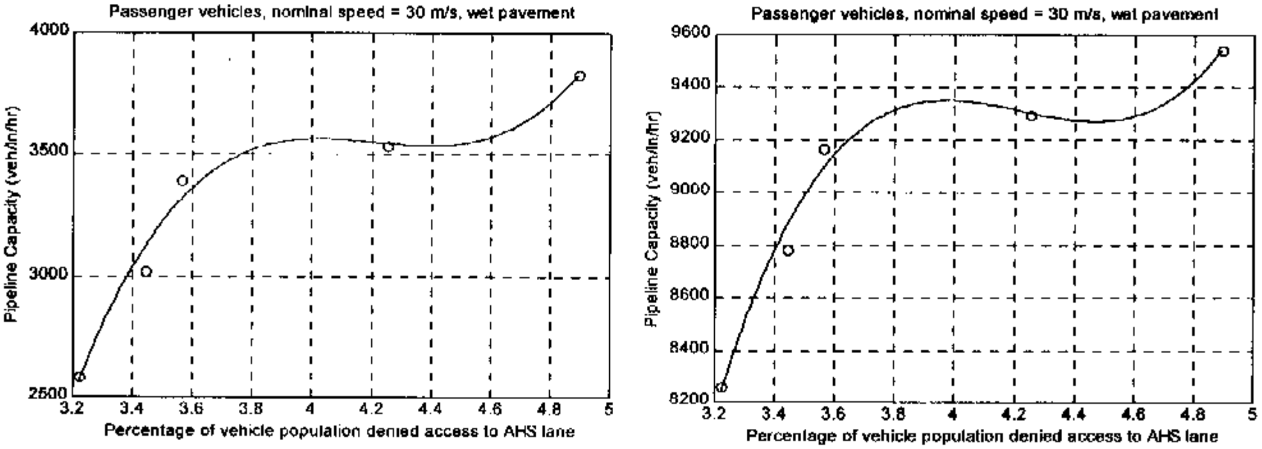
Table 10.4.1.28. Percentage of the vehicle population excluded from AHS pipeline given progressively stricter lower bounds on the maximum braking rate performance of automated vehicles

Braking Rate Requirement for Entry to the AHS Pipeline	Percentage of Vehicle Population Excluded from AHS Pipeline
$b_d \geq 0.76$	3.22
$b_d \geq 0.76 \wedge b_w \geq 0.56$	3.44
$b_d \geq 0.76 \wedge b_w \geq 0.60$	3.56
$b_d \geq 0.76 \wedge b_w \geq 0.61$	4.25
$b_d \geq 0.76 \wedge b_w \geq 0.63$	4.89
$b_d \geq 0.76 \wedge b_w \geq 0.64$	6.86
$b_d \geq 0.76 \wedge b_w \geq 0.65$	7.43
$b_d \geq 0.76 \wedge b_w \geq 0.66$	9.93
$b_d \geq 0.76 \wedge b_w \geq 0.67$	12.4
$b_d \geq 0.76 \wedge b_w \geq 0.68$	14.2
$b_d \geq 0.76 \wedge b_w \geq 0.69$	16.7
$b_d \geq 0.76 \wedge b_w \geq 0.70$	22.5



(a) (b)

Figure 10.4.1.12. Pipeline capacity versus speed for $b_d = 0.76$ g while varying the value of b_w, (a) autonomous individual vehicles and (b) low-cooperative individual vehicles



(a) (b)

Figure 10.4.1.13. Pipeline capacity versus speed for $b_d = 0.76$ g while varying the value of b_w, (a) high-cooperative individual vehicle and (b) platoon operation

References

Michael, J. B., D. N. Godbole, R. Sengupta, and J. Lygeros. "Capacity Analysis of Traffic Flow over a Single-Lane Automated Highway System." *ITS Journal*, vol. 4, No. 1, March 1998.

10.4.1.8 Raw Data

10.4.1.8.1 Raw Data for Cars

Table 10.4.1.29. Sales volume and braking rates of budget cars

Model	1994 Sales	1995 Sales	Total Sales	Dry (ft)	Dry (g)	Wet (ft)	Wet (g)
Plymouth Neon	85,660	106,205	191,865	140	0.868	153	0.794
Dodge Neon	93,300	133,984	227,284	140	0.868	153	0.794
Nissan Sentra	172,129	134,854	306,983	142	0.856	158	0.769
Toyota Tercel	88,627	76,289	164,916	156	0.779	195	0.623
Chevrolet-Geo Metro	79,598	75,697	155,295	151	0.805	172	0.707
Ford Aspire	0	59,191	59,191	146	0.833	165	0.737
Ford Festiva/Aspire	35,737	0	35,737				
Hyundai Excel	52,335	0	52,335				
Dodge Shadow	49,366	0	49,366				
Hyundai Accent	0	47,908	47,908	137	0.887	172	0.707
Mitsubishi Mirage	40,007	42,902	82,909	142	0.856	167	0.728
Plymouth Sundance	37,510	0	37,510				
Kia Sephia	12,163	16,725	28,888				
Eagle Summit	11,021	9,443	20,464	171	0.711	244	0.498
Suzuki Swift	7,136	3,807	10,943				
Suzuki Swift/Esteem	0	4,385	4,385	143	0.85	162	0.75
Dodge Colt	4,628	682	5,310				
Subaru Justy	3,732	0	3,732				
Plymouth Vista	2,378	0	2,378				
Plymouth Colt	3,732	611	4,343				
Mitsubishi Precis	409	0	409				
Total	779,468	712,683	1,492,151				

Table 10.4.1.30. Sales volume and braking rates of small cars

Model	1994 Sales	1995 Sales	Total Sales	Dry (ft)	Dry (g)	Wet (ft)	Wet (g)
Ford Escort	336,967	285,570	622,537	147	0.827	181	0.672
Saturn	286,003	285,674	571,677	142	0.856	158	0.769
Honda Civic	267,023	289,435	556,458	136	0.894	152	0.8
Toyota Corolla (DX)	210,926	213,640	424,566	143	0.85	153	0.794
Chevrolet Cavalier	187,263	212,767	400,030	144	0.844	172	0.707
Chevrolet/Geo Prism	117,496	87,295	204,791	140	0.868	152	0.8
Dodge Stratus	0	75,439	75,439	150	0.81	162	0.75
Mazda Protégé	93,716	62,849	156,565	135	0.9	167	0.728
Pontiac Sunbird	65,809	763	66,572				
Mercury Tracer	57,266	51,988	109,254	143	0.85	157	0.774
Hyundai Elantra	45,056	37,653	82,709	140	0.868	166	0.732
Subaru Impreza	30,868	24,413	55,281	146	0.833	220	0.553
Hyundai Scoupe	15,365	4,762	20,127				
Mitsubishi Expo	6,781	3,752	10,533				
Mazda 323	6,047	27	6,074	135	0.9	167	0.728
Chevrolet/Geo Storm	4,869	51	4,920				
Volkswagen Fox	3,922	112	4,034				
Mitsubishi Expo LRV	2,988	9	2,997				
Pontiac Sunfire	1,940	74,424	76,364	135	0.9	153	0.794
Nissan 200SX	0	32,663	32,663	125	0.972	136	0.894
Nissan NX	423	3	426				
Isuzu Stylus	96	15	111				
Isuzu Impulse	13	1	14				
Nissan Stanza	9	0	9				
Mitsubishi Spyder	0	232	232				
Mitsubishi Sigma	1	0	1				
Total	1,740,847	1,743,537	3,484,384				

Table 10.4.1.31. Sales volume and braking rates of lower mid-range cars

Model	1994 Sales	1995 Sales	Total Sales	Dry (ft)	Dry (g)	Wet (ft)	Wet (g)
Pontiac Grand Am	262,310	234,226	496,536	150	0.81	171	0.711
Chevrolet Corsica-Beretta	222,129	192,361	414,490	153	0.794		
Nissan Altima	163,090	148,172	311,262	132	0.921	149	0.816
Ford Tempo	94,712	1,780	96,492				
Acura Integra	67,426	61,316	128,742	142	0.856	170	0.715
Plymouth Acclaim	63,837	6,457	70,294				
Buick Skylark	60,583	44,522	105,105	142	0.856		
Dodge Spirit	59,422	6,158	65,580				
Oldsmobile Achieva	57,735	44,787	102,522	149	0.816	165	0.737
Volkswagen Jetta	55,688	75,393	131,081	134	0.907	156	0.779
Mercury Topaz	32,597	399	32,996				
Ford Contour	25,997	174,214	200,211	138	0.881	167	0.728
Volkswagen Golf/GTI	16,385	18,429	34,814	134	0.907	149	0.816
Mercury Mystique	8,701	62,609	71,310	140	0.868	165	0.737
Subaru Loyale	5,530	2	5,532				
Plymouth Breeze	0	0	0	146	0.833	160	0.76
Total	1,196,142	1,070,825	2,266,967				

Table 10.4.1.32. Sales volume and braking rates of mid-range cars

Model	1994 Sales	1995 Sales	Total Sales	Dry (ft)	Dry (g)	Wet (ft)	Wet (g)
Ford Taurus	397,037	366,266	763,303	142	0.856	165	0.737
Honda Accord	367,615	341,384	708,999	133	0.914	163	0.746
Toyota Camary	321,979	328,602	650,581	137	0.887	176	0.691
Oldsmobile Ciera	141,100	128,860	269,960	144	0.844	155	0.784
Buick Century	138,948	93,361	232,309	144	0.844	155	0.784
Dodge Intrepid	133,475	147,576	281,051	137	0.887	155	0.784
Ford Thunderbird	130,713	104,254	234,967	131	0.928	153	0.794
Chevrolet Lumina	122,314	214,595	336,909	139	0.874	165	0.737
Pontiac Grand Prix	118,229	131,747	249,976	143	0.85	168	0.724
Mercury Sable	113,282	102,565	215,847	140	0.868	172	0.707
Oldsmobile Cutlass Supreme	104,596	89,629	194,225	133	0.914	151	0.805
Mazda 626	88,516	89,699	178,215	143	0.85	149	0.816
Mercury Cougar	77,982	53,387	131,369	131	0.928	153	0.794
Buick Regal	75,304	90,896	166,200	138	0.881	150	0.81
Mitsubishi Galant	65,665	55,284	120,949	144	0.844	150	0.81
Subaru Legacy	58,880	74,191	133,071	125	0.972	153	0.794
Chrysler LeBaron J	37,547	30,189	67,736				
Chevrolet Monte Carlo	34,325	74,924	109,249	139	0.874	165	0.737
Eagle Vison	23,794	23,345	47,139	137	0.887	155	0.784
Chrysler LeBaron A	13,534	0	13,534				
Hyundai Sonata	13,339	4,010	17,349	135	0.9	158	0.769
Chrysler Cirrus	12,997	60,554	73,551	145	0.838	167	0.728
Volkswagen Passat	11,021	0	11,021	132	0.921	154	0.789
Toyota Cressida	6	2	8				
Total	2,602,198	2,605,320	5,207,518				

Table 10.4.1.33. Sales volume and braking rates of upper mid-range cars

Model	1994 Sales	1995 Sales	Total Sales	Dry (ft)	Dry (g)	Wet (ft)	Wet (g)
Buick LeSabre	159,500	141,410	300,910	155	0.784	184	0.661
Nissan Maxima	128,604	128,599	257,203	133	0.914	158	0.769
Ford Crown Victoria	103,040	98,163	201,203	126	0.965	153	0.794
Mercury Grand Marquis	96,631	90,367	186,998	126	0.965	153	0.794
Pontiac Bonneville	93,027	83,364	176,391	138	0.881	159	0.764
Chevrolet Caprice	97,732	78,890	176,622	133	0.914	151	0.805
Oldsmobile Eighty-Eight	74,023	61,897	135,920	163	0.746		
Chrysler Concorde	63,714	49,521	113,235	137	0.887	155	0.784
Buick Roadmaster	37,038	25,235	62,273	167	0.728		
Infiniti G20	16,778	16,818	33,596	136	0.894	149	0.816
Volvo 200 series	746	0	746				
Total	870,833	774,264	1,645,097				

Table 10.4.1.34. Sales volume and braking rates of near luxury cars

Model	1994 Sales	1995 Sales	Total Sales	Dry (ft)	Dry (g)	Wet (ft)	Wet (g)
Chrysler New Yorker LH/LHS	69,550	46,462	116,012	132	0.921	149	0.816
Buick Park Avenue	57,314	53,045	110,359				
Volvo 800 series (850)	47,943	59,369	107,312	125	0.972	139	0.874
BMW 3 series (325i)	46,301	48,914	95,215	131	0.928	145	0.838
Lexus ES300	39,108	41,507	80,615	133	0.914	167	0.728
Volvo 900 series	32,113	0	32,113				
Mazda Millenia	24,423	21,561	45,984	136	0.894	157	0.774
Oldsmobile Ninety Eight	24,016	20,008	44,024				
Buick Riviera	18,149	23,350	41,499	133	0.914	147	0.827
Mitsubishi Diamante	18,096	10,335	28,431				
Saab 900 S	15,530	19,441	34,971	131	0.928	155	0.784
Mazda 929	9,206	3,773	12,979				
Acura Vigor	8,469	0	8,469				
Acura Vigor/TL	0	16,792	16,792	133	0.914	152	0.8
Acura 3.5 RL	0	0	0	133	0.914	159	0.764
Toyota Avalon	6,603	66,445	73,048	129	0.942	146	0.833
Audi 90	5,347	0	5,347				
Saab 9000 CS	4,548	4,692	9,240				
BMW M3	2,954	5,806	8,760				
Saab 9000 Aero	933	708	1641				
Saab 9000 CD	510	0	510				
Saab 9000 CDE	0	610	610	129	0.942	142	0.856
Audi V8 Quattro	77	1	78				
Volvo 700 Series	4	7	11				
Infiniti M30	4	0	4				
Audi 80	2	0	2				
Chrysler Sebring	0	28,438	28438				
Volvo 940 series	0	27,645	27645	133	0.914	143	0.85
Infiniti I30	0	16,096	16096	138	0.881	156	0.779
Audi A4	0	8,556	8556	130	0.935	149	0.816
Total	431,200	523,561	954,761				

Table 10.4.1.35. Sales volume and braking rates of luxury cars

Model	1994 Sales	1995 Sales	Total Sales	Dry (ft)	Dry (g)	Wet (ft)	Wet (g)
Cadillac DeVille	124,804	106,581	231,385				
Lincoln Town Car	120,191	92,673	212,864				
Lincoln Continental	32,145	40,708	72,853	137	0.887	156	0.779
Cadillac Seville	37,868	37,025	74,893	137	0.887	153	0.794
Mercedes-Benz C class (C280)	23,804	27,119	50,923	126	0.965	150	0.81
Oldsmobile Aurora	22,377	26,544	48,921	136	0.894	155	0.784
Mercedes-Benz E class (320)	26,885	24,915	51,800	125	0.972	148	0.821
Lexus LS 400	22,443	23,658	46,101	133	0.914	170	0.715
Cadillac Eldorado	24,837	23,200	48,037	134	0.907	146	0.833
BMW 5 series (528i,540i)	24,163	22,636	46,799	125	0.972	148	0.821
Acura Legend	35,709	18,159	53,868				
Infiniti J30	22,718	17,899	40,617				
Mercedes-Benz S class	16,388	17,754	34,142				
Lincoln Mark VIII	26,830	17,433	44,263	134	0.907	149	0.816
BMW 7 series (740i)	10,022	15,005	25,027				
Cadillac Fleetwood/Brougham	22,218	13,698	35,916				
Jaguar XJ6	10,903	12,682	23,585	132	0.921	164	0.741
Audi 100/A6	6,612	8,619	15,231				
Infiniti Q45	11,949	7,803	19,752	136	0.894	151	0.805
Lexus GS 300	13,939	6,449	20,388	135	0.9	158	0.769
Jaguar XJS	4,292	5,403	9,695				
Lexus SC 400	7,392	4,364	11,756	120	1.013	141	0.862
Lexus SC 300	4,537	3,356	7,893				
BMW 850i	1,047	949	1,996				
Audi S4/S6	535	948	1483				
Alfa Romeo	0	386	386				
Rolls/Bentley	360	302	662				
Acura Vigor	357	0	357				
Aston Martin	60	0	60				
BMW M5	10	0	10				
BMW 635 Csi	4	0	4				
Audi 200 Quattro	2	0	2				
Total	655,401	576,268	1,231,669				

Table 10.4.1.36. Sales volume and braking rates of sporty cars

Model	1994 Sales	1995 Sales	Total Sales	Dry (ft)	Dry (g)	Wet (ft)	Wet (g)
Ford Mustang	158,421	136,962	295,383	132	0.921	146	0.833
Chevrolet Camaro (V6)	116,592	97,525	214,117	134	0.907	152	0.8
Ford Probe	86,644	52,696	139,340	131	0.928	156	0.779
Mitsubishi Eclipse	51,826	52,555	104,381				
Pontiac Firebird	45,028	42,302	87,330	118	1.03	141	0.862
Toyota Celica	34,787	21,384	56,171	132	0.921	168	0.724
Eagle Talon	27,680	20,824	48,504	124	0.98	143	0.85
Mazda MX-5 Miata	21,400	20,174	41,574	124	0.98	169	0.719
Mazda MX-6	20,649	16,153	36,802	130	0.935	146	0.833
Mazda MX-3	16,630	8,076	24,706				
Honda Prelude	15,467	12,517	27,984	136	0.894	161	0.755
Nissan 240SX	15,209	13,175	28,384				
Toyota Paseo	10,467	5,618	16,085				
Dodge Avenger	4,967	34,757	39,724	129	0.942	157	0.774
Plymouth Laser	4,696	0	4,696				
Mercury Capri	3,948	0	3,948				
Volkswagen Cabrio	2,882	5,435	8,317				
Subaru SVX	1,609	1,801	3,410				
Volkswagen Corrado	1,514	172	1,686				
Volkswagen Cabriolet	956	103	1059				
Toyota MR2	908	387	1295				
Total	642,280	542,616	1,184,896				

Table 10.4.1.37. Sales volume and braking rates of specialty cars

Model	1994 Sales	1995 Sales	Total Sales	Dry (ft)	Dry (g)	Wet (ft)	Wet (g)
Chevrolet Corvette *	21,839	19,966	41,805				
Mitsubishi 3000GT	15,230	10,198	25,428				
Mercedes-Benz SL Coupe/Roadster	5,925	6,964	12,889				
Nissan 300ZX	6,246	4,176	10,422				
Dodge Stealth	7,090	4,087	11,177				
Porsche 911 Carrera 2	380	1,070	1450				
Porsche 911 Carrera Coupe *	3,881	2,720	6,601				
Toyota Supra *	3,422	2,273	5,695				
Mazda RX-7	2,212	1,399	3,611				
Dodge Viper	1,926	1,227	3,153				
Acura NSX	533	884	1417				
Porsche 911 Carrera 4	110	866	976				
Porsche Carrera Turbo	114	655	769				
Ferrari	480	625	1105				
Porsche 968/Cabriolet	1,269	365	1,634				
Lotus	120	120	240				
Porsche 928S4/GT	84	95	179				
Lamborghini	120	35	155				
Alfa Romeo Spider	208	28	236				
Cadillac Allante	959	0	959				
Total	72,148	57,753	129,901				

10.4.1.8.2 Raw Data for Light-Trucks

Table 10.4.1.38. Sales volume and braking rates of minivans

Model	1994 Sales	1995 Sales	Total Sales	Dry (ft)	Dry (g)	Wet (ft)	Wet (g)
Dodge Caravan	268,013	264,937	532,950	144	0.844	155	0.784
Ford Windstar	123,924	222,147	346,071	135	0.9	179	0.679
Plymouth Voyager	211,494	178,327	389,821	137	0.887	152	0.8
Chevrolet Astro	131,214	119,510	250,724	154	0.789	184	0.661
Ford Aerostar	168,163	87,547	255,710	165	0.737		
Mercury Villager	76,844	75,052	151,896	140	0.868	161	0.755
Nissan Quest	49,597	54,050	103,647	140	0.868	161	0.755
Chrysler Town & Country	33,656	50,733	84,389	146	0.833	155	0.784
Chevrolet Lumina minivan	47,037	47,428	94,465	145	0.838	146	0.833
GMC Safari	46,153	40,085	86,238	158	0.769	184	0.661
Pontiac Trans Sport	34,841	32,297	67,138	145	0.838	167	0.728
Honda Odyssey (EX)	230	25,911	26141	143	0.85	158	0.769
Toyota Previa	18,005	18,234	36,239	152	0.8		
Mazda MPV	28,217	14,784	43,001	144	0.844	160	0.76
Oldsmobile Silhouette	14,508	11,874	26,382				
Dodge Caravan C/V	8,950	2,083	11,033				
VW EuroVan/Vanagon	4,675	1,460	6,135				
Mitsubishi van	2	0	2				
Dodge Grand Caravan	0	0	0	146	0.833	155	0.784
Total	1,265,523	1,246,459	2,511,982				

Table 10.4.1.39. Sales volume and braking rates of full-size vans

Model	1994 Sales	1995 Sales	Total Sales	Dry (ft)	Dry (g)	Wet (ft)	Wet (g)
Ford Econoline	171,899	157,803	329,702				
Chevrolet G van	81,922	86,838	168,760				
Dodge Ram van	59,100	56,004	115104				
Ford Club Wagon	32,180	37,232	69,412				
GMC G van	31,923	34,570	66,493				
Dodge Ram Wagon	25,976	16,273	42,249				
Chevrolet Sportvan	6,141	7,090	13,231				
Total	409,141	395,810	804,951				

Table 10.4.1.40. Sales volume and braking rates of compact sport utility vehicles

Model	1994 Sales	1995 Sales	Total Sales	Dry (ft)	Dry (g)	Wet (ft)	Wet (g)
Ford Explorer	278,065	395,227	673,292	148	0.821	181	0.672
Jeep Grand Cherokee	283,512	252,186	535,698	144	0.844	159	0.764
Chevrolet Blazer	193,722	214,661	408,383	156	0.779	172	0.707
Jeep Cherokee	122,981	110,552	233,533				
Toyota 4Runner	74,590	75,962	150,552	132	0.921	161	0.755
GMC Jimmy	65,016	71,807	136,823	156	0.779	172	0.707
Nissan Pathfinder	64,162	69,934	134,096	153	0.794	158	0.769
Jeep Wrangler	74,952	63,890	138,842				
Isuzu Rodeo	59,721	60,908	120,629	141	0.862	200	0.608
Chevrolet Geo Tracker	46,488	41,643	88,131	143	0.85	155	0.784
Honda Passport (EX)	25,758	27,981	53,739	141	0.862	200	0.608
Isuzu Trooper	26,897	23,607	50,504	156	0.779		
Suzuki Sidekick	25,224	22,046	47,270	142	0.856	161	0.755
Mitsubishi Montero	15,859	17,747	33,606	143	0.85		
Kia Sportage	0	8,015	8,015				
Oldsmobile Bravada	10,590	3,946	14,536				
Mazda Navajo	6,185	1,813	7,998				
Isuzu Amigo	5,963	1,561	7,524				
Suzuki Sport	0	1,182	1,182				
Suzuki Samurai	0	624	624				
Suzuki X-90	0	388	388	149	0.816	164	0.741
Acura SLX	0	200	200				
Isuzu Samari	1,312	0	1,312				
Toyota RAV4	0	0	0	135	0.9	151	0.805
Total	1,380,997	1,465,880	2,846,877				

Table 10.4.1.41. Sales volume and braking rates of full-size sport utility vehicles

Model	1994 Sales	1995 Sales	Total Sales	Dry (ft)	Dry (g)	Wet (ft)	Wet (g)
Chevrolet Tahoe	24,337	81,031	105,368	158	0.769	187	0.65
Chevrolet Suburban	91,393	78,544	169,937				
Ford Bronco	37,367	34,210	71,577				
GMC Suburban	33,567	30,435	64,002				
GMC Yukon	10,303	29,049	39,352	158	0.769	187	0.65
Toyota Land Cruiser	11,051	14,240	25,291	136	0.894	156	0.779
Land Rover (Discovery)	12,045	20,026	32,071	143	0.85	202	0.602
Total	220,063	287,535	507,598				

Table 10.4.1.42. Sales volume and braking rates of compact pickups

Model	1994 Sales	1995 Sales	Total Sales	Dry (ft)	Dry (g)	Wet (ft)	Wet (g)
Ford Ranger (XLT)	344,744	309,085	653,829	141	0.862	166	0.732
Chevrolet S pickup	250,991	207,193	458,184	156	0.779	178	0.683
Toyota pickup (Tacoma LX)	204,212	143,472	347,684	163	0.746	200	0.608
Nissan pickup	123,287	126,662	249,949				
Dodge Dakota (SLT)	116,445	111,677	228,122	142	0.856	165	0.737
GMC Sonoma (SLE)	61,333	50,517	111,850	156	0.779	178	0.683
Mazda pickup	58,215	43,437	101,652	141	0.862	166	0.732
Isuzu pickup	24,580	14,770	39,350				
Mitsubishi pickup	13,414	5,045	18,459				
Total	1,197,221	1,011,858	2,209,079				

Table 10.4.1.43. Sales volume and braking rates of full-size pickups

Model	1994 Sales	1995 Sales	Total Sales	Dry (ft)	Dry (g)	Wet (ft)	Wet (g)
Ford F-series pickups (150)	646,039	691,452	1,337,491	153	0.794	189	0.643
Chevrolet C/K pickups (C1500)	580,445	536,901	1,117,346	149	0.816	175	0.695
Dodge Ram pickups (1500)	232,092	271,501	503,593	149	0.816	191	0.636
GMC Sierra pickup	189,346	176,957	366,303	149	0.816	175	0.695
Toyota T100 pickup	15,080	37,467	52,547				
GMC W4 Forward	4,503	3,099	7,602				
GMC P-model chassis	2,281	5,487	7,768				
Total	1,669,786	1,722,864	3,392,650				

10.4.2 MIXED TRAFFIC THROUGHPUT ANALYSIS

Authors Mark Miller and Steve Shladover

10.4.2.1 INTRODUCTION

The issue of automation only in dedicated lanes (where automated vehicles are segregated from non-automated or manual vehicles) versus mixed traffic automated operations (where automated and manual vehicles travel in the same lane) is a significant one which draws divergent views both from within the AHS research community as well as from AHS stakeholder groups.

With the objective of trying to better understand some of the differences between dedicated lane and mixed traffic operations, the focus of mixed traffic throughput analysis has been on the derivation of throughput estimates for mixed traffic operations. The work presented in this appendix provides an update of work performed during the NAHSC's C2 Task conducted in 1996 and documented in the C2 Final Report (*Automated Highway System (AHS) Milestone 2 Report --Task C2: Downselect System Configurations and Workshop #3, June 1997 Appendix I*). This updated work was also presented at the ITS America 7th Annual Meeting in June 1997 and published in the Proceedings of that conference under the title *Analysis of Throughput Achievable with Automated and Manual Vehicles Sharing A Lane*.

10.4.2.2 SUMMARY OF UNCHANGED COMPONENTS

10.4.2.2.1 ASSUMPTIONS and METHODOLOGY

- Manual driving behavior is unchanged from that of today.

- Analysis is carried out for light-duty vehicles only, which are assumed to be approximately five meters long.

- Positioning of Vehicles on the Roadway: A random sequencing of manual and automated vehicles governs the placement of these vehicles on the roadway and this requires a derivation of the probability of occurrence of the four possible manual/automated vehicle relative positions on the roadway. This forms the core of the methodology used to derive estimates for lane throughput (vehicles per hour) as a function of the percentage of automated vehicles in the highway lane. Full details are found in Appendix I of the C2 Final Report.

Table 1

Four Vehicle Pair Positioning Possibilities

DESCRIPTION	SYMBOL
Automated vehicle followed by an automated vehicle	AA
Automated vehicle followed by a manual vehicle	AM
Manual vehicle followed by an automated vehicle	MA
Manual vehicle followed by a manual vehicle	MM

- Spacing of AM relative to MM: A manual vehicle will follow an automated vehicle at the same distance that it would follow another manual vehicle, since the driver of the manual vehicle would not necessarily know that he/she is following an automated vehicle. Even if the driver was aware that he/she was following an automated vehicle, it is assumed that his/her behavior would not change.

- Spacing of MM relative to MA: The final relationship to consider is that of an automated vehicle following a manual vehicle compared to a manual following a manual vehicle. While being tailgated is unpleasant, it is nevertheless tolerated better by some drivers than by others. Whether to assume that an automated vehicle will follow a manual vehicle closer than a manual vehicle would follow a manual vehicle was considered for such tailgating reasons. That is, if the spacing between an automated vehicle and a preceding manual vehicle were strictly less than the spacing between two manual vehicles, would that mean that the automated vehicle was necessarily tailgating the lead manual vehicle? The data from which the manual throughput was estimated was based on tests performed under actual driving conditions, but during off-peak hours of the day. The data sample consisted of 35 drivers traveling around a circumferential freeway loop near Detroit. Because of the relatively low traffic density, drivers were able to maintain a speed of 30 meters/sec and not feel as though they had to fill the empty spaces between vehicles (See Endnote 1). Thus, having an automated vehicle follow a manual vehicle at a shorter distance than a manual would follow another manual vehicle, *based on the data available from* (See Endnote 1), would not necessarily mean that such an automated vehicle was tailgating the manual vehicle and thus tailgating would not necessarily be a concern if the spacing between an automated vehicle and a preceding manual vehicle were less than the spacing between two manual vehicles. Care must be taken when the data, valuable though it may be, is very limited in size.

10.4.2.2.2 PARAMETER INPUT VALUES

- Number of automated lanes: 1

- Light-duty passenger vehicle length: 5 meters

10.4.2.3 MODIFICATIONS

10.4.2.3.1 ASSUMPTIONS

- Distribution of intelligence: The primary attribute for the automated vehicle are that all the intelligence is concentrated within the vehicle. If there is no cooperation among vehicles, that is, no communication of information with one another, then this type of automated vehicle is referred to as an independent autonomous vehicle. With limited cooperation, that is, communication of emergency messages from a vehicle to vehicles behind it, then this type of automated vehicle is referred to as a low cooperative vehicle. The updated work considers both the autonomous and low cooperative cases.

- Spacing of AA relative to MA: An automated vehicle follows a manual vehicle no closer than it, the automated vehicle, would follow another automated vehicle. Compared to the safe following distance between two such automated vehicles, an application of an additional time gap to further separate an automated vehicle following a manual vehicle due to the fact that a manual vehicle may exhibit unpredictable and erratic driving behavior was also investigated. Values for this additional time gap range from 0 to one second and the associated spacing values depend on the vehicles' speed. Thus, an automated vehicle follows a manual vehicle at a distance equal to the minimum safe following distance of an automated vehicle following another automated vehicle plus an extra time gap up to a maximum value of one second.

10.4.2.3.2 PARAMETER INPUT VALUES

- Vehicle speed: 30 meters/second (no variation)

- Merge derating factor: 25% (percentage applied to all minimum spacings to represent the potential reduction in throughput experienced due to merging and lane changing, no variation).

- All-Manual throughput values: Multiple values for the all-manual throughput case are allowed consisting of 1600, 2000, and 2400 vehicles per hour per lane (vphpl).

- Additional time gap for manual following automated relative to automated following automated: 0-1 second

- Inter-vehicle safe spacing: Spacing used for automated following an automated vehicle has been calculated to be the minimum safe inter-vehicle spacing. Two types of such safe inter-vehicle spacings were derived and used, referred to as uniform and non-uniform. Full details for the estimation of these minimum safe spacings may be found in Appendix 10.4.1. In particular, for the autonomous non-uniform case, such vehicles know their own braking performance and assume the worst case (i.e. maximum braking performance) with respect to the preceding vehicle. Values for each of the two minimum safe spacing cases (uniform and non-uniform) for each of the two distribution of intelligence cases (autonomous and low cooperative) are shown in Table 2.

Table 2

Inter-vehicle Safe Spacing at 30m/s (meters)

	Minimum Safe Spacing Cases	
Distribution of Intelligence	**Uniform**	**Non-Uniform**
Autonomous	**22.4**	**21.3**
Low Cooperative	**20.0**	**15.6**

Table 3
Inter-vehicle Spacing Values (in meters) under Alternative Sensitivity Analysis Regimes
30m/s speed, 25% derating factor, Uniform Spacing,
Autonomous DOIA, 1600 vphpl (All-manual Throughput)

Additional Time Gap Parameter (s)	**S[A,A]**	**S[M,A]**	**S[A,M]**	**S[M,M]**
0	**36.6**	**36.6**	**67.5**	**67.5**
0.25	**36.6**	**44.1**	**67.5**	**67.5**
0.5	**36.6**	**51.6**	**67.5**	**67.5**
1.0	**36.6**	**66.6**	**67.5**	**67.5**

Table 4
Inter-vehicle Spacing Values (in meters) under Alternative Sensitivity Analysis Regimes
30m/s speed, 25% derating factor, Uniform Spacing,
Autonomous DOIA, 2000 vphpl (All-manual Throughput)

Additional Time Gap Parameter (s)	**S[A,A]**	**S[M,A]**	**S[A,M]**	**S[M,M]**
0	**36.6**	**36.6**	**54.0**	**54.0**
0.25	**36.6**	**44.1**	**54.0**	**54.0**
0.5	**36.6**	**51.6**	**54.0**	**54.0**
1.0	**36.6**	**66.6**	**54.0**	**54.0**

Table 5
Inter-vehicle Spacing Values (in meters) under Alternative Sensitivity Analysis Regimes
30m/s speed, 25% derating factor, Uniform Spacing, Autonomous DOIA, 2400 vphpl (All-manual Throughput)

Additional Time Gap Parameter (s)	S[A,A]	S[M,A]	S[A,M]	S[M,M]
0	**36.6**	**36.6**	**45.0**	**45.0**
0.25	**36.6**	**44.1**	**45.0**	**45.0**
0.5	**36.6**	**51.6**	**45.0**	**45.0**
1.0	**36.6**	**66.6**	**45.0**	**45.0**

Table 6
Inter-vehicle Spacing Values (in meters) under Alternative Sensitivity Analysis Regimes
30m/s speed, 25% derating factor, 0 second Additional Time Gap, 1600 vphpl (All-manual Throughput)

Inter-vehicle Spacing/DOIA	S[A,A]	S[M,A]	S[A,M]	S[M,M]
Uniform/autonomous	**36.6**	**36.6**	**45.0**	**45.0**
Non-uniform/autonomous	**35.0**	**35.0**	**45.0**	**45.0**
Uniform/low cooperative	**33.3**	**33.3**	**45.0**	**45.0**
Non-uniform/low cooperative	**27.5**	**27.5**	**45.0**	**45.0**

Table 7
Inter-vehicle Spacing Values (in meters) under Alternative Sensitivity Analysis Regimes
30m/s speed, 25% derating factor, 0 second Additional Time Gap, 2000 vphpl (All-manual Throughput)

Inter-vehicle Spacing/DOIA	S[A,A]	S[M,A]	S[A,M]	S[M,M]
Uniform/autonomous	**36.6**	**36.6**	**45.0**	**45.0**
Non-uniform/autonomous	**35.0**	**35.0**	**45.0**	**45.0**
Uniform/low cooperative	**33.3**	**33.3**	**45.0**	**45.0**
Non-uniform/low cooperative	**27.5**	**27.5**	**45.0**	**45.0**

Table 8
Inter-vehicle Spacing Values (in meters) under Alternative Sensitivity Analysis Regimes
30m/s speed, 25% derating factor, 0 second Additional Time Gap,
2400 vphpl (All-manual Throughput)

Inter-vehicle Spacing/DOIA	S[A,A]	S[M,A]	S[A,M]	S[M,M]
Uniform/autonomous	**36.6**	**36.6**	**45.0**	**45.0**
Non-uniform/autonomous	**35.0**	**35.0**	**45.0**	**45.0**
Uniform/low cooperative	**33.3**	**33.3**	**45.0**	**45.0**
Non-uniform/low cooperative	**27.5**	**27.5**	**45.0**	**45.0**

10.4.2.4 SENSITIVITY ANALYSIS

A sensitivity analysis was performed to account for uncertainty in the values of the following parameters: additional time gap for MA relative to AA, all manual throughput at 30m/s, minimum inter-vehicle safe spacings, and distribution of intelligence attributes. As discussed in Section 10.4.2.3.1 the values for the additional time gap parameter for MA relative to AA range from no additional time gap to a 1 second extra time gap, with the following values used in this sensitivity analysis: 0, 1/4, 1/2, and 1 second. The alternative values for all manual throughput at 30m/s used are 1600, 2000, and 2400 vphpl. Two types of the distribution of intelligence attributes were examined, referred to as autonomous and low cooperative (Section 10.4.2.3.1). Two types of inter-vehicle safe spacings are used, uniform and non-uniform spacings (Section 10.4.2.3.2).

10.4.2.5 RESULTS

The results are shown in Figures 1 through 6, in which throughput is depicted as a function of α, the market penetration of automated vehicles. Figures 1 through 3 show sensitivity to alternative values of all-manual throughput in which each of these three figures examine sensitivity in the additional time gap parameter. The input data is provided for Figures 1-3 in Tables 3-5, respectively. Figures 4 through 6 show sensitivity to alternative values of all-manual throughput in which each of these three figures examine sensitivity in the distribution of intelligence attribute and minimum inter-vehicle safe spacing. The input data is provided for Figures 4-6 is in Tables 6-8, respectively.

Figures 1 through 3 display throughput as a function of market penetration and the sensitivity of this relationship to changes in the additional time gap parameter for MA relative to AA on each figure. The parameters with fixed values are vehicle operating speed (30m/s), merge derating factor (25%), inter-vehicle spacing (uniform), and distribution of intelligence attribute (independent autonomous). Another varying parameter is the all-manual throughput (vphpl) and consists of values 1600, 2000, and 2400 for Figure 1 through 3, respectively. Throughput varies with increasing market penetration with considerably large throughput changes for all values of the additional time gap parameter, that is, throughput is sensitive to changes in additional time gap throughout the entire range of market penetration percentages for each value of all-manual throughput. In Figure 1, for each additional time gap value, throughput increases with market penetration since the spacing of a manual vehicle followed by an automated vehicle (S[M,A]) is less than the spacing of a manual vehicle followed by another manual vehicle (S[M,M]) (See Table 3). In Figure 2, for additional time gap parameter value of 1 second, throughput initially decreases since S[M,A] is greater than S[M,M] (See Table 4). For Figure 1, as the additional time gap increases, however, throughput increases at a slower rate for values of α up to approximately 60%. The greatest sensitivity to this parameter occurs within the 55% to 65% range for the market penetration, α. Note that even for the largest value for the additional time gap, i.e. a full one second, at a market penetration of 50%, which is high enough to provide strong political justification for dedicating a lane for automated vehicles' exclusive use, throughput increases 24.8% over the all-manual base case. Note, however, that these percentage throughput increases depend on the all manual throughput value of 1600 vphpl and for larger such values, such as 2000 vphpl, the percentage throughput increase at the same value for α would be less for a given value of the headway penalty parameter.

FIGURE 1

Throughput vs. Market Penetration
Sensitivity to Additional Time Gap Parameter
Autonomous DOIA, Uniform Spacing, All-Manual Throughput (1600 vphpl)

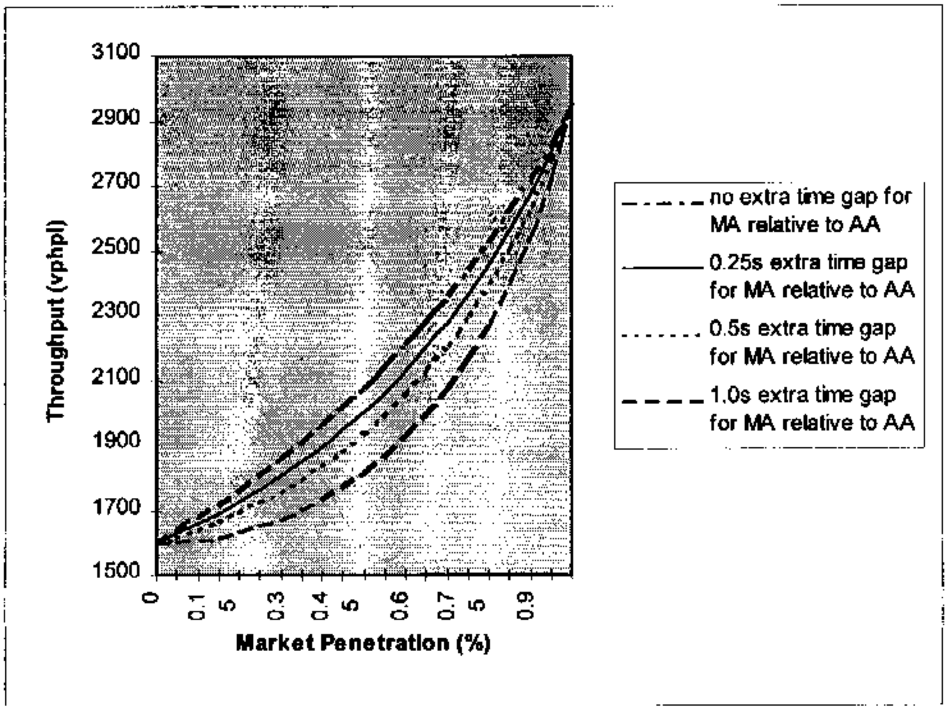


FIGURE 2

Throughput vs. Market Penetration
Sensitivity to Additional Time Gap Parameter
Autonomous DOIA, Uniform Spacing, All-Manual Throughput (2000 vphpl)

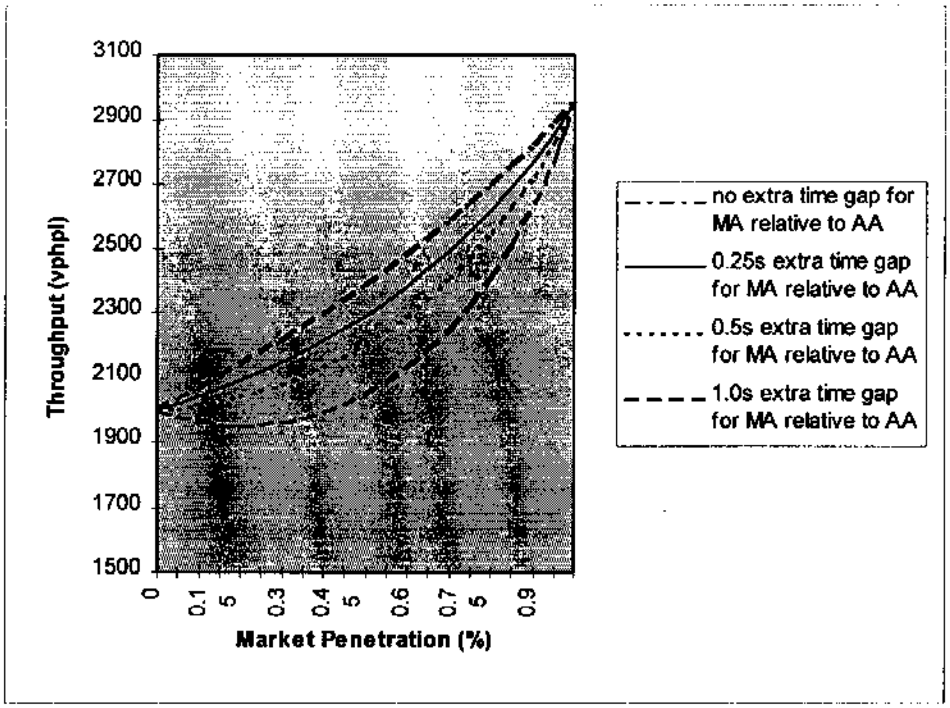
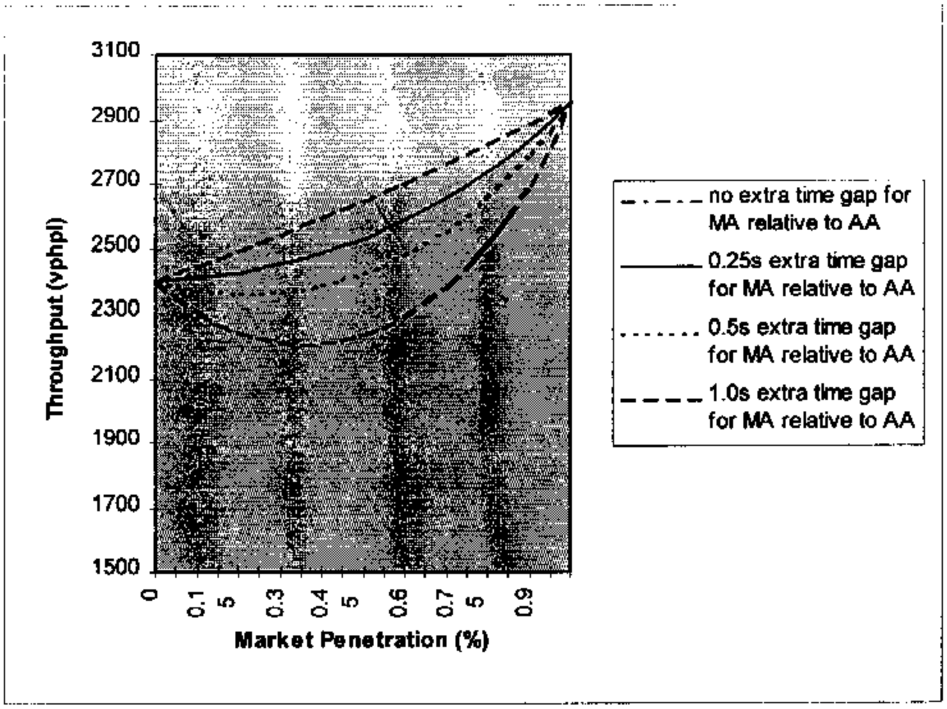


FIGURE 3

Throughput vs. Market Penetration
Sensitivity to Additional Time Gap Parameter
Autonomous DOIA, Uniform Spacing, All-Manual Throughput (2400 vphpl)



Figures 4 through 6 display throughput as a function of market penetration and the sensitivity of this relationship to changes in inter-vehicle spacing and the distribution of intelligence attribute. The parameters with fixed values are merge derating factor (25%), additional time gap for MA relative to AA (0 seconds), and vehicle operating speed (30m/s). Another varying parameter is the all-manual throughput (vphpl) and consists of values 1600, 2000, and 2400 for Figure 4 through 6, respectively. Throughput increases with increasing market penetration with considerably larger throughput increases corresponding to the cooperative distribution of intelligence attribute relative to the independent autonomous cases. Throughput also increases at a faster rate as the market penetration increases for all four cases depicted in Figure 4. The throughput changes between uniform and non-uniform inter-vehicle spacings depends on the distribution of intelligence attribute. Such throughput changes are relatively minor for the independent autonomous case over the entire market penetration range, yet substantially larger for the low cooperative case, especially for larger values of α. For example, in Figure 4, at 30% market penetration and for the independent autonomous case, throughput increases of 15.9% and 16.9% over the all-manual driving base case (1600 vphpl), for uniform and non-uniform spacings, respectively. The corresponding throughput increases for the low cooperative case are

17.9% and 21.6% again for uniform and non-uniform spacings, respectively. At 70% market penetration and for the independent autonomous case, throughput increases of 47.1% and 50.8% over the all-manual driving base case, for uniform and non-uniform spacings, respectively. The corresponding throughput increases for the low cooperative case are 54.9% and 70.9%.

FIGURE 4

Throughput vs. Market Penetration
Sensitivity to Inter-vehicle Spacing and Distribution of Intelligence Parameters
Additional Time Gap Parameter (0 seconds), All-Manual Throughput (1600 vphpl)

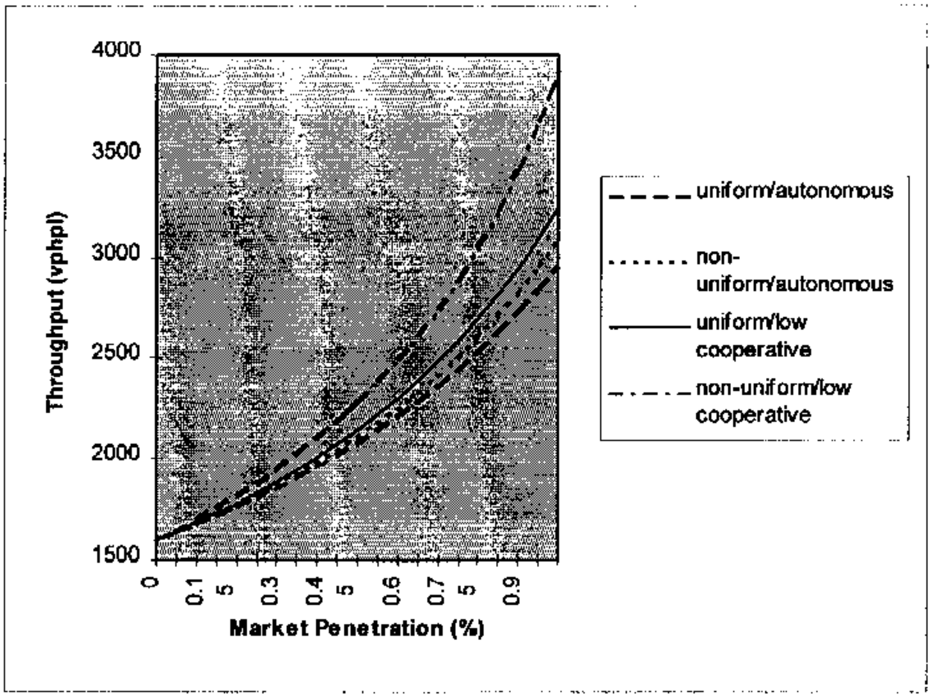


FIGURE 5

Throughput vs. Market Penetration
Sensitivity to Inter-vehicle Spacing and Distribution of Intelligence Parameters
Additional Time Gap Parameter (0 seconds), All-Manual Throughput (2000 vphpl)

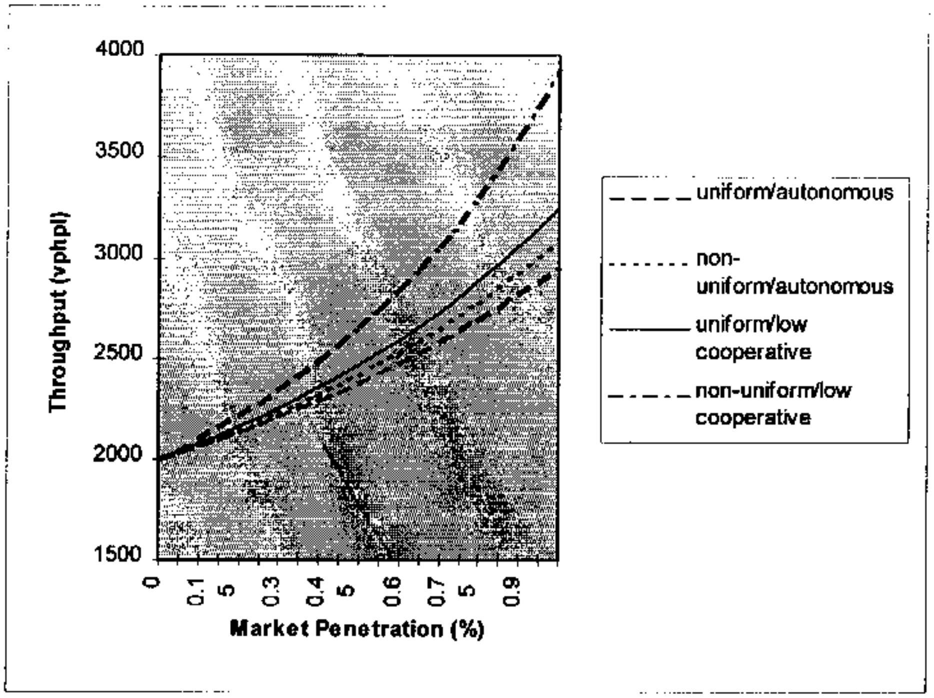
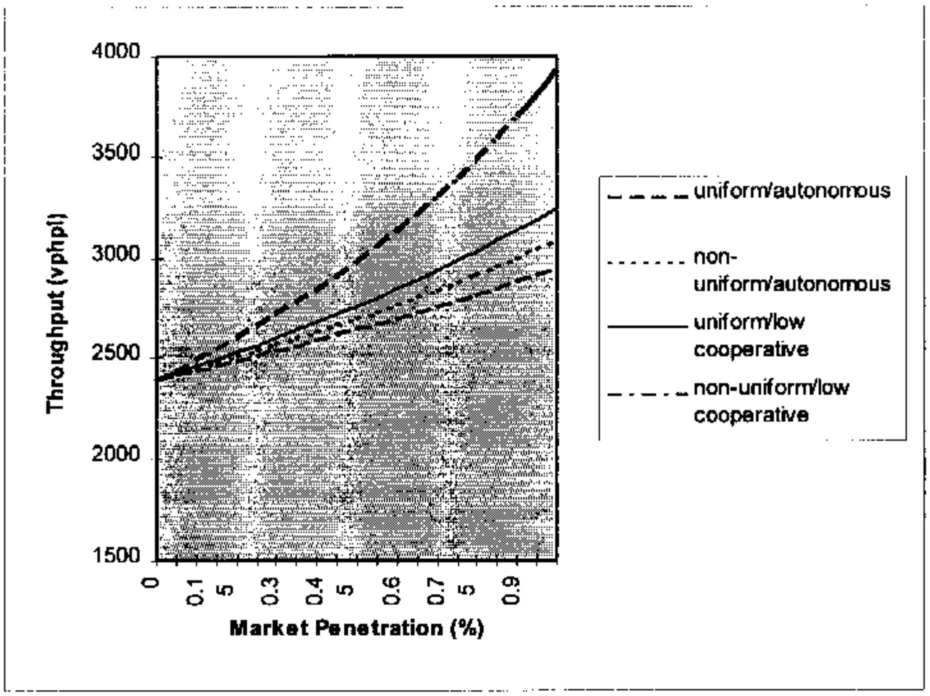


FIGURE 6

Throughput vs. Market Penetration
Sensitivity to Inter-vehicle Spacing and Distribution of Intelligence Parameters
Additional Time Gap Parameter (0 seconds), All-Manual Throughput (1600 vphpl)



10.4.2.6 CONCLUSIONS

The throughput analysis results presented indicate that in almost all cases examined throughput increases with increasing market penetration, however, at different rates of increase. Figures 2 and 3 indicate that for the largest values examined for the additional time gap parameter, throughput initially decreases prior to increasing in value. Such throughput reductions may be unacceptable, and so would have an impact on system design requirements.

The primary parameters for which parametric analyses were performed showed sensitivity. The percentage throughput increases depend on all manual throughput values. At a given value of market penetration, as manual throughput increases, the percentage throughput increases decrease. Throughput levels increase as additional time gaps decrease for a given market penetration. Non-uniform inter-vehicle safe spacings yield greater throughput values than for uniform spacings, all else being equal. Low cooperative distribution of intelligence attribute yields greater throughput than for the independent autonomous attribute. Based on this analysis, relatively small values of market penetration are associated with small changes in throughput and it seems that substantial market penetration of automated vehicles is required before appreciable throughput gains can be achieved.

10.4.2.7 ENDNOTES

1. Fancher, Paul S., et al., *Annual Research Report, ARR-5-15-95, Fostering Development, Evaluation, and Deployment of Forward Crash Avoidance Systems (FOCAS), Report Number: UMTRI-95-31*, University of Michigan Transportation Research Institute, Ann Arbor, Michigan , May 15, 1995.

10.4.3 The Connection Between Safety and Congestion

Author Mark Miller

10.4.3.1 MOTIVATION AND OBJECTIVES

Numerous issues are being investigated within the overall scope of research conducted by the National Automated Highway Systems Consortium (NAHSC). Such issues include traffic mix, deployment sequencing, distribution of intelligence, vehicle separation policy, obstacle management, and driver role (*1*).

In the overall context of research into these issues, numerous analyses have been and continue to be performed in such areas of investigation as safety, congestion, vehicle emissions, civil infrastructure cost, and societal and institutional concerns (liability, integration with metropolitan planning process, integration with transit operations) to elicit just a few.

While all such areas of examination are important and while safety is of prime significance, there are linkages among these areas. The work presented in this appendix provides a first step at understanding the linkages between two such areas of investigation: safety and congestion and how insight into one can provide understanding into the other.

As the consortium continues in its case study investigations which examine the impacts of AHS in a multitude of multimodal (transit, commercial vehicle, all vehicles, etc.) settings (urban, interurban, rural), certain case study scenarios focus on congestion as of paramount importance to certain stakeholders. For example, in a densely populated metropolitan urban environment with limited access highways (freeways, expressways), metropolitan planning organizations (MPOs) focus their efforts on issues of mobility and air quality.

The consortium has focused its work onto comparative analyses across alternative AHS concepts. While some initial research has been conducted that has studied mobility-related impacts of AHS compared to non-AHS roadway settings (*2,3,4*), additional research would be beneficial as the state of knowledge of automated highway systems has grown considerably since these earlier studies, and some improvements have been made in currently used transportation demand modeling tools at some MPOs. Understanding the linkages between safety and congestion will also assist in providing a baseline from which to assess potential AHS impacts compared to non-AHS impacts. Such linkage analysis will also help provide input to answer the "what" question from numerous stakeholders, that is, "What are the AHS benefits?"

In understanding the linkages between congestion and safety, focus is placed on vehicle crashes. There have been past studies of quantifying costs of congestion due to crashes. Differences exist in assumptions, and results need to be understood and reconciled. Thus, an understanding of current linkages between congestion and safety needs to be obtained.

10.4.3.2 TWO-WAY DIRECTIONAL LINKAGES

There are two directional linkages to be studied in the relationship between safety and congestion, as follows:

- Crashes ===> congestion

The primary question to ask is: what are the costs of congestion attributable to crashes? Improvements in safety via decreases in crashes would yield a reduction in congestion

- Congestion ===> crashes

The primary questions are: is there a link in this direction? To what extent is it supported by the data?

10.4.3.3 METHODOLOGICAL CONSIDERATIONS

10.4.3.3.1 The Extent To Which Crashes Yield Congestion

In answering the questions above, understanding the causes of congestion is a necessary first step. Congestion is usually classified as either recurring or non-recurring (due to incidents). Recurring congestion is due to the usual and fairly predictable occurrence of congestion during morning and afternoon commute times. Non-recurring congestion is due to some unique event (e.g. an accident) that may be due to one of many causes. An important initial statistic to estimate is the percentage split between how much congestion is due to recurring events and how much to non-recurring events. Considerable variability exists in estimates for this percentage split. For example, in California, Caltrans uses the "conventional wisdom" estimate of a 50/50 split. A range in the percentage split from 45/55 through 65/35 (non-recurring/recurring) exists based on earlier studies (*5,6*). In addition to such previous studies, there has been research into developing a methodology to quantify non-recurrent congestion delay in order not to have to rely on conventional wisdom which is not always correct and to provide a more systematic approach to estimating the percentage split.

The next step is to disaggregate incidents (the non-recurring component) into their constituent elements. Such elements include crashes, vehicle disablements, roadway construction, weather, and others. Focusing on crashes, the following information then needs to be obtained:

- Percentage of incidents accounted for by crashes. An estimate of this quantity is 10% (*7*).
- Average delay per type of incident and per type of crash

The next step is to understand assumptions of cost data associated with each type of crash, and to reconcile differences that exist among different cost estimates. For example, congestion (travel delay) costs due to incidents/crashes in 1994 provide the following cost estimates:

Upper bound = 35 billion $ (TTI) (all incidents)
Lower bound = 4.4 billion $ (NHTSA) (crashes only) (*8*)

Even applying the 10% estimate for percentage of incidents due to crashes to the upper bound estimate would yield a 20% difference between these two cost estimates. Differences in assumptions have to be reconciled in types of roadways, geographical coverage, etc.

10.4.3.3.2 The Extent that Congestion May Lead to Crashes

According to the 1994 GES database of crashes on interstates involving two vehicles, crash causes are attributed to

- Driver actions
- Obstacles
- Road conditions
- Vehicle defects

Important questions to pose are:

- What led to these causes?
- To what extent was congestion a factor?

Known data from this database is the time-of-day of the accident. The route on which the accident occurred and the traffic density are unknown. With such data or lack of data, time-of-day could be used as a surrogate for congestion levels, however, the usefulness and acceptability of this surrogate is problematic. Otherwise, effort should be placed on the "crashes yielding congestion" directional linkage which has sufficient data.

10.4.3.4 CONCLUSIONS

The work in this area performed during the first year of the C3 task has been a statement of the problem, its motivation, why it is important and valuable to pursue, and the development of a methodology to implement beginning in the second year of the C3 task.

10.4.3.4 ENDNOTES

(*1*) National Automated Highway Systems Consortium, 1996. C2 Final Report (*Automated Highway System (AHS) Milestone 2 Report --Task C2: Downselect System Configurations and Workshop #3, June 1997.*

(*2*) Miller, M.A. et al. 1997. "Regional Mobility Impacts Assessment of Highway Automation", Chapter 14 of *Automated Highway Systems,* Plenum Publishing, 1997.

(*3*) Johnston, R.A. and Ceerla, R., 1993. A Continuing Systems-Level Evaluation of Automated Urban Freeways, UCB-ITS-PRR-93-15, University of California, Berkeley, 1993.

(*4*) Calspan Corporation, AHS Roadway Analysis, Volume 3, FHWA-RD-95-121, 1995.

(*5*) Lindley, J.A., 1987. Urban Freeway Congestion: Quantification of the Problem and Effectiveness of Potential Solutions, ITE Journal, January 1987.

(*6*) Miller, M.A. and Li, K., 1994. *An Investigation of the Costs of Roadway Traffic Congestion: A Preparatory Step for IVHS Benefits' Evaluation,* University of California Berkeley, Institute of Transportation Studies, California PATH Program Research Report, UCB-ITS-PRR-94-15, May 1994.

(*7*) Grenzeback, L.R. and Woodle, C.E., 1992. The True Costs of Highway Congestion, ITE Journal, March 1992.

(*8*) Blincoe, L.J, 1996. *The Economic Cost of Motor Vehicle Crashes 1994,* U.S. Department of Transportation, National Highway Traffic Safety Administration, NHTSA Technical Report Number DOT HS 808 425, July 1996.

(*9*) Epps, A. et al, 1993. *Developing a Methodology for Quantifying Non-Recurring Freeway Congestion Delay - Phase I: Identification of Alternative Methodologies,* University of California Berkeley, Institute of Transportation Studies Research Report, UCB-ITS-RR-93-8, October 1993.

(*10*) Epps, A. et al, 1993. *Developing a Methodology for Quantifying Non-Recurring Freeway Congestion Delay - Phase II Working Paper: Initial Analysis for Non-Recurring Freeway Congestion Delay Methodologies,* University of California Berkeley, Institute of Transportation Studies Research Report, UCB-ITS-WP-93-14, December, 1993.

10.4.4.1 Driving Environment Hazard Analyses

Author, Steve Schuster

The Need for Accident Statistics

Most of the proposed safety levels for the AHS are stated in terms such as "at least as safe as today's highways" or "an xx% reduction in current accident levels". Accepting a performance goal stated in this manner, and designing a system to meet it, require that we understand what kinds of accidents occur at present, how often they occur, what factors make them more or less likely, and the associated levels of injury and damage. Accident statistics can help us to do this by breaking down total accidents by type, triggering event, geometry, and other factors such as environmental conditions and driver mental state. They must, however, be interpreted with caution and judgment - saying that 10% of accidents occurred on icy roads is not the same as saying 10% of accidents occurred because the road was icy - but they nonetheless represent a start in understanding the factors which can be used to reduce the likelihood of accidents, thereby improving on current levels of safety.

Existing Accident Analyses

Numerous analyses of accident types and causes have been done under NHTSA sponsorship, and many of these appear as part of the precursor studies (PSA) which laid the groundwork for Automated Highway System design and development. Approximately two dozen such accident studies were reviewed for applicability to AHS safety issues during C3 Phase 1 design activities. These design activities have so far been primarily aimed at AHS implementations on interstate highways or similar roads. But almost all of the prior accident analyses failed to distinguish between surface street and freeway accidents. For the purpose of designing an AHS system to operate on "interstate type" highways this was unsatisfactory, since it introduced accident types (such as intersection accidents) which do not occur on freeways, and it biased the statistics for the remaining types. These studies also tended to have little or no information on the less common objective hazards (e.g., vehicle system failures) which cause accidents.

Selection of an Accident Database

The three major NHTSA accident databases were examined for suitability in generating statistics on interstate accident types and causes.

- The CDS database has detailed information on accident dynamics and human factors due to the extent of the investigation. However, the database provides no easy way to identify interstate highways, and because it is limited to 5000 accidents per year, there are only about 300 interstate accidents in the database each year, too small a number to allow statistically valid conclusions about some of the less frequent accident types.

- The FARS database records only accidents which result in fatalities. This means that accident types likely to result in serious injuries are over-represented, and those less likely to result in serious injuries are under-represented.
- The GES database is the most suitable of the three for the purpose of generating interstate accident statistics. The 50,000+ accidents in the database are a random sample of motor vehicle accidents resulting in property damage, injury, or death for which a police report was filed. Interstate accidents are clearly marked, and statistical weights permit generation of national statistics.

Limitations of the GES Database

To use the GES database effectively in generating accident statistics, one must understand its limitations. Among these are -

- The GES reports only one triggering, or causative, event for the accident. If the accident was caused by the driver losing control of the vehicle while speeding on icy roads, then only one of those three factors can be listed as the critical event, or primary cause.
- The GES leaves out some important accident causes having to do with the driver's actions and state of mind. While "distracted", "sleepy/asleep", and "ill/blackout" appear in the database, "inattentive", "angry", and "failed to look" do not.
- The GES does not allow state of mind to be listed as the critical event (or primary cause) of the accident. If the driver runs into the rear end of the preceding vehicle because he is not paying attention, then the critical event will most likely be "In another vehicle's lane: traveling in the same direction with higher speed". This is a better explanation of how than why.
- The GES has information concerning accident type and cause in a number of different fields. This means that some accidents will fall into the Other/Unknown category because the information on them is either ambiguous or contradictory.

Summary Statistics

Out of the approximately 6,113,200 accidents reported to the police in 1994 and recorded in the GES database, there are about 371,000 interstate accidents. Slightly more than 227,500 of these involve two or more vehicles. In about 197,000 of these accidents the role of the second (and any additional vehicles) vehicles is passive - in other words, they are struck without being at fault. Since the statistics presented below are concerned with accident causes, and passively involved vehicles do not cause accidents, the passive "vehicle events" will not be included in the statistics after Table 1. The sum of the first and second vehicles actively involved in these accidents will be referred to as "vehicle events". All of the subsequent statistics are based on vehicle events, rather than accidents.

Summary Statistics	
Vehicular Accidents Reported to Police	6,113,200
Interstate Accident Count	370,986
First Vehicle Event Count (F)	370,911
Second Vehicle Event Count (S)	227,528
Passive Vehicle Event Count (P)	197,156
Total Active Vehicle Event Count (F+S-P)	401,283

Table 1

Hazard Taxonomy Used

The hazard taxonomy used as a basis for generating these accident statistics was developed at the April C3 Team meeting in Pittsburgh in an attempt to remedy some of the deficiencies of the previous one-dimensional taxonomy. This previous taxonomy emphasized objective hazards, downplayed driver error, ignored crash geometry, and attributed all accidents to a single primary cause. The new hazard taxonomy is three-dimensional. The three dimensions are critical event, apriori condition, and crash geometry. These dimensions collectively characterize the accident in terms of the event precipitating the accident, the condition of the driver and the driving environment, and the geometric relationship between the vehicles and the roadway at impact.

Statistics on Critical Events

A critical event is the action of the driver, failure of the vehicle, or event on the roadway which most directly caused the accident to occur. Critical events are active events such as lane changes; passive events such as road surface condition or driver state of mind are included under Apriori Condition in Table 3. The three numeric columns of Table 2 list major groupings of critical events from the 1994 GES database. The total number of vehicle events on which the percentages in each column are based is given at the bottom of the column. The critical events listed for each column are mutually exclusive and collectively exhaustive with respect to the event totals at the bottom of the column.

The percentages in the "Includes" column include the categories More Than 2 Vehicles Involved, and Other/Unknown. More Than Two Vehicles Involved is a critical event category because it is the critical event coded in the database for multi-vehicle accidents, preventing further classification of the events causing the accident. The Other/Unknown category includes both the critical event codes Other and Unknown from the database, and any other accidents whose combinations of GES fields fail to meet the logic of the other listed critical event categories.

Since the rows in Table 2 are sorted in order of decreasing frequency by critical event, one can identify the major accident types by reading from top to bottom - speed difference, loss of control, lane change, and (perhaps) obstacle. The "normalized" and "normalized and weighted" columns can be used in combination to see the effect of weighting critical event frequency by accident severity. The "normalized" column gives the unweighted frequency; the "normalized and weighted" column gives the frequency weighted by maximum injury severity. The scale for maximum injury severity is 0 to 4, where 4 is a fatality, 3 is an incapacitating injury, 2 is a non-incapacitating injury, and 1 is a possible injury. The total for each critical event type is generated by taking the GES statistical weight times ten raised to the injury level power, and summing this over all accident records of this critical event type (Equation 1).

$$CrEv = \frac{\sum_{\forall Acc \in Typ} StatWgt * 10\textasciicircum InjLvl}{\sum_{\forall Acc} StatWgt * 10\textasciicircum InjLvl}$$

Equation 1

where

CrEv is the fraction for each critical event type

StatWgt is the GES caseweight for each accident report

InjLvl is the injury level code (0 - 4)

Acc is an accident record in GES

Typ is the set of all accident records having a specified critical event type

There is no change in the relative importance of the accident types between unweighted and weighted statistics.

Critical Event	All types	Selected types; normalized	Selected types; normalized and weighted
Speed Difference, Non-Junction	27.7%	38.5%	37.6%
Loss of Control, Other	21.1%	29.3%	34.7%
Lane Change, Non-Junction	12.5%	17.4%	14.4%
Obstacle In/Near Roadway	6.1%	8.5%	6.6%
Vehicle Defect	2.4%	3.3%	3.6%
Merge at Ramp or Freeway Junction	1.5%	2.2%	1.8%
Vehicle Avoidance Maneuver	0.4%	0.5%	0.8%
Opposite Direction	0.2%	0.3%	0.6%
More Than 2 Vehicles Involved	18.3%	NA	NA
Other/Unknown	9.7%	NA	NA
Total Vehicle Events	401,494	288,577	288,577

Table 2

Statistics on Apriori Conditions

An apriori condition is loosely defined as any condition of the environment or driver which makes an accident more likely to occur. The three numeric columns of Table 3 list major groupings of apriori conditions from the 1994 GES database. The total number of vehicle events on which the percentages in each column are based is given at the bottom of the column. This vehicle event total is comparable to the righthand one in Table 2; it is larger because the number of Unknown/Other conditions is smaller for Apriori Conditions than for Critical Events.

The figures in the “Events including” column represent the percentage of vehicle events for which the listed apriori condition was present; it need not have been the only apriori condition present. The figures in the “Events with only...unweighted” column represent the percentage of vehicle events for which the listed apriori condition was the only one present. Taken together, the figures from these two columns give us a target range for the fraction of accidents which could be eliminated by countermeasures addressing each apriori condition. For example, if we introduce both a new type of headlight which is highly effective in all reduced light conditions, and polarized windshields which reduced glare when facing into the sun, and we estimate (hypothetically) that these will eliminate

50% of all light condition caused accidents, then we can expect a reduction of between 9.5% and 21.4% (50% of 19% to 42.7%) of accidents on interstates.

By contrasting the figures in the "Events with only...unweighted" and the "Events with only... weighted" columns, we can see the effect of weighting the frequencies by maximum injury severity. As with the critical events above, there is almost no change in the relative ordering. Overall, the apriori conditions which most often contribute to accidents are light condition, road surface, atmospheric visibility, and speeding/reckless driving. An important caveat is that driver inattention, which other studies have identified as a major factor, does not appear explicitly in the GES database; if it did, it would almost certainly be included in this list.

Apriori Condition	Events including this condition	Events with only this condition - unweighted	Events with only this condition - weighted
Light Condition	42.7%	19.0%	17.4%
No Apriori Condition	35.8%	35.8%	33.5%
Road Surface Condition	33.6%	2.9%	2.6%
Atmospheric Visibility	25.7%	0.2%	0.1%
Speeding/Reckless Driving	17.3%	4.0%	4.7%
Alcohol or Drugs	5.0%	0.5%	0.7%
Sleepy/Asleep	4.7%	1.7%	2.1%
Distracted	3.7%	1.5%	1.5%
Obstructions to Visibility	0.9%	0.3%	0.2%
Ill/Blackout	0.4%	0.2%	0.2%
Total Vehicle Events	319,458	319,458	319,458

Table 3

Statistics on Crash Geometry

Crash geometry is the geometric relationship of the vehicle(s) and the roadway at the moment of the accident. Many of the crash geometry categories are similar to the critical event categories; for example, a rear-end accident sounds similar to a speed difference accident. While it is true that speed difference accidents frequently have rear-end crash geometry, sometimes this is not the case. Depending on the driver's actions just before the crash, a speed difference accident can result in roadway departure, sideswipe, or rear-end crash geometry.

The three numeric columns of Table 4 list crash geometry categories from the 1994 GES database. The total number of accidents on which the percentages in each column are based is given at the bottom of the column. The crash geometry categories listed for each column are mutually exclusive and collectively exhaustive with respect to the event totals at the bottom of the column.

The importance of the "All types" column is that it identifies five major crash geometries - rear-end, road departure/vehicle avoidance, sideswipe, angle, and object/vehicle impact. By contrasting the figures in the "normalized" and the "normalized and weighted" columns, we can see the effect of weighting the frequencies by maximum injury severity. The maximum injury severity scale and the weighting scheme are the same ones which were used for the critical event statistics above. Two pairs of crash geometries change order with one another in relative importance when the weighting is applied. However, since the five major crash geometries remain the same, the importance of this change in order is minimal.

Crash Geometry	All types	Selected types; normalized	Selected types; normalized and weighted
Rear-End	24.8%	35.3%	35.0%
Road Departure/Vehicle Avoidance	22%	31.3%	36.1%
Sideswipe	8.7%	12.4%	10.1%
Angle	8.0%	11.4%	10.4%
Object/Vehicle Impact	5.7%	8.2%	6.5%
Rollover/Jackknife/Other Non-Collision	0.5%	0.7%	1.2%
Head-On	0.3%	0.4%	0.7%
T-Bone	0.1%	0.2%	0.1%
More Than 2 Vehicles Involved	18.3%	NA	NA
Other/Unknown	11.5%	NA	NA
Total Vehicle Events	401,323	281,701	281,701

Table 4

Conclusions

- Interstate accidents comprise about 6% of total vehicular accidents reported to police.
- Speed difference, loss of control, lane change, and obstacle accidents make up two thirds of all interstate accidents, and are also the most serious critical event types based on frequency or frequency times maximum injury severity.
- The apriori conditions which most often contribute to interstate accidents are light condition, road surface, atmospheric visibility, and speeding/reckless driving. The results are insensitive to whether frequency or frequency times maximum injury severity is used to rank them. Light condition is the largest single contributor, being the only apriori condition present for one interstate accident in five. Driver inattention would almost certainly be listed, but it does not appear explicitly in the GES database.

- The most frequent crash geometries are rear-end, road departure/vehicle avoidance, sideswipe, angle, and object/vehicle impact, comprising two thirds of all interstate accidents. The order is somewhat sensitive to whether frequency or frequency times maximum injury severity is used, but these geometries remain the top five in either case.

10.4.4.2 Driving Environment Obstacle Analyses

Author, Steve Schuster

The Need for Obstacle Statistics

Out of the approximately 6,113,200 accidents reported to the police in 1994 and represented in the GES database, there are about 371,000 interstate accidents. Of these, about 6% involve obstacles. Preliminary analysis of accident data for highways with a speed limit of 55 mph and up (both interstate and non-interstate) indicates that here obstacles play an even more important role, causing about 15% of all accidents (see Table 1).

Summary Statistics for 1994	
Vehicular Accidents Reported to Police	6,113,200
Interstate Accident Count	370,986
Interstate Obstacle Accident Count	22,778
High Speed Highway Accident Count	1,493,704
High Speed Highway Obstacle Accidents	233,866

Table 1

Since these obstacles will not disappear with the advent of the Automated Highway System (AHS), design of the AHS must include methods to minimize the number of obstacle-caused collisions, and the resulting injury and damage. To accomplish this, the AHS design will incorporate a two-part obstacle management strategy. The first part is obstacle prevention, which attempts to keep intruders such as deer and rocks off the highway, and which also attempts to identify and exclude vehicles more likely than most to lose wheels, mufflers, or loads, since these become obstacles on the highway. The second part of the strategy is obstacle detection, and avoidance either by coordinated braking or lane change. In order to implement this obstacle management strategy in a cost-effective manner, it is necessary to know the relative proportion of different types of obstacles on current highways, where they originate, whether they are usually stationary or moving when seen, and the distribution of injuries and vehicle damage caused by colliding with them.

Obstacle Statistics Available from the DOT Crash Databases

The GES database, which was used for assembling the analysis of crash causes discussed in Section 10.4.4.1, has about half a dozen types of critical events associated with obstacles. These critical event types distinguish between people, animals, and objects, and between obstacles which are in the roadway, and those which are approaching the roadway. The database record of each crash also notes the level of injury to the vehicle occupants, the damage to the vehicle, and the type of accident (obstacle/vehicle collision, run-off-the road,...) which results. However, the database record of the crash does not record the type of the animal or object, the nature of its motion, or where it was first seen relative to the vehicle's lane. This information may be absent from the police report; even if it is present, however, it is not coded into the database. As a result, assembly of the information needed to design an effective obstacle management strategy requires that the relevant crash records from the GES database be supplemented with information from the police report which was used to create the record.

Generation of Detailed Obstacle Statistics

Although the GES database is available to the general public, the police reports from which it is created contain information identifying specific persons and vehicles and are therefore considered to be restricted information. Consequently, the simplest way to obtain additional information from the police reports which had been used to create the GES crash records was to hire the DOT's data entry contractor (ISSI) to do the job. With ISSI's permission, a subcontract was let to one of their employees to identify all the obstacle crash reports in the 1996 GES database, and to extract selected non-restricted information from the database record and the accompanying police report. The data items extracted from the database were -

- Case number
- Critical event
- Accident type
- Vehicle body type
- Number of persons injured
- Maximum injury severity
- Vehicle damage
- Statistical weight

To this list of data items from each crash report involving an obstacle, was appended the relevant details from the associated police report. These include the type of animal or object, the motion (falling, bouncing, lying in the lane, ...), the source (vehicle, surroundings, ...) and the origin (same lane, one lane over, shoulder, ...) when that information was available.

Limitations of these Statistics

Estimates based on the GES database, that so many accidents of a particular type occurred in the U.S. in a particular year, are computed using statistical weighting of reports from selected police jurisdictions. This works well for common accident types, and less well for singular occurrences. These statistical weights are multipliers which allow the selected subset of accident reports which are input to GES to be used to generate representative national accident statistics. For example - there were 77 reports of vehicles colliding with deer in 1996; using the appropriate statistical weights gives us a national estimate of 12827 vehicle-deer collisions, which is probably "in the ballpark". There was one report of a vehicle colliding with a turkey in 1996; the appropriate statisical weight gives a national estimate of 279 vehicle-turkey collisions. It is instructive to note that if either the driver or the turkey had reacted a little faster in this one incident, the national estimate for vehicle-turkey collisions would be zero.

Two kinds of crashes are listed below. There are crashes involving a vehicle colliding with a person, animal or object; these are referred to collectively as "simple obstacle collisions", and listed in the tables by the description of the obstacle - "deer", or "wood", or "people". There are also crashes in which the vehicle struck another vehicle, or struck a fixed object like a tree, or rolled over while trying to avoid striking the obstacle. These are listed in the tables as "another vehicle", "fixed object", and "rollover", respectively. In these three cases, the primary vehicle successfully avoided the obstacle, but became involved in a secondary accident. Statistics for these three accidents types are consolidated by type (e.g., rollover), regardless of the nature of the obstacle. There are seven additional accidents which are more complex than these, for example, one in which the primary vehicle struck the obstacle and then a tree, which will be referred to as 'multiple collisions". The accident types "another vehicle", "fixed object", "rollover", and "multiple collision" will be referred to collectively as "other obstacle accidents".

As mentioned previously, a subcontract was let for collection of obstacle accident data from the 1996 GES database and accompanying police reports. What was received was data on the primary vehicle involved in the crash - that is to say, in obstacle crashes involving two vehicles, data on only the vehicle more closely involved with the obstacle was collected. For seven crashes, however, both vehicles were equally involved, and both were included in the received data. The estimated number of accident totals have been corrected for this double counting of these seven accidents by halving the GES caseweights associated with each of the two vehicle "incidents" making up these accidents. Accidents in which a motorcycle was the primary vehicle have been deleted since motorcycles will not be part of the traffic on dedicated or designated AHS lanes.

Frequency of Accidents Due to Obstacles on Interstate Highways

Obstacle or Accident (*) Type	Est Number of Accidents	Number of Reports	Avg Injury Level	Avg Damage Level
deer	12827	77	0.05	1.74
rock	2219	10	0.03	1.00
fixed object *	2171	30	0.76	2.89
tire debris	1994	17	0.17	1.74
metal scrap	1834	26	0.20	1.96
tire	1702	27	0.02	1.87
wheel	1229	15	0.58	1.59
unknown object	1183	16	0.25	1.04
another vehicle *	1167	15	0.24	1.72
vehicle load	1078	12	0.43	1.46
unknown debris	859	8	0.08	1.71
dog	831	7	0.00	1.03
ladder	789	6	0.00	1.00
rollover *	785	12	1.75	2.73
wood	769	10	0.63	2.02
unknown animal	693	3	0.00	1.00
muffler	602	5	0.00	1.66
bricks	589	2	0.00	NA
furniture	579	6	0.00	3.00
person	421	21	3.09	1.07
multiple collision *	318	7	1.84	2.91
construction barrel	313	3	0.19	1.98
vehicle debris	305	12	0.83	2.05
window for house	300	1	0.00	1.00
ice	297	1	0.00	1.00
cement block	297	1	0.00	1.00
light standard	297	3	0.00	2.50
camper shell	294	2	0.00	1.00
steel pipes	293	1	0.00	NA
light fixture	291	1	0.00	1.00
bathtub	290	1	0.00	2.00
pig	289	1	NA	NA
grill	289	1	0.00	1.00
vehicle dolly	287	1	0.00	NA

Table 2

Obstacle or Accident (*) Type	Est Number of Accidents	Number of Reports	Avg Injury Level	Avg Damage Level
turkey	279	1	0.00	NA
wheel assembly	197	2	0.00	NA
box	185	2	NA	NA
load strap	115	2	0.00	2.19
traffic cone	106	1	NA	NA
metal plate	100	1	NA	NA
tree trunk	99	1	1.00	1.00
elk	99	2	0.05	3.00
oppossum	95	1	NA	NA
snow bank	94	1	NA	NA
sign	93	1	0.00	NA
plastic barrel	93	1	NA	NA
construction sign	91	1	0.00	NA
trash can	90	1	NA	NA
expansion joint	87	1	0.00	3.00
bales of hay	65	3	0.00	NA
sheep	54	1	0.00	NA
cow	31	1	1.54	3.00
steel rolls	31	3	1.93	1.00
concrete median	31	3	0.87	1.00
drive shaft	17	4	0.12	2.39
loading ramp	16	1	0.00	3.00
trailer	14	1	2.00	3.00
building material	8	2	NA	NA
metal object	7	1	2.00	2.00
truck cargo housing	6	1	1.00	NA
storage trunk	6	1	2.00	3.00
fencing	5	1	1.00	NA
bridge railing	5	1	0.00	NA
axle & tire	5	1	0.00	NA
pedalcyclist	2	1	NA	NA

Table 2 (continued)

Table 2 lists all accidents which were reported to the GES database as having been caused by an obstacle on an interstate highway in 1996. Simple obstacle collisions are listed by the object type as it appeared on the police report. Other obstacle accident types are listed by the accident description. The categories in Table 2 are not mutually exclusive - a rollover involving a deer is listed both under rollover and under deer. Estimated Number of Accidents is a statistical estimate of the number of crashes on interstate highways in the U.S. in 1996 caused by this obstacle or accident type. This is computed from the number of police reports submitted, and the GES statistical multipliers of the police jurisdictions in which the obstacle crashes occurred.

Number of Reports is the number of police reports entered into the GES database in 1996 which cited this object type as having caused the crash. (As pointed out earlier, statistics based on a single reported incident should be used with caution.) The Average Injury Level lists the average maximum injury for each obstacle type, averaged over the estimated number of accidents nationally. Injury level codes are from the GES Maximum Injury Severity field, where 0 is no injury, 1 is possible injury, 2 is non-incapacitating injury, 3 is incapacitating injury, and 4 is a fatality. Average Damage Level lists the average damage sustained by the vehicle. For each obstacle type, the damage figure is averaged over the estimated number of accidents nationally. Damage Level codes are from the GES (Vehicle) Damage Severity field where 0 is no damage, 1 is minor damage, 2 is functional (moderate) damage, and 3 is disabling (severe) damage. "NA" appears in Table 2 in place of an average injury or damage level for some obstacle types. This occurs either because the police report listed the injury or damage level as unknown, or because none of the accidents involving this obstacle type were simple obstacle collisions.

It is immediately obvious from Table 2 that there are a large number of obstacle types which cause crashes on interstate highways. However, for the purpose of designing an obstacle exclusion policy we can group them into seven categories, shown in Table 3.

Category	Est # of Accidents	Percentage
Environmental Intruders	15,292	42.3
Vehicle Loads	6764	18.7
Vehicle Component	6478	17.9
Highway Components/Maintenance	1495	4.2
People (as Obstacles)	423	1.2
Malicious Mischief	279	1.1
Other/Unknown	5309	14.7

Table 3

Excluding for the moment the Highway Components/Maintenance and the Other/Unknown categories, the sources of the obstacles in the remaining categories is well known. Obstacles enter the highway from its surroundings, or they come from vehicles (people, loads, and components). Consequently, if we want to reduce obstacle crashes on the AHS, we must control both the surroundings and the configuration of the vehicles entering the system. If there is a surprise in the above list, it is that about one time in twenty five, a highway component is the obstacle.

Injury Due to Obstacles

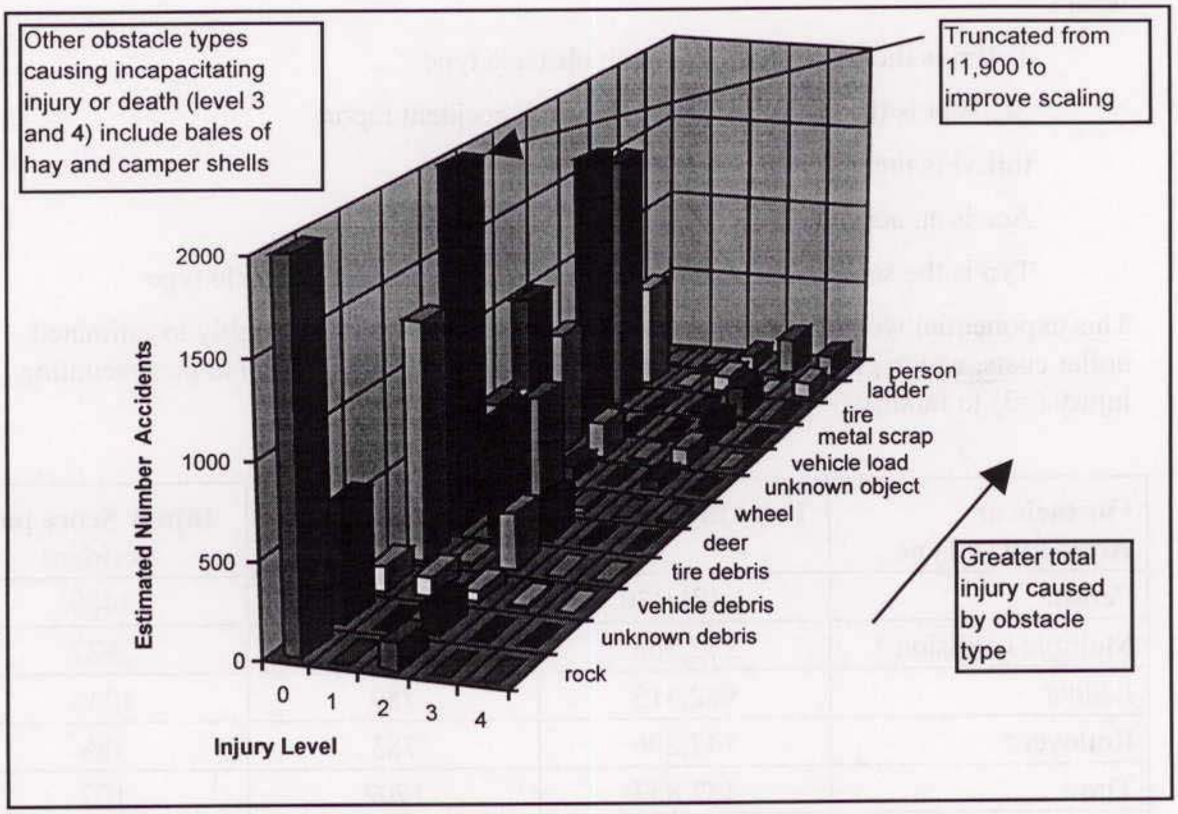


Figure 1

Figure 1 shows the distribution of injury levels caused by a dozen obstacle types in interstate crashes. Obstacle types were chosen on the basis of their total injury score (see below) and the number of police reports entered into GES involving the obstacle type (minimum of five). All reports were classified on the basis of the obstacle type involved, without regard to secondary accidents (e.g., rollover). The x (transverse) axis is the seriousness of the worst injury sustained in each accident, where 0 is no injury, 1 is possible injury, 2 is non-incapacitating injury, 3 is incapacitating injury, and 4 is a fatality. The z (vertical) axis is the estimated number of accidents on interstate highways in the U.S. in 1996, based on police reports to the GES database. The y (longitudinal) axis lists the twelve most serious obstacle types. The listed obstacle types are ordered from least serious (rock) to most serious (person). This ordering is based on a "total injury" score which is computed by weighting the number of accidents at each injury level by ten raised to the "injury level" power (Equation 1).

$$TotInj = \sum_{Acc \in Typ} StatWgt * 10^{\wedge} InjLvl$$

Equation 1

where

TotInj is the injury score for each obstacle type

StatWgt is the GES caseweight for each accident report

InjLvl is the injury level code (0 - 4)

Acc is an accident record in GES

Typ is the set of all accident records having a specified obstacle type

This exponential weighting was chosen because it corresponded roughly to estimated dollar costs, which go up steeply from non-incapacitating injury (=2) to incapacitating injury (=3) to fatality (=4).

Obstacle or Accident(*) Type	Total Injury Score	Est Number of Accidents	Injury Score per Accident
Person	1,476,330	423	3489
Multiple Collision *	932,363	318	2927
Ladder	982,315	789	1244
Rollover *	147,296	785	188
Tire	182,837	1702	107
Vehicle Load	97,397	992	98
Metal Scrap	116,536	602	67
Unknown Object	59,190	749	79
Fixed Object *	146,042	2171	67
Vehicle Debris	16,868	303	56
Unknown Object	60,408	1184	51
Wheel	49,028	1229	40
Unknown Debris	16,053	769	21
Another Vehicle *	65,484	1167	56
Tire Debris	32,445	1608	20
Dog	12,025	831	14
Wood	5338	488	11
Rock	15,505	2219	7
Deer	40,895	12,827	3
Furniture	628	579	1

Table 4

Table 4 shows similar injury data as Figure 1, but there are a few key differences. The accident types from Table 2 have been added back in, the obstacle and accident types have been ordered by injury score per accident, rather than total injury score, and the statistics for the obstacles now include all accidents involving this obstacle type, regardless of whether a secondary accident such as a rollover occurred. This means that the obstacle categories (e.g., tire) and the accident categories (e.g., rollover) in Table 4 are not mutually exclusive.

Whether we use the total injury score (Figure 1) or the injury score per accident (Table 4), the top seven obstacle/accident types remain the same. These include two accident types: multiple collision and rollover, and five obstacle types: people, ladders, tires, vehicle loads, and metal scrap. It should be noted that in a vehicle-person collision, injuries to both the vehicle occupants and the person struck by the vehicle are counted. This accounts in part for the dramatic difference between simple obstacle collisions involving people and the other obstacles types. Looking for the moment just at obstacle types (excluding the accident types to avoid double-counting), it is noteworthy that the first two obstacle types, people and ladders, account for more than half of the total injury score for all obstacle types.

Damage Due to Obstacles

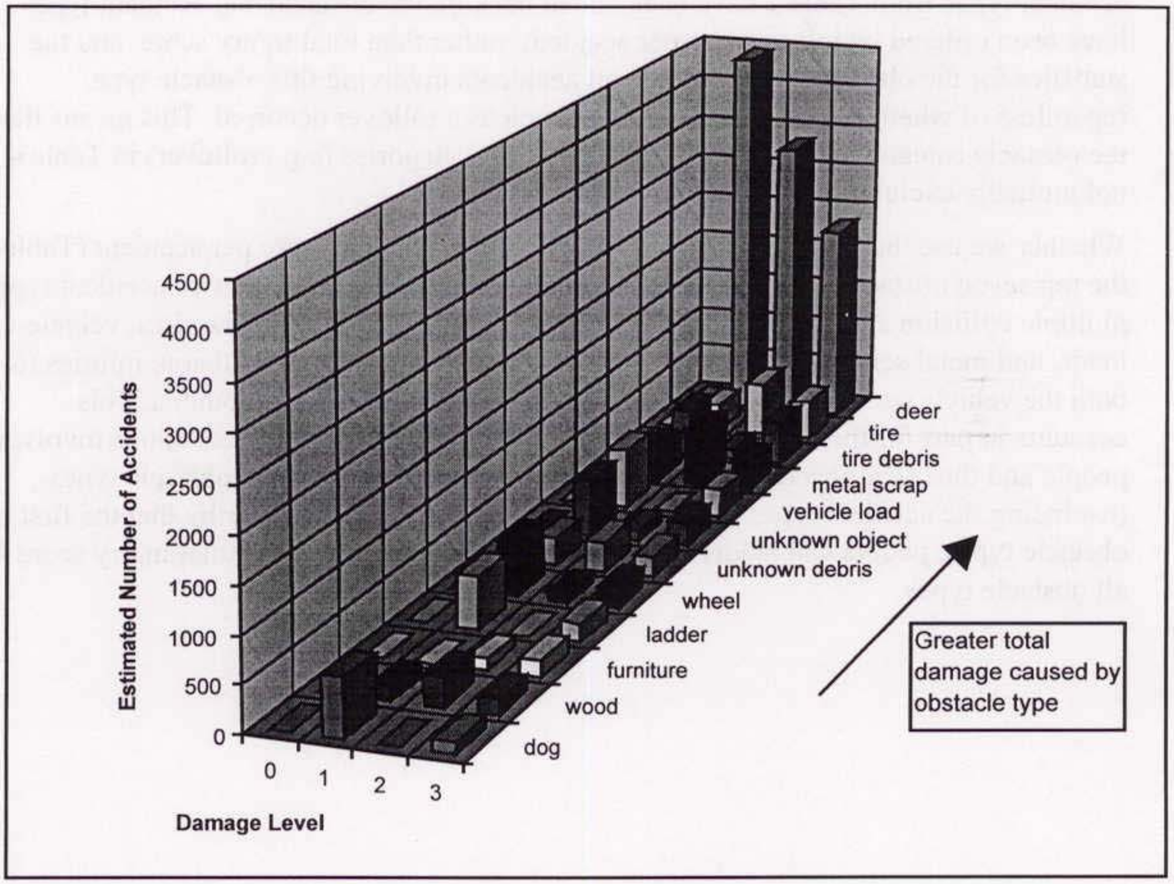


Figure 2

Figure 2 shows the distribution of damage levels caused by a dozen of the most serious obstacle types in interstate crashes. Obstacle types were chosen on the basis of their total damage score (see below) and the number of police reports entered into GES involving the obstacle type (minimum of five). All reports were classified on the basis of the obstacle type involved, without regard to secondary accidents (e.g., rollover). The x (transverse) axis is the seriousness of the damage to the vehicle closest to the obstacle, where 0 is no damage, 1 is minor damage, 2 is functional (moderate) damage, and 3 is disabling (severe) damage. The z (vertical) axis is the estimated number of accidents on interstate highways in the U.S. in 1996, based on police reports to the GES database. The y (longitudinal) axis lists the twelve most serious obstacle types. The listed obstacle types are ordered from least serious (dog) to most serious (deer). This ordering is based on a "total damage" score which is computed by weighting the number of crashes at each injury level by ten raised to the "damage level" power. This is the same as Equation 1, but with damage level substituted for injury level.

Obstacle or Accident(*) Type	**Total Damage Score**	**Est Number of Accidents**	**Damage Score per Accident**
Multiple Collision *	294,107	318	923
Fixed Object *	1,456,746	1623	898
Rollover *	433,789	570	760
Furniture	198,340	310	639
Vehicle Debris	119,271	230	519
Tire Debris	507,989	1141	445
Tire	522,787	1415	369
Vehicle Load	318,220	987	323
Wood	196,642	629	313
Unknown Debris	261,112	859	304
Metal Scrap	417,914	1422	294
Unknown Object	281,471	1002	281
Deer	2,696,291	10,051	268
Ladder	206,815	789	262
Wheel	238,630	929	257
Another Vehicle *	155,115	868	179
Dog	122,942	745	165
Person	9162	237	39
Rock	14,942	1494	10

Table 5

Table 5 shows similar damage data to Figure 2, but there are a few key differences. The accident types from Table 2 have been added back in, the obstacle and accident types have been ordered by damage score per accident, rather than total damage score, and the statistics for the obstacles now include all accidents involving the obstacle type, regardless of whether a secondary accident such as a rollover occurred. This means that the obstacle categories (e.g., tire) and the accident categories (e.g., rollover) in Table 5 are not mutually exclusive.

Unlike the injury scores per accident, which fall dramatically after the first three obstacle/accident types, the damage scores per accident in Table 5 descend much more gradually. Interestingly, the three highest payoff crash types from a damage per accident perspective are not obstacle collisions at all, but accident types (multiple collision, collision with fixed object, and rollover) which happen when manual drivers try to avoid hitting obstacles.

Statistics on Types of Obstacle Motion

Obstacle Motion	Number of Crashes	Percentage
Entering Onto Roadway	13795	38.1
Lying/Standing In Traffic Lanes	9616	26.6
Falling/Detaching From Vehicle	5878	16.2
Bouncing/Flying/Thrown Up By Vehicle	4242	11.7
Falling From Overhead	415	1.1
Attached To Roadway	187	0.5
Unknown	2035	5.7

Table 6

Table 6 lists the different types of motion which characterize obstacles involved in accidents on the interstate. Most types are self-explanatory; the two which may need explanation are Entering Onto Roadway (e.g., a deer) and Attached To Roadway (e.g., an expansion joint sticking up above the lane surface). Number of Crashes gives the estimated number of interstate crashes from the U.S. in 1996 in which the obstacle was characterized by this type of motion. Remember that this is a statistical projection based on the number of reports to the GES database in that year, and the statistical multipliers of the reporting jurisdictions.

The obstacle motion statistics in Table 6 suggest that the task of detecting and tracking obstacles on and near the highway will be challenging for two reasons. First, about half of these obstacles were to the side of the vehicle, or above the road surface, shortly before the collision. Detecting and classifying them quickly will require a wide sensor field of view (or regard), and also the ability to recognize a deer (or other animal) before it enters a traffic lane. Second, about two thirds of the obstacles were in motion. In many cases this motion included frequent changes of direction due to collisions with vehicles and fixed objects, making it very hard to predict. In such a circumstance, braking would be the preferred obstacle avoidance method, being less dependent than lane changing on correctly predicting the path of the obstacle.

Statistics on Obstacle Location

Obstacle Origin	Number of Crashes	Percentage
Same Lane	14,718	40.7
Opposite Direction Lanes	6147	17.0
Shoulder (Same Dir.)	4674	12.9
Adjacent Lane	2061	5.7
2 or More Lanes Over	154	0.4
Overhead	8	0.0
Unknown	8403	23.2

Table 7

Table 7 lists the different origins which characterize obstacles on the interstate. The origins listed are self-explanatory; opposite direction lanes includes both roadways with center barriers, and those with parkway strips (grass, dirt, etc.). Two or more lanes over is limited to lanes with traffic in the same direction. Number of Crashes gives the estimated number of interstate crashes in the U.S. in 1996, in which the location from which the obstacle originated is as shown. Remember that this is a statistical projection based on the number of reports to the GES database in that year, and the statistical multipliers of the reporting jurisdictions.

The main thrust of Table 7 is that obstacles are not just objects which lie in the traffic lane in front of the vehicle. They frequently coming running (or rolling) from an adjacent lane, or they come bouncing over the median, or they may even drop from overhead. An obstacle detection system must therefore have a sensor with a wide field of view (or regard), a rapid cycle time, and a good tracker. Another interesting insight provided by Table 7 is that about one obstacle in six originates in the opposite direction lanes, and crosses either the median strip, or the concrete barrier separating opposite direction lanes. Reducing obstacle accidents of this sort will probably require a combination of reducing the source of the obstacles and intercepting more of them. In practical terms, reducing the source might mean requiring minimum quality standards for tires and truck retreads, and a warning system for loose lug nuts for vehicles using the AHS. Intercepting more obstacles could be accomplished by raising the height of the concrete median, and adding a fence where opposite direction lanes are separated by a median strip.

Conclusions

- Environmental intruders (42%), vehicle loads (19%), and vehicle components (18%) are the three most frequent obstacle categories.
- Although people (in the role of being struck by the vehicle) and ladders are involved in only a small percentage of interstate obstacle accidents, they are responsible for more than half of the total injury score.
- Deer are involved in about one interstate obstacle accident in five, and cause about one third of the total damage score for all obstacle types.
- The four "other obstacle accident" types - rollover, collision with fixed object, collision with another vehicle, and multiple collisions - rate high in terms of both injury and damage per accident. These are the result of attempts by the manual driver to avoid colliding with the obstacle.
- For injury cost, the five worst obstacle types, both in terms of total injury and injury per accident, are people, ladders, tires, vehicle loads, and metal scrap.
- If one looks at damage cost, tires, tire debris, and vehicle loads are in the top five for both total damage and damage per accident. For total damage, the remaining two are deer and metal scrap. For damage per accident, they are furniture and vehicle debris.
- The most common types of obstacle motion are - entering the roadway under their own power (38%), lying/standing in traffic lanes (27%), falling/detaching from a vehicle (16%), and bouncing/flying/thrown up by a vehicle (12%).
- Obstacles are frequently first seen in the same lane as the vehicle involved in the crash (41%), coming from the opposite direction lanes (17%), from the shoulder in the same direction (13%), or from one lane over (6%).

AHS Obstacle Management

AHS obstacle management policy has two parts -
Obstacle exclusion
Obstacle detection and avoidance

Obstacle Exclusion

There are four major avenues through which obstacle exclusion can reduce the injury and damage resulting from obstacle crashes on the AHS -

1) provide a means of keeping animals and objects from the surroundings off the highway
2) require methods of vehicle inspection and self-monitoring to keep vehicle components from separating from the vehicle during operation
3) enforce a policy regarding vehicle loads backed up by inspection which greatly reduces the probability that cargo will be lost during operation on AHS lanes or highways
4) keep people who do not belong on the AHS off the roadway, and safeguard those who do belong there

Table 8 explores the effectiveness of these four obstacle exclusion policies in reducing the number of obstacle accidents, and the resulting injury and damage cost. The cost function is the same one as was used above. The figures shown represent the maximum possible reduction in number of accidents or cost.

Obstacle Exclusion Policy Aimed At...	**Max Obstacle Accidents Avoided**	**Maximum Injury Cost Avoided**	**Maximum Damage Cost Avoided**
Animals/Objects from Environment	42.3%	2.2%	43.6%
Vehicle Loads	18.7%	35.2%	15.2%
Vehicle Components	17.9%	9.1%	21.8%
People	1.2%	46.6%	0.1%

Table 8

The figures in the Accidents Avoided column are estimates based on all accidents reported to the GES database. The figures in the Maximum Injury Cost Avoided column are based on the subset of these reported accidents for which a maximum injury level was reported (excluding unknowns). The figures in the Maximum Damage Cost Avoided column are based on the subset of these reported accidents for which a damage level was reported (excluding unknowns). Consequently, the total number of estimated accidents from which the percentages in each column are calculated is slightly different.

Obstacle Detection and Avoidance

If an automated or semi-automated vehicle responding to an obstacle in the roadway can be kept from striking a fixed object, striking another vehicle, or rolling over, a substantial reduction in injuries and damage caused by obstacles can be achieved.

AHS obstacle detection and tracking should have the following characteristics -

Wide field of view (or regard) both horizontally and vertically
Rapid cycle time
Ability to determine quickly and precisely what objects are on the roadway and what objects are off, even on curved sections of highway
Ability to make a gross determination of object size
Ability to quickly establish a track on obstacles with regular motion
Ability to quickly recognize that an obstacle is moving erratically

10.4.5 Driver Involvement Analyses

Author, Robert M. Hogan

10.4.5.1 Introduction

The C3 Driver Role and Acceptance Critical Issues Team was created in October, 1996, to make specific recommendations with regard to degree of driver involvement for the AHS architecture definition and deployment tasks. Driver role issues will exist even after the driver is disengaged from most control responsibilities, but the driver role is particularly important in determining which AHS-antecedent systems can be useful along the path to full automation.

Critical driver role issues were determined using three significant sources of input:

- A review of Precursor Systems Analyses for AHS
- A review of the psychology of automation and a variety of semi-automated automotive tasks [1], contracted to Dr. Thomas Dingus of VTI
- The judgment of Team members.

Based on these factors, the top three priority driver role issues were judged to be:

- How will evolution effect the driver role and what general constraints do driver limitations place on pre-AHS driver assist configurations?
- For different degrees of driver disengagement, how will lessened vigilance impact driver safety, specifically through critical tasks like obstacle detection and hazard classification?
- What role should the driver have in the event of malfunction?

The other issues of highest priority concerned driver intervention, transfer from automatic to manual control, and compatibility of driver role with specific forms of partial automation.

The year's strategy for addressing the three top priority issues was a set of directed literature reviews supplemented by a limited set of contracted research activities. The results are reported below. Following the program reorientation in March, the Team also participated in an ongoing review of driver performance and behavior modeling literature.

10.4.5.1.1 Reference

[1] Neale, V.L., Martin,D. and Dingus, T.A. (1996). Human Factors Analysis and Design Support for the National Automated Highway System Consortium," Phase One Draft Final Report: Center for Transportation Research, Virginia Polytechnic Institute and State University, Blacksburg, VA.

10.4.5.2 Implications of Vigilance, Monitoring, and Supervisory Control Literature for "Hands-off, Feet-off, Brain-on" Driver Role

In high-end precursors of full AHS, will disengagement of driver from physical aspects of vehicle control turn the driver role into a vigilance task (with driver showing low alertness and an inability to intervene quickly)?

This topic is directly relevant to each of the three highest priority issues. The following summary of directed literature reviews indicates that the answer is a clear yes, to the extent that a disengaged operator cannot intervene as quickly or as appropriately as an engaged operator; the answer could also be yes in a stronger sense if future driver-in-the-loop simulation studies similar to the one reported in Section 10.4.5.2.4 can demonstrate decrements in obstacle detection capability and physiological changes correlated with degree of physical disengagement.

10.4.5.2.1 Introduction

Driver disengagement is a top level service objective for AHS users [1]. Full automatic control with "hands-off and feet-off driving" will be provided, once issues of hazard control, detection, and avoidance are resolved and full disengagement can occur with sufficient safety and reliability.

Safe, reliable driver disengagement is technically challenging, more so in a mixed environment where the automated vehicles would share lanes with conventional vehicles. Faced with this challenge, some analysts [2,3] having advocated "keeping the driver in the loop" as a means of dealing with system malfunctions or unanticipated situations, and have even considered the driver as obstacle detector of last resort. Recommendations for achieving this have not been specific but seem to cluster around the following two ideas:

- The driver performs "hands-off and feet-off driving" while integrated headway, lane keeping, and collision avoidance capabilities control the vehicle, but must remain sufficiently alert to deal with the rare obstacle which the system cannot avoid.
- The driver performs "hands-on and feet-on driving," retaining usual steering and pedal responsibilities, backed up by a fallback system of integrated headway, lane keeping, and collision avoidance capabilities which are only activated in emergency conditions.

In a precursor system with substantial but not yet full automation, the driver might remain involved in either of these two ways, which contrast sharply in degree of physical driving involvement.

There is a body of supervisory control literature which provides context for evaluating these two driver roles. Ordinary driving is frequently described as involving three levels of responsibility: navigation, guidance, and control [4]. These levels fit naturally within Rasmussen's [5] conceptual framework for supervisory and process control. Rasmussen distinguishes three hierarchically structured loops, an inner (closed) loop mode, where standard control theory is applicable, an intermediate level loop, where monitoring occurs but not control, and an outer loop which is open and has to do with goal setting and the current relation to the goal. Within this framework, the essential difference between engaged and disengaged driver roles is the proportion of time spent on inner loop control. Insights from reviewing the supervisory control literature are presented in Section 10.4.5.2.2.

From a different point of view, removing all the driver's responsibilities except following the detection of an infrequent obstacle makes the disengaged driver's task very much like a vigilance task [6]. The new driver role requires sustained attention for the occurrence of an infrequent, unpredictable event over long periods of time, essentially the definition of a vigilance task. There is a larger, older literature (reviewed in [6]) which deals with human performance in vigilance/monitoring situations. In this literature, different theories prevail and different quantities are measured in what are generally simpler situations. Vigilance literature suggests the possibility that a physically disengaged driver's level of arousal may become so low that the driver's obstacle detection capability suffers relative to the physically involved condition. Precise guidance with regard to the conditions that induce low alertness was not found but existing experimental techniques appear relevant. These aspects of the vigilance/monitoring literature are discussed in Section 10.4.5.2.3 and a driver-in-the-loop simulation study to investigate driver alertness across driver roles is described in Section 10.4.5.2.4.

Drawing from these three avenues of investigation, Section 10.4.5.2.5's conclusion is:

In precursor systems with substantial but not yet full automation, it is recommended that the driver retain usual steering (and possibly pedal) responsibilities until such time and circumstances that the system can achieve adequate hazard avoidance and safety without driver intervention.

10.4.5.2.2 Supervisory Control Literature

The choice of removing the driver from all or almost all physical driving involvement would follow a trend which has been continuously implemented, studied, and critically evaluated, in aviation, in air traffic control, and in process control. As Moray [7] characterizes it, there is a progression in supervisory control, from situations where the computer is just a passive servant to ones where the human role is reduced to a minimum, merely to monitor the system and make sure that it is functioning normally. The human is freed from his usual level of involvement, to participate in a higher level of control (in many cases) or to enjoy disengagement as ultimately promised by AHS.

But, Moray cautions that there is a likely price for the advantages. "It could be that the information processing demands become so alien to the operator that if called upon in an emergency to reenter the control loop such reentry is no longer possible. Too much information must be processed to update the operator's knowledge of the system state. The system will be poorly understood and the operator will lack practice in exercising control, so that the possibility of human error in emergencies will increase." This is a central concern and a source of contention in cockpit automation [8] and in the automation of air traffic control [9].

Wiener [10] describes how cockpit designers have emphasized reduction of manual workload, while not adequately accounting for mental workload. While crews can appreciate being relieved of some duties (such as maintaining airspeed), they also find that each new device creates its own "scanning demand," and that the overall responsibility sometimes requires more cognitive processing, not less. In fact, automation may sometimes have the unintended consequence of increasing extremes of workload, both very low and (infrequently but sometimes tragically) very high. Interviews with pilots of highly automated aircraft suggest both, often mentioning boredom and complacency, but even more significant, a strong sense of being "out of the loop", with the implication of possible failure to regain adequate control in an extraordinary, hard to understand condition.

Concern with "operator out of the loop" problems is generating a growing body of experimental research, much of it linked to models of the human operator. Studies of the speed with which system faults can be diagnosed are considered within the context of Rasmussen's model by Moray. Some rather sophisticated insights are possible, including the generalization that detection rate depends "on the rate of change of dynamics at the moment of the fault, and the tightness with which the operator is coupled to the system". On balance, it appears that drivers will usually intervene more quickly, particularly for sudden faults, if they have been actively controlling the system.

A similar hierarchical framework has proved useful in characterizing problems of training for supervisory control. Sheridan [11] finds that serious problems occurred in the nuclear power industry when operators were initially hired as outer loop problem solvers, but then "expected to react at high speed and in inner loop modes in emergencies, despite their having an inadequate knowledge of the values of the state variables." And drawing on training research by Duncan [12], Moray concludes that "only frequent hands-on control experience in a simulator will enable a supervisor to retain an accurate model of a process that is monitored under automatic control". Training must aim to make each mode of operation (inner, intermediate, and outer loop) available for moments when the operator needs it.

Wickens [13] considers additional studies which show hands-on advantage, and suggests that "out of the loop unfamiliarity" may have impact in two different ways, by causing loss of information about the momentary state of the system or by causing loss of proficiency as less hands on experience is received.

This body of research suggests caution in changing the balance of a driver's usual responsibilities, which are now part physical control, part monitoring and supervisory control. There seems to be a direct warning of danger in totally removing the driver's physical input (as proposed in AHS driver disengagement) if the now disengaged commuter is to be relied on for rapid judgments of system malfunction or sudden acceptance of driving responsibilities in an emergency situation. Research and theory agree that a disengaged commuter will show less capability in these situations than an involved driver thrust into the same situation.

A disengaged driver can be expected to be slow in responding to a sudden emergency, and to be less aware than the engaged driver of relevant aspects of the situation. But it is not clear from this supervisory control literature whether the physically disengaged driver, because of an alertness deficit, would also be less capable of detecting an infrequent, unpredictable obstacle. The vigilance literature has more to say about this question.

10.4.6.2.3 Vigilance/Monitoring Literature

It is easy to briefly attend to a predictable event, but if the scheduling of the event becomes infrequent and unpredictable over a long time period, sometimes it will not be noticed. Many demonstrations of this fact in the laboratory and some in the field have shown lowered detection probabilities over time, a phenomenon known as the vigilance decrement [6].

Attention possesses both a selective and an intensive dimension, in that it can be directed to one or more signals or positions, and it may be deployed with greater or lesser intensity. Parasuraman [6] finds it useful to distinguish vigilance tasks, which involve only the intensive dimension of attention, from monitoring tasks, which require more. Monitoring tasks have sometimes used signals more complex than those common in vigilance tasks, and may involve some component of spatial uncertainty, as well as the temporal uncertainty characteristic of vigilance tasks.

Parasuraman argues that whatever cognitive mechanism causes a vigilance decrement in a vigilance task is also likely to cause a decrement in a monitoring task. Here is another direction from which to approach the issue of driver alertness with or without physical driving involvement. Would a disengaged driver show more of a vigilance decrement than an engaged driver in the detection of an equivalent set of infrequent, unpredictable obstacles? Either driving or disengaged monitoring of the highway environment varies in some obvious ways from maintaining watch for a simple, predefined signal (like the double step of a pointer on a clock face in Mackworth's [14] historic research, for example). But the persistent hope underlying this body of research is that basic variables or general principles isolated in simpler lab situations will be relevant to situations of practical importance.

The expectation of an alertness decrement in the less physically involved condition may be a manifestation of the long term influence of the Yerkes-Dodson law which in a general way relates performance (either human or animal) to task complexity and to level of physiological arousal. The law was initially based on data obtained from rats, in a discrimination learning task under various levels of stress induced by electric shock. As Wickens [13] relates, it has been useful in understanding stress effects in human performance and the surprisingly complex pattern of interaction between them.

The law is, essentially, that:

- An inverted U-shaped function relates performance to level of arousal, and
- For a simpler task performance is better, and the optimal level of arousal is higher, than for a more complex task.

As Wickens explains "The upward limb may be thought of as the result of an 'energizing,' which simply expands the amount of resources available" while "the downward limb is the consequence of a more specific effect of high arousal on the selectivity of attention or 'tunneling' to different environmental or internal cues." Most people are aware of a tendency toward "tunnel vision" under conditions of stress, and a tendency toward boredom in the absence of stimulation.

One concern with a physically disengaged driver is that the level of arousal may become so low that detection capability suffers relative to the physically involved condition. Unfortunately, this theory cannot take us much further in terms of concrete expectations in a specific situation. "One of the problematic characteristics of the Yerkes-Dodson law is that it is difficult if not impossible to know, a priori, where the optimum level of arousal is for a particular task and, hence, whether the introduction of a stressor will lead to an increase or decrease in task performance" [13]. We are left with two sources of information to guide an informed judgment about the impact of disengagement on obstacle detection while driving. The sources are whatever highway research data is available with bearing on the effect of physical driving involvement, and whatever empirical vigilance or monitoring results speak to the issue.

From highway researchers there has been concern about the impact of fatigue on long term driving with emphasis on physiological measurement. Brown [15] has written about the dangers of driver underinvolvement, and research on driver drowsiness continues with Knipling and Wierwille [16] providing an informative review. This is a literature in which physiological measures have been taken during long-term on-road or simulated driving but productive correlation of physiological and performance measures has been infrequent; interpretation has sometimes been complicated by wide individual differences. We have found no highway study which correlated physiological and obstacle detection measures (although correlation between physiological measures and infrequent detection has been demonstrated in the radar watch situation [e.g., 17].) We have also found no study in which degree of physical driving involvement was used as an independent variable.

The other avenue is to search the vigilance and monitoring literature for cases where a researcher explored the low arousal reaches of the Yerkes-Dodson performance curve. The effect of the primary task's intrinsic demand on arousal has been discussed [18] but appears not to have been systematically investigated in the vigilance context. However, the arousal demanded by a passive detection task is generally assumed low and some vigilance researchers have attempted to build on this assumption by demonstrating the beneficial impact of a simultaneous, presumably arousing secondary task. Such demonstrations have not been easily achieved. McGrath [19] reported a vigilance result in which detection of easy signals was enhanced by requiring simultaneous attention to difficult signals in another sensory modality, but he questioned the completeness of an "arousal" explanation. Wiener, Curry, and Faustina [20] report a beneficial effect of manual tracking on a monitoring task, but also review a series of similar attempts where the hoped for result was not obtained. Related research (e.g., in [17]) argues against the completeness of a unidimensional arousal theory and finds methodological flaws in much of the preceding research. More recent opinions [13,21] agree that arousal will be a necessary part of a comprehensive theory of vigilance, but that current versions of arousal theory are seriously incomplete.

A small body of published evidence nevertheless indicates that driver alertness in monotonous, long-term driving tasks can be enhanced by involvement in a secondary task [17,22]. It is not a large step to hypothesize that greater alertness might result from more active involvement in the primary driving task. So in spite of the lack of precise guidance from theory, it does appear reasonable that driving alertness can be enhanced by increased driving involvement. And it is at least worth testing experimentally whether infrequent obstacle detection would be lowered by decreasing physical driving involvement. This was the reasoning behind the experimental driver-in-the-loop simulation research described next.

10.4.5.2.4 Experimental Study

An initial study has been performed by Systems Technology, Inc. using their research driving simulator STISIM. Wade Allen, Zareh Parseghian, and Brenda Page of STI have analyzed data recorded during the study, and submitted a report on the results of this study which is attached as 10.4.5. Appendix A. STI found increased head pitch and head roll activity, which they interpret as evidence of increased driver drowsiness and microsleeps, with higher levels of automation.

10.4.5.2.4.1 Objective

The objective of the study was to investigate how the extent of active driving involvement in a car following task impacts driver alertness and the driver's ability to detect potential hazards.

10.4.5.2.4.2 Experimental Design

The design was a one factor repeated measures design with three levels of driving involvement: 1) full automatic lane position and headway control; 2) automatic headway control plus manual steering; 3) manual driving requiring both steering and speed control. Each subject experienced all three driving conditions, allowing a within group comparison of the experimental treatments. The order of conditions was balanced across subjects.

Dependent variables included measures of driving performance and psychophysiological response. Detection accuracy and detection time were measured on a subsidiary obstacle detection task in which a standing vehicle was present by the side of the highway about once a minute, with appropriate randomization, and a pedestrian was along side the vehicle about one time out of four. The pedestrian was the target signal; pressing the horn was the correct response. Under manual control conditions measures of headway and lateral lane position control were obtained as appropriate. Psychophysiological variables included heart rate, brain activity (electroencephalogram or EEG), brain blood flow (BBF), eye activity (electrooculogram or EOG), and pitch and roll head movements.

The recorded data was initially preprocessed to compute means and standard deviations of all variables over 3 minute epochs to give 10 measures during a half hour block within any condition. This data was then placed in spread sheets and subjected to multivariate statistical analysis designed to detect differences in driver behavior and/or psychophysiological response between the three experimental driving control conditions.

More detailed time histories were obtained for head pitch, head roll, and EOG, by plotting the average value of each measure over one second intervals, where the raw data was collected sixteen times per second. The one second average smoothes out fast transients in the data, but shows changes that have some persistence.

10.4.5.2.4.3 Results

Mean detection times reliably decreased (that is, they improved) across 1/2 hour intervals for each of the three experimental conditions. Measures of detection did not differ reliably across levels of driving involvement nor did this change with time on task.

Measures of steering performance generally improved over the ½ hour intervals for each condition where steering performance was relevant. Steering performance did not differ reliably across levels of driving involvement where comparisons were possible and this did not change with time on task.

Analysis of the psychophysiological measures is complex and subject to some interpretation. However, the most sensitive of the six recorded measures, head pitch, showed clear evidence of downward "spiking" which is interpreted in 10.4.5. Appendix A as head droops due to micro-sleeps. This interpretation is consistent with experimenters' reports of obviously drowsy subjects 'nodding' occasionally under the experimental conditions. The interpretation is also consistent with the more detailed second by second analysis which showed a strong correlation of head roll activity (presumably due to loss of neck muscle tension) with head drop episodes.

Four different psychophysiological variables showed reliable differences among the manual, semiautomatic, and fully automated conditions, with each showing a maximum of activity under full automation. Of the four, only head pitch activity showed a reliable change within half-hour blocks (It increased, see Figure 3 of Appendix A) and only head pitch and head roll showed significant or marginally significant interactions between automation conditions and time segments (Head activity was greatest for the combination of late segments with full automation, see Figures 4a and 4b). This pattern of head activity over time segments is consistent with the 'microsleeps' interpretation, as one would expect more drowsiness with longer time at the task. It is not clear on the basis of this analysis whether higher EOG and BBF activity in the fully automated condition might also be related to the head nodding.

In their discussion of the more detailed microsleep data reduction and analysis, the STI researchers consider measurement problems inherent in counting the number of microsleeps which are sporadic and vary in amplitude. They introduce a method of analysis which limits computing demands and minimizes the impact of poorly motivated assumptions about the size and duration of microsleeps by considering an equal number of one second intervals of highest amplitude activity within each statistical data cell. They report an application of this method which used only the eight highest amplitude intervals in each 10 minute data cell. In the example, there was a reliable effect of automation condition but no reliable effect of time segment (Beginning, Middle or End of a 30 minute run).

10.4.5.2.4.4 Discussion of Results

In this study subjects experienced conditions that did *not* cause decreases over time in detection performance (i.e., the vigilance decrement reported in numerous studies) or a lessening of driving control over time (as reported, e.g., in an STI study [23] using the same simulator). Instead, there were beneficial effects of practice as subjects gradually improved their control in manual vehicle conditions and learned to detect pedestrians faster.

There is some precedent for observing improved detection times over an extended period of driving. Brown Simmonds, and Tickner [24] found response times to improve over 12 hours of virtually continuous driving, where the signal to be detected was not an obstacle or potential hazard but a light visible through the rear view mirror. Brown, et al note that their results were obtained under the stimulating conditions of city traffic and not the more monotonous conditions of motorway driving, where "levels of arousal and performance could be depressed".

The benefit of practice in the present study might have been partly attributable to the "within subjects" strategy of allowing a single subject to experience all three conditions, introducing novelty and possible confusion into the task. Other likely contributors were the use of a car following task rather than an empty highway task and the added complexity of the pedestrian detection task while driving. Any one of these factors could have established a sufficiently challenging situation for progressive improvement with practice to occur. The original goal of comparing vigilance detection decrements across levels of automation could not be achieved.

That goal requires a situation where the overall task is simple enough and well enough overlearned that the waning of sustained attention is not masked by benefits of practice.

The same argument would hold for the driving performance results. However, driving performance decrements would not have been available for the fully automated condition, in any case, so this data was less critical than the detection and physiological data.

Physiological evidence of alertness decrements need not have been masked in the same way. Some physiological measures recorded in this study show changes over time on task that are plausibly interpreted as alertness decrements. Declining driver alertness appears to be most clearly shown by measured head pitch activity which reliably increased with time on task. The STI researchers interpret this activity as head movements associated with microsleeps. The presence of head droops under monotonous task conditions is consistent with other research including Dinges and Graeber [25] who report that long-haul airline pilots show brief periods of microsleep which are not usually noticed by other crew members.

If the microsleep interpretation is correct, then this physiological evidence of declining alertness was obtained in a situation where other vigilance decrements (measured by detection or by driver control) were masked by benefits of practice. Learning and the waning of alertness can occur together, within the same person, although learning curves and vigilance decrements tend to appear in separate parts of the experimental literature.

Certainly, the conditions of this study were more demanding (and presumably more arousing) than conditions established in most laboratory vigilance studies. On the other hand, it was not clear *a priori* how low a level of alertness or arousal was really needed to pursue the objective of the study (See the comment on "a problematic characteristic" of the Yerkes-Dodson Law in Section 10.4.5.2.3). Subjects in this study appeared in the laboratory after a full day's work and dinner, then participated in what was a rather monotonous two hours of simulated driving even if it was challenging enough to show practice effects. It is plausible that subjects could give evidence of declining alertness under such conditions, even though the tasks were complex enough to show practice effects as well.

If the interpretation of head pitch activity as evidence of lessened alertness is correct, then the same measure provides clear evidence relevant to the experimental objective (Section 10.4.5.2.4.1). Head droops increased reliably from manual to fully automated driving, and so *driver alertness decreased as level of automation increased.*

Analysis of data gathered in one second intervals was analyzed to further quantify the head movement and EOG activity. The largest few amplitudes in each data cell were looked at as an indication of the microsleep phenomenon. This analysis confirmed that there was reliably more of the highest amplitude activity in the automated condition. However, this initial analysis of the second by second results should be considered preliminary rather than definitive. As Allen points out in a cover letter, the analysis of physiological measures was limited because of funding, time, and computing capacity. The data collected is rich enough to merit further analysis beyond what was accomplished during this period. In particular, more certain linking of the frequency and duration of head nodding with time on task would be desirable to support and clarify the interpretation offered here, as would detailed analysis of correlations with the other physiological measures of alertness.

In summary, the initial plan of comparing vigilance detection decrements was not accomplished, but suggestive evidence with regard to driver alertness was still obtained. Level of automation clearly influenced the degree of driver alertness. Less physical involvement in driving led to more evidence of head droops (which are plausibly interpreted as microsleeps). If this nodding reflects a deficit in alertness, the deficit would also be shown in those measures of obstacle detection which are sufficiently sensitive.

10.4.5.2.5 Conclusions

From the review of supervisory control literature comes the generalization that when a set of responsibilities can be understood in terms of hierarchically nested loops as in Rasmussen's model, the key to effectiveness is allowing the operator the necessary tools (and freedoms) to perform productively at each level and to quickly switch between levels. This is a surprisingly robust generalization which appears equally applicable to controlling a complex industrial process, to piloting an aircraft, to controlling air traffic, or to driving. It follows in the latter case that the driver will benefit from retaining moment-to-moment familiarity with aspects of the inner control loop, if there is any likelihood of his needing to resume control or to make decisions or interpretations that would benefit from a ready grasp of aspects (physical or cognitive) of control. While it is not clear from the supervisory control literature that obstacle detection would be worse with physical disengagement, it is clear that the ability to quickly resume vehicle control in the case of an obstacle would be worse, because of a lack of situation specific awareness including physical aspects of vehicle control. This generalization would extend to any time constrained resumption of control responsibilities resulting from system malfunction or other reasons.

From the vigilance/monitoring literature review comes the theoretical possibility that even the ability to detect an obstacle may be worse if the driver is disengaged from his physical control responsibilities, because the driver's level of arousal may become dangerously low. Attempts to facilitate performance at the low end of the Yerkes-Dodson performance curve have rarely been successful in the laboratory, but the problem of driver alertness under monotonous conditions is certainly real and provides motivation to attempt a link with other vigilance research.

However, even if the simple detection capability shows no evidence of a decrement due to physical disengagement, more complex hazard classification, response selection, and response execution tasks would suffer from lesser situation specific awareness. In particular, the task of distinguishing obstacles which the automatic collision avoidance system is unlikely to avoid (in addition to requiring significant training for the disengaged driver) would involve studying every potential obstacle on or near the freeway to the point where it can be categorized as threat or non-threat. This involves classification of obstacles in the context of the vehicle's control situation, so the disengaged driver will not be able to make judgments concerning the relevant obstacles as quickly or as well.

In extrapolating beyond the simple detection task, one should not overlook that in order to intervene the physically disengaged driver has an additional task, the replacement of hands and/or feet at appropriate positions on the steering wheel and the floor pedals. The replacement time under the most optimistic of scenarios, when the driver is posturally prepared to resume control, would be significant in most emergency braking situations. The most optimistic scenario would include the steering wheel and pedals being configured exactly as this (previously disengaged) driver expects they will be on the basis of his incomplete system specific awareness; if they are not as expected there will be additional delay as the driver revises his inappropriate expectation, or makes errors of control.

In judging the wisdom of a physically disengaged driver role with monitoring responsibilities, customer acceptance should also be kept in mind. A major expected benefit [1] of driver disengagement in AHS is relieving the driver of his driving responsibility, allowing him to relax. Obviously, the perpetual monitoring necessary to detect an infrequent, unpredictable obstacle which the system cannot avoid brings us to a situation more stressful than conventional driving, where most hazards can be avoided by defensive driving. It is doubtful that customers will be drawn to a precursor system which misses this very fundamental objective.

In reviewing this analysis, all considerations point in the same direction. In precursor systems with substantial but not yet full automation, it is recommended that the driver retain usual steering (and possibly pedal) responsibilities until such time and circumstances that the system can achieve adequate hazard avoidance and safety without driver intervention.

10.4.5.2.6 References

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10.4.5.3 Definition of Driver's Role in Two High-end Partially Automated Alternatives to Hands-off, Feet-off, Brain-on"

A definition of driver role in two high end temporary emergency control services was developed by Dr. Thomas Dingus and associates at VPI. Their report of this work is attached as 10.4.5 Appendix B.

This task was a natural extension of the "Hands-off, Feet-off, Brain-on" investigation, because if continual passive monitoring is not an acceptable role for an otherwise disengaged driver, then the deployment progression must either:

- Include high end collision avoidance capabilities with driver still actively involved or
- Jump from lower levels of control to full automation.

The objectives of the contract were 1) a detailed definition of the driver role, 2) identification of driver related human factors issues, and 3) assessment of concept feasibility from the driver's point of view, in each of two operational scenarios defined below. The concepts for the two scenarios are chosen from the range of partially automated vehicular control services, with Concept A thought to be representative and Concept B at the high end of the range.

The representative concept is A. Background Free Agent/Self Contained. Aside from its background nature, this concept is deliberately similar to the Free Agent/Self Contained concept defined by PATH/Honeywell for human factors functional analysis purposes [1]. In Concept A the driver actively controls the vehicle under most conditions, with automated headway or lanekeeping only activated at critical situations. In this concept the background control functions work independently.

The high end concept is B. Background Integrated Longitudinal and Lateral Control with Temporary Emergency Control. This concept is characterized in [2] as Service Category 6.4. In this concept the background control functions work in an integrated fashion, allowing a wider range of emergency control actions than in A.

To illustrate the difference between concepts, with a stopped lead vehicle, the Concept A response would be an in-lane braking action, but the Concept B response could also accommodate an emergency lane change maneuver. In either concept driver override is always possible.

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10.4.5.4 Does the Possibility of Driver Modes Confusion and the Need for Driver System State Awareness Place Strong Constraints on Partially Automated Precursor Configurations?

The following sections describe a number of different ways in which the answer is yes. Several driver mode confusion related questions were posed in Honeywell and Raytheon/USC PSAs [1,2]. These questions are central to an understanding of how driver limitations will constrain precursors to the fully automated system. The questions were addressed in a literature review by the Team and were the core topics for a directed review of aviation psychology and other relevant areas conducted by Diane Damos, co-author of the Raytheon/USC PSAs.

In addition to the aviation literature, Damos considered driver braking and steering times and manual tracking and control (with regard to single vs. multi-axis tracking and also the detection of system failures). She provided insights (with regard to bundling issues, override of collision avoidance, collision warning system design, and fallback schemes) which have been incorporated into Sections 10.4.5.4.1 through 10.4.5.4.5. Her review also included a brief description of the automated flight system of a commercial jet aircraft, to allow readers to draw informed analogies between automated aircraft and proposed versions of intelligent vehicles. Damos' review is attached as 10.4.5 Appendix C.

10.4.5.4.1 Does Roles Confusion and the Need for System State Awareness Call for "Bundling" of Automated Functions?

Riley [1] provided a detailed analysis of how AHS functions should be allocated between driver and automation. With regard to the free agent scenario (mentioned in Section 10.4.5.3) he advised against either: 1) allowing lateral and longitudinal control to be automated separately if they could be automated together or 2) separating collision warning from collision avoidance, because of possible mode confusions. Dickerson, et al [2] expressed similar concerns with regard to certain "evolutionary representative system configurations" and applied an analogous argument to other issues, like whether collision avoidance in one dimension, with evasive actions still required in second dimension, was workable. Dickerson, et al also expressed a more general concern, whether all automatic systems need to be controlled by one switch or many: "It may not be a good idea to allow a vehicle to have different modes of operation." (p.166).

How important is the "bundling" of separable automated functions of a partially automated vehicle? Wierwille [3] contrasts the degree of collision danger in driving with that of an aircraft in flight. The lane is narrow and sometimes turning; because of the proximity of stationary and moving objects, the driver "has no choice but to monitor the driving scene very carefully". Unlike a pilot, the driver looks within the vehicle only occasionally. Eyes-off-road time [3] and more direct methods of experimental control (like the occlusion technique used to limit visual sampling in [4]) show that under demanding driving conditions, the conventional driver has little spare time to monitor additional states. Driver attention to even the simplest secondary tasks requires multiple glances at the secondary control or display [3], and influences lanekeeping performance as well (in a number of unpublished driving simulator studies by the author). A consequence of the need for second-by-second highway monitoring is that unexpected behavior by the vehicle while in motion may have extreme consequences.

Unexpected vehicular behavior could result from a mode confusion. We know that drivers (and all humans) are prone to confusions in simple, repetitive tasks (see, e.g., [5], particularly the sections on short term memory and divided attention). Research on the usability of automotive controls, including unpublished research by the author, indicates that errors in using secondary controls while driving are common. From a different direction, Lings [6] provides evidence of drivers performing steering and braking actions which are irrelevant to the simulated driving task. Inadvertent steering or brake inputs could complicate the design problem for some precursor configurations since steering or braking are likely candidates for overriding an automated mode. In every case, whether confusion results from momentary inattention or an overt action, if a confusion error is made possible then it is made likely.

In a precursor vehicle, the danger of a confusion between the automated state and the manual state is probably an acceptable risk, comparable to what already exists with current cruise control. However, allowing the separable control of longitudinal and lateral control modes, or the use of separable collision avoidance and collision warning modes, doubles the number of states that can be confused one with the other, in a situation where recovery time is limited and no more confusions are acceptable.

Are there lessons to be learned from closely comparable systems? Early, propeller driver aircraft may be relevant because the simplicity of their operation is closer than current jet aircraft to present or future automotive vehicles. Fitts & Jones [7] analyzed the factors contributing to 460 pilot error experiences in operating early aircraft controls. The main contributions to pilot error were that A) different aircraft had controls for the same function located in different places, B) the controls were too close together, and C) the controls could not be identified by touch alone. Aircraft manufacturers acknowledged these problems and corrected them; pilot confusion errors and inadvertent activations are no longer considered a problem in modern propeller-driven aircraft. However, there is less space in an automotive vehicle than in a plane, protruding shapes may be the cause of injury in sudden automotive maneuvers, the driver has less time than a pilot to rectify errors, and drivers are a relatively unselected population. So each of Fitts & Jones' primary recommendations is either problematic or insufficient with regard to any mode confusion problem which might be introduced in a partially automated vehicle.

With regard to stringent time constraints on the driver in a high speed highway situation, the closest comparable system may be the fighter cockpit. In developing recommendations for the automation of fighter cockpits, McDaniel [8] describes the critical difference between a pilot's ability to intervene in about a second when a task has his undivided attention, or in a few extra seconds if he needs to refresh his awareness of the situation, detect and interpret a malfunction, and act to resolve it. In driving, the time to initiate braking is about 0.6 sec when the driver is alert and fully prepared to stop and a lack of preparation at least doubles this time [9]. Being a driver is not as demanding as being a fighter pilot, but introducing a single extraneous task (like resolving a mode confusion) into high speed driving could also make a few extra seconds critical.

Recommendation: *Conventional driving has no automated mode confusion problem more complex than cruise control ACTIVE/INACTIVE. Don't introduce one.*

Each precursor system of the AHS should include a choice, from all the possible automated functions, of a subset which is useful and intelligible as a group. The activation/deactivation of this subset should be treated as the activation/deactivation of a single state for purposes of driver awareness. The driver workload in using the automation should at no time exceed the driver workload in using current cruise control.

10.4.5.4.2 Collision Warning System Design

In a dynamic environment, warning information must be presented in a timely manner, i.e., the recipient must have sufficient time to process and respond to the message. If the recipient has no means to respond to the message or insufficient time to respond, then the message may simply contribute to the recipient's information overload. A warning intended to alert the inattentive driver might confuse or annoy someone who has no need of assistance.

Multiple warning systems may introduce confusion problems and response delays beyond those due to the presence of a single warning system. It is well documented (see, e.g., [5], Chapter 8) that response time will increase with the number of choices that the driver must consider. Other factors such as stimulus-response compatibility, location compatibility, or movement compatibility [5] may be critical in single or multiple warning system design.

Useful lessons can be drawn from the warning systems in commercial airliners. As Billings [10] notes, by the mid-1960's, many commercial airliners had several hundred warnings. One crash was attributed in part to the overwhelming number of warnings presented to the pilots. After this accident, aircraft manufacturers began to rethink the design of warning systems, especially in terms of the priority of messages, and how or when the messages are displayed. There is a more urgent need to limit messages to a driver, because of the much shorter time the driver has available to process them.

The effects of warning system false alarms in modern aircraft are discussed in a recent article by Carbaugh and Cooper [11]. The article documents failures of airline pilots to respond adequately to ground proximity warnings and suggests possible reasons for the poor response. In some cases the crew turned off the warning because, based on its prior history of false alarms, they believed it was malfunctioning. In other cases, the crew did not respond quickly enough because, again, they believed it was a false alarm. Similar response failures may be anticipated on the part of drivers of intelligent vehicles.

Design of an adequate collision warning system may also be complicated by a low base rate of collision events. Parasuraman, Hancock, and Olofinboba [12] argue that winning the confidence of users requires not just high hit rates and low false alarm rates, but relatively high values of posterior true alarm probability (the probability that given an alarm, it was appropriate) as well. This could pose a challenge because with low a priori probabilities of collision, Bayes' theorem can be used to show examples where the system is very sensitive and yet posterior true alarm probabilities are low[12].

Recommendations: *Designers should use the fewest possible number of warnings. Warnings should only be presented when the driver has sufficient time to respond effectively. The cost of a false alarm may be greater than the cost of failing to warn, but the details of this tradeoff require careful study. Posterior true alarm probability should also be considered.*

Current research at PATH [13] is developing a framework within which such a detailed study can be conducted.

10.4.5.4.3 Fallback Schemes

Some indications about the problems that may occur with fallback schemes involving degraded modes of automation were obtained by examining an analogous system in commercial airliners. By interviews [14] and by well-controlled experimentation in simulated cockpits [15], it has been determined that pilots of these systems have problems understanding when transitions will occur and predicting which level of automation will be active after the transition. These problems are primarily attributable to the complexity of the algorithms governing the transitions, the number of possible transitions, and the infrequency with which certain transitions are encountered.

Given the operating speeds and density of traffic in mature automated systems, fallback schemes that involve reversions to manual control after a failure of the control system of the vehicle may not be generally satisfactory; the driver may be unable to control the vehicle sufficiently to maintain lane keeping and spacing. Fallback schemes involving reversions to lower levels of automation could also be difficult to implement for this reason, or due to problems with driver understanding and lack of familiarity. Dickerson, et al ([2], p.205) suggested that the number of reversion paths should be kept to a minimum to avoid confusing the driver.

Recommendation: *Making the fallback scheme contingent on the traffic situation could help, but this requires a well-designed and thoroughly evaluated driver/vehicle interface to give the driver clear guidance under hazardous conditions. Fallback schemes may be complex in terms of their dependence on the traffic situation, but choices must be easy to understand and simple to execute from the driver's point of view.*

10.4.5.4.4 Override Capabilities

To explore the issue of system state awareness under conditions of time-constrained intervention, Damos [Appendix A] reviewed the literature of failure detection in continuous control tasks and in simulated aircraft. She concludes that an override capability will not aid in collision avoidance in most instances on a high-speed, high density highway because of the length of human response times. Automated systems should be used for collision avoidance.

Nevertheless, she recommends that an override capability should be included in intelligent vehicles to permit the driver to become actively involved under certain circumstances. In this regard, her recommendations are similar to those expressed in Battelle AHS PSA's [16], where it is argued that "capitalizing on the sophisticated observation and control system skills embedded in the driver as an additional source of input information to the zone controller could be very helpful to the overall system (just as pilot reported information is helpful to current air-traffic control center personnel)." Battelle also argued that maintaining some active role for the driver during entry, exit, or other stages might minimize the extent and cost of infrastructure modifications, that using the driver to handle a certain limited range of malfunctions (e.g., driving an ejected car on the breakdown lane to the nearest exit or changing a flat tire while in the breakdown lane) could greatly lessen incident management costs, and that maintaining some meaningful role for the driver (such as input to control in emergency situations) could counter possible user resistance. Damos and Battelle agree that the override capability should not be thought of as a second-by-second backup system for failures of components of the automatic systems; human failure detection times are too long and too variable to avoid many types of collisions that could result from the failure of a component of an automatic system.

Recommendation: *"AHS should be developed to accept inputs from the driver (e.g., a panic type signal or a verbal communication regarding an observed hazard) ... but not expect driver inputs" [16, p.82]. However, there needs to be systematic study of the appropriate system response to driver inputs (particularly panic inputs) in specific traffic situations. System responses may be complex in terms of their dependence on the traffic situation, but should be easy to understand from the driver's point of view.*

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10.4.5.5 Review of driver performance and behavior modeling literature

Since April, the Team has actively searched driver modeling and related literature. Here are six sources that seem useful, with descriptions of the value found in each. Three of them ([1], [2], and [5]) are reviews published in the '80s and two are recent releases from Wade Allen of STI [3] and from William Levison [6]. The book by Evans [4] is a thorough treatment of traffic safety, with some comments about driver modeling.

10.4.5.5.1 Michon (1985).

The primary value of Michon's [1] article is not so much as a review of driver models (Reid [2] gives a more thorough, detail-oriented review of nine models) but as a suggestion of where they could go after 1985. Michon notes that there was "bustling activity ... and quite a few interesting, novel approaches" to driver behavior in the 60's but a downward slope from then until he spoke in 1984. He gives reasons, including "an inability to incorporate a sufficiently wide range of interesting driver behaviors in our models." In the 60's researchers were excited "by new possibilities of information processing models which relied heavily on the communication channel and the thermostat analogy" and driver modeling was a part of this. But in the passing decades cognitive research moved on "to representational and computational theories and models" while driver modeling did not. Considering driving as a continuous or intermittent tracking task has been fruitful "for modeling the low level steering skills involved in straight or curved road driving." These models of adaptive dynamic control, first developed and applied by STI, have been refined over the years, but the improvements "have been in a very narrow range of tasks, and these find practically no ramifications into other aspects of the driving task." [The later summary of Allen, Rosenthal, and Hogue [3], shows that since 1985 STI has appreciably broadened the range of tasks they can deal with.] Michon also notes the conclusion of Reid [2] that "the prevailing dynamic control models do not yet successfully cope with driver tasks other than following straight and smoothly curved roads. The model forms for the other task scenarios are not yet fully developed."

The remainder of Michon's review is concerned with suggesting how to get beyond this inadequate state of affairs. He describes with favor the extensive driving task analysis developed by McKnight & Adams [7] and suggests that it could " ... serve as the database for a cognitive model that, by virtue of the scope of the analysis, would pretty well cover the two lower levels of the driver control hierarchy, that is, the tactical and the operational levels." He suggests that Fuller's [8] threat avoidance model provides a general scheme for "dealing with danger," an important part of driving safety , and judges that Fuller's model "brings us closer to a cognitive processing model, though it is, in its present form, not quite explicit in this respect." He notes that two fields, perception and vehicle control, are "still lacking a theoretical integration. Combining them would constitute a major breakthrough, and it seems likely that the increasing importance of robotics will provide a new impulse for this problem ..." He endorses the production system formalism of Newell & Simon [9] which "offers an eminent formal basis for artificial intelligence, linguistics, and cognitive psychology."

10.4.5.5.2 Evans (1991), Evans & Schwing (1985)

In addition to [1], the Evans and Schwing (1985) volume contains other papers and discussions from a Symposium held at GM Research Laboratories. The introductory and summary remarks by Leonard Evans suggest caution in anticipating traffic safety results directly from the application of existing driver models. Evans notes the existence of studies of a wide variety of driver skills, such as detection of small changes in relative speed, or small changes in longitudinal or lateral acceleration, and reaction time to a wide variety of stimuli. These studies all measure driver performance or capability, not driving behavior. "In recent years it has become increasingly clear that such measures of performance, although they can have some relevance to accidents, are not the most central or critical issues in determining aggregate accident involvement rates." For example, 19 year old males are probably near optimal for all perceptual motor skill capabilities, and yet are involved in 300% more accidents than older adults. All participants at this Symposium understood that it was concerned with driving *behavior*, not driving *performance*. Two of the participants (Summala and Wilde) discussed models of driver's risk taking behavior that explore and seek to explain the very indirect relationship between driver capability and measures of traffic safety. However, this area of driver modeling appeared to be in a very early stage of development.

One unique, useful Chapter in Evans [4] is concerned with User Responses to Changes in Traffic Systems. Evans considers 24 instances where actual safety impacts have been compared to the impacts expected assuming no road-user behavior change. There is a surprising diversity of results, ranging from greater than expected safety increase (55 mph speed limit) to reduced safety (pedestrian crosswalk marking). The analysis finds that if a safety change affects vehicle performance, it is likely to be used to increase mobility. For example, improved braking or handling characteristics lead to increased speeds, closer following, and faster cornering. Safety may increase, but by less than if there had been no user behavior change. When the safety change is invisible to the user, there is no evidence of human behavior feedback.

With regard to models of driver behavior, Evans reaffirms and extends his arguments for the inadequacy of the skill model. However, he is critical of the motivational approaches which have been proposed to fill the void, including a complete rejection of the "risk homeostasis theory." Other risk theories are dealt with less harshly, but since "risk is not necessarily a dominant, and certainly not the sole, determinant of driver behavior, terms like *risk compensation* ... should be avoided. All that is observed is a user response; to call it risk compensation is to imply knowledge of why it happened, an implication without justification."

Evans does not seem impressed by whatever modeling was done between Michon's paper in 1985 and his own book in 1991. "While attempts to describe driver behavior in terms of a single stimulus, such as risk, are too simple to be realistic, attempts using large numbers of decision-based rules requiring computer processing seem to me to be too complicated." His advice is to attempt to model more specific driving situations.

10.4.5.5.3 Reid (1983)

Reid [2] carried out a literature survey for the years 1975-1980 in the area of driver models describing steering behavior. His intent was to locate models which could be applied to potential roadway accident scenarios. A range of candidate driver models was found and their main features briefly outlined. Reid, like Michon and STI, endorsed the concept that driving is appropriately considered a hierarchy of navigation, guidance, and control. Like Michon, he only found models to deal with "the steering control aspect of driving." It was found that "... no well developed and validated model for the detailed study of accidents yet exists."

Reid gives three limitations of the models reviewed:

- All the models (except for a simple unproven brake and steer model in DRIVEM) are limited to a constant forward speed.
- In validating the models against human operator data most researchers have employed an open-loop fit to steering wheel response without checking how well the model matches the driver/vehicle lateral position in a closed-loop application. Because lateral position control is so important this omission can be a serious one.
- From the accident study point of view, the fact that essentially linear vehicle dynamics have been employed in developing these models is a real limitation because many accident situations involve skidding from other violent nonlinear vehicle behavior.

Reid provides a brief assessment of the merits of the nine models presented. His concluding points:

- For compensatory and pursuit lane tracking tasks no model has proved to be significantly better than the linear STI driver models.

- With regard to an obstacle avoidance model developed by Reid and others at U. of Toronto:
  - It is appealing because no precognitive control is required.
  - Nonlinear features in several of the lane tracking models could be incorporated.
  - There is need for field trials and simulator trials representing the obstacle avoidance maneuver to generate a data base for model calibration purposes.
- There is need for a driving simulator capable of representing large scale motions for applications involving accident avoidance maneuvers.
- Driver models should be developed which incorporate both lane tracking and speed control. These models should take into account nonlinear vehicle dynamics.

10.4.5.5.4 Allen, Rosenthal, and Hogue (1996)

Allen, Rosenthal, and Hogue [3] show that the STI methods can be extended beyond Michon's expectations by providing a generic model for guidance as well as control functions. They also incorporate nonlinear features, and deal with pursuit as well as compensatory operations for both lane position and speed. The steering and speed control models have been implemented "in conjunction with a reasonably well validated vehicle dynamics computer simulation" referred to as Vehicle Dynamics Analysis, Nonlinear or VDANL. Emergency control or crash avoidance is dealt with by incorporating Reid's obstacle avoidance model, "a simple model involving driver gain and time delay in following a line of sight error" which had previously been developed to explain test track data. There is no mention of a plan to add production systems (Michon's suggestion) or a supervisory element such as the one described by Moray in 10.4.5.5.5 or Levison and Cramer in 10.4.5.4.6.

The authors' conclusions follow: "The above driver model implementation and analysis has demonstrated stable control of a complex, nonlinear vehicle dynamics computer simulation. Severe test cases have been run that show stable driver model behavior over a wide range of operating conditions up to near limit vehicle maneuvering performance. These examples show generally rational model behavior with respect to past driver behavior studies. Steering control stability has been achieved with simple open loop compensation over a wide speed range as demonstrated herein. Stable speed control has been achieved in response to perceived road curvature, and the conditions for speed stability are relatively straight forward." It appears that STI has models which are ready to be used in some crash avoidance research although the extent of their validation was not totally clear.

10.4.5.5.5 Moray (1986)

Moray's [5] review doesn't mention driving but does provide a thorough discussion of the Optimal Control Theory as a model of the human operator. Work incorporating OCT as well as an additional supervisory element appears to be at the cutting edge of driver modeling today (see[6]) and progress in this direction was anticipated in the Moray review.

In his section on Control Theory Models of Sampling, Moray suggests that the applicability of the classic work of human as manual controller using frequency-domain analysis (such as the STI models) may not be suitable for application to "supervisory control with little manual control and where the process bandwidth is so low that control actions are a series of aperiodic discrete corrections rather than continuous movements." He mentions Young's suggestion that below 0.1 Herz control becomes discrete and cannot be modeled using classical control theory.

In a later section, Moray reviews work germane to the topics of slow process control (by which he means some of the topics treated in Edwards and Lees [10]) and supervisory control. Optimal control theory has been used as a model for predicting behavior of humans in the time domain, in decision making, reliability assessment, and modeling workload. There are also a series of papers devoted to the design of optimal displays. It should be noted that this theory predicts optimal behavior, and that it has been validated (i.e., has showed good correspondence to operator performance) only in situations where the operator or observer is very highly practiced, to the extent that the behavior is 'almost automatic" with little conscious thought about what is being accomplished.

One fundamental criticism of either OCT or classical control theory for modeling the behavior of the process control operator was made by Bainbridge [11]. She argued that "operators use strategies best described by verbal plans for action made on the basis of a cognitive diagnosis of the system state through observations ... of the displayed-state variables." Responding to this criticism, BBN modelers in the early 1980's "used Optimal Estimation Theory to provide a best estimate of the system state, and a kind of pattern recognition system to identify concatenations of state variables as indicating the overall condition of the system. The output of the pattern recognition algorithms produces appropriate actions by means of a production system computer language." The system produces verbal messages, plans for action, and tactical behavior. This system had been partly tested (the review was published in 1986) as a simulation of an aircraft flight deck crew. Moray writes that "further validation is required but the attempt to combine radically different kinds of modeling in a single system designed to account for both perceptual motor skills and higher cognitive and symbolic activity is of great interest. While it is much more complex than earlier models, the air of realism at the conceptual level is striking."

10.4.5.5.6 Levison & Cramer (1995)

Levison & Cramer [6] are following the BBN strategy of combining an OCT model for continuous control with a second (cognitive) model to deal with task selection and attention allocation for in-vehicle tasks.

Levison & Cramer developed what they call the Integrated Driver Model (IDM) in support of experimental studies, performed at UMTRI for USDOT, to develop evaluation methods and human factors guidelines for in-vehicle information systems. Data obtained in the laboratory and in on-road studies were used to help calibrate and validate the model. The objective of the modeling effort was to serve as an adjunct to experiments conducted by UMTRI and to perform one or more of the following functions:

- Provide a basic foundation for understanding driver behavior and performance
- Design of laboratory simulation and on-road experiments
- Extrapolation of experimental results to situations not explicitly explored
- Development and evaluation of guidelines for in-vehicle displays and controls
- Analytic evaluation of candidate in-vehicle systems.

The IDM is an integration of two previously existing computerized models which are referred to as the procedural model and the driver/vehicle model. The procedural model represents the driver in terms of perceptual, neuromotor, and cognitive responses. It deals primarily with in-vehicle auxiliary tasks (e.g., tasks other than continuous vehicle control) and with task-selection and attention-allocation procedures. The driver/vehicle model predicts closed-loop continuous control behavior. The model is based on the Optimal Control Model for manually controlled systems [12].The IDM described in this report deals with lower level tasks of maintaining lane position while intermittently performing additional in-vehicle monitoring and control tasks.

The structure and predictive value of the OCM have been verified via extensive application to laboratory and operational manual control tasks. In the present work, "independent model parameters were largely based on either previous model work or engineering judgment and were fixed throughout the calibration process." However, the calibration and validation of the IDM requires a more extended discussion which is provided (page 53 and following).

Levison & Cramer offer the following guidelines for further application of IDM:

- As with any mathematical model of the human operator, one has to be cautious in extending the model beyond known results because of the complexity of human response behavior. There is still much to be learned in terms of human information processing before the IDM can be fully calibrated.

- For this and other reasons, the IDM is most reliably used to explore performance trends, rather than to predict absolute levels of driver/vehicle performance.
- The IDM, suitably enhanced, has the potential to serve as a driver element in a variety of all-digital simulations in which micro-models of individual car/driver systems are desired. Candidate applications include the study of advanced traffic management systems and advanced vehicle control systems. AVCS issues particularly amenable to model analysis include collision warning systems and transition between manual and automatic control, where system performance may be especially sensitive to attentional factors.
- For IDM to be applied to simulations in which the driver reacts to the behavior of other vehicles, or to otherwise accommodate realistic driving situations, the model needs to be enhanced to include speed and headway control as well as the currently implemented constant-speed steering control. Such a modification would require a non-trivial implementation effort, but would not require a significant advance in the conceptual model.
- One issue that needs to be studied experimentally to allow more faithful modeling of the driver in a task-sharing environment is the effect of in-vehicle *control* activity. The discussion up to now has been devoted to auxiliary *monitoring* tasks that do not require the driver to remove a hand from the wheel. .... When the driver performs an in-vehicle manual control function, the hand remaining on the steering wheel may not compensate perfectly for the imbalance of forces due to the hand operating the in-vehicle control, resulting in an unwanted control input that integrated over a substantial period of time, could have consequences overshadowing the effects of information loss. This factor can be readily accommodated with the IDM by a constant of stochastic wheel movement added to the intended wheel movement; experimental data are required, however, to quantify this process.

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C3 Interim Report

10.4.5 Appendix A - The Influence of Automated Driving Conditions on Driver Vigilance

NAHSC

Technical Report 2588-1

THE INFLUENCE OF AUTOMATED DRIVING CONDITIONS ON DRIVER VIGILANCE

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INTRODUCTION

This paper describes a human factors study of driver vigilance under automated driving conditions. The study was conducted in a research driving simulator (Allen and Rosenthal, 1994; Allen, Rosenthal and Parseghian, 1995) developed to study a range of driver behavior and driver/vehicle system performance issues. Based on past research work on ITS (Intelligent Transportation System) projects (e.g. Allen, 1994; Allen, Magdaleno, et al., 1997), simulator capability has been developed for automated steering and headway control. Based on past driver impairment research (Allen, Parseghian, et al., 1994; Stein, Allen and Parseghian, 1992), the simulator also has the capability to provide subsidiary tasks and a range of psychophysiological measurements that are appropriate to assessing driver arousal. The simulator has commonly been referred to by its acronym STISIM.

The objective of this study was to investigate the extent to which driving involvement impacts driver alertness and the driver's ability to detect potential obstacles. Past vigilance research (e.g. Mackie, 1977) has shown that human operator alertness is dependent on the degree of task involvement. The human operator can show degraded performance under both low arousal and high arousal conditions, with optimum performance occurring at some optimum but undefined arousal level (i.e. according to the Yerkes-Dodson law as discussed in Wickens, 1992). Vehicle control automation proposed for future systems such as the automated highway system (e.g. Herridge and Pittenger, 1996) will clearly reduce driver involvement in the driving task. The issue to be considered here is the degree to which this reduced involvement reduces driver alertness and vigilance to emergency situations.

APPROACH AND METHODS

Simulator Conditions and Driving Tasks

The subject's basic driving task was to follow a lead vehicle at a safe distance and maintain lane position. The lead vehicle was set to travel at a constant speed of 65 mph. The semi-automatic and full automatic control conditions were implemented with STISIM autopilot features for both speed and lane position. During semi-automatic driving, the equivalent of an automated cruise control condition, the simulator controlled headway with respect to the lead vehicle while the driver controlled steering. During the fully automatic condition, the simulator controlled both headway to the lead vehicle and lateral lane position.

During automatic control of headway the accelerator pedal did not move. During automatic lateral lane position control the steering wheel did not move. During manual steering some road crown was simulated to give some difficulty to the lateral lane keeping task. The roadway also included curved sections, so active steering was required. During manual speed control some small divergence was added to speed to give some difficulty to the headway task. Some gentle road curvature was randomly introduced throughout about one third of the run. At 65 mph the curvature required less than 0.1 g of lateral acceleration to negotiate, and the time in each curve was about 10 seconds. Each element of curvature started and ended with spiral transitions as in typical roadway design. The curve locations were randomized between each run.

An obstacle detection task was implemented using the current subsidiary task features of STISIM. Subjects were required to detect pedestrians next to parked cars, which were randomly, place on either side of the road, with locations varied randomly between runs. On the average, parked cars occurred once every minute with variability on the order of 30-90 seconds. Pedestrians were placed next to approximately every 4th vehicle, so the signal (car plus pedestrian) rate was about once per 3.5 to 4 minutes which is appropriate for a vigilance task (e.g. Mackie, 1977). The vehicle locations, timing and occurrence of pedestrians were randomized both within and between runs so that no pattern would be apparent to the driver. Subjects were required to respond to the signal conditions (parked car plus pedestrian) with the horn button mounted on the spoke of the steering wheel.

Experimental Design

Subjects were administered four experimental conditions during a single experimental session. The conditions included a baseline manual control condition used for purposes of orientation and practice, a second experimental manual control condition, a semi-automatic condition involving automatic car following and manual steering, and a fourth fully automated condition requiring no manual control. The experimental conditions were administered in succeeding half hour segments interspersed by short breaks during which a questionnaire was administered. The baseline manual control condition was always administered first. The three experimental conditions were then administered in a different order to twelve subjects. Two subjects were assigned to each of the possible six orderings of the three experimental conditions.

Dependent variables included measures of driver performance, psychophysiological response and subjective reaction elicited with a questionnaire. Measures of detection accuracy and response time were measured on a subsidiary obstacle detection task (parked cars with nearby pedestrians). Under manual control conditions measures of speed and lateral lane position control were obtained as appropriate. Psychophysiological variables included heart rate, eye and head movement, EEG activity, and brain blood flow.

Subjects and Procedures

The subject population consisted of twelve licensed drivers over an age range of 24 to 58 years, including six males and six females. Each subject was run in the evening at the end of his or her daily routine, having been awake and active for at least eight hours. Prior to each experimental session, the subject was treated to a meal of their choice. This was done to emphasize fatigue and drowsiness stemming from normal daily activities. At the beginning of the session, subjects were asked to read an overview of the experiment, which described the procedures that would be implemented during setup and the tasks that were ~~to be performed throughout~~. A pre-simulation questionnaire was filled out as well as an informed consent agreement.

A five-minute orientation drive was given to introduce drivers to the simulator and the scenarios that would be encountered during the run. Pedestrians were specifically identified in order to dispel any confusion regarding the secondary task. Next, the subjects were instrumented with psychophysiological sensors which included: a plethysmograph attached to the ear lobe to monitor heart rate, a head band to measure brain blood flow, surface mounted electrodes to measure eye movement and brain activity and a head tracking device to measure head movement. The subjects were then sent on the baseline, manual control drive that lasted for thirty minutes.

Following the baseline drive, subjects were given a five-minute break in which they were offered water and asked to fill out a questionnaire. Subjects were then administered the first experimental driving condition for one half hour followed by another five-minute break and questionnaire response. This sequence was repeated for the second and third experimental conditions. During the manual and semi-automatic runs subjects were required to maintain the posted speed limit of 65 mph and remain behind the pace car in the assigned lane. Tickets were given randomly for exceeding the speed limit, which could only happen in the manual control condition. Tickets were recorded automatically by the simulation computer, and this process did not interrupt the flow of a run.

At the end of the session subjects were paid for their participation which included a fixed fee plus a reward/penalty bonus. The fixed fee was $65.00 for approximately two and one half-hours of their time. The reward/penalty bonus included rewards for completion of all runs and for finishing before the computer reference time during the manual drive. Penalties were extracted for not maintaining the required speed limit of 65 mph, for having an accident during manual or semi-automatic driving conditions or for incorrectly responding to the secondary task (pedestrians located alongside vehicles on the side of the road). A maximum of $15 in bonuses could be earned for safe and diligent driving. The reward/penalty bonus was meant to serve as a surrogate for the rewards (e.g. on time arrival) and risks (e.g. trip delays, accidents) in the real world driving environment.

Measurements and Analysis

During manual control, measures were obtained of steering and speed control. Steering control variables included steering angle, lateral acceleration, heading error, and lateral lane deviation. Speed control variables included throttle angle and longitudinal acceleration and speed. The mean and standard deviation of these variables were obtained over three minute epochs so that 10 measurement epochs were contained within the half-hour driving blocks. Measures on the vigilance task include response time and missed signals (cars plus pedestrians). Eight response times were obtained during the half-hour measurement blocks.

Psychophysiological variables include pitch (PHM) and roll (RHM) head movements, brain blood flow (BBF), eye activity (EOG), brain activity (EEG) and heart rate (HR). Head pitch and roll were sensed with a small tilt meter positioned at the back of the head with a headband. BBF was measured with a forehead sensor held in place with a headband. The sensor included IR and red light sources and a detector. EOG was obtained with electrodes mounted on the skin around the eyes. This is the same location as used with the UDEMS sensor reported in Allen, Parseghian, et al. (1994). EEG was obtained with an electrode mounted at the back of the head. Heart rate was obtained from an ear-lobe mounted IR plethysmograph and a tachometer. A separate psychophysiological measurement computer was set to obtain PHM, RHM, BBF, EOG, EEG and HR sixteen times a second. Because of the high frequency of the EEG signal, the standard deviation of the signal was calculated online every sixteenth of a second (the bandwidth of useful EEG information is on the order of 20 Hz, which cannot be captured in a time history recorded at 16 times a second).

The recorded data was preprocessed to compute means and standard deviations of all variables over 3 minute epochs to give 10 measures during a half hour block. Additional processing of the head motion (PHM and RHM) and EOG time series data was carried out to investigate the influence of mirosleeps. This data was then placed in spread sheets for subsequent statistical analysis. The data was then submitted to

MANOV (multivariate analysis of variation) and ANOV (single variable analysis of variance) procedures according to the experimental design.

RESULTS

The results are divided up into measures that were available under all experimental conditions, including performance on the vigilance task, psychophysiological measures and subjective ratings, and driver performance measures that were available only during the manual control and semiautomatic conditions.

Vigilance Task

The vigilance task required the driver to detect parked cars with pedestrians standing along side. For every vehicle with pedestrians there were several without pedestrians. Measures included response time and missed targets (cars with pedestrians).

ANOV of the response time results showed that it varied reliably within the half-hour blocks (p=.0000), but did not vary reliably between the automation conditions (p=.6835). The data was also analyzed in terms of the half-hour block (first, second, third and fourth half-hour test blocks) irrespective of the control condition, and half-hour block was also found to not have a reliable effect on response time (p=.6436). Figure 1 a shows the average response time throughout each of the half-hour measurement blocks, and we see that response time decreases with time on task. The initial decline in response time is quite consistent. The response time profile at the end of the half-hour block is not very consistent between half-hour blocks although there is some tendency for a leveling and perhaps upturn in response time.

Response time profiles for each subject are shown in Figure 1 b. Here we see some variation in response profile: Subject 7 shows little change during the half hour interval while subject 5 shows significant decrease in response time throughout the half hour block with exception of the last measurement. Subject 9 shows a uniformly low response time throughout the half-hour measurement block. This subject responded to every vehicle, and thus was responding when vehicles were first visible and was not waiting to determine the presence of pedestrians. When asked after the session, subject 9 expressed some confusion with the objective of the vigilance task.

Analysis of the missed pedestrian presentation showed this result to not be reliably different between the automation conditions (p=.1896). The misses were on the order of one per half-hour block.

Psychophysiological Response

The reliability of the psychophysiological variables was tested with a multivariable analysis of variance (MANOVA). This analysis showed there to be a reliable difference between the automation conditions on the first four psychophysiological variables as summarized in Table 1 a (EEG and heart rate were not reliably influenced). The response of the variables showing reliable differences is shown in Figure 2. These plots generally show increasing psychophysiological activity in going from the manual, to semi-automatic to full automatic conditions. When the data were analyzed by half-hour block (1st, 2nd, 3rd, and 4th), the differences were not reliable as summarized in Table 1 b. Only head pitch activity varied reliably within the half-hour blocks as illustrated in Figure 3. There was some reliable interaction between the automation conditions and time segment within the half-hour blocks for head pitching (significant, $p=.0277$) and rolling (marginally significant, $p=.0774$) which is illustrated in Figure 4. This analysis shows a general tendency for increased psychophysiological activity with increasing level of automation.

Questionnaire

The reliability of results from the Stanford Sleepiness Scale (SSS) and the eleven (11) questions were analyzed with MANOVA procedures. Subjective opinion was reliably influenced by the automation condition as summarized in Table 2. Average results are plotted in Figure 5. Subjects generally reported feeling better or more alert with increasing automation, and also for the first half-hour baseline block. One exception was the workload scale with subjects reporting increasing workload with increasing automation.

Control Performance

Driver control performance can only be measured on the non-automated tasks with each condition. The baseline and manual conditions were under full manual control. The semi-automatic condition involved driver steering control.

Driver steering control performance could be measured in the baseline, manual and semi-automatic conditions, while speed control could be measured only on the baseline and manual control conditions. Table 3 shows a generally reliable influence of time on task on steering control variables but not on speed control variables. There was no effect of control condition or interaction between control condition and time on task. Figure 6 shows a curious `M' shaped steering performance variation through out the half-hour blocks. This response is similar to the response time plot in that a minimum value occurs past the mid point of the half-hour block.

Accidents could be measured on the baseline, manual and semi-automatic conditions. An average of about 2.5 accidents were measured per run, and by definition no accidents could occur under the fully automatic vehicle control condition. There was no reliable effect due to automation condition.

Microsleep Data Reduction

Activity in psychophysiological variables would ordinarily be an indicator of arousal and alertness, but there were indications during the experiment that subjects were suffering significant drowsiness and perhaps microsleeps. To investigate this further, we undertook additional analysis of the head movement data. As illustrated in Figures 7 and 8 for two different subjects, there are significant incidences of large, abrupt head drops in the head Pitch data that we attribute to microsleeps. This time history was produced by taking averages of the psychophysiological data, which was collected at a sample rate of 16 Hz, over one second intervals. The standard deviation of the head pitch time series was also taken over these one second intervals. The standard deviation of head pitch gives a strong indication of the fast head drop intervals, while minimizing the effect of slow head movement. Furthermore, note in Figures 7 and 8 that there is a strong correlation of head Roll activity with the head drop episodes. The EOG shows much less activity. The head roll is most likely due to loss of neck muscle tension that leads to the head drop during microsleeps. Finally, Subject 4 (Figure 7) shows much less activity than Subject 7 (Figure 8), a between subject difference that is not unexpected in this type of research.

From the above data we conclude that head pitch and roll activity as measured by the standard deviation of these variables over 16 samples in a one second interval is indication of microsleep activity. Interpretation of the EOG data is not clear at this stage. Given these observations, the next challenge is to develop a continuous variable that can quantify the microsleep effect. One could count the number of episodes over some period of time, but the data in Figures 7 and 8 suggest that the microsleeps are very sporadic and vary in amplitude. At this point it was decided to look at distributions of amplitude data, and select the largest few amplitudes as an indication of the microsleep phenomenon. Each half-hour run was divided into a beginning, middle and end segment of 10 minutes (i.e. 600 one second) each. The samples were then arranged in descending amplitude to achieve a cumulative distribution function of decreasing amplitude. Example plots of amplitude distributions for several subjects are illustrated in Figure 9 for the first 25 largest amplitudes. Note in general the amplitudes decrease fairly rapidly during a segment, and also that in Figures 7 and 8 the number of microsleep episodes are rather small for a given run. Generally, the amplitude decays relatively rapidly, and for the cases with the largest amplitudes (i.e. the largest microsleep response) the Roll and EOG effect descends to a near asymptotic level of activity by the fifth interval.

For further statistical analysis, since we have divided the runs into three segments (beginning, middle and end) we decided to limit the number of analysis intervals to eight per segment, which would permit a total number of 24 episodes per half hour session. A multivariate analysis was conducted with head Pitch and Roll and EOG activity as the dependent variables. The independent variables were Subjects as a random effect and automation Condition (Manual, Semiautomatic, fully Automatic), Segment (Beginning, Middle and End), and Interval (first eight highest standard deviation amplitudes) as fixed effects. The analysis summary in Table 4 shows that Condition and Interval were significant first order effects, while the Condition x Interval interaction term was not significant. The Segment first order effect was also not significant, and the third order interaction between Condition, Segment and Interval was also decidedly non-significant. Not surprisingly, differences between subjects were highly significant, and all of the interactions between subjects and other effects were also highly significant.

Now, let us focus on the significant differences due to Condition and Interval. Table 5 summarizes univariate analysis results for Condition and Interval. Here we see for Condition that SDROLL and SDEOG reach reasonable significance levels, while SDPITCH just misses being marginally significant (i.e. $.05 < p < .10$). For Interval, the three effects are highly significant. Plots of the head and EOG activity as a function of automation Condition and Interval are illustrated in Figure 10. Here we see that the fully Automatic control condition gives the largest activity for all three dependent variables. For SDEOG the Automatic control condition is distinctly larger than the Semiautomatic and Manual conditions which are both about equal. For SDROLL the Semiautomatic condition is intermediate between the Automatic and Manual conditions. For SDPITCH, the Manual condition shows slightly more activity than the Semiautomatic condition, however the statistical analysis showed Condition differences in this variable not to be very reliable.

Now consider an interpretation of the above results in terms of our original goal of counting the number of microsleep episodes in a given 10 minute segment of the 30 minute runs. If we pick a 5 degree amplitude change, for example, as the level of SDROLL that defines a microsleep, we see that on the average we get about 2 episodes (i.e. intervals) for the Manual condition, about 3 episodes for the Semiautomatic condition, and about 4 episodes for the fully Automatic control condition. If we pick .015 for the SDEOG activity that defines a microsleep episode, then we get about one episode for the Manual and Semiautomatic conditions, and about 5 episodes for the fully Automatic control condition. Remember that for this analysis we defined activity in SDPITCH, SDROLL and SDEOG as a surrogate measure of microsleep episodes, and chose the cumulative amplitude distributions as a continuous measure of these episodes. The activity amplitudes we picked for this example were strictly illustrative, and the amplitude data was averaged across subjects and the 10-minute run segments. Nonetheless, the order of magnitude of episodes across conditions (i.e. 1-5) per segment translates to 3-15 per half-hour run which is not inconsistent with the data shown in Figures 7 and 8.

DISCUSSION

Complex variations in driver performance were found as a function of time on task within the half-hour blocks for the basic 3 minute epoch data processing. These variations could be interpreted as improvement past the midpoint of the run followed by deterioration in the later half of the block. It is possible if the blocks had been run for an hour or more that a longer term deterioration trend would emerge. There were no differences between blocks that could be attributed either to total time from the beginning of the session (i.e. differences between half hour blocks), or to differences between the automation conditions. The interaction between within-block and between-block effects was also not significant. Thus, the interpretation of basic 3 minute epoch data does not suggest the anticipated increased driver drowsiness with more automated vehicle control conditions.

Based on experimenters reports of subjects `nodding' (i.e. microsleeps), additional time series analysis was carried out on the head pitch and roll motion and EOG variables. This analysis did not reveal any differences between the beginning, middle and end of the half-hour runs, but did reveal differences between the automation conditions. These differences were similar to the 3 minute epoch data results in that there was indication of increasing activity in going from manual to semiautomatic to automatic vehicle control conditions. In this analysis, however, the increased activity was associated with head movements associated with microsleeps. Thus, the more detailed time series analysis indicates that the increased activity is indicative of increased drowsiness, which is most prevalent with the fully automatic vehicle control condition.

The one half-hour driving period presented here would represent a fairly long stretch of automated highway system (30 miles at 65 miles per hour). Based on the current results, it would appear that there is an identifiable driver drowsiness problem associated with automation condition that occurs within the first half-hour of exposure to the AHS. This increased drowsiness with increasing automation is not reflected in the side task measure of attention however. Both the microsleep episodes and the appearance of the side task targets are discrete and relatively sporadic occurrences. Thus, the confluence of a microsleep and a side task target that would obscure the roughly 5 second appearance of a target was probably a relatively rare event. The sporadic and discontinuous nature of microsleeps raises the issue of how to measure this phenomenon. Microsleeps can be identified with psychophysiological measurements, but may not show up very sensitively in continuous task measurements and may be missed completely with discrete task measurements.

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Table 1. Statistical Analysis Summary of Psychophysiological Measures

a) Analyzed by automation condition

STAT. GENERAL MANOVA	MAIN EFFECT: CONDITN (ahs-5a.sta) 1-SUBJECT, 2-CONDITN, 3-SEGMENT			
depend. variable	Mean sqr Effect	Mean sqr Error	F(df1,2) 3,33	p-level
1	19.32848	3.37717	5.723281	.002873
2	33.44691	5.04213	6.633487	.001248
3	3.76835	.54844	6.871033	.001010
4	12.87321	3.88498	3.313586	.031833
5	3.51807	5.85481	.600886	.619015
6	3.29282	12.29589	.267798	.848121

b) Analyzed by half hour test block

STAT. GENERAL MANOVA	MAIN EFFECT: HHOUR (ahs-5a.sta) 1-SUBJECT, 2-HHOUR, 3-SEGMENT			
depend. variable	Mean sqr Effect	Mean sqr Error	F(df1,2) 3,33	p-level
1	3.24769	4.83906	.671141	.575841
2	15.04315	6.71520	2.240164	.101964
3	1.87273	.72077	2.598245	.068768
4	6.46628	4.46743	1.447429	.246756
5	5.11828	5.70934	.896475	.453319
6	8.75472	11.79936	.741966	.534693

Table 2. Questionnaire Subjective Ratings

a) Questions and numerical rating definitions

- Stanford Sleepiness Scale - 1=wide awake; 7=sleep onset soon
- Q1 - How do you feel at the moment? 1=awake; 5=sleepy
- Q2 - Did you experience any microsleeps during your drive? 1=never; 5=often
- Q3 - How alert did this type of driving keep you? 1=not alert; 5=very alert
- Q4 - To what extent did this type of driving allow you to be in control of the vehicle? 1=not in control; 5=fully in control
- Q5 - What level of workload did this type of driving create? 1=low; 5=high
- Q6 - What effect did this type of driving have on detecting vehicles with pedestrians? 1=negative effect; 5=positive effect
- Q7 - What type of an effect did this type of driving have on your alertess? 1=negative effect; 5=positive effect
- Q8 - What type of an effect did this type of driving have on your wandering attention? 1=negative effect; 5=positive effect
- Q9 - What type of an effect did this type of driving have on your ability to stay awake? 1=negative effect; 5=positive effect
- Q10 - What type of an effect did this type of driving have on your Vigilance? 1=negative effect; 5=positive effect
- Q11 - What did this type of driving make you feel like? 1=alert; 5=sleepy

b) Statistical analysis

STAT. GENERAL MANOVA	MAIN EFFECT: SCENARIO (rating1.sta) 1-SUBJECT, 2-SCENARIO			
depend. variable	Mean sqr Effect	Mean sqr Error	F(df1,2) 3,33	p-level
SSSCALE	1.07639	.440025	2.44620	.081238
Q1	.39931	.423927	.94192	.431536
Q2	3.37500	.688447	4.90234	.006307
Q3	2.96701	.547506	5.41914	.003830
Q4	19.25347	.440972	43.66142	.000000
Q5	10.00868	.459438	21.78461	.000000
Q6	.46181	.708018	.65225	.587222
Q7	4.73785	.668718	7.08497	.000837
Q8	3.25174	.784880	4.14297	.013453
Q9	4.45964	.502249	8.87933	.000186
Q10	2.85764	.398359	7.17353	.000775
Q11	3.20269	.553070	5.79075	.002698

Table 3. Statistical Analysis of Control Performance

a) Steering Only Conditions (1=SD lat. accel.; 2=SD lat. vel.; 3=SD lat. lane dev.; 4=SD heading error; 5=SD steering wheel angle)

STAT. GENERAL MANOVA	MAIN EFFECT: STRVARS (ahs-5.sta) 1-SUBJECT, 2-CONDITN, 3-STRVARS			
depend. variable	Mean sqr Effect	Mean sqr Error	F(df1,2) 8,88	p-level
1	1.2374	.07665	16.14260	.000000
2	.0237	.00366	6.49306	.000001
3	.1582	.04785	3.30586	.002393
4	.0000	.00000	6.45420	.000001
5	341.8743	21.67537	15.77248	.000000

b) Steering and Speed Control Conditions (1=SD long. accel.; 2=SD lat. accel.; 3=SD long. vel.; 4=SD lat. vel.; 5=SD lat. lane dev.; 6=SD heading error; 7=SD steering angle; 8=SD throttle position)

STAT. GENERAL MANOVA	MAIN EFFECT: STR-SPD (ahs-5.sta) 1-SUBJECT, 2-CONDITN, 3-STR-SPD			
depend. variable	Mean sqr Effect	Mean sqr Error	F(df1,2) 8,88	p-level
1	.0110	.11684	.094116	.999309
2	.5981	.11106	5.384988	.000016
3	.6795	1.76217	.385606	.925660
4	.0139	.00388	3.586806	.001203
5	.1118	.03645	3.066290	.004301
6	.0000	.00000	3.382259	.001985
7	167.0349	32.73030	5.103374	.000031
8	.0112	.11932	.093918	.999315

Table 4. Statistical Analysis Summary of Microsleep Data

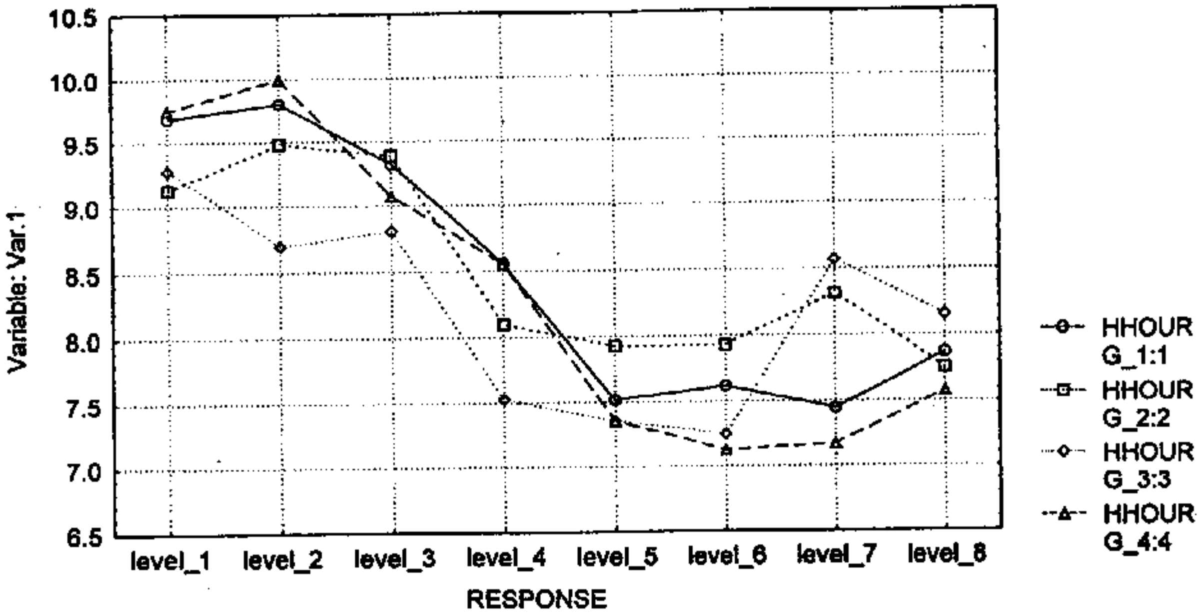
a) Multivariate Results

STAT. GENERAL MANOVA	Summary of all Effects; design: (compl.sta) 1-SUBJECT, 2-CONDITIO, 3-SEGMENT, 4-INTERVL				
Effect	Wilks' Lambda	Rao's R	df 1	df 2	p-level
1	.000000*	14940.70*	33*	206*	0.000000*
2	.463926*	3.12*	6*	40*	.013269*
3	.757985	.99	6	40	.444654
4	.104308*	12.31*	21*	215*	.000000*
12	.000000*	3313.78*	66*	209*	0.000000*
13	.000000*	1806.17*	66*	209*	0.000000*
23	.648252	1.65	12	111	.087307
14	.000000*	506.98*	231*	210*	0.000000*
24	.725165	1.23	42	451	.159458
34	.732425	1.19	42	451	.199446
123	.000000*	1026.88*	132*	210*	0.000000*
124	.000000*	190.98*	462*	210*	0.000000*
134	.000000*	268.22*	462*	210*	0.000000*
234	.805945	.82	84	916	.881466
1234	.000000*	26.78*	924*	747*	0.000000*

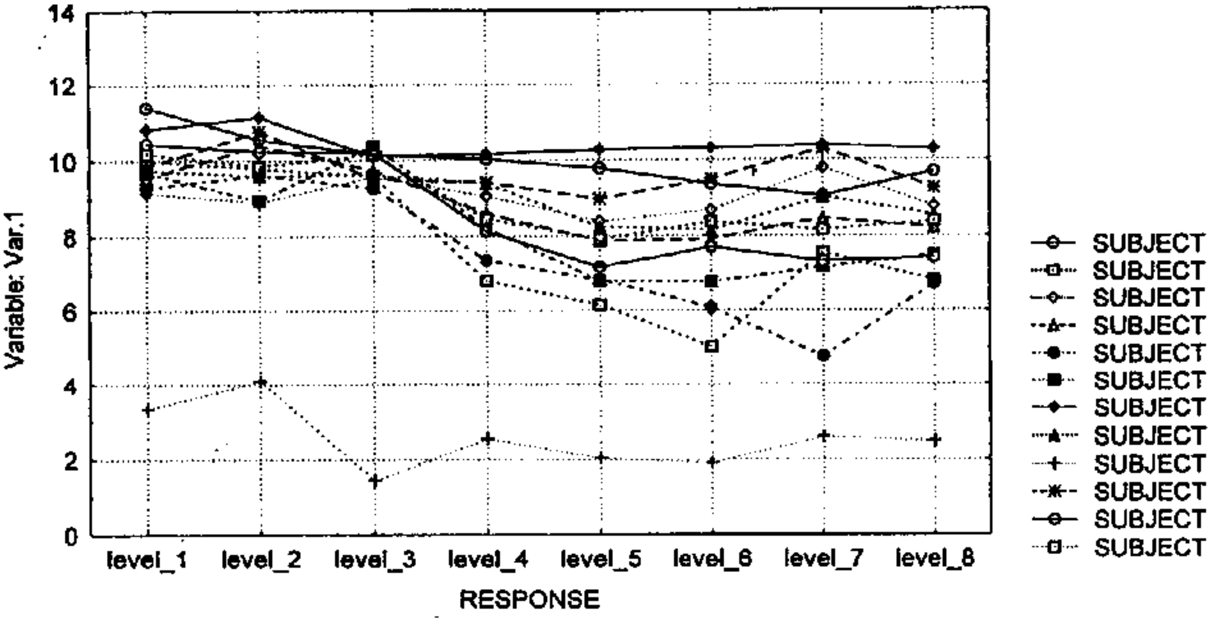
b) Univariate Results

STAT. GENERAL MANOVA	MAIN EFFECT: CONDITIO (compl.sta) 1-SUBJECT, 2-CONDITIO, 3-SEGMENT, 4-INTERVL			
depend. variable	Mean sqr Effect	Mean sqr Error	F(df1,2) 2,22	p-level
SDPITCH	82.7505	32.75858	2.526072	.102904
SDROLL	156.2575	35.55849	4.394378	.024793
SDEOG	.0065	.00096	6.793521	.005040

STAT. GENERAL MANOVA	MAIN EFFECT: INTERVL (compl.sta) 1-SUBJECT, 2-CONDITIO, 3-SEGMENT, 4-INTERVL			
depend. variable	Mean sqr Effect	Mean sqr Error	F(df1,2) 7,77	p-level
SDPITCH	169.1471	2.833324	59.69917	.000000
SDROLL	187.9218	6.443089	29.16641	.000000
SDEOG	.0038	.000247	15.40155	.000000

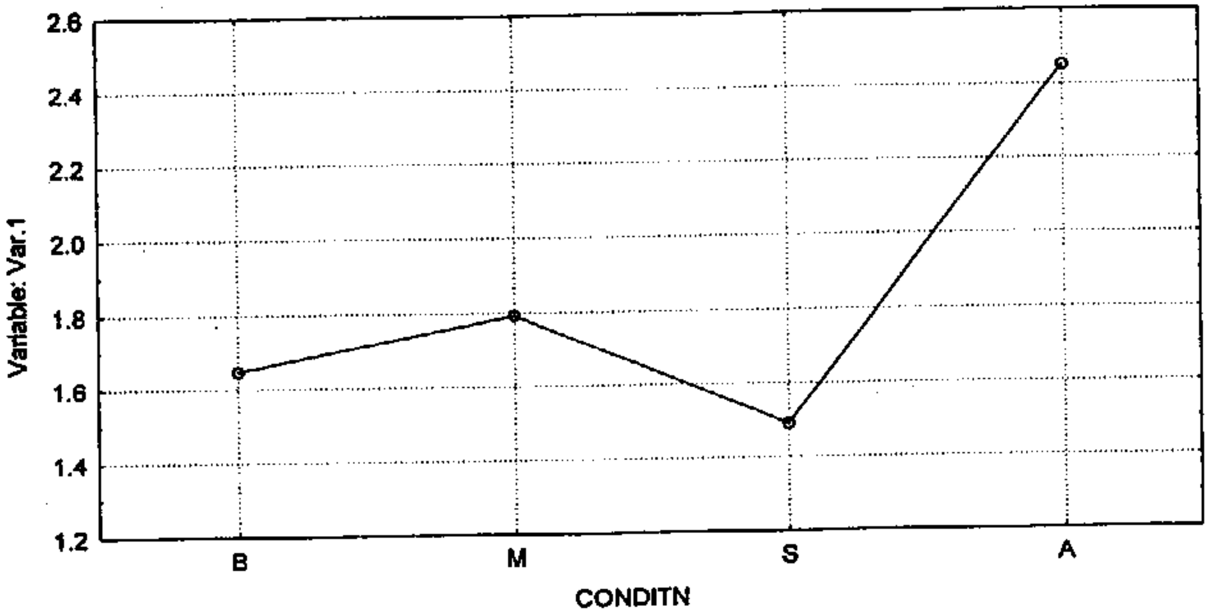


a) Response profile for each half hour test block

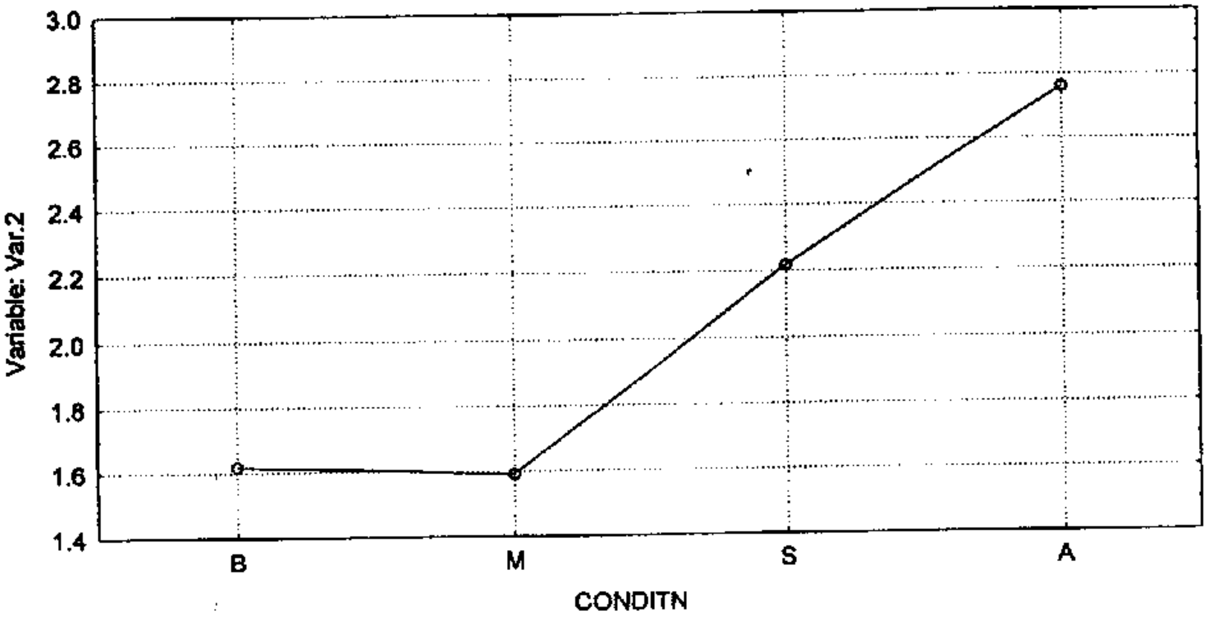


b) Response profile for each subject

Figure 1. Subject Vigilance Task Response Time Profiles Within Half Hour Test Blocks

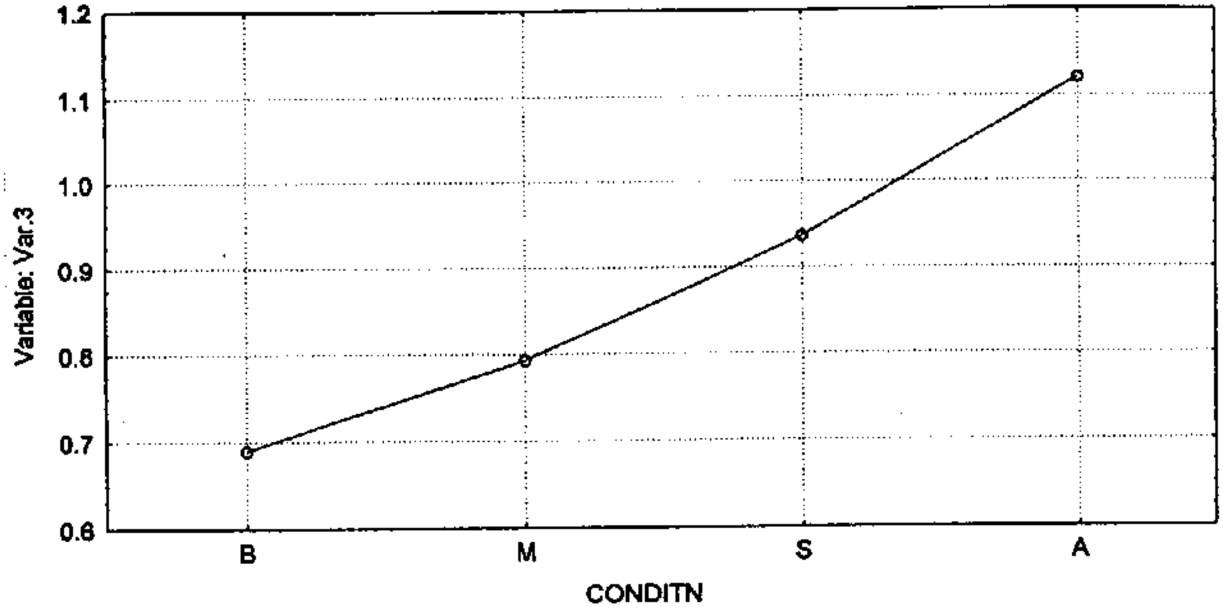


a) Head Pitch Angle Activity

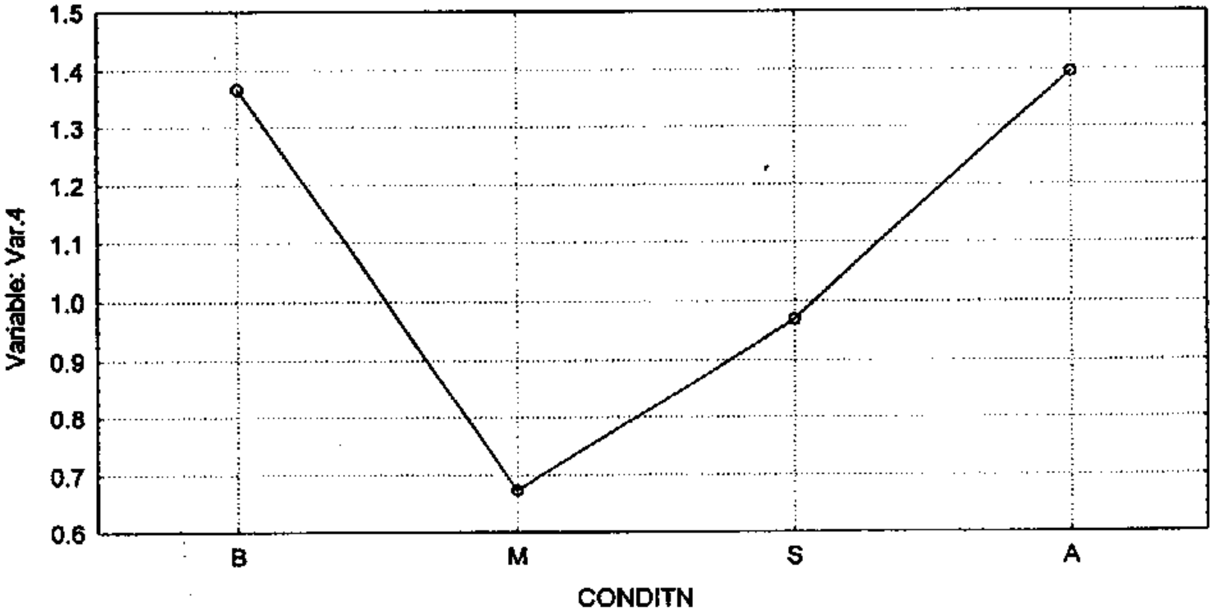


b) Head Roll Angle Activity

Figure 2. Psychophysiological Variable Response Between Automation Conditions



c) Brain Blood Flow (% Oxygenation)



d) EOG (Eye Activity)

Figure 2. (Concluded)

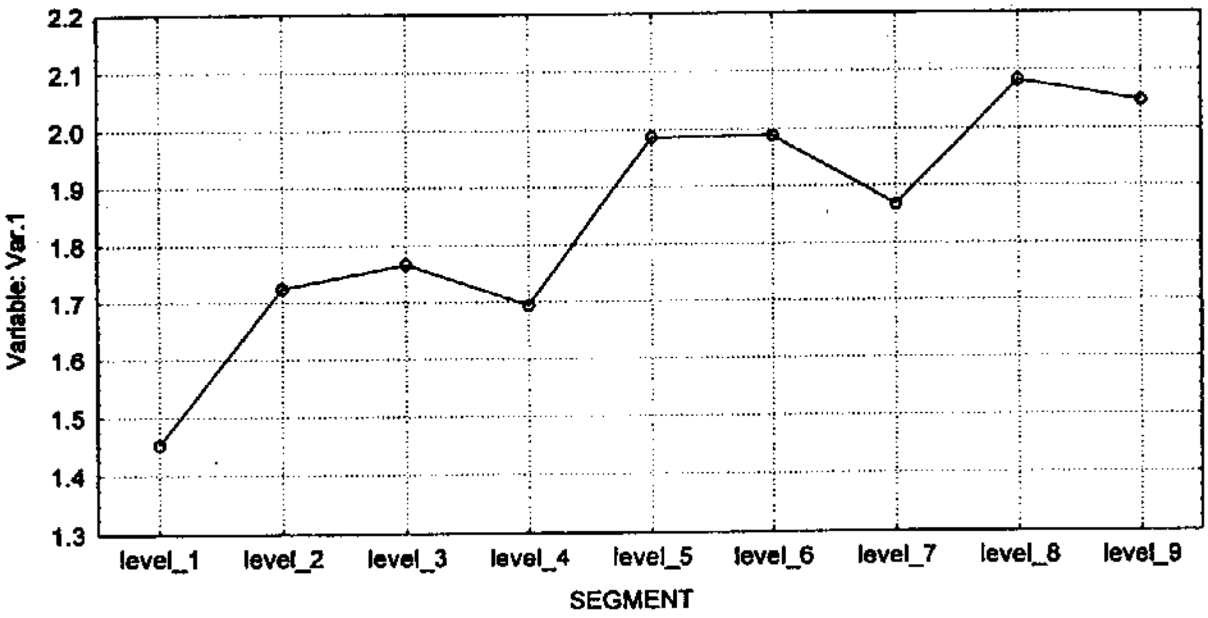
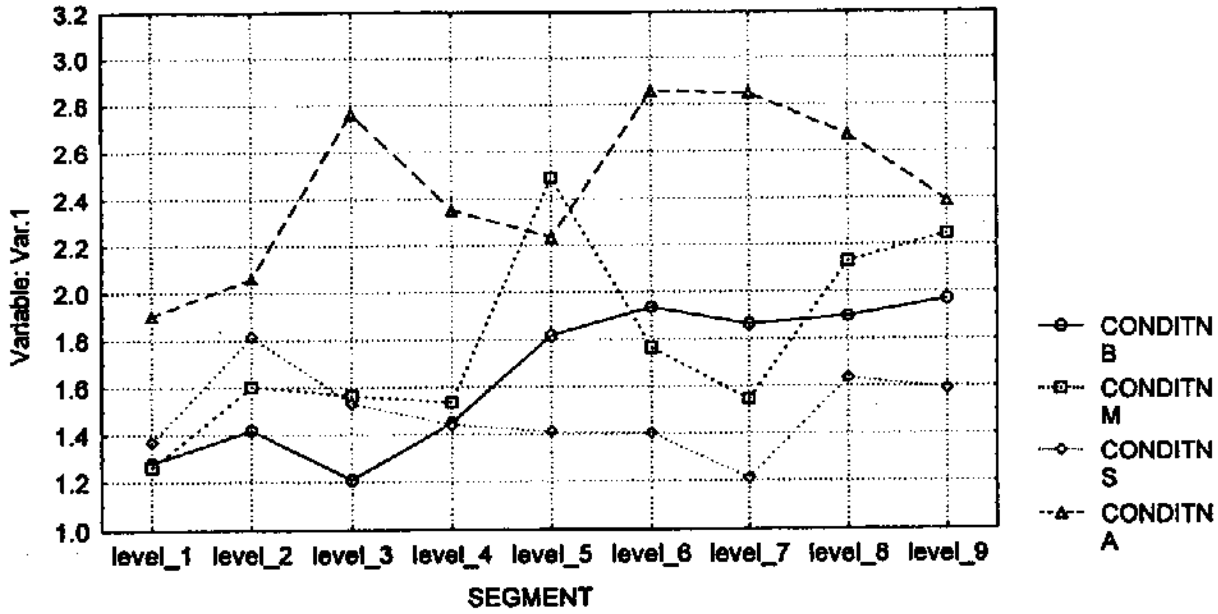
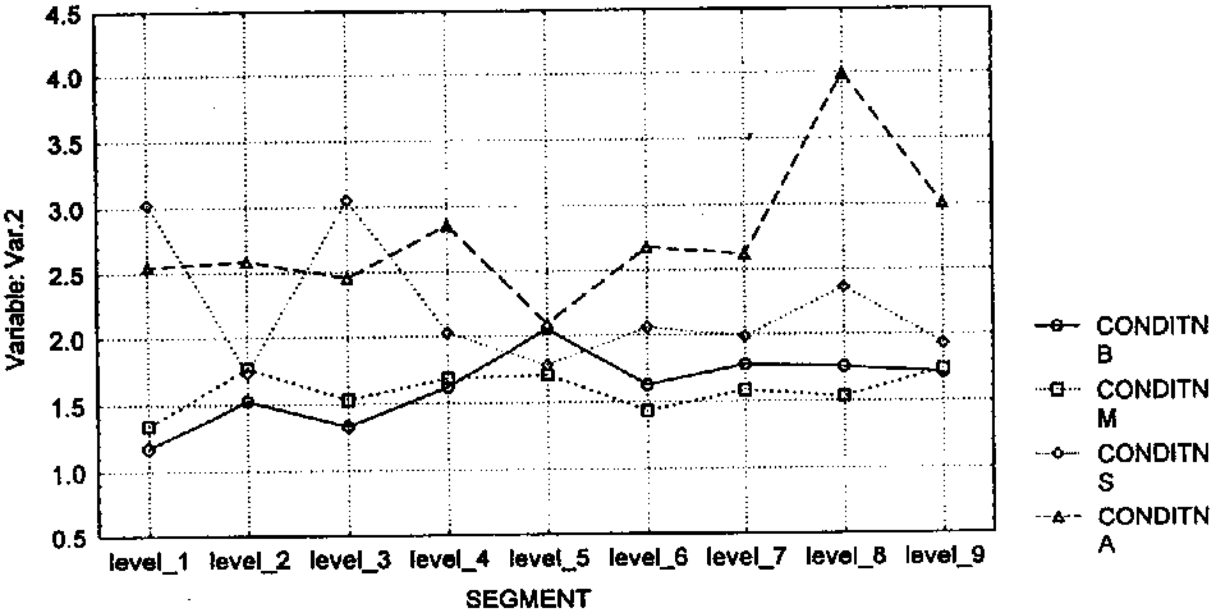


Figure 3. Head Pitching Activity Profile Within Half Hour Test Blocks



a) Pitch Angle



b) Roll Angle

Figure 4. Head Motion Activity Profiles: Interaction of Within Block and Between Automation Conditions

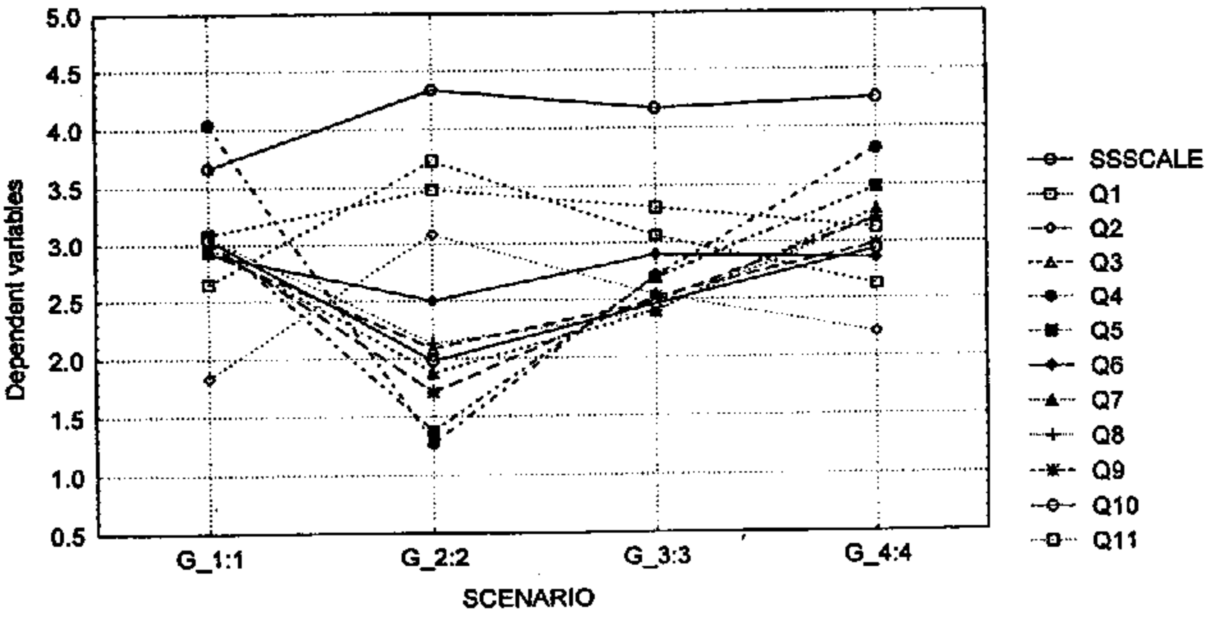
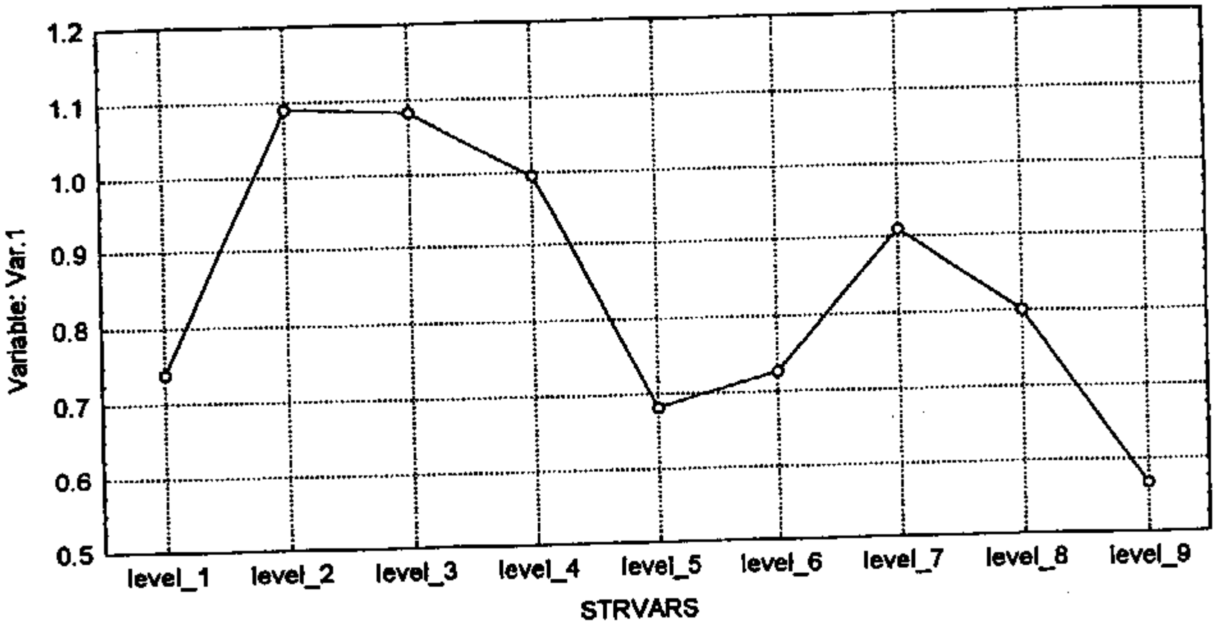
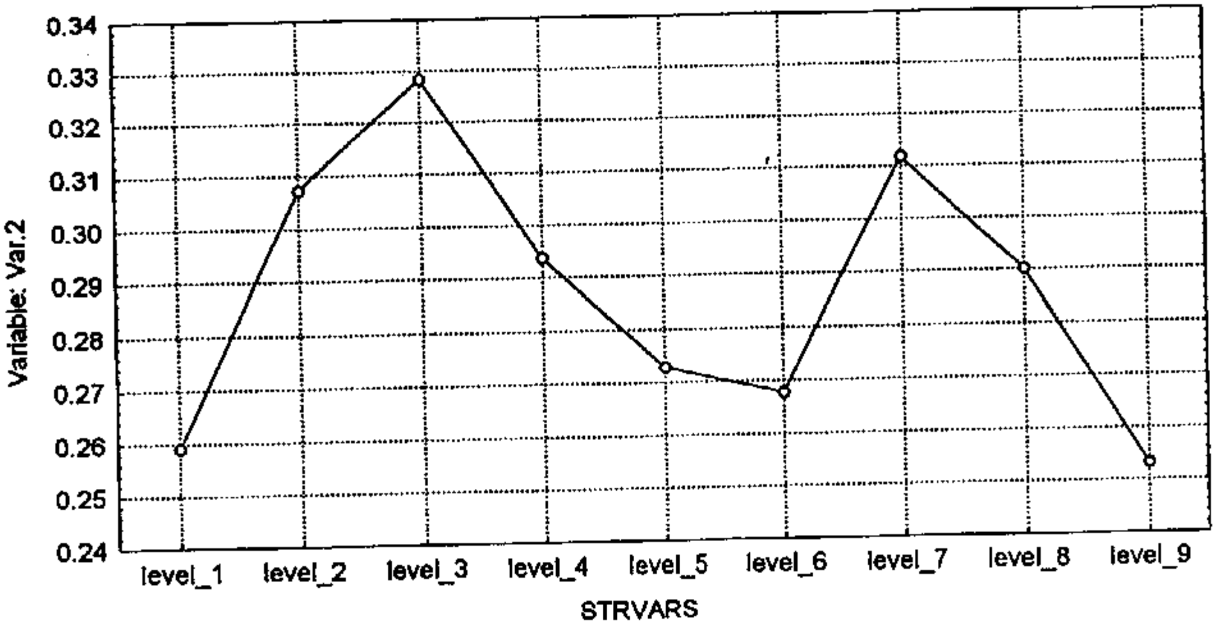


Figure 5. Questionnaire Responses
(Questions given in Table 2 along with numerical scale definitions)

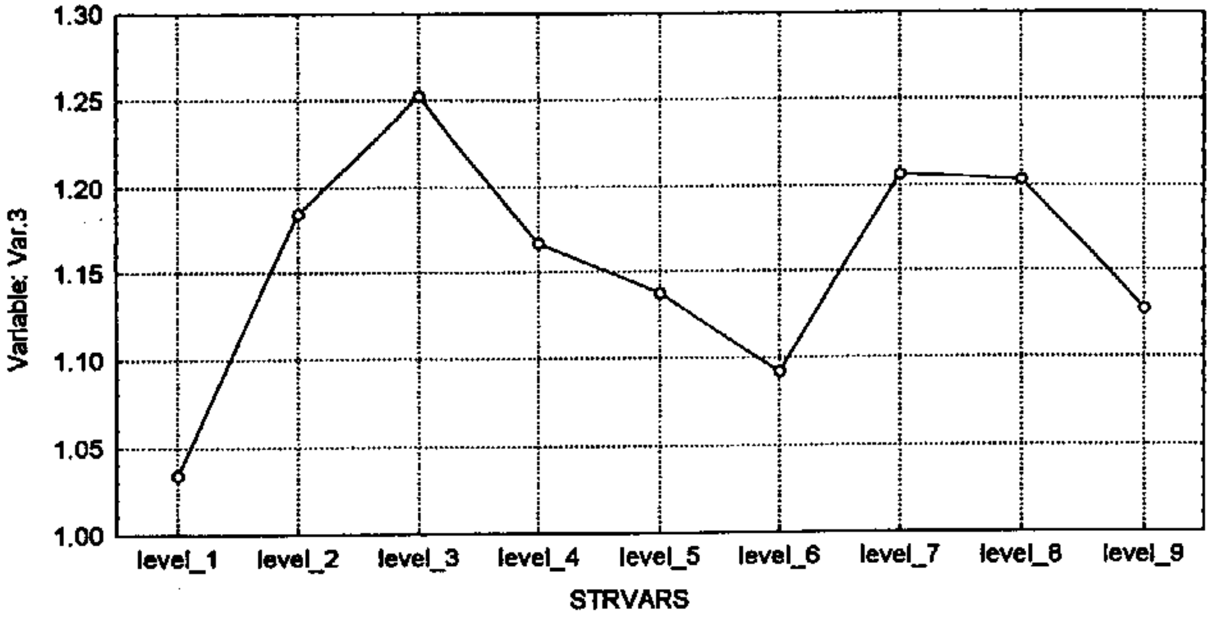


a) SD of Lateral Acceleration

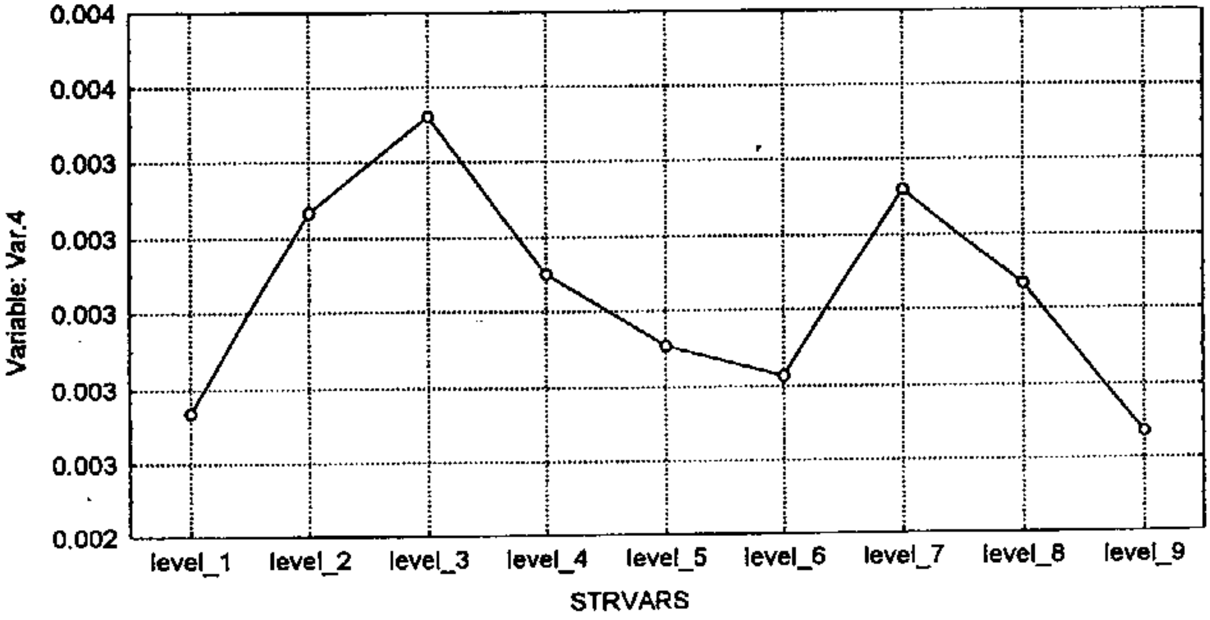


b) SD of Lateral Velocity

Figure 6. Steering Performance Profile Within Half Hour Test Blocks

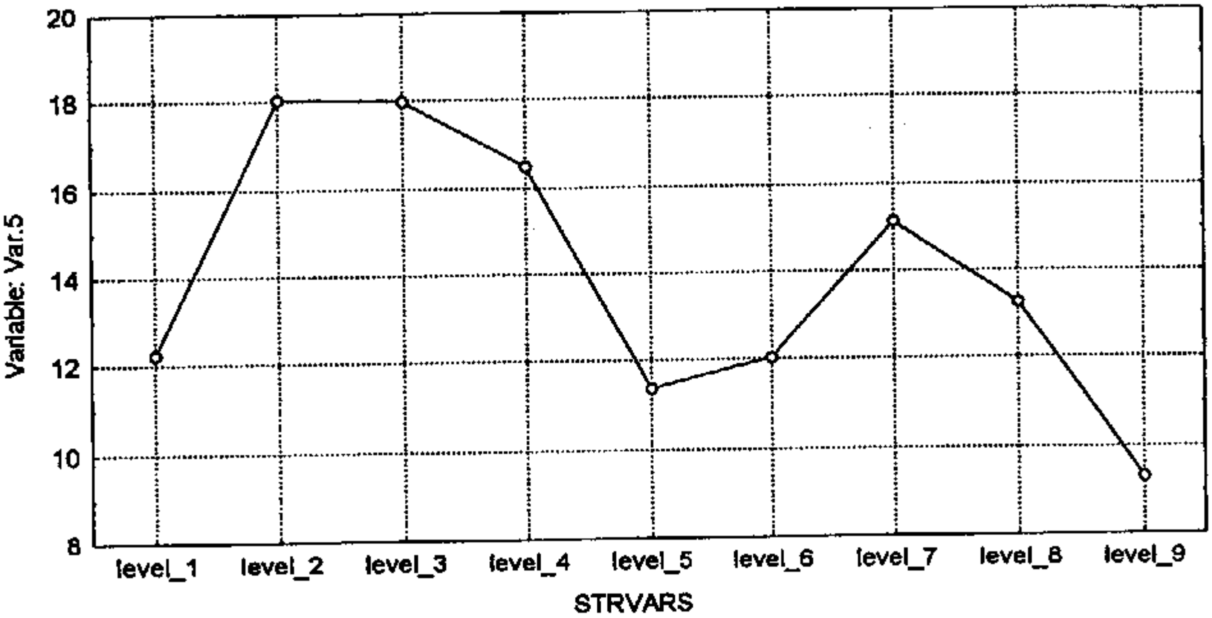


c) SD of Lateral Lane Deviation



d) SD of Heading Error

Figure 6. (Continued)



e) SD of Steering Wheel Angle

Figure 6. (Concluded)

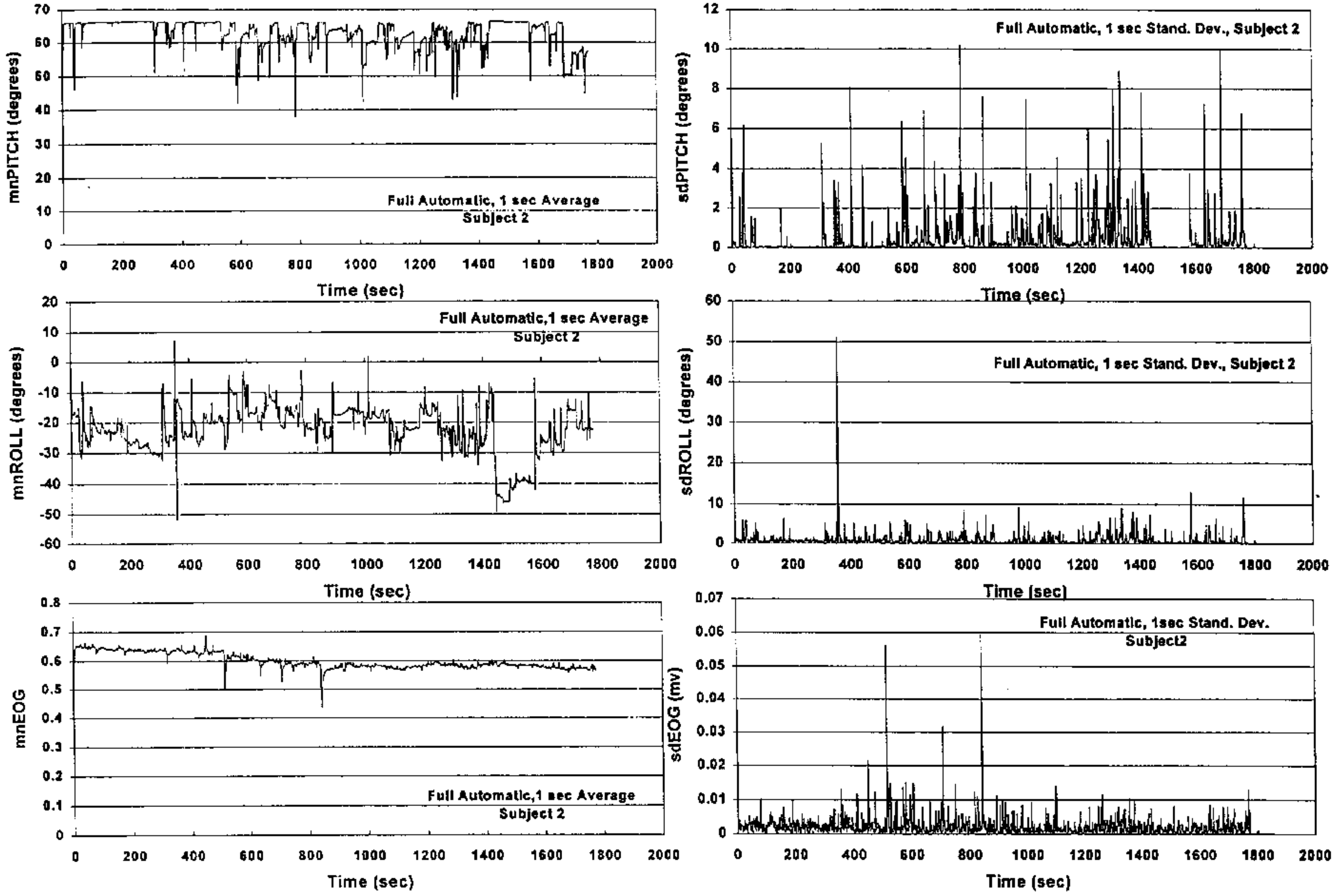


Figure 7. Time Histories of Head and EOG Activity for Subject 2.

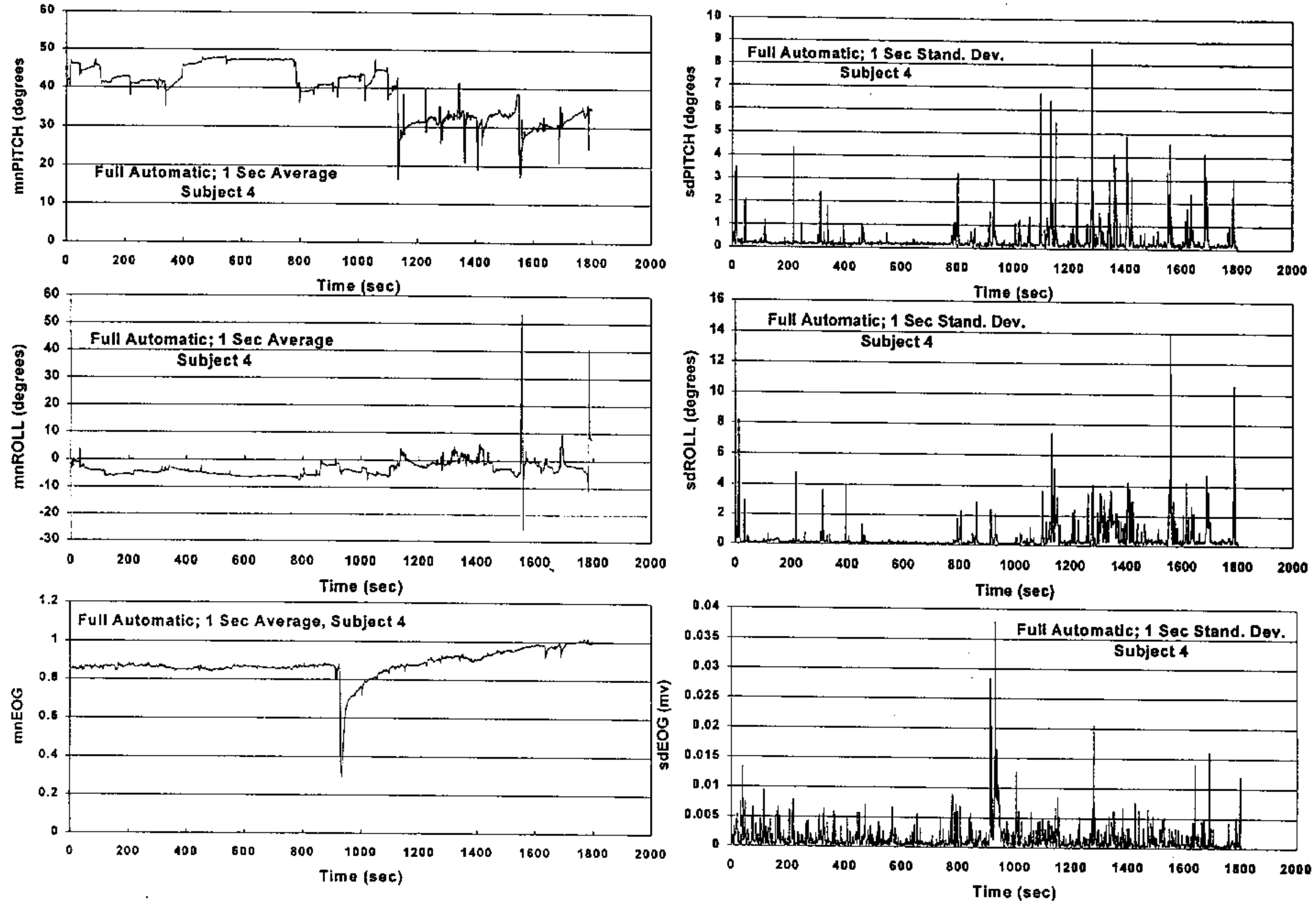


Figure 8. Time Histories of Head and EOG Activity for Subject 4

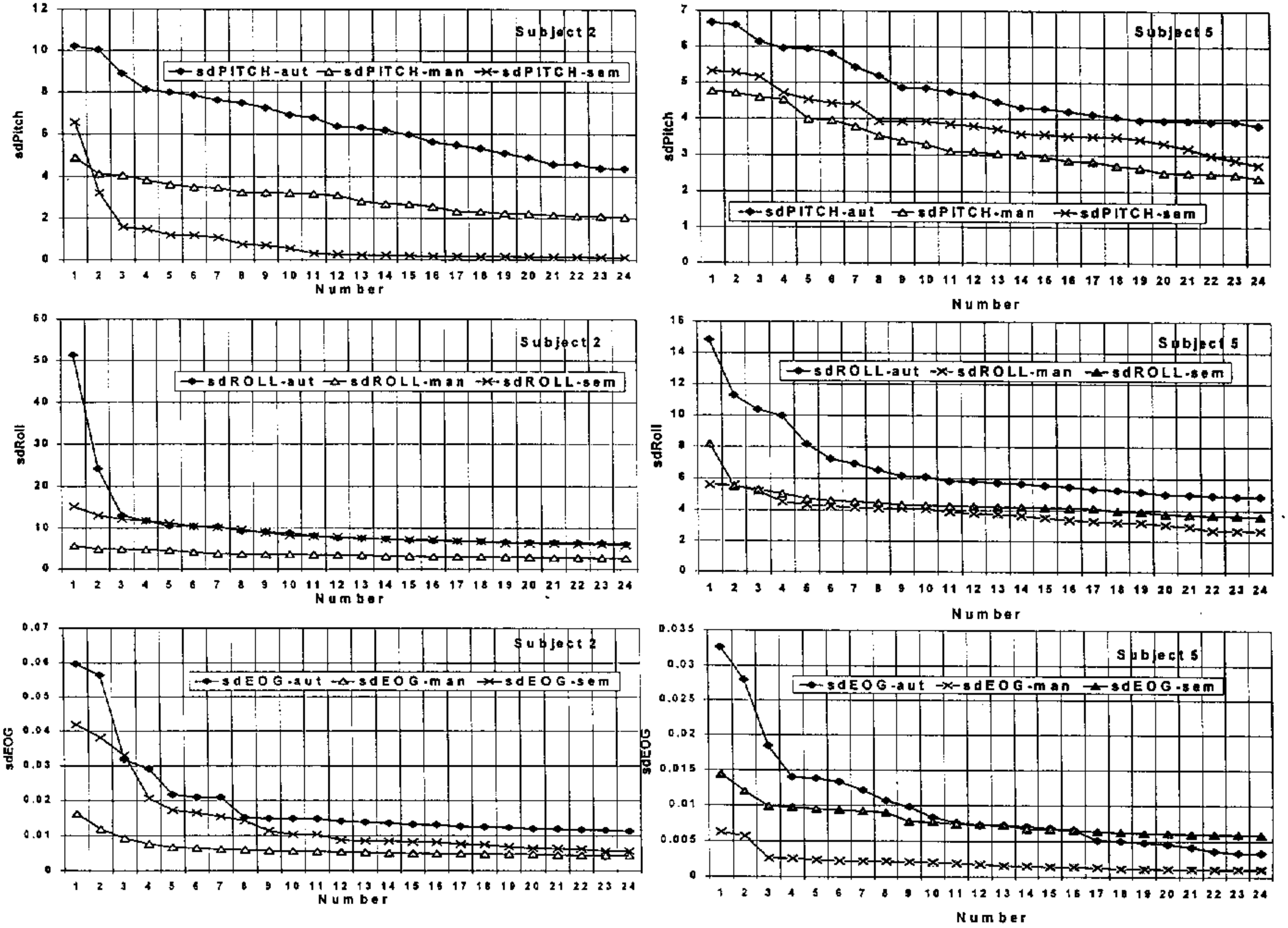
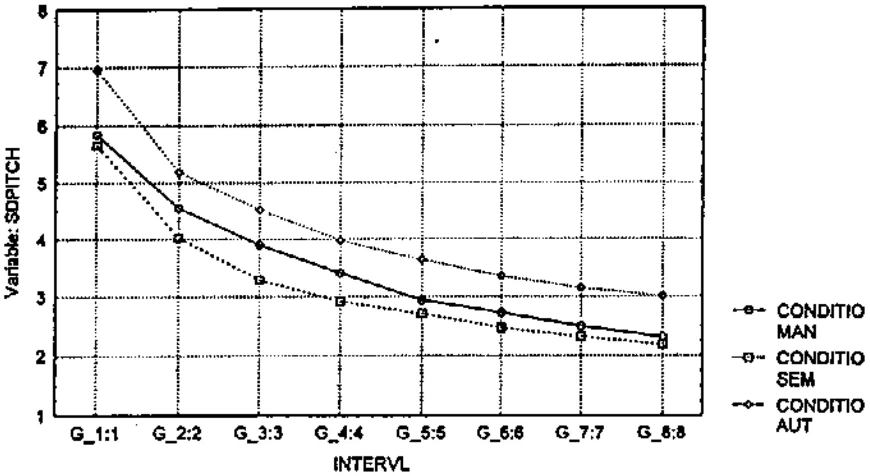
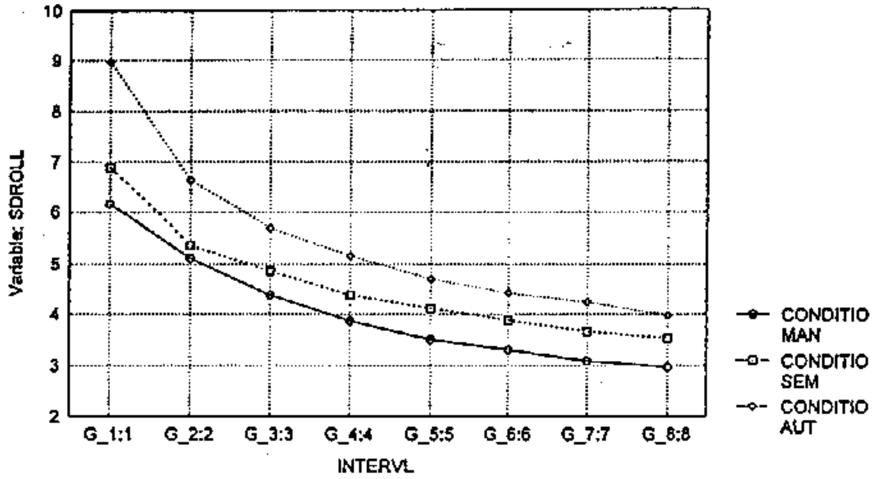


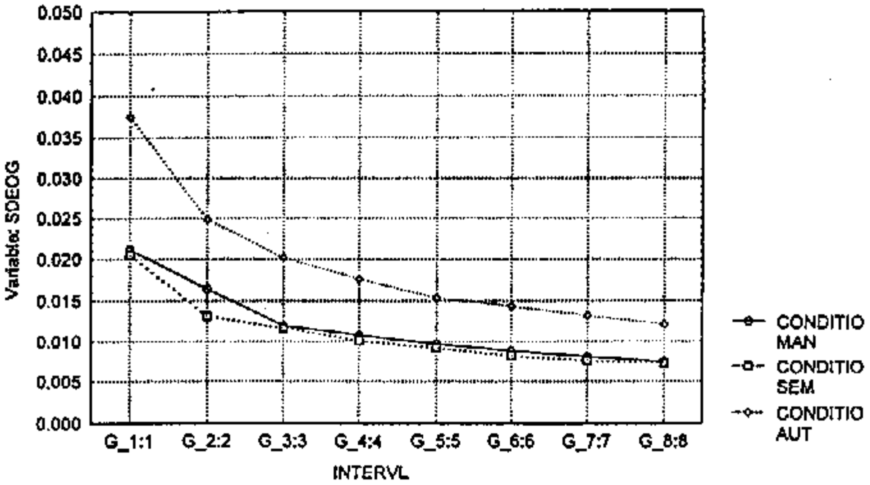
Figure 9. Amplitude Distributions for One Second Interval Standard Deviations of Psychophysiological Variables



a) SDPITCH



b) SDROLL



c) SDEOG

Figure 10. Head and EOG Activity as a Function of Automation Condition and Interval

C3 Interim Report

10.4.5 Appendix B - Human Factors Assessment of Two Background Collision Avoidance System Concepts

NAHSC

Human Factors Assessment of Two Background Collision Avoidance System Concepts

Final Report

Submitted to:

National Automated Highway System Consortium

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EXECUTIVE SUMMARY

The paper is a human factors analysis of two similar background collision avoidance (CA) concepts that have a high level of driver involvement for vehicle control. For each concept analyzed, the driver is responsible for controlling the vehicle's lateral and longitudinal position under most driving conditions, with an automated vehicle response only in emergency situations (e.g., to avoid a collision with a slower moving or stationary vehicle, or to maintain the vehicle within its lane of travel).

The two "high-end" collision avoidance concepts are defined as follows. Concept A is termed the Background Free Agent (BFA) system, wherein emergency headway control and lane keeping functions are provided to the driver by the system. This concept is modeled after the Free Agent system concept developed by Tsao, Hall, Shladover, Plocher, and Levitan (1994). A key characteristic of the BFA system is that lateral and longitudinal control operate independently of one another. Concept B is termed the Background Integrated Longitudinal and Lateral Control (BILLC) system, wherein full emergency collision avoidance, including lanekeeping, is provided to the driver by the system. The system is able to make lane-change maneuvers to avoid slower moving or stationary vehicles. Both lateral and longitudinal control are integrated under this concept.

The driver steers and controls vehicle speed manually under both CA concepts. Automated vehicle control is initiated in response to critical conditions, and the automated response can be overridden by the driver. As an example, with a stopped lead vehicle ahead of the CAS-equipped vehicle, the Concept A automated response would be an in-lane throttle-down or braking action (i.e., brake-only frontal collision avoidance), and the Concept B automated response would be similar, but could also accomplish an emergency lane-change maneuver. The major difference between the concepts is that for Concept A, the background control functions operate independently from each other and can be overridden independently, while for Concept B, the background control functions operate in an integrated fashion and are both deactivated when either lateral or longitudinal control is overridden by the driver.

Function analysis/allocation, task analysis, and fault tree analysis were used to evaluate the two CA concepts. The contribution that each analytic approach provided was an improved and thorough understanding of the driver and collision avoidance system (CAS) roles under emergency conditions. This improved understanding afforded the authors the ability to identify critical driver-related human factors issues relevant to each CA concept so that these issues could be addressed as development of such systems progressed. In addition, the feasibility of each CA concept from the driver's viewpoint was assessed based on the information provided by the analyses.

The results from the various analyses provided insight into potential driver-related human factors issues that need to be addressed before either the Background Free Agent or the Background Integrated Lateral and Longitudinal Control CA concepts become operational. The following is a list and brief description of the major human factors issues identified from the various human factors analyses:

- Driver reliance on automation. After gaining experience with the CAS, drivers may expect the automation to maintain safe operation of the vehicle (i.e., maintain the vehicle within safe operating parameters) and/or recover the vehicle from an emergency or critical driving situation.
- Startle response by the driver. Both CA concepts have the potential for producing a startle response, or natural response, by the driver which could inadvertently deactivate the automated controls at inopportune times during a critical or emergency driving situation.
- Transfer of control between the driver and the automation. Issues regarding the transition of vehicle control from both manual to automated and automated to manual control must be addressed. The primary concerns are "fighting" for vehicle control, inadvertent deactivation of automated control, and type(s) of warning information regarding the initiation and cessation of automated control.
- Independent versus bundled direction controls. The primary difference between the two CA concepts analyzed, from the driver's perspective, is that if an automated control response is overridden, all automated control is deactivated for the BILLC system, while only the directional control response overridden by the driver is deactivated for the BFA system (i.e., the other directional control remains active, or can become activated if control limit parameters are exceeded). Questions concerning which control approach is optimal and what types of warning/status information should be provided to the driver need to be addressed.
- Nuisance alarms and false alarms for automated control. Developers of CAS must be cognizant of the potential for nuisance alarms and false alarms produced by an automated control response. Nuisance and false alarms can quickly become an annoyance to the driver. Therefore, CAS developers must carefully consider the activation criteria for the activation of automated controls and select sensors and hardware that minimize the number of false detections and activations. False alarms and/or nuisance alarms could result in a startle response by the driver along with the consequences that could result from such a response, and could also lead to a decrease in driver acceptance and satisfaction with such a device.
- Driver response time to emergency conditions. An issue that may influence the success of automated response(s) to emergency events is driver response time. Automating the response to an emergency event while driving, which is currently performed under complete human control, may introduce negative consequences as a result of the changes that will occur within the driver-vehicle interface. Changes can include relegating the driver to monitoring status once automated control is activated, increasing overall system complexity, and potentially reducing the diagnostic capability of the driver. Each of these changes has the potential to reduce the motivation and/or capability of the driver to perform required driving tasks or maintain alertness. The effective driver response times with either CAS concept may be substantially greater than driver response times under manual-only driving conditions.
- Underload versus overload of driver resources. The issue of driver workload, both mental and physical, appears to be handled in a reasonable manner by the two CAS concepts analyzed. Both systems require that the driver remain in the loop for vehicle control and that automated control be initiated only when specific lateral and longitudinal control limits are exceeded, based on CAS sensor inputs.

The authors acknowledge that the list is not exhaustive. More driver-related issues are sure to arise as each concept becomes more defined and the interface between driver and automation is developed in greater detail.

The current visions for the BFA and BILLC system concepts warrant further development based on the results from the analyses. Based on the analyses, there do not appear to be any significant problems regarding the safety and usability of either concept from the driver's point of view. An important difference between the two CA concepts that should be analyzed further under experimental conditions is the issue of independent versus bundled controls and whether automated responses are overridden independently (i.e., overridden by a control input in the dimension that is currently automated) or are completely overridden regardless of the control input dimension.

The driver-related human factors issues described above, as well as other issues that arise as an operational system is developed, must be addressed if either CAS concept is to provide an improved safety benefit over current modes of travel. In addition, driver satisfaction and acceptance of automated vehicle control during emergency events must be evaluated. As the issues are considered in greater detail and the CAS concepts are refined, new human factors issues are expected to arise. It is important to note that the development of such complex systems will require an iterative process of design and evaluation.

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INTRODUCTION

OVERVIEW

An automated highway system (AHS) can be described as a vehicle-roadway system that is designed to move vehicles under some level of automated control along designated highway lanes in a manner that is compatible with, and evolvable from, the present highway system (Bishop, Leasure, and Stevens, 1994; Levitan, 1996). An AHS is envisioned to significantly improve both the safety and comfort of travelers while substantially increasing highway service and efficiency. The U.S. Department of Transportation (DOT) predicts that highway traffic will double by the year 2020 (U.S. DOT, 1989). An AHS has the potential to (1) increase safety, (2) increase maximum throughput, (3) improve traffic flow under all conditions, and (4) improve trip quality.

The first step in conceptualizing an AHS is to determine the subsystems, or technologies, to be included (e.g, object detection, collision warning, and longitudinal/lateral control capabilities). However, as long as a system remains in the conceptual design phase, the specifics on how subsystems might interact will remain undeveloped at any level of detail. As more complete models or concepts of an AHS are developed, a number of issues related to the technology and driver involvement must be addressed. Examples of technological issues include detailed descriptions of sensor/control capabilities and limitations. Examples of driver involvement issues include determining the degree of driver control. Disciplines such as mechanical and electrical engineering will be called upon to investigate the technological issues related to an AHS concept. Human factors engineering theory and tools will be required to address issues related to driver involvement.

Neale, Martin, and Dingus (1996) identified a number of human factors issues pertaining to an AHS. They note that because the AHS is not well defined, there are a myriad of potential scenarios that need to be assessed in terms of human factors issues. Concerning the driver specifically, one of the primary issues is the role of the driver in an AHS. Currently, in a non-AHS environment, drivers are in total control of all aspects of operating their vehicles. This is contrary to the "hands-off, feet-off" approach to driving envisioned in several AHS concepts. Some AHS concepts present drastic change from the current environment in which drivers operate. Changes brought about by an AHS can affect the role that drivers currently play on the highway. In other words, requirements of the driver when driving on an AHS and/or while under automated vehicle control may be different from requirements of the driver when driving under non-AHS conditions. Neale et al. (1996) note that under certain AHS concepts, a driver's role would consist primarily of supervisory control over the vehicle's operation. Other AHS concepts propose a more active role for the driver in controlling the vehicle, and automated controls would only be initiated in critical situations.

As an initial step to the development and deployment of AHS technologies, a number of collision warning and avoidance systems have been developed and tested (see Hogan, 1997; Janssen, 1989; McGehee, Dingus, and Horowitz, 1992; Neale et al., 1996). Collision avoidance (CA) systems typically have the driver engaged in all aspects of the driving task (e.g., lateral and longitudinal control and obstacle detection). It is believed that driver disengagement (i.e., lateral and longitudinal control are automated at some level), coupled with continual monitoring or obstacle detection responsibility, is unsatisfactory as a concept scenario for AHS (Hogan, 1997). Therefore, CA system concepts provide a logical progression towards a fully automated system. The idea behind initial development of CA systems is to maintain the driver in the vehicle control loop while providing greater and greater levels of automated collision avoidance capabilities. As CA concepts are realized and proven effective, work can continue on making the jump from low levels of automation to a fully automated highway system. The objective of this paper is to identify driver-related human factors issues for two CA concepts: utilizing human factors theory and analysis tools.

As previously noted, some AHS concepts may have a "hands-off, feet-off" approach to driving, while other concepts have drivers functioning in a more active role for vehicle control. Regardless of the concept envisioned, there are three questions that must be addressed as a given concept is developed: (1) What will the driver's role be in controlling the lateral and longitudinal position of the vehicle? (2) What will the driver's role be in obstacle detection? (3) What will the driver's role be in responding to critical/emergency situations? If the driver is in complete control of the vehicle, as he/she is in current non-automated scenarios, allocation of vehicle control, obstacle detection, and emergency response tasks are solely the driver's responsibility. However, the driver's role changes from one of primary operator to one of system supervisor as more and more automation is introduced. An AHS designer must answer the following function allocation questions when considering an increase in the amount of automation: Would vehicle control be best delegated to the driver or the system under normal operating conditions? Is obstacle detection best delegated to the system or to the driver? Would response to a critical/emergency situation be best delegated to the driver or the system? In addition, what are the implications of delegating these tasks to either the system or the driver? These are primary questions that can be addressed, at least partially, through a human factors analytic approach.

This paper is a human factors analysis of two similar background collision avoidance concepts that have a high level of driver involvement for vehicle control. For each concept analyzed, the driver is responsible for controlling the vehicle's lateral and longitudinal position under most driving conditions, with an automated vehicle response only in emergency situations (e.g., to avoid a collision with a slower moving or stationary vehicle, or to maintain the vehicle within its lane of travel). The types of automated response differ between the two concepts in whether only a braking response is automated, or whether there is an integrated braking and steering response that is automated to avoid a collision or mitigate the results of a collision. The operational scenarios for each concept are described below.

PROBLEM STATEMENT

Listed below are problem statements and related definitions for the current analytical effort. The purpose of the problem statements is to define the objectives and scope for this project.

1. Provide a detailed definition of the driver's role under two different background CA concepts.

- The driver's role is defined through performance of function and task analyses.
- The analyses consider driver's perceptual, cognitive, and motor capabilities with regard to time constraints, human error, and the driver-vehicle relationship.

2. Identify driver-related human factors issues for each CA concept.
   - Human factors issues include areas of difficulty for collision avoidance system (CAS) design with regard to safety and user acceptance.
   - Human factors issues are identified from the function and task analyses, as well as through performing a fault tree analysis.
   - Environmental factors and individual differences among drivers are also considered.

3. Assess the feasibility for each CAS concept from the driver's point of view.

Two CAS concepts were considered for the analyses, and driver-related human factors issues relevant to each concept were identified. The two "high-end" collision avoidance concepts are defined as follows. Concept A is termed the Background Free Agent (BFA) system, wherein emergency headway control and lane keeping functions are provided to the driver by the system. This concept is modeled after the Free Agent system concept developed by Tsao, Hall, Shladover, Plocher, and Levitan (1994). A key characteristic of the BFA system is that lateral and longitudinal control operate independently of one another. Concept B is termed the Background Integrated Longitudinal and Lateral Control (BILLC) system, wherein full emergency collision avoidance, including lanekeeping, is provided to the driver by the system. The system is able to make lane-change maneuvers to avoid slower moving or stationary vehicles. Both lateral and longitudinal control are integrated under this concept.

The driver steers and controls vehicle speed manually under both CAS concepts. Automated vehicle control is initiated in response to critical conditions, and the automated response can be overridden by the driver. As an example, with a stopped lead vehicle ahead of the CAS-equipped vehicle, the Concept A automated response would be an in-lane throttle-down or braking action (i.e., brake-only frontal collision avoidance), and the Concept B automated response would be similar, but could also accomplish an emergency lane-change maneuver. The major difference between the concepts is that for Concept A, the background control functions operate independently from each other and can be overridden independently, while for Concept B, the background control functions operate in an integrated fashion and are both deactivated when either lateral or longitudinal control is overridden by the driver. Both concepts are described in greater detail in the next section.

PROPOSED SYSTEM CONCEPTS

CONCEPT A: BACKGROUND FREE AGENT SYSTEM

An operational scenario is described for the Background Free Agent (BFA) system including the overall system vision, specific features of the system, normal operational events for the system, and emergency events that result in engagement of the system. In general, the system is envisioned to operate on any non-signalized, access-controlled highway (both rural and urban), at any level of traffic congestion. The system is not designed to work at intersections or off-highways where pedestrians may be present. The system will have day-night and all-weather capabilities, however, it is anticipated that the system may work in a degraded capacity under off-nominal conditions. All system hardware, including sensors and actuators, is contained within the host vehicle. An assumption is made that no inter-vehicle or vehicle-roadway communication will be required. However, there may be a physical or electronic infrastructure installed to assist in lateral and longitudinal control. This would depend on the state of the technology to be adopted. It is anticipated that CAS-equipped and non-equipped vehicles will share the same highway lanes and will mix freely. This technology will be available to all classes of vehicles, except motorcycles.

Currently, the following features are assumed for the Background Free Agent system:

- The driver controls the vehicle while traveling on the roadway under normal operating conditions.
- Automated lane keeping or headway control is initiated when pre-determined lateral or longitudinal control limits are exceeded.
- Pre-determined lateral and longitudinal control limits are based on safety considerations for vehicle control and accident mitigation.
- Driver override of automated control is possible, allowing for tactical decisions such as overtaking slower vehicles, lane selection, entry and exit from the CAS-capable roadway, speed and headway distance, and lane positioning to avoid small objects in the travel lane.
- Automated control features (i.e., braking or lane keeping) may or may not be preceded by warning(s). This will depend on timing of response to the emergency event and other human factors considerations.

From a driver's perspective, the Background Free Agent system is activated only by an emergency event. Therefore, there is not a normal operational mode for such a system. However, there is a continual normal background operation (i.e., non-emergency) of the system that includes monitoring the driver's lane keeping, distance to the next immediate lead vehicle (i.e., vehicle separation), and vehicle speeds by the system sensors. There are three sub-functions performed by the system while operating in the normal background condition. The sub-functions include:

- Lane keeping. This subfunction monitors the vehicle's position in the lane and compares it to a safety criteria reference point. Lane geometry preview is critical for negotiating curves. The system also monitors vehicle state variables such as lateral velocity, lateral acceleration, and yaw rate.

- Speed supervision. The vehicle's speed is monitored and compared to a safety reference point that is based in part on the lead vehicle's speed.
- Headway distance supervision. This subfunction monitors the safe headway distance between the CAS-equipped vehicle and the vehicle directly in front. Safe headway distance could be determined in terms of a fixed time or fixed distance, and could vary according to known characteristics of vehicle braking, speed, and vehicle class. Weather and/or road surface conditions would factor in determining critical limits for headway distance.

The Background Free Agent system is automatically enabled in the longitudinal dimension (i.e., deceleration) when a safety-critical headway distance is exceeded. This safety-critical distance could be reached when approaching a slower moving or stopped vehicle, or when a vehicle cuts in from another lane. The system should engage deceleration smoothly, first using the powertrain and then the brakes. A tradeoff exists between nuisance alarms that would occur when the system has a long-range engagement distance, allowing for smoother engagement, and abrupt engagement, typically including hard braking, which would be the result of a system that has a short-range engagement distance.

The system is automatically engaged in the lateral dimension (i.e., steering control) when the vehicle transitions past a defined lateral deviation from a lane reference system. The control objective is to center the vehicle within the lane while adhering to lateral acceleration and jerk constraints.

It is important to note that for both situations where automated control is enabled, there must be a reliable and robust driver override capability. This would allow the driver to perform normal traffic maneuvers such as lane changes or allow for cut-ins without having to compete with the system for control of the vehicle. The driver is allowed to take over control of the vehicle when the automated control is engaged, and the transition between automated and manual control should be fluid and reasonable to the driver. Lateral control can be overridden independently of longitudinal control and vice versa for the BFA system concept.

An emergency event is defined as any safety-motivated vehicle maneuver in response to a disturbance in the normal operation of the vehicle. The control objective of the Background Free Agent system is to address the impact of the disturbance in a "graceful" manner that allows for a quick recovery, either by the system or by the driver. The only automated response allowed for a longitudinal emergency event is braking, or deceleration, with the magnitude of deceleration contingent on the criticality of the emergency (e.g., time to collision). The system must be able to reliably detect safety-critical events, and accurately and quickly formulate the appropriate response. The only automated response for a lateral emergency event is to center the vehicle in the travel lane according to lateral acceleration and jerk constraints. An example of a lateral emergency event would be the vehicle drifting out of the travel lane and onto the shoulder.

As part of an automated response to an emergency event, the Background Free Agent system must perform a number of sub-functions related to handling the presence of obstacles in the road ahead of the vehicle (e.g., cars, significant roadway debris, and possibly black ice) or other roadway hazards. Sub-functions to be performed by the system in order to respond to an emergency event include: (1) the detection, classification, and verification of obstacles in front of the vehicle; and (2) the formulation of a decision strategy in response to the emergency event (e.g., the degree of deceleration required, including hard braking, or the amount of steering input necessary to center the vehicle).

CONCEPT B: BACKGROUND INTEGRATED LONGITUDINAL AND LATERAL CONTROL SYSTEM

The operational scenario description for the Background Integrated Longitudinal and Lateral Control (BILLC) system, including the overall system vision, specific features of the system, normal operational events for the system, and emergency events that result in engagement of the system, is similar to the Background Free Agent system, with a few critical exceptions. Similar to the BFA system, the BILLC system is envisioned to operate on any non-signalized, access-controlled highway (both rural and urban), at any level of traffic congestion. The system is not designed to work at intersections or off-highways where pedestrians may be present. The system will have day-night and all-weather capabilities, however, it is anticipated that the system may work in a degraded capacity under off-nominal conditions. All system hardware, including sensors and actuators, is contained within the host vehicle. An assumption is made that no inter-vehicle or vehicle-roadway communication will be required. However, there may be a physical or electronic infrastructure installed to assist in lateral and longitudinal control. This would depend on the state of the technology to be adopted. It is anticipated that CAS-equipped and non-equipped vehicles will share the same highway lanes and will mix freely. This technology will be available to all classes of vehicles, except motorcycles.

Currently, the following features are assumed for the BILLC system:

- The driver controls the vehicle while traveling on the roadway under normal operating conditions.
- Automated background-maneuver control is initiated when pre-determined lateral or longitudinal control limits are exceeded. Lane keeping and headway control are integrated under this system concept, compared to being independent functions in the BFA system.
- Automated responses, when control limits are exceeded, include: (1) braking to yield various deceleration rates; (2) lane-change maneuvers (either left or right) for integrated collision avoidance; and (3) lane keeping functions similar to the BFA system concept, only when not in conflict with an integrated collision avoidance response.
- Pre-determined lateral and longitudinal control limits are based on safety considerations for vehicle control and accident mitigation.
- Driver override of automated control is possible, allowing for tactical decisions such as overtaking slower vehicles, lane selection, entry and exit from the CAS-capable roadway, speed and headway distance, and lane positioning to avoid small objects in the travel lane.
- Automated control features (i.e., braking and lane keeping) may or may not be preceded by warning(s). This will depend on timing of response to the emergency event and other human factors considerations.

From a driver's perspective, the BILLC system is activated only by an emergency event. Therefore, there is not a normal operational mode for such a system. However, there is a continual normal background operation (i.e., non-emergency) of the system that includes monitoring the driver's lane keeping, distance to the next immediate lead vehicle (i.e., vehicle separation), and vehicle speeds by the system sensors. In addition, sensors are able to monitor obstacles in the surrounding travel lanes to support maneuvering around obstacles or to the side of the road. There are three sub-functions performed by the system while operating in the normal background condition. The sub-functions include:

- Lane keeping. This subfunction monitors the vehicle's position in the lane and compares it to a safety criteria reference point. Lane geometry preview is critical for negotiating curves. The system also monitors vehicle state variables such as lateral velocity, lateral acceleration, and yaw rate.
- Speed supervision. The vehicle's speed is monitored and compared to a safety reference point that is based in part on the lead vehicle's speed.
- Headway distance supervision. This subfunction monitors the safe headway distance between the CAS-equipped vehicle and the vehicle directly in front. Safe headway distance could be determined in terms of a fixed time or fixed distance, and could vary according to known characteristics of vehicle braking, speed, and vehicle class. Weather and/or road surface conditions would be factors in determining critical limits for headway distance.
- Surrounding lane(s) supervision. This subfunction monitors for obstacles in the other travel lane(s) or shoulder to support the system's ability to maneuver around obstacles in order to avoid collisions or mitigate the impact of a collision. In addition, this subfunction determines whether to execute the avoidance maneuver and the trajectory or path that is optimal for the vehicle to follow during this maneuver.

The BILLC system is automatically enabled in the longitudinal dimension (i.e., deceleration) when a safety-critical headway distance is exceeded. This safety-critical distance could be reached when approaching a slower moving or stopped vehicle, or when a vehicle cuts in from another lane. The system should engage deceleration smoothly, first using the powertrain and then using the brakes. A tradeoff exists between nuisance alarms that would occur when the system has a long-range engagement distance, allowing for smoother engagement, and abrupt engagement, typically including hard braking, which would be the result of a system that has a short-range engagement distance.

The system is automatically engaged in the lateral dimension (i.e., steering control) when the vehicle transitions past a defined lateral deviation from a lane reference system. The control objective is to center the vehicle within the lane while adhering to lateral acceleration and jerk constraints.

In addition, both lateral and longitudinal control can function in an integrated fashion to automatically maneuver the vehicle around an obstacle and/or maneuver the vehicle to the side of the road. This is distinctively different from the BFA system which can only automatically decelerate the vehicle while keeping the vehicle in the travel lane. This additional function adds a level of complexity to the system's sensor capabilities and response algorithms.

It is important to note that for situations where automated control is enabled, there must be a reliable and robust driver override capability. This would allow the driver to perform normal traffic maneuvers such as lane changes or allow for cut-ins without having to compete with the system for control of the vehicle. The driver is allowed to take over control of the vehicle when the automated control is engaged, and the transition between automated and manual control should be fluid and reasonable to the driver. Since automated vehicle control is integrated, when one control dimension is overridden, the other control dimension is disabled for the BILLC system concept.

An emergency event is defined as any safety-motivated vehicle maneuver in response to a disturbance in the normal operation of the vehicle. The control objective of the BILLC system is to address the impact of the disturbance in a "graceful" manner that allows for a quick recovery, either by the system or by the driver. The automated responses performed by the BILLC system include integrated braking, with the magnitude of deceleration contingent on the criticality of the emergency (e.g., time to collision), and steering, with the objective to either center the vehicle in the travel lane or steer around an obstacle for collision avoidance. The system must be able to reliably detect safety-critical events, and accurately and quickly formulate the appropriate response.

As part of an automated response to an emergency event, the BILLC system must perform a number of sub-functions related to handling the presence of obstacles in the road ahead of the vehicle (e.g., cars, significant roadway debris, and possibly black ice) or other roadway hazards. Sub-functions to be performed by the system in order to respond to an emergency event include: (1) the detection, classification, and verification of obstacles in front of the vehicle; (2) the formulation of a decision strategy in response to the emergency event (e.g., determining an appropriate maneuver based on the present state of the vehicle, and the likely future states); (3) the formulation of a response strategy to the emergency event, including the degree of braking required, and whether to maneuver around the obstacle and/or to the side of the road. The response maneuver subfunction could consist of a lane change, a lateral movement within the lane (either to the left or to the right), or the performance of an evasive maneuver and stopping by the side of the road. A mayday signal could be enabled by the driver once the vehicle is stopped on the roadside. The added ability to automatically change lanes to avoid a collision under the BILLC system places a significant demand on the sensor capabilities of the system to assess the occupancy of the adjacent lane.

ANALYTIC APPROACH

OVERVIEW

This section describes the analytical methods used to evaluate the two background CA concepts described in this paper. Assumptions were made to scope the concepts in a form manageable for analysis. The analytical techniques are described briefly in this section, and the results for each of the concepts are presented in the following section. The contribution that each analytic approach provides is an improved and more thorough understanding of the driver and CAS roles under emergency conditions. This improved understanding affords the authors and reader the ability to identify critical driver-related human factors issues relevant to each CA concept so that these issues can be considered as development of such systems progress. In addition, the feasibility of each CA concept from the driver's viewpoint can be assessed based on the information provided by the analyses.

ASSUMPTIONS

Several assumptions regarding critical phases of CAS operation to be considered for analysis, and how each of the CA concepts are expected to operate, were made to meet the project goals. The authors realize that assumptions can affect the outcome of the analysis techniques applied to determine drivers' roles in the CAS concepts and the critical driver-related human factors issues. However, both concepts remain ill-defined to the point that detailed analyses would be impractical without making several critical assumptions. To perform the function, task, and fault tree analyses, the following assumptions regarding the CA concepts were made:

- Since the driver controls the vehicle under most conditions, the analytic methods only addressed the functions, tasks, and events during critical conditions. The critical conditions are defined as events during travel that would enable automated control of the vehicle, including the time period just prior to automated control.
- The driver is alerted whenever automated control is initiated and when automated control is overridden. Feedback to the driver about the status of automated control is required so that the driver knows at all times who, or what, is ultimately controlling the vehicle. Additional feedback may be required to inform the driver what aspect(s) of vehicle control is under automation when the system is enabled. For example, a warning signal with a specific frequency and temporal pattern would indicate that lateral control is engaged, while a warning signal with a different frequency and/or temporal pattern would indicate that longitudinal control is engaged. This is particularly important when only lateral control or longitudinal control is activated without the other directional response. However, in the case where lateral and longitudinal controls are bundled (e.g., BILLC), singular feedback indicating when automation is active may be more appropriate.
- Automated control capabilities can be overridden by the driver manually through either a steering input or a brake/accelerator pedal input. Once overridden, automated control(s) become operative again only after a specific time period (e.g., 2 seconds) has passed where the sensors have not detected an obstacle within range that would have initiated an automated control response. This assumption solves two potential problems for automated control: (1)

the driver will not constantly be fighting the vehicle for control when attempting a manual response to a critical situation, and (2) the driver will know that he/she is now responsible for the particular aspect of vehicle control (i.e., either lateral or longitudinal) that was overridden. The system should indicate to the driver by some interface that it is ready to respond automatically to a critical situation, after the time period has elapsed.

A potential problem that may arise is that of inadvertent deactivation (e.g., a startle response to the steering wheel when automated lateral control is initiated which disengages the automation). Therefore, driver inputs required to override automated controls must be designed to accommodate such factors.

FUNCTION ANALYSIS/ALLOCATION

The process of function analysis/allocation consists of determining which functions should be performed by the human operator and which functions should be performed by the machine in a complex system. Once completed, the extent of operator involvement in the control of a system is defined (Kirwan and Ainsworth, 1992). The division of functions between person and machine, in particular, the driver of an automobile and an automated highway system, is addressed in this report. Driver functions and CA concept functions were derived from the operational scenarios described above.

Formal systematic approaches to function allocation are described by Price (1985) and Kantowitz and Sorkin (1987). The two approaches are five-step procedures that designers can use in the assignment of functions to either the human operator or the machine in complex systems. Price's (1985) approach is more qualitative in nature, while the five-step approach described by Kantowitz and Sorkin (1987) is more quantitative. The practice of formal function allocation has been under scrutiny from both designers and systems engineers. There has been a lack of evidence demonstrating that a formal process of function allocation has improved the design of complex systems. The literature is devoid of cases, successful or otherwise, in which formal allocation has been applied to actual system design (Fuld, 1993). However, recent function analysis research has proposed the use of operator role theory to guide function allocation during the system design process: "The conceptual framework provided by operator role theory has been used in analyzing design requirements and in designing actual systems (especially the operator interfaces)" (Folds and Mitta, 1995, p. 1155). The concepts and approach appear to overcome some of the weaknesses inherent in the methods previously described.

Operator role theory was first developed as a conceptual framework for describing operator activities in complex systems and evaluating operator contributions to system capabilities and limitations in the context of their roles (Folds and Mitta, 1995). According to operator role theory, the human operator of a given system design can be assigned to one of four roles: (1) Direct Performer, (2) Manual Controller, (3) Supervisory Controller, and (4) Executive Controller. Only one role can be assigned to an operator per system function, but an operator may have different roles in different system functions. Each role is described by a point along a hypothetical continuum of increasing automation. As system automation increases, the responsibilities of the operator shift.

Performance of system functions is described by a four-stage information processing loop (see Figure 1). The four stages are: (1) sensors, (2) processors, (3) actuators, and (4) decision makers, which close the loop. The decision making stage initiates control actions based on sensed information from the task environment. The operator role in a system function is defined by how information processing (i.e., how much of each stage of the information processing loop) is performed by humans versus machines.

The role of Direct Performer describes one extreme of the automation continuum where no automation is used. The human operator executes all four stages of the information processing loop when performing a system function.

The role of Manual Controller describes the next point along the automation continuum. Machine capabilities may be used as sensors, processors, and/or actuators, but the human operator performs all decision-making activities related to the system function. The human operator may also be involved in sensing and processing information, and/or in actuating responses.

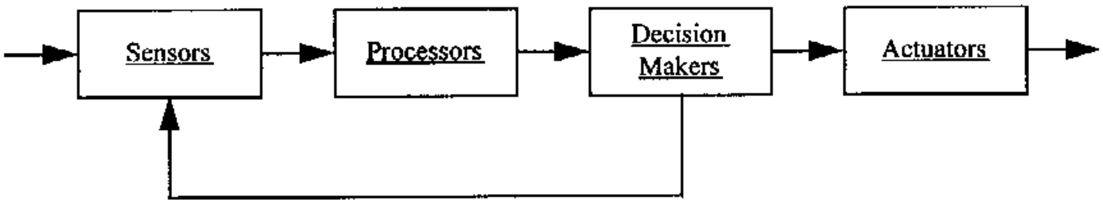

Figure 1. Four-stage information processing loop for performance of system functions considered by Operator Role Theory.

The role of Supervisory Controller describes the next point along the increasing automation continuum. Machine capabilities are not only used as sensors, processors, and actuators, but the machine is allowed to make decisions. The operator's responsibility is to monitor the performance of the machine and intervene when necessary.

Finally, the role of Executive Controller describes the opposite extreme of the automation continuum where functions are fully automated. The machine performs all four stages of the information processing loop for a function without intervention from the human operator.

The concepts of operator role theory were used to develop a structured method for analyzing and allocating system functions (Folds and Mitta, 1995). The analyst considers each lowest-level function (i.e., the most basic function or operation that must be performed to accomplish the task or sub-task) and judges whether the two extreme operator roles can meet the performance requirements or other relevant criteria for that function. If so, the analyst considers whether any significant increase in capabilities can be expected if a different operator role is assigned for that function. If not, the operator role that is expected to fulfill the known requirements is designated for that function.

Next, the analyst considers the remaining functions--those functions with performance requirements that are not met by the machine alone or the human alone, or that could be met by either the machine or operator, but are expected to be performed significantly better by a combination of operator and machine. Appropriateness of assigning the Manual Controller or Supervisory Controller role is determined by whether performance requirements of the function are met by a specific role, and if so, whether significant gains can be expected from the other, non-selected role. The operator role expected to meet the requirements is selected for that function. The final step is to specify the details of the allocation of information processing stages in each function. For each function, the analyst considers the possible configurations for the applicable operator role, as identified in Table 1, and identifies the configuration that would meet the performance requirements. If more than one configuration meets the performance requirements, the analyst should select the configuration that provides the best expected performance, including such factors as cost and safety.

Table 1. Possible configurations of human and machine components for each operator role (adapted from Folds and Mitta, 1995).

Operator Role	Sensors	Processors	Decision Makers	Actuators
Direct Performer	H or Hm	H	H	H or Hm
Manual Controller	H or Hm or M	H or Hm or M	H	H or Hm or M
Supervisory Controller	M or Mh	M or Mh	Mh	M or Mh
Executive Controller	M	M	M	M

Note: H = Performed by human
Hm = Performed by human supplemented by machine
M = Performed by machine
Mh = Performed by machine supplemented by human

TASK ANALYSIS

The general process for task analysis is to generate a list of all task descriptions and order that list in the sequence in which tasks must be performed to accomplish the functions in which an operator is involved (e.g., the functions in which the driver is involved with a CAS concept). Each task is further broken down into the steps required to carry out the particular task. The individual steps are analyzed to determine (1) the inputs required to initiate or carry out the step (i.e., actions by the driver), (2) the decisions or processing the operator must make to perform the step, and (3) the actions required for each step.

The task analyses performed for each CAS concept were adapted from Levitan, Plocher, and DeMers (1996), and include the following:

- A brief description of the task to be performed by the driver.
- The specific step in the process of completing the task.
- The specific inputs to the driver or system that are required to initiate an action.
- The specific information processing, or decisions, made by the driver or system.

- The specific driver or system responses, or actions, given the information provided and the decision(s) made.

The analyses were based on the functions derived from the function analysis/allocation, and the assumptions made for each of the CAS concepts.

FAULT TREE ANALYSIS

The fault tree analytic method structures the relations between events in a system into a Boolean logic model so that they lead to a specified outcome (Roland and Moriarty, 1990). The specified outcome becomes the top event in the tree, and the process of deductive reasoning is used in determining the specific events that can lead to the specified outcome. This analytic method provides a graphical depiction of the relationship between events that lead to an accident when driving an AHS-equipped vehicle.

A fault tree analysis can be described as an analytical technique, whereby an undesired state of the system is specified (usually a state that is critical from a safety standpoint), and the system is then analyzed in the context of its environment and operation to find all credible ways in which the undesired event can occur. The fault tree itself is a graphical model of the various parallel and sequential combinations of faults that will result in the occurrence of the predefined undesired event. The faults can be events that are associated with component hardware failures, human errors, or any other pertinent events that can lead to the undesired event. Therefore, a fault tree depicts the logical interrelationships of basic events that lead to the undesired event--the top event of the fault tree.

A fault tree is not a model of all possible system failures or all possible causes for system failure. A fault tree is tailored to its top event, which corresponds to some particular system failure mode, and the fault tree therefore includes only those faults that contribute to this top event. In addition, these faults are not exhaustive. They cover only the most credible faults assessed by the analyst.

A fault tree is a network of entities known as "gates" which serve to permit or inhibit the passage of fault logic up the tree. The gates show the relationships of events needed for the occurrence of a "higher" event. The "higher" event is the "output" of the gate; the "lower" events are the "inputs" to the gate. The gate symbol denotes the type of relationship of the input event required for the output event. Figure 2 shows the event symbols and the gate symbols, including their definitions.

EVENT SYMBOLS

BASIC EVENT - A basic initiating fault requiring no further development.

CONDITIONING EVENT - Specific conditions or restrictions that apply to any logic gate.

INTERMEDIATE EVENT - A fault event that occurs because of one or more antecedent causes acting through logic gates.

UNDEVELOPED EVENT - An event that is not further developed either because it is of insufficient consequence or because information is unavailable.

EXTERNAL EVENT - An event that is normally expected to occur.

GATE SYMBOLS

AND GATE - Output fault occurs if all of the input faults occur.

OR GATE - Output fault occurs if at least one of the input faults occurs.

EXCLUSIVE OR GATE - Output fault occurs if exactly one of the input faults occurs.

PRIORITY AND GATE - Output fault occurs if all of the input faults occur in a specific sequence (the sequence is represented by a CONDITIONING EVENT drawn to the right of the gate).

INHIBIT GATE - Output fault occurs if the (single) input fault occurs in the presence of an enabling condition (the enabling condition is represented by a CONDITIONING EVENT drawn to the right of the gate).

Figure 2. Basic fault tree symbols and definitions.

CONCEPT EVALUATION

CONCEPT A: BACKGROUND FREE AGENT SYSTEM

The results from the function, task, and fault-tree analyses can be used to provide a detailed definition of the driver role for the Background Free Agent system. The approaches to the function and task analyses are modeled after the efforts of DeMers (1994) and Levitan, Plocher, and DeMers (1996), who performed similar analyses for other AHS operational concepts. In addition, fault tree analysis was added to provide further insight into the driver's role when operating under the BFA system concept. The results from the various analyses are used to identify driver-related human factors issues, and are presented separately. Following the description of Concept Evaluation results is a section on driver-related human factors issues. Comments regarding concept feasibility from the driver's point of view are included in the Conclusions section.

Function Analysis/Allocation

The following paragraphs present a list of driver and system functions for the BFA system. Driver and system functions are derived from the operational scenario described above. Since the driver controls the vehicle under most conditions, the functions described are during critical conditions only. Critical conditions are defined as events during travel that would enable the automated control of the vehicle, including the time period just prior to automated control. Driver functions under manual control (i.e., the time period just prior to the initiation of automated control) are listed first, followed by driver and system functions under automated control. Table 2 summarizes the functions performed by the driver and by the BFA system while traveling on a roadway.

Driver Functions under Manual Control:

- The driver controls the lateral position of the vehicle in the lane while under travel.
- The driver controls the longitudinal position of the vehicle (i.e., acceleration and deceleration) while under travel.
- The driver observes the traffic conditions and traffic flow (e.g., other vehicles slowing, accidents, hazardous behavior of other drivers) while under travel. The driver is looking for hazardous situations that would require lateral and longitudinal control of the vehicle to avoid an accident.
- The driver observes the roadway and environmental conditions (e.g., road surface conditions, weather, roadside hazards) while under travel. Again, the driver is looking for hazardous situations that would require lateral and longitudinal control inputs to the vehicle to avoid an accident.
- The driver decides how to respond/react to traffic conditions and traffic flow (e.g., slow down, increase headway distance, pass slower moving vehicles) that present a critical condition while under travel.

- The driver decides how to respond/react to roadway and environmental conditions (e.g., slow down, increase headway distance, maneuver around hazard, pull off road) that present a critical condition while under travel.

Table 2. Summary of driver and Background Free Agent system functions.

Driver Functions	Background Free Agent System Functions
1. control lateral position of vehicle while under travel	1. monitor vehicle lateral position with respect to travel lane reference (e.g., lane edge, lane marker) while on the highway
2. control longitudinal position of vehicle while under travel	2. monitor vehicle headway-distance/time-to-collision to objects in front of vehicle's path of travel (e.g., other vehicles, road debris) while on the highway (this includes detection, classification, verification, and selection of decision strategy for automated control response)
3. observe traffic conditions and traffic flow (e.g., other vehicles slowing, accidents, hazardous behavior of other drivers) while under travel	3. monitor road surface and environmental conditions and modify lateral/longitudinal control limits accordingly (this includes detection, classification, verification, and selection of decision strategy for modifying control limits)
4. observe roadway and environmental conditions (e.g., road surface conditions, weather, roadside hazards) while under travel	4. engage lateral control actuator(s) when pre-determined lateral control limit has been exceeded (i.e., steering control to center vehicle within travel lane) while traveling on the highway
5. respond/react accordingly to traffic conditions and traffic flow (e.g., slow down, increase headway distance, pass slower moving vehicles) while under travel	5. engage longitudinal control actuator(s) when pre-determined longitudinal control limit has been exceeded (i.e., powertrain followed by braking) while traveling on the highway
6. respond/react accordingly to roadway and environmental conditions (e.g., slow down, increase headway distance, maneuver around hazard, pull off road) while under travel	6. present information on status and/or operability of automation
7. receive and interpret information on status/ operability of automation during vehicle startup and while under travel	7. warn/alert driver when lateral control is engaged and/or warn/alert driver when longitudinal control is engaged
8. decide whether to override automated control(s) during critical/emergency situations when automated control is activated	8. disengage lateral control when overridden by driver inputs and/or disengage longitudinal control when overridden by driver inputs

Driver and System Functions under Automated Control:

The driver may perform all of the functions listed under the Manual Control functions described above. In addition, the driver and the BFA system perform the following functions under automated control:

- The driver receives and interprets information on the status and operability of automation during vehicle startup and while on the highway.
- The BFA system presents information regarding the status and/or operability of the automation capabilities.
- The BFA system monitors the vehicle's lateral position with respect to the travel lane reference (e.g., lane edge, lane marker) while on the highway.
- The BFA system monitors the vehicle's headway-distance/time-to-collision to objects in front of the vehicle's path of travel (e.g., other vehicles, road debris) while on the highway. This function includes detection, classification, verification, and selection of a decision strategy for an automated longitudinal control response.
- The BFA system monitors the road surface and environmental conditions and modifies the lateral/longitudinal control limits accordingly. This function includes detection, classification, verification, and selection of a decision strategy for modifying lateral/longitudinal control limits.
- The BFA system engages lateral control actuator(s) when a pre-determined lateral control limit has been exceeded (i.e., steering control to center vehicle within travel lane). This function is performed only while traveling on the highway.
- The BFA system engages longitudinal control actuator(s) when a pre-determined longitudinal control limit has been exceeded (i.e., powertrain followed by braking). This function is performed only while traveling on the highway.
- The BFA system warns/alerts the driver when automated control is engaged. It is assumed that this function is performed regardless of whether there is enough time to alert the driver prior to engagement of the automation.
- The driver decides whether to override automated control(s) during the critical/emergency situation when the automated control(s) are activated.
- The BFA system disengages either the lateral or the longitudinal control when that automated control is overridden by the driver's inputs.

Operator role theory can be used to determine the function allocation requirements for the BFA system. The role of *Direct Performer* is appropriate for describing the functions performed by the driver under manual control conditions. Under normal operating conditions, the driver is responsible for performing all functions related to the safe operation of the vehicle. The role of *Supervisory Controller* is appropriate for describing the functions performed by the driver and the BFA system during critical situations (e.g., a stopped vehicle ahead in the travel lane). For critical situations, the BFA system is used to sense, process, and respond to emergency events, but the driver is afforded the decision-making activity to override the system if necessary. Tables 3 and 4 show the allocation configuration of the driver/machine functions for the manual control condition and the automated control conditions for the BFA system concept.

The operator roles assigned for manual control and critical situations were based on the functional descriptions for the BFA system concept. However, the operator role assignment of *Supervisory Controller* may be less than optimal for a CAS concept. Following the structured methodology for function allocation outlined previously, designers of CAS should first consider either the role of *Direct Performer* or *Executive Controller* for describing the functions to be performed by the driver and the AHS during critical situations. The role of *Direct Performer* fails to meet the requirements for handling functions during critical driving conditions based on the fact that a large number of accidents result each year from such events. The role of *Executive Controller* also fails to meet the requirements for handling functions during critical driving situations because automation technology has not reached a level to reliably and satisfactorily handle these types of driving scenarios. In addition, the purpose for evaluating the two background CA concepts was to study the driver role in systems in which the driver is part of the vehicle control loop.

Table 3. Function allocation configuration for the driver function performed during the manual control driving conditions.

Operator Role	Sensors	Processors	Decision Makers	Actuators
Direct Performer	H	H	H	Hm

Note: H = Performed by human
Hm = Performed by human supplemented by machine

Table 4. Function allocation configuration for the driver and BFA system functions performed during the critical driving conditions (e.g., potential accident situations).

Operator Role	Sensors	Processors	Decision Makers	Actuators
Supervisory Controller	Mh	Mh	Mh	Mh

Note: Mh = Performed by machine supplemented by human

The roles of *Manual Controller* or *Supervisory Controller* appear to be more appropriate for performing driving functions during critical situations compared to the two extreme operator roles. The major difference between the *Manual Controller* and *Supervisory Controller* role is whether the driver or the system makes the initial decision to respond to the critical event. Under the *Manual Controller* role, the driver would make the decision to (a) respond manually to the critical event, or (b) activate the system (i.e., the automated lateral/longitudinal controls) to respond to the event. Making the driver responsible for activating the automated controls could create additional problems compared to just having the driver respond manually, as if in the *Direct Performer* role. Under the *Supervisory Controller* role, the system could initiate a response to the critical event and the driver could override any decisions made by the system if the response is determined to be inappropriate. A point that should be considered by designers of CAS regarding the *Supervisory Controller* role is whether the driver should be able to override the automated controls once they are activated. Another possibility is that the system could alert the driver that automatic controls will be initiated shortly, allowing the driver to prevent automatic control to be activated. Otherwise, the system would take over control of the vehicle until the vehicle is returned to "normal" operating parameters. However, the time available to respond to a critical situation becomes an important issue because a response may be required before the driver can be alerted of impending automated control. One question that must be answered before this point can be considered is whether the current state of technology could support a reliable and safe response to all possible critical events without allowing driver override. The point being made here is that trade-offs exist for function allocation between the driver and a CAS such as the BFA system concept. Trade-offs must be addressed as they arise before the concept can be made a reality.

Task Analysis

Analyses were performed for the tasks allocated to both the driver and the system during operation on a highway. Tasks are based in part on the functions performed both by the driver and by the BFA system. Again, we are considering only the tasks performed during a critical driving condition, including the time period just prior to engagement of automated control and the transfer of control back to the driver. A series of tables are presented that show the specific task being performed, the step(s) for that task, the inputs that the driver and/or system receive, the processing performed by the driver and/or system, and the possible driver and/or system responses or outputs for the given step.

Certain assumptions were made regarding BFA system operations in order to perform the task analyses. The authors recognize that assumptions can affect the outcome of the analyses; therefore, all assumptions for BFA system operations are listed here so that the reader can understand the basis for the tasks analyzed and the decisions made:

- Automated lateral and longitudinal control operate independently of one another. Consequently, if the driver overrides the automated lateral control response, the automated longitudinal control response can still be initiated if the sensors detect an object directly in front of the vehicle.
- The driver is alerted whenever automated control is initiated and when automated control is overridden. Feedback to the driver about the status of automated control is required so that the driver knows at all times who, or what, is ultimately controlling the vehicle.
- Automated control capabilities, once overridden, become operative again only after a specific time period (e.g., 2 seconds) has passed where the sensors have not detected an obstacle within range that would have initiated an automated control response. The assumption solves two potential problems for automated control: (1) the driver will not constantly be fighting the vehicle for control when attempting a manual response to a critical situation, and (2) the driver will know that he/she is now responsible for the particular aspect of vehicle control (i.e., either lateral or longitudinal) that was overridden. The system will indicate to the driver through some interface that it is ready to respond automatically to a critical situation, after the time period has elapsed.
- System override has been designed to minimize the probability of inadvertent deactivation (e.g., a startle response to the steering wheel when automated lateral control is initiated,

which disengages the automation). However, the authors believe this to be an important issue for the design of the BFA system concept; therefore, inadvertent deactivation is addressed in the section on driver-related human factors issues.

Because we are only looking at tasks performed by the driver and/or system during a critical condition, including the time period just prior to when automated control would be initiated, there are a limited number of tasks and steps to be analyzed. The three tasks of primary importance for analysis are (1) collision avoidance under manual control, (2) collision avoidance under automated control, and (3) collision avoidance under automated control that is overridden by the driver. Three primary steps were identified for analysis for each task condition. The steps are (1) hazard/obstacle detection, (2) response formulation, decision making, strategy selection, and (3) response execution. Analyses of the three primary steps for each task condition are presented in Tables 5 through 7. Again, results from the analyses will help to identify driver-related human factors issues relevant to the BFA system concept.

Table 5. Task analysis for manual driving and collision avoidance.

Task: Collision avoidance under manual driving control.
Step: Hazard detection.

Input(s)	Processing	Response
The roadway environment presents a hazardous condition in the travel lane.	The driver receives information about the hazard, either from direct observation or is alerted by an in-vehicle warning system.	N/A

Task: Collision avoidance under manual driving control.
Step: Response formulation, strategy selection, and decision making.

Input(s)	Processing	Response
A hazardous condition is present and recognized, and requires a decision to respond.	The driver processes the location of the hazard, determines the degree of threat for collision/impact, and strategizes a response(s) to avoid the hazard or mitigate a collision with the hazard. In addition, the driver processes information regarding potential traffic conflicts in all lanes surrounding the travel lane.	N/A

Task: Collision avoidance under manual driving control.
Step: Response execution.

Input(s)	Processing	Response
N/A	The driver determines an appropriate response to the hazard. Based on the decision, the driver initiates the response.	The driver manually: • Brakes to avoid the hazard. • Steers to avoid the hazard. • Both steers and brakes to avoid the hazard. • Runs over the hazard. The driver continues to manually control the vehicle after the hazard is passed and the vehicle is not damaged.

Table 6. Task analysis for automated driving and collision avoidance.

Task: Collision avoidance under automated driving control.
Step: Hazard detection.

Input(s)	Processing	Response
The roadway environment presents a hazardous condition in the travel lane.	The BFA system sensors detect, classify, and verify the hazard.	N/A
The vehicle begins to drift outside the current lane of travel, creating a hazardous situation, or the vehicle is following too close to a lead vehicle and the headway distance is closing.	The BFA system sensors detect, classify, and verify the hazardous situation.	N/A

Task: Collision avoidance under automated driving control.
Step: Response formulation, strategy selection, and decision making.

Input(s)	Processing	Response
A hazardous condition or situation is present and recognized by system sensors and requires some type of automated response.	The BFA system formulates a decision strategy to respond to the hazardous condition or situation based on inputs from its sensors. The system is attempting to provide a response solution that avoids a collision with the hazard, mitigates a collision with the hazard, and/or returns the vehicle to safe lane position and headway distance parameters. The driver is responsible for processing information regarding potential traffic conflicts in all lanes surrounding the travel lane.	N/A

Table 6. Task analysis for automated driving and collision avoidance (continued).

Task: Collision avoidance under automated driving control.
Step: Response execution.

Input(s)	Processing	Response
N/A	The BFA system selects an appropriate response to the hazardous condition or situation. The system initiates the response.	The system alerts the driver that automatic control is initiated. The system then automatically: • Brakes to avoid the hazard. • Steers to return the vehicle to safe lateral operating parameters. • Brakes to return the vehicle to safe headway distance parameters. • Brakes to avoid hazard or return vehicle to safe headway distance parameters, and steers to return the vehicle to safe lateral operating parameters.

Task: Collision avoidance under automated driving control.
Step: Transfer of control from automated to manual driving.

Input(s)	Processing	Response
1. The BFA system displays an automated control warning to the driver, indicating what directional control or controls are currently enabled.	1. The BFA system determines that the hazardous condition no longer exists and returns the vehicle to manual control.	1. The BFA system alerts the driver that automatic control is about to be terminated.
2. The driver perceives and recognizes the BFA system alert that automated control is about to be terminated.	2. The driver prepares to take over manual control of the vehicle.	2. The driver returns to manually controlling the vehicle after the hazard is passed and the vehicle is no longer under automated control.

Table 7. Task analysis for automated driving that was overridden, and collision avoidance.

Task: Collision avoidance under automated driving control that is overridden by the driver.
Step: Hazard detection.

Input(s)	Processing	Response
The roadway environment presents a hazardous condition in the travel lane.	The BFA system sensors detect, classify, and verify the hazard.	N/A
The vehicle begins to drift outside the current lane of travel, creating a hazardous situation, or the vehicle is following too close to a lead vehicle and the headway distance is closing.	The BFA system sensors detect, classify, and verify the hazardous situation.	N/A

Task: Collision avoidance under automated driving control that is overridden by the driver.
Step: Response formulation, strategy selection, and decision making.

Input(s)	Processing	Response
A hazardous condition or situation is present and recognized by system sensors and requires some type of automated response.	The BFA system formulates a decision strategy to respond to the hazardous condition or situation based on inputs from its sensors. The system is attempting to provide a response solution that avoids a collision with the hazard, mitigates a collision with the hazard, and/or returns the vehicle to safe lane position and headway distance parameters. The driver is responsible for processing information regarding potential traffic conflicts in all lanes surrounding the travel lane.	N/A

Table 7. Task analysis for automated driving that was overridden, and collision avoidance (continued).

Task: Collision avoidance under automated driving control that is overridden by the driver.
Step: Response execution.

Input(s)	Processing	Response
1. N/A	1. The BFA system selects an appropriate response to the hazardous condition or situation. The system initiates the response.	1. The system alerts the driver that automatic control is initiated. The system then automatically: • Brakes to avoid the hazard. • Steers to return the vehicle to safe lateral operating parameters. • Brakes to return the vehicle to safe headway distance parameters. • Brakes to avoid hazard or return vehicle to safe headway distance parameters, and steers to return the vehicle to safe lateral operating parameters.
2. The BFA system displays an automated control warning to the driver, indicating what directional control or controls are currently enabled. The driver perceives and recognizes the hazardous situation that initiated a response by the BFA system and that may require manual control by the driver.	2. The driver processes the location of the hazard, determines the degree of threat for collision/impact, and strategizes response(s) to avoid the hazard or mitigate a collision with the hazard. The driver determines that a more appropriate response to the hazard can be made by overriding the system. Based on the decision, the driver initiates the response.	2. The driver overrides the automated response(s) to return the vehicle to manual control. The driver continues manual control of the vehicle after the hazard is passed.

Fault Tree Analysis

The fault tree analysis performed for the BFA system concept is depicted in Appendix A. The top event selected for analysis was an accident that occurred while under BFA system control. This event was chosen to help identify driver-related issues that might lead to an accident while driving with the CAS so that these issues can be addressed as the concept continues to be developed. Tree development was stopped when failures specific to the BFA system were found to contribute to the next "higher" event. The analysis was concerned primarily with events related to the driver (i.e., events that would provide insight into the driver's role while operating under a BFA system), not failure events attributable to system components. In addition, tree development was stopped when failures specific to errors by the driver were found to contribute to the next "higher" event. Failure events attributable to human error are difficult to analyze and may require a more thorough understanding of the situation under which the failure occurred and the operator's state of mind at that point in time. Therefore, analysis was stopped when either driver error or BFA system failure events contributed to the next "higher" event due to the complexity of the analysis and the fact that results from the analysis would fail to yield any additional significant contribution to identifying the driver-related issues under the BFA system.

The objective for performing the fault tree analysis was to supplement the function and task analyses for identifying driver-related human factors issues pertaining to the envisioned BFA system concept. The fault tree analysis provided an additional perspective for looking at the BFA concept and identified driver-related human factors issues that could result in an accident while operating under the BFA system concept. It is important to note that developing a complete fault tree for the BFA system concept would be extremely time consuming, particularly if the analyst is interested in exercising a number of possible top events. The fault tree analysis performed for the BFA system helped identify and confirm several driver-related human factors issues that are discussed later in the paper. The issues brought forth by the analysis include the following, and are addressed in greater detail in a later section of the paper:

- driver reliance on the system to return vehicle to normal operating parameters (e.g., return vehicle to center of travel lane) or to prevent the accident from occurring;
- the need to alert the driver to system failure(s) so that a manual response can be initiated;
- the possibility for a startle response, or a natural response (e.g., harder braking), by the driver to the activation of automated control, which in turn deactivates the automation and places the driver back in control of the vehicle when he/she may believe the vehicle is still under automated control;
- driver mistrust in the system when responding to an emergency event, resulting in the driver overriding automated controls at inappropriate times or when the system was controlling the vehicle in an optimal manner for crash avoidance/mitigation.

CONCEPT B: BACKGROUND INTEGRATED LONGITUDINAL AND LATERAL CONTROL SYSTEM

The results from the function, task, and fault-tree analyses can be used to provide a detailed definition of the driver role for the Background Integrated Longitudinal and Lateral Control system. Again, the approaches to the function and task analyses are modeled after the efforts of DeMers (1994) and Levitan, Plocher, and DeMers (1996), who performed similar analyses for other AHS operational concepts. Fault tree analysis was added to provide further insight into the driver's role when operating under the BILLC system concept. Results from the various analyses are used to identify driver-related human factors issues and are presented separately. Following the description of Concept Evaluation results is a section on driver-related human factors issues. Comments regarding CAS concept feasibility are included in the Conclusions section.

Function Analysis/Allocation

The following paragraphs present a list of driver and system functions specific to the BILLC system. Driver and system functions are derived from the operational scenario described above. Since the driver controls the vehicle under most conditions, the functions described are during critical conditions only. Critical conditions are defined as events during travel that would enable the automated control of the vehicle, including the time period just prior to automated control. Driver functions under manual control (i.e., the time period just prior to the initiation of automated control) are listed first, followed by driver and system functions under automated control. Table 8 summarizes the functions performed by the driver and by the BILLC system while traveling on a highway.

Driver Functions under Manual Control:

- The driver controls the lateral position of the vehicle in the lane while under travel.
- The driver controls the longitudinal position of the vehicle (i.e., acceleration and deceleration) while under travel.
- The driver observes the traffic conditions and traffic flow (e.g., other vehicles slowing, accidents, hazardous behavior of other drivers) while under travel. The driver is looking for hazardous situations that would require lateral and longitudinal control of the vehicle to avoid an accident.
- The driver observes the roadway and environmental conditions (e.g., road surface conditions, weather, roadside hazards) while under travel. Again, the driver is looking for hazardous situations that would require lateral and longitudinal control inputs to the vehicle to avoid an accident.
- The driver decides how to respond/react to traffic conditions and traffic flow (e.g., slow down, increase headway distance, pass slower moving vehicles) that present a critical condition while under travel.
- The driver decides how to respond/react to roadway and environmental conditions (e.g., slow down, increase headway distance, maneuver around hazard, pull off road) that present a critical condition while under travel.

Driver and System Functions under Automated Control:

The driver performs all of the functions listed under the Manual Control functions described above. In addition, the driver and the BILLC system perform the following functions while traveling on a highway:

- The driver receives and interprets information on the status and operability of automation during vehicle startup and while on the highway.
- The BILLC system presents information regarding the status and/or operability of the automation capabilities.
- The BILLC system monitors the vehicle's lateral position with respect to the travel lane reference (e.g., lane edge, lane marker) while on the highway.
- The BILLC system monitors the vehicle's headway-distance/time-to-collision to objects in front of the vehicle's path of travel (e.g., other vehicles, road debris) while on the highway.

This function includes detection, classification, verification, and selection of a decision strategy for an automated longitudinal control response.

- The BILLC system monitors the road surface and environmental conditions and modifies the lateral/longitudinal control limits accordingly. This function includes detection, classification, verification, and selection of a decision strategy for modifying lateral/longitudinal control limits.

Table 8. Summary of driver and Background Integrated Longitudinal and Lateral Control system functions.

Driver Functions	Background Integrated Longitudinal and Lateral Control System Functions
1. control lateral position of vehicle while under travel	1. monitor vehicle lateral position with respect to travel lane reference (e.g., lane edge, lane marker) while traveling on non-signalized, access-controlled highways
2. control longitudinal position of vehicle while under travel	2. monitor vehicle headway-distance/time-to-collision to objects in front of vehicle's path of travel (e.g., other vehicles, road debris) while traveling on non-signalized, access-controlled highways (this includes detection, classification, verification, and selection of decision strategy for automated control response)
3. observe traffic conditions and traffic flow (e.g., other vehicles slowing, accidents, hazardous behavior of other drivers) while under travel	3. monitor road surface and environmental conditions and modify lateral/longitudinal control limits accordingly (this includes detection, classification, verification, and selection of decision strategy for modifying control limits)
4. observe roadway and environmental conditions (e.g., road surface conditions, weather, roadside hazards) while under travel	4. engage lateral control actuator(s) when pre-determined lateral control limit has been exceeded (i.e., steering control to center vehicle within travel lane, or avoid/mitigate collision with a detected object) while traveling on non-signalized, access-controlled highways
5. respond/react accordingly to traffic conditions and traffic flow (e.g., slow down, increase headway distance, pass slower moving vehicles) while under travel	5. engage longitudinal control actuator(s) when pre-determined longitudinal control limit has been exceeded (i.e., powertrain followed by braking) while traveling on non-signalized, access-controlled highways
6. respond/react accordingly to roadway and environmental conditions (e.g., slow down, increase headway distance, maneuver around hazard, pull off road) while under travel	6. present information on status and/or operability of automation
7. receive and interpret information on status/ operability of automation during vehicle startup and while under travel	7. warn/alert driver when automated control is engaged
8. decide whether to override automated control during critical/emergency situations when automated control is activated	8. disengage both lateral and longitudinal controls when either is overridden by driver inputs
9. activate mayday function after vehicle is brought to a stop by automated control	

- The BILLC system engages lateral control actuator(s) when a pre-determined lateral control limit has been exceeded (i.e., automated steering to avoid or mitigate collision with detected objects, or return vehicle to travel lane center). Steering control can include a lane centering maneuver or a lane-change/off-center-lane maneuver to avoid a collision with detected object(s). This function is performed only while traveling on the highway.
- The BILLC system engages longitudinal control actuator(s) when a pre-determined longitudinal control limit has been exceeded (i.e., powertrain followed by braking). Combined with the lateral control function, the vehicle can be brought to a complete stop in the breakdown lane, or on the side of the road, after automated control is engaged. This function is performed only while traveling on the highway.
- The BILLC system warns/alerts the driver when automated control is engaged. It is assumed that this function is performed regardless of whether there is enough time to alert the driver prior to engagement of the automation. Since lateral and longitudinal control are integrated under the BILLC system, only one type of warning or alert is necessary to indicate to the driver that automation is active or inactive.
- The driver decides whether to override automated control during the critical/emergency situation when the automated control(s) are activated.
- The BILLC system disengages both lateral and longitudinal control when an automated control is overridden by the driver's inputs. Driver inputs include either a steering input or brake/accelerator pedal input, and would result in the deactivation of all automated controls to the vehicle.
- If the BILLC system initiates the automated response to bring the vehicle to a complete stop at the side of the road, the driver is able to activate a mayday function if the situation warrants emergency response.

Operator role theory was used to determine the function allocation requirements for the BILLC system. Again, the role of *Direct Performer* is appropriate for describing the functions performed by the driver under manual control conditions. Under normal operating conditions, the driver is responsible for performing all functions related to the safe operation of the vehicle. The role of *Supervisory Controller* is appropriate for describing the functions performed by the driver and the BILLC system during critical situations (e.g., a stopped vehicle ahead in the travel lane). For critical situations, the BILLC system is used to sense, process, and respond to emergency events (including an evasive lane change response), but the driver is afforded the decision-making activity to override the system if necessary. Tables 9 and 10 show the allocation configuration of the driver/system functions for the manual control condition and the automated control conditions for the BILLC system concept.

The operator roles assigned for manual control and critical situations were based on the functional descriptions for the BILLC system concept. However, the operator role assignment of *Supervisory Controller* may be less than optimal for a CAS concept. Following the structured methodology for function allocation outlined previously, designers of CAS should first consider either the role of *Direct Performer* or *Executive Controller* for describing the functions to be performed by the driver and the CAS during critical situations. The role of *Direct Performer* fails to meet the requirements for handling functions during critical driving conditions based on the fact that a large number of accidents result each year from such events. The role of *Executive Controller* also fails to meet the requirements for handling functions during critical driving situations because automation technology has not reached a level to reliably and satisfactorily handle these types of driving scenarios. In addition, the purpose for evaluating the two background CA concepts was to study the driver role in systems in which the driver is part of the vehicle control loop.

The roles of *Manual Controller* or *Supervisory Controller* appear to be more appropriate for performing driving functions during critical situations compared to the two extreme operator roles. The major difference between the *Manual Controller* and *Supervisory Controller* role is whether the driver or the system makes the initial decision to respond to the critical event. Under the *Manual Controller* role, the driver would make the decision to (a) respond manually to the critical event, or (b) activate the system (i.e., the automated lateral/longitudinal controls) to respond to the event. Making the driver responsible for activating automated controls could create additional problems compared to just having the driver respond manually, as if in the *Direct Performer* role. Under the *Supervisory Controller* role, the system could initiate a response to the critical event and the driver could override any decisions made by the system if the response is determined to be inappropriate.

Table 9. Function allocation configuration for the driver function performed during the manual control driving conditions.

Operator Role	Sensors	Processors	Decision Makers	Actuators
Direct Performer	H	H	H	Hm

Note: H = Performed by human
Hm = Performed by human supplemented by machine

Table 10. Function allocation configuration for the driver and BILLC system functions performed during the critical driving conditions (e.g., potential accident situations).

Operator Role	Sensors	Processors	Decision Makers	Actuators
Supervisory Controller	Mh	Mh	Mh	Mh

Note: Mh = Performed by machine supplemented by human

A point that should be considered by designers of CAS regarding the *Supervisory Controller* role is whether the driver should be able to override the automated controls once they are activated. Another possibility is that the system could alert the driver that automatic controls will be initiated shortly, allowing the driver to prevent automatic control to be activated. Otherwise, the system would take over control of the vehicle until the vehicle is returned to "normal" operating parameters. However, the time available to respond to a critical situation becomes an important issue because a response may be required before the driver can be alerted of impending automated control. One question that must be answered before this point can be considered is whether the current state of technology could support a reliable and safe response to all possible critical events without allowing driver override. In addition, designers must consider whether bundling automated controls, and having both lateral and longitudinal controls become deactivated by either a steering or brake/accelerator input, is optimal from the driver's perspective in response to critical situations. The point being made is that trade-offs exist for function allocation between the driver and a CAS such as the BILLC system concept. These trade-offs must be addressed before the concept can be made a viable reality.

Task Analysis

Analyses were performed for the tasks allocated to both the driver and the system during operation on a highway. Tasks are based in part on the functions performed both by the driver and by the BILLC system. Only tasks performed during a critical driving condition, including the time period just prior to engagement of automated control(s) and the transfer of control back to the driver, are considered in the analyses. A series of tables are presented that show the specific task being performed, the step(s) for that particular task, the inputs that the driver and/or system receive, the processing performed by the driver and/or system, and the possible driver and/or system responses or outputs for the given step.

Certain assumptions were made regarding BILLC system operations in order to perform the task analyses. The authors recognize that assumptions can affect the outcome of the analyses; therefore, all assumptions for BILLC system operations are listed here so that the reader can understand the basis for the tasks analyzed and the decisions made:

- Automated lateral and longitudinal control operate as an integrated (i.e., bundled) unit to provide full emergency collision avoidance. If the driver overrides the automated lateral control response, the automated longitudinal control response will be deactivated. Likewise, if the driver overrides the automated longitudinal control response, the automated lateral control response will be deactivated.
- The driver is alerted whenever automated control is initiated and when automated control is overridden. Feedback to the driver about the status of automated control is required so that the driver knows at all times who, or what, is ultimately controlling the vehicle.
- Automated control capabilities, once overridden, become operative again only after a specific time period (e.g., 2 seconds) has passed where the sensors have not detected an obstacle within range that would have initiated an automated control response. The assumption solves two potential problems for automated control: (1) the driver will not constantly be fighting the vehicle for control when attempting a manual response to a critical situation, and (2) the driver will know that he/she is now responsible for vehicle control (i.e., both lateral or longitudinal control), regardless of which control dimension was overridden. The system will indicate to the driver by some interface that it is ready to respond automatically to a critical situation, after the time period has elapsed.
- System override has been designed to minimize the probability of inadvertent deactivation (e.g., a startle response to the steering wheel when automated lateral control is initiated, which disengages the automation). However, the authors believe this to be an important

issue for the design of the BFA system concept; therefore, inadvertent deactivation is addressed in the section on driver-related human factors issues.

As stated in the task analysis for the BFA system, we are only looking at tasks performed by the driver and/or system during a critical condition, including the time period just prior to where automated control would be initiated. Therefore, there are a limited number of tasks and steps to be analyzed. The three tasks of primary importance for analysis are (1) collision avoidance under manual control, (2) collision avoidance under automated control, and (3) collision avoidance under automated control that is overridden by the driver. Three primary steps were identified for analysis for each task condition. These steps are (1) hazard/obstacle detection, (2) response formulation, decision making, and strategy selection, and (3) response execution. Analyses of the three primary steps for each task condition are presented in Tables 11 through 13. Again, results from the analyses help to identify driver-related human factors issues relevant to the BILLC system concept.

Table 11. Task analysis for manual driving and collision avoidance.

Task: Collision avoidance under manual driving control.
Step: Hazard detection.

Input(s)	Processing	Response
The roadway environment presents a hazardous condition in the travel lane.	The driver receives information about the hazard, either from direct observation or is alerted by an in-vehicle warning system.	N/A

Task: Collision avoidance under manual driving control.
Step: Response formulation, strategy selection, and decision making.

Input(s)	Processing	Response
A hazardous condition is present and recognized that requires a decision to respond.	The driver processes the location of the hazard, determines the degree of threat for collision/impact, and strategizes response(s) to avoid the hazard or mitigate a collision with the hazard. In addition, the driver processes information regarding potential traffic conflicts in all lanes surrounding the travel lane.	N/A

Task: Collision avoidance under manual driving control.
Step: Response execution.

Input(s)	Processing	Response
N/A	The driver determines an appropriate response to the hazard. Based on the decision, the driver initiates the response.	The driver manually: • Brakes to avoid the hazard. • Steers to avoid the hazard. • Both steers and brakes to avoid the hazard. • Runs over the hazard. The driver continues to manually control the vehicle after the hazard is passed and the vehicle is not damaged.

Table 12. Task analysis for automated driving and collision avoidance.

Task: Collision avoidance under automated driving control.
Step: Hazard detection.

Input(s)	Processing	Response
The roadway environment presents a hazardous condition in the travel lane.	The BILLC system sensors detect, classify, and verify the hazard.	N/A
The vehicle begins to drift outside the current lane of travel, creating a hazardous situation, or the vehicle is following too close to a lead vehicle and the headway distance is closing.	The BILLC system sensors detect, classify, and verify the hazardous situation.	N/A

Task: Collision avoidance under automated driving control.
Step: Response formulation, strategy selection, and decision making.

Input(s)	Processing	Response
A hazardous condition or situation is present and recognized by system sensors and requires some type of automated response.	The BILLC system formulates a decision strategy to respond to the hazardous condition or situation based on inputs from its sensors; this would include sensor information regarding the presence of hazards in the lanes to either side of the vehicle if a lane-change maneuver is one of the collision avoidance options. The system is attempting to provide a response solution that avoids a collision with the hazard, mitigates a collision with the hazard, or returns the vehicle to safe lane position and headway distance parameters. The driver is also responsible for processing information regarding potential traffic conflicts in all lanes surrounding the travel lane.	N/A

Table 12. Task analysis for automated driving and collision avoidance (continued).

Task: Collision avoidance under automated driving control.
Step: Response execution.

Input(s)	Processing	Response
N/A	The BILLC system selects an appropriate response to the hazardous condition or situation. The system initiates the response.	The system alerts the driver that automated control is initiated. The system then automatically: • Brakes to avoid the hazard. • Steers to avoid the hazard. • Both brakes and steers to avoid the hazard, possibly bringing the vehicle to a complete stop at the side of the road. • Steers to return the vehicle to safe lateral operating parameters. • Brakes to return the vehicle to safe headway distance parameters. • Both brakes and steers to return the vehicle to safe lateral and headway-distance parameters.

Task: Collision avoidance under automated driving control.
Step: Transfer of control from automated to manual driving.

Input(s)	Processing	Response
1. The BILLC system displays a single automated control warning to the driver, indicating that some type of automated directional control or controls are currently enabled.	1. The BILLC system determines that the hazardous condition no longer exists and returns the vehicle to manual control.	1. The BILLC system alerts the driver that automated control is about to be terminated.
2. The driver perceives and recognizes the BILLC system alert that all automated control is about to be terminated.	2. The driver prepares to take over manual control of the vehicle.	2. The driver returns to manually controlling the vehicle after the hazard is passed and the vehicle is no longer under automated control.

Table 13. Task analysis for automated driving that was overridden, and collision avoidance.

Task: Collision avoidance under automated driving control that is overridden by the driver.
Step: Hazard detection.

Input(s)	Processing	Response
The roadway environment presents a hazardous condition in the travel lane.	The BILLC system sensors detect, classify, and verify the hazard.	N/A
The vehicle begins to drift outside the current lane of travel, creating a hazardous situation, or the vehicle is following too close to a lead vehicle and the headway distance is closing.	The BILLC system sensors detect, classify, and verify the hazardous situation.	N/A

Task: Collision avoidance under automated driving control that is overridden by the driver.
Step: Response formulation, strategy selection, and decision making.

Input(s)	Processing	Response
A hazardous condition or situation is present and recognized by system sensors and requires some type of automated response.	The BILLC system formulates a decision strategy to respond to the hazardous condition or situation based on inputs from its sensors; this would include sensor information regarding the presence of hazards in the lanes to either side of the vehicle if a lane-change maneuver is one of the collision avoidance options. The system is attempting to provide a response solution that avoids a collision with the hazard, mitigates a collision with the hazard, or returns the vehicle to safe lane position and headway distance parameters. The driver is also responsible for processing information regarding potential traffic conflicts in all lanes surrounding the travel lane.	N/A

Table 13. Task analysis for automated driving that was overridden, and collision avoidance (continued).

Task: Collision avoidance under automated driving control that is overridden by the driver.
Step: Response execution.

Input(s)	Processing	Response
1. N/A	1. The BILLC system selects an appropriate response to the hazardous condition or situation. The system initiates the response.	1. The system alerts the driver that automatic control is initiated. The system then automatically: • Brakes to avoid the hazard. • Steers to avoid the hazard. • Both brakes and steers to avoid the hazard, possibly bringing the vehicle to a complete stop at the side of the road. • Steers to return the vehicle to safe lateral operating parameters. • Brakes to return the vehicle to safe headway distance parameters. • Both brakes and steers to return the vehicle to safe lateral and headway-distance parameters.
2. The BILLC system displays a single automated control warning to the driver, indicating that some type of automated directional control or controls are currently enabled. The driver perceives and recognizes the hazardous situation that initiated a response by the BILLC system and that may require manual control by the driver.	2. The driver processes the location of the hazard, determines the degree of threat for collision/ impact, and strategizes response(s) to avoid the hazard or mitigate a collision with the hazard. The driver determines that a more appropriate response to the hazard can be made by overriding the system. Based on this decision, the driver initiates the response.	2. The driver overrides all automated responses to return the vehicle to complete manual control. The driver continues manual control of the vehicle after the hazard is passed.

Fault Tree Analysis

The fault tree analysis performed for the BILLC system concept is depicted in Appendix B. Again, the top event selected for analysis was an accident while under BILLC system control. This event was chosen to help identify driver-related issues that might lead to an accident while driving with this type of AHS so that these issues can be addressed as the concept continues to be developed. As was done for the BFA system concept, tree development was stopped when failures specific to the BILLC system were found to contribute to the next "higher" event. In addition, tree development was stopped when failures specific to errors by the driver were found to contribute to the next "higher" event. Driver error and BILLC system failure events were not explored further due to the complexity of analysis.

The objective for performing the fault tree analysis was to supplement the function and task analyses for identifying driver-related human factors issues pertaining to the envisioned BILLC system concept. Developing a complete fault tree for the BILLC system concept would be extremely time consuming, particularly if the analyst is interested in exercising a number of possible top events. Therefore, the fault tree analysis was conducted at a "high" level for the BILLC system to assist in identifying and confirming a number of driver-related human factors issues that are discussed later in the next section. The issues brought forth by the analysis include the following:

- driver reliance on the system to return vehicle to normal operating parameters (e.g., return vehicle to center of travel lane) or to prevent the accident from occurring;
- the need to alert the driver to system failure so that a manual response can be initiated;
- the possibility for a startle response, or a natural response (e.g., harder braking), by the driver to the activation of "bundled" automated controls, which in turn would deactivate all automation and place the driver back in control of the vehicle when he/she may believe the vehicle is still under automated control;
- driver mistrust in the system when responding to an emergency event, resulting in the driver overriding automated controls at inappropriate times or when the system was controlling the vehicle in an optimal manner for crash avoidance/mitigation; and
- driver failure to comprehend the emergency situation so that an appropriate response (i.e., an override of the system, or allowing the system to remain in control) is performed.

It is important to note that fault tree analysis failed to identify any significant differences between the BFA and BILLC concepts. The two concepts are very similar in design, with the major differences being independent versus bundle control automation, and the fact that the BILLC concept provides the ability for a lateral collision avoidance response. However, designers must be cognizant of the fact that any startle response that deactivates automated control will deactivate all automated response capabilities for the BILLC concept. For the BFA concept, an automated control response will be deactivated only for startle responses in which the control dimension is affected (e.g., if the driver applies the brake as a startle response to an automated lateral control action, the automated control would not be deactivated; however, if the startle response was a steering input, the automated lateral control would be deactivated).

Table 13. Task analysis for automated driving that was overridden, and collision avoidance (continued).

Task: Collision avoidance under automated driving control that is overridden by the driver.
Step: Response execution.

Input(s)	Processing	Response
1. N/A	1. The BILLC system selects an appropriate response to the hazardous condition or situation. The system initiates the response.	1. The system alerts the driver that automatic control is initiated. The system then automatically: • Brakes to avoid the hazard. • Steers to avoid the hazard. • Both brakes and steers to avoid the hazard, possibly bringing the vehicle to a complete stop at the side of the road. • Steers to return the vehicle to safe lateral operating parameters. • Brakes to return the vehicle to safe headway distance parameters. • Both brakes and steers to return the vehicle to safe lateral and headway-distance parameters.
2. The BILLC system displays a single automated control warning to the driver, indicating that some type of automated directional control or controls are currently enabled. The driver perceives and recognizes the hazardous situation that initiated a response by the BILLC system and that may require manual control by the driver.	2. The driver processes the location of the hazard, determines the degree of threat for collision/ impact, and strategizes response(s) to avoid the hazard or mitigate a collision with the hazard. The driver determines that a more appropriate response to the hazard can be made by overriding the system. Based on this decision, the driver initiates the response.	2. The driver overrides all automated responses to return the vehicle to complete manual control. The driver continues manual control of the vehicle after the hazard is passed.

Fault Tree Analysis

The fault tree analysis performed for the BILLC system concept is depicted in Appendix B. Again, the top event selected for analysis was an accident while under BILLC system control. This event was chosen to help identify driver-related issues that might lead to an accident while driving with this type of AHS so that these issues can be addressed as the concept continues to be developed. As was done for the BFA system concept, tree development was stopped when failures specific to the BILLC system were found to contribute to the next "higher" event. In addition, tree development was stopped when failures specific to errors by the driver were found to contribute to the next "higher" event. Driver error and BILLC system failure events were not explored further due to the complexity of analysis.

The objective for performing the fault tree analysis was to supplement the function and task analyses for identifying driver-related human factors issues pertaining to the envisioned BILLC system concept. Developing a complete fault tree for the BILLC system concept would be extremely time consuming, particularly if the analyst is interested in exercising a number of possible top events. Therefore, the fault tree analysis was conducted at a "high" level for the BILLC system to assist in identifying and confirming a number of driver-related human factors issues that are discussed later in the next section. The issues brought forth by the analysis include the following:

- driver reliance on the system to return vehicle to normal operating parameters (e.g., return vehicle to center of travel lane) or to prevent the accident from occurring;
- the need to alert the driver to system failure so that a manual response can be initiated;
- the possibility for a startle response, or a natural response (e.g., harder braking), by the driver to the activation of "bundled" automated controls, which in turn would deactivate all automation and place the driver back in control of the vehicle when he/she may believe the vehicle is still under automated control;
- driver mistrust in the system when responding to an emergency event, resulting in the driver overriding automated controls at inappropriate times or when the system was controlling the vehicle in an optimal manner for crash avoidance/mitigation; and
- driver failure to comprehend the emergency situation so that an appropriate response (i.e., an override of the system, or allowing the system to remain in control) is performed.

It is important to note that fault tree analysis failed to identify any significant differences between the BFA and BILLC concepts. The two concepts are very similar in design, with the major differences being independent versus bundle control automation, and the fact that the BILLC concept provides the ability for a lateral collision avoidance response. However, designers must be cognizant of the fact that any startle response that deactivates automated control will deactivate all automated response capabilities for the BILLC concept. For the BFA concept, an automated control response will be deactivated only for startle responses in which the control dimension is affected (e.g., if the driver applies the brake as a startle response to an automated lateral control action, the automated control would not be deactivated; however, if the startle response was a steering input, the automated lateral control would be deactivated).

DRIVER-RELATED HUMAN FACTORS ISSUES

Results from the various analyses provide insight into potential driver-related human factors issues that need to be addressed before either the Background Free Agent or the Background Integrated Lateral and Longitudinal Control CA concepts become operational. The following is a list and brief description of the major human factors issues identified from the various human factors analyses. The authors acknowledge that the list is not exhaustive. More driver-related issues are sure to arise as each concept becomes more defined and the interface between driver and automation is developed in greater detail.

ISSUE 1. DRIVER RELIANCE ON AUTOMATION

An important issue that was made evident by the analyses is the potential for drivers to become reliant on the automation. After gaining experience with the CAS, drivers may begin to expect the automation to maintain the safe operation of the vehicle (i.e., maintain the vehicle within safe operating parameters) and/or recover the vehicle from an emergency or critical driving situation. Over-reliance on the automation can present several problems in the driving environment.

First, if the driver becomes reliant on automated controls, he/she may increase his/her probability of an accident when traveling on roads that do not support the automation (e.g., non-marked or signalized roads with pedestrian traffic). The driver may expect the automation to take control of the vehicle and return it to safe operating parameters, but now the automation and its sensors are not "active" for the roadway being traveled on, or the system experiences a catastrophic failure of which the driver is unaware. By the time the driver realizes that the automation is not responding, it could be too late to avoid an accident.

A second problem with over-reliance on automation is that modifications to driver behavior may occur. This may include a carry-over effect described by Neale et al. (1996). Driving behavior (speed maintenance, headway distance control, lane position control, etc.) may change after experience with a CAS, resulting in unsafe behaviors that exceed the capabilities of the automated controls and can increase the number of accidents. The introduction of anti-lock braking systems, and the types of accidents that have arisen from such a technological advance, serve as an example of what might be expected as automated vehicle control systems for emergency situations are made available.

Finally, automated response to critical driving situations could modify drivers' reactions to such events. Drivers may learn appropriate, or inappropriate, responses to specific driving scenarios based on the type(s) of response experienced from the automated systems (i.e., provided that the driver did not override the system). It is too early to tell whether this might be a benefit or a detriment to the driver. However, the outcome for a positive learning experience will be highly dependent on the reliability and the appropriateness of response by the automated system to critical events while driving.

ISSUE 2. STARTLE RESPONSE BY DRIVER

For both CAS concepts, there exists the potential for either a startle response or a natural response (i.e., braking or steering) to an emergency event by the driver which could deactivate automated control(s) at inopportune times during critical driving situations. The proprioceptive cues provided by the system in response to an event may be unexpected by the driver and the driver may accidentally override the automation. If this occurs, the driver would need to quickly assess the situation, determine why an automated response was initiated, and react manually to the event.

The driver may also be startled by the emergency event. Again, a driver's startle response to such an event could result in inadvertent deactivation of an automated response. Deactivation may occur at a time when the driver is unable to respond manually to avoid the accident.

In addition, the driver may not realize that he/she has deactivated automated control(s) and may expect the system to respond. Adequate warnings must be provided to the driver about the status of automated controls so that the driver knows whether to expect an automated response or to begin a manual response to the event. The warnings must also convey information about what controls are currently automated (e.g., lateral control, longitudinal control, or both). Issue 4 addresses the question of whether lateral and longitudinal controls should operate independently or be "bundled," which can impact the type(s) of warning information that should be presented to the driver.

ISSUE 3. TRANSFER OF CONTROL

The issue of control transfer includes both the transition from manual control to automated control (i.e., either lateral control, longitudinal control, or combined lateral and longitudinal control), and the transition from automated control back to manual control by the driver. Transfer of control from the driver to the system should occur in such a manner that (1) the driver understands what is happening and why automated control is being activated, and (2) the driver does not begin to fight the controls, thinking something else may be wrong with vehicle handling, or become startled by control activation. If the driver does not understand why automated control is initiated, he/she may purposefully or inadvertently deactivate the automation. This deactivation could occur at an inappropriate time during response to a critical event.

The transfer from automated control back to the driver should be intuitive to perform by the driver, and it should be obvious to the driver that he/she is now back in control of the vehicle. Appropriate warning alarms or cues should be provided by the system to inform the driver that automated control is about to be disengaged. In addition, designers of these CAS concepts must consider the possibility that the driver may not return to manually controlling the vehicle, even after being alerted that automated control is about to be deactivated (e.g., inattention or misunderstanding by the driver that manual control is about to resume). Therefore, the system must be ready to immediately respond with automated controls should the vehicle exceed any control limit parameters. It is important to note that this is different from the assumption made earlier that when automated control(s) are overridden, they become operative again only after a specific time period (e.g., 2 seconds) has passed where the sensors have not detected an obstacle within range that would have initiated an automated control response.

ISSUE 4. INDEPENDENT VERSUS BUNDLED DIRECTIONAL CONTROLS

The BFA system has lateral and longitudinal controls that operate independently of one another, while the BILLC system has integrated lateral and longitudinal controls (i.e., "bundled" controls). The primary difference between the two systems from the driver's perspective is that if an automated control response is overridden, all automated controls become deactivated for the BILLC system, while only the directional control response overridden by the driver is deactivated for the BFA system (i.e., the other directional control response remains active, or can become activated if control limit parameters are exceeded). A steering input or brake input would deactivate a BILLC automated response, while a steering input would only deactivate a BFA automated lateral response, and a brake/accelerator input would only deactivate a BFA automated longitudinal response.

Depending on the system, different warnings should be provided to the driver so that he/she understands what directional controls are currently automated, or that the "bundled" response is activated. There is the potential that distinct warning signals for the different automated control dimensions could confuse the driver about what directional control is under automation. In addition, the mere presence of different control states (e.g., lateral only, longitudinal only, or both lateral and longitudinal control), which would underlie the need for different warning signals, allows for possible confusion by the driver. Therefore, the argument might be made that only a single warning indicating that automation is active should be presented to the driver. The issue of warnings may require empirical research to arrive at an optimal solution.

Another area warranting empirical study is how drivers perform with both independent and bundled directional controls. The purpose for having automated controls is to respond to critical/emergency driving situations. A potential problem with the "bundled" controls concept (e.g., the BILLC) is that once a lateral or longitudinal automated response is overridden, all automated response becomes deactivated. Scenarios may occur where the driver inputs a steering maneuver, overriding the "bundled" system, but fails to maintain an appropriate amount of braking to avoid or mitigate an accident. Under an independent directional control system (e.g., the BFA concept), the driver can override one control dimension in response to an emergency event while still having automated support in the other control dimension if the control limit parameters are exceeded. An independent control system still maintains a simple override response by the driver (i.e., the driver can deactivate the automation with either steering or brake/accelerator inputs) while providing the driver with automated response support in critical situations, even if one directional control dimension has been overridden and is unavailable for a specific time period. The point being made is that it may be more beneficial to the driver to provide some level of automated control during an emergency event, even if partially overridden, than just providing the driver with an "all or none" type of control response.

ISSUE 5. NUISANCE ALARMS AND FALSE ALARMS FOR AUTOMATED CONTROL

The developers of both the BFA and BILLC system concepts must be cognizant of the potential for nuisance alarms and false alarms of automated control by the system. A false alarm is described as the activation of an automated response when no automated response is required. For example, the system sensors indicate the detection of an object in front of the vehicle and activate an automatic control response and appropriate warning when no object physically exists in front of the vehicle. A nuisance alarm is described as the activation of an automated response to an actual event or situation, but the response was earlier than the driver expected and/or desired. In this example, system parameters may be set too liberally for the driver's preference, causing the system to respond to driving events before the driver expects or believes a response is necessary.

Nuisance and false alarms can quickly become an annoyance to the driver. Therefore, CAS developers must carefully consider the trigger criteria for the activation of automated controls and select sensors and hardware that minimize the number of false detections and activations. False alarms and/or nuisance alarms could result in a startle response by the driver along with the consequences that could result from such a response, and could also lead to a decrease in driver acceptance and satisfaction with such a device.

ISSUE 6. DRIVER RESPONSE TIME TO EMERGENCY CONDITIONS

An issue that may influence the success of automated response(s) to emergency events is driver response time. Response time is comprised of three components: (1) perception, (2) reaction, and (3) movement. Response time encompasses the time required for an individual to perceive an event, make a decision for an appropriate response, and carry out that response. Driver response to an emergency condition could include a steering response, a braking/ accelerating response, or a combined steering and braking/accelerating response. In addition, response time increases with age.

Automating the response to an emergency event while driving, which is currently performed under complete human control, may introduce negative consequences as a result of the changes that will occur within the driver-vehicle interface. Changes can include relegating the driver to monitoring status once automated control is activated, increasing overall system complexity, and potentially reducing the diagnostic capability of the driver. Each of these changes has the potential to reduce the motivation and/or capability of the driver to perform required driving tasks or maintain alertness. The effective driver response times with either CAS concept may be substantially greater than driver response times under manual-only driving conditions. A possible solution to this problem might be that drivers would be unable to override an automated response once that response is initiated. The lack of driver override capability would raise a number of other issues, such as automated response capability and appropriateness given state-of-the-art technology, driver preference/acceptance of such responses, and control transfer between driver and system and back to driver. An alternative is to still provide override capability, but the response would be some combination of what the driver is attempting and what the system determines is safe (e.g., a dampened control input by the driver so as not to exceed a specified lateral/longitudinal acceleration force). All of these issues would require experimental testing to determine the best approach to interfacing the driver with the system during critical driving events.

ISSUE 7. UNDERLOAD VERSUS OVERLOAD OF DRIVER RESOURCES

The issue of driver workload, both mental and physical, appears to be handled in an appropriate fashion by the two CAS concepts analyzed. Both systems require that the driver remain in the loop for vehicle control and that automated control be initiated only when specific lateral and longitudinal control limits are exceeded, based on CAS sensor inputs.

However, it is important to recognize that in-vehicle secondary task demands and other distracters can impact the level of workload a driver is experiencing. If driver workload exceeds some level, due to performance of an in-vehicle task or some other distraction, and an automated response is initiated, the driver may not be in the best situation to be allowed to override the automated response. The driver may be so removed from the mental model of vehicle performance and the driving environment when performing a secondary task that he or she may not be capable of responding manually in a quick and appropriate manner to an event that triggered the automated controls. This would suggest that driver override of automated controls should not be possible.

A number of arguments can be made for and against allowing driver override of automated controls. The previous example was presented to raise the awareness of CAS developers to the possibility of systems that cannot be overridden and the reason for such a decision. However, before such a possibility should even be entertained, the technology must be capable of reliably responding to a myriad of emergency situations in a manner that outperforms a manual response by the driver.

CONCLUSIONS

The current visions for the BFA and BILLC system concepts warrant further development based on the results from the analyses. Based on the analyses, there do not appear to be any significant problems regarding the safety and usability of either concept from the driver's point of view. An important difference between the two CA concepts that should be analyzed further under experimental conditions is the issue of independent versus bundled controls and whether automated responses are overridden independently (i.e., overridden by a control input in the dimension that is currently automated) or are completely overridden regardless of the control input dimension. Given the current state of technology, the BFA concept appears feasible for implementation. However, the BILLC concept appears less feasible unless it is assumed that technology is not a limiting factor for this concept.

The driver-related human factors issues discussed above, as well as other issues that arise as an operational system is developed, must be addressed if either CAS concept is to provide an improved safety benefit over current modes of travel. In addition, driver satisfaction and acceptance of automated vehicle control during emergency events must be evaluated. As the issues are considered in greater detail, and the CAS concepts are refined, new human factors issues are expected to arise. It is important to note that the development of such complex systems will require an iterative process of design and evaluation.

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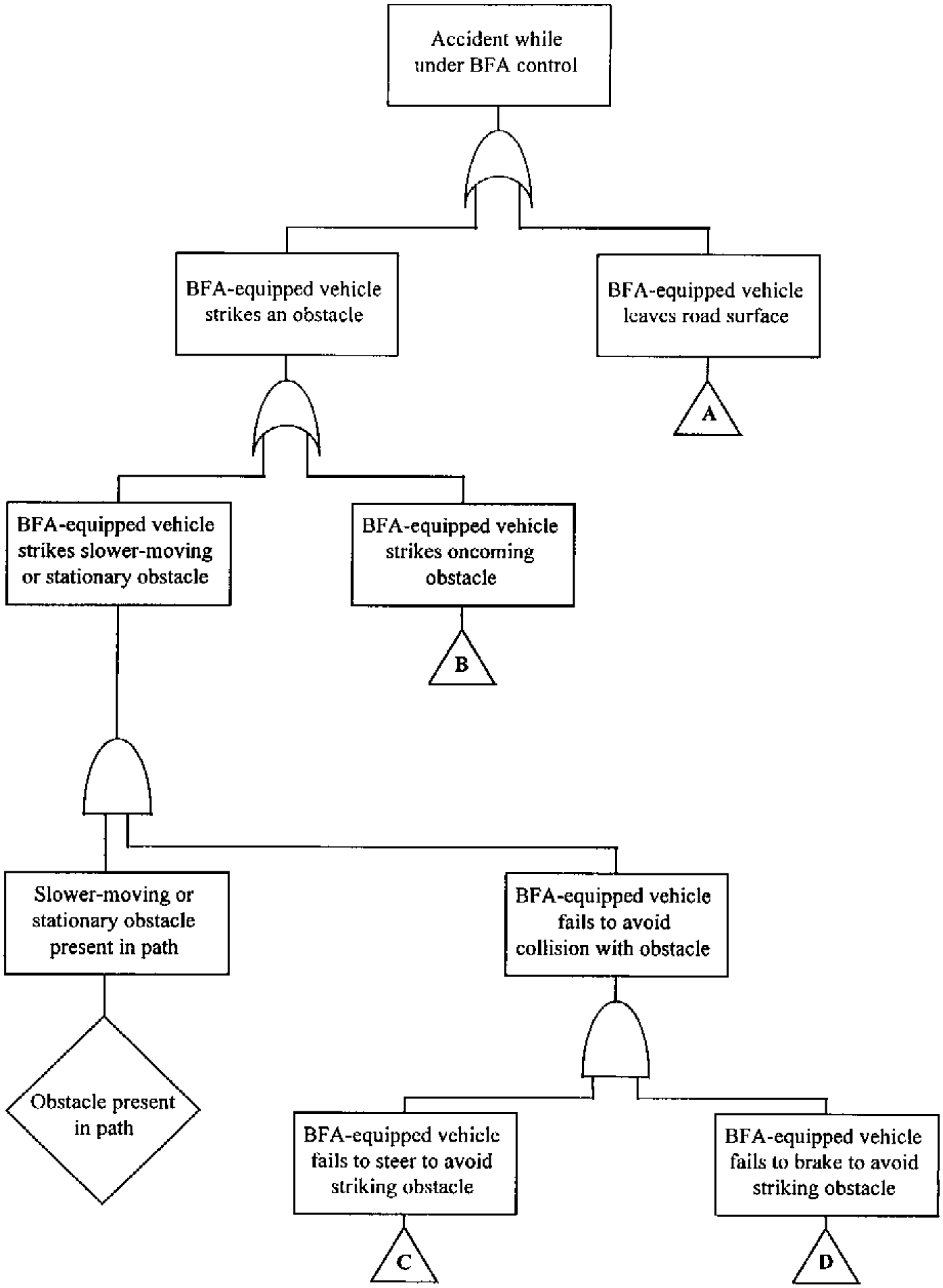
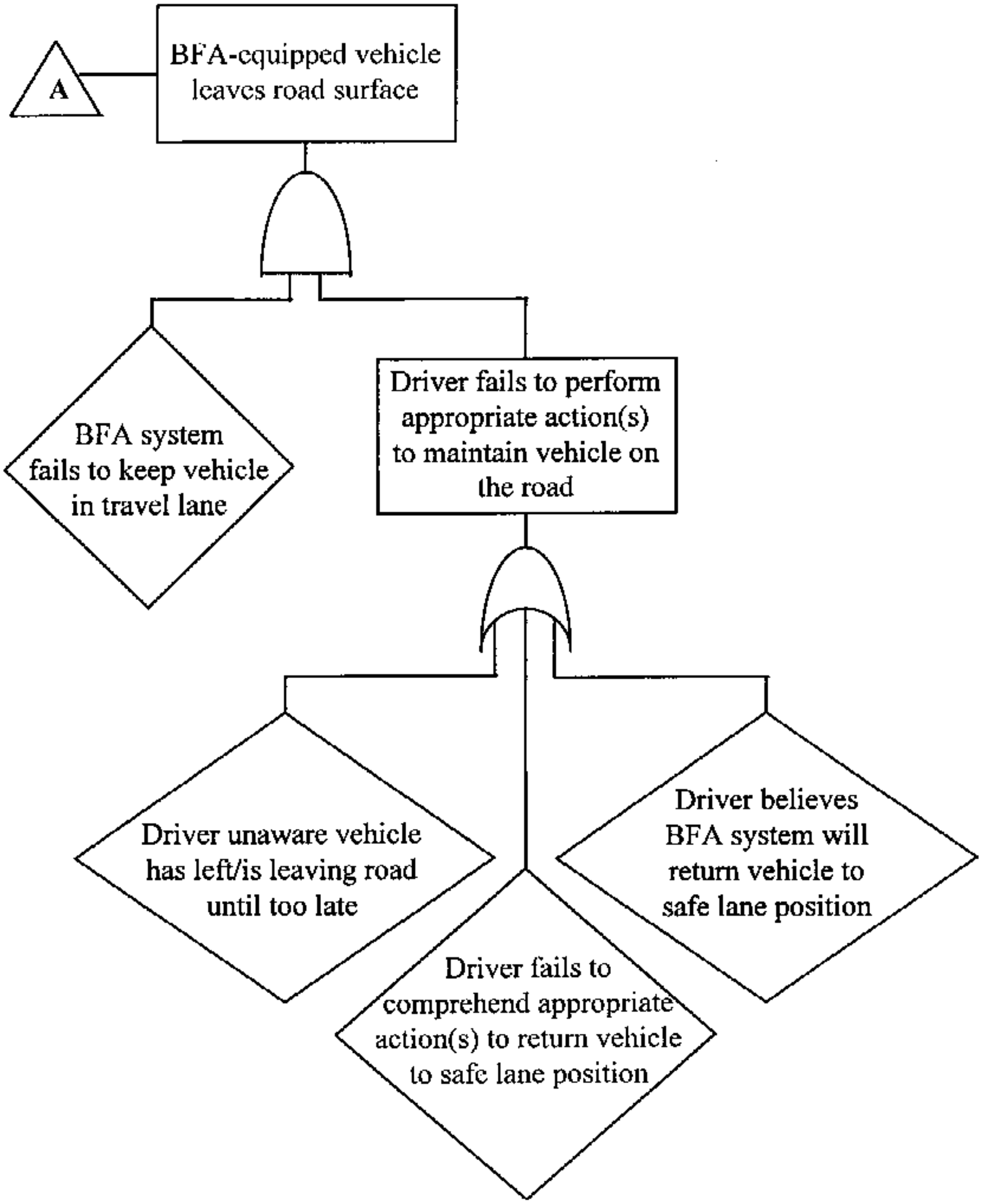
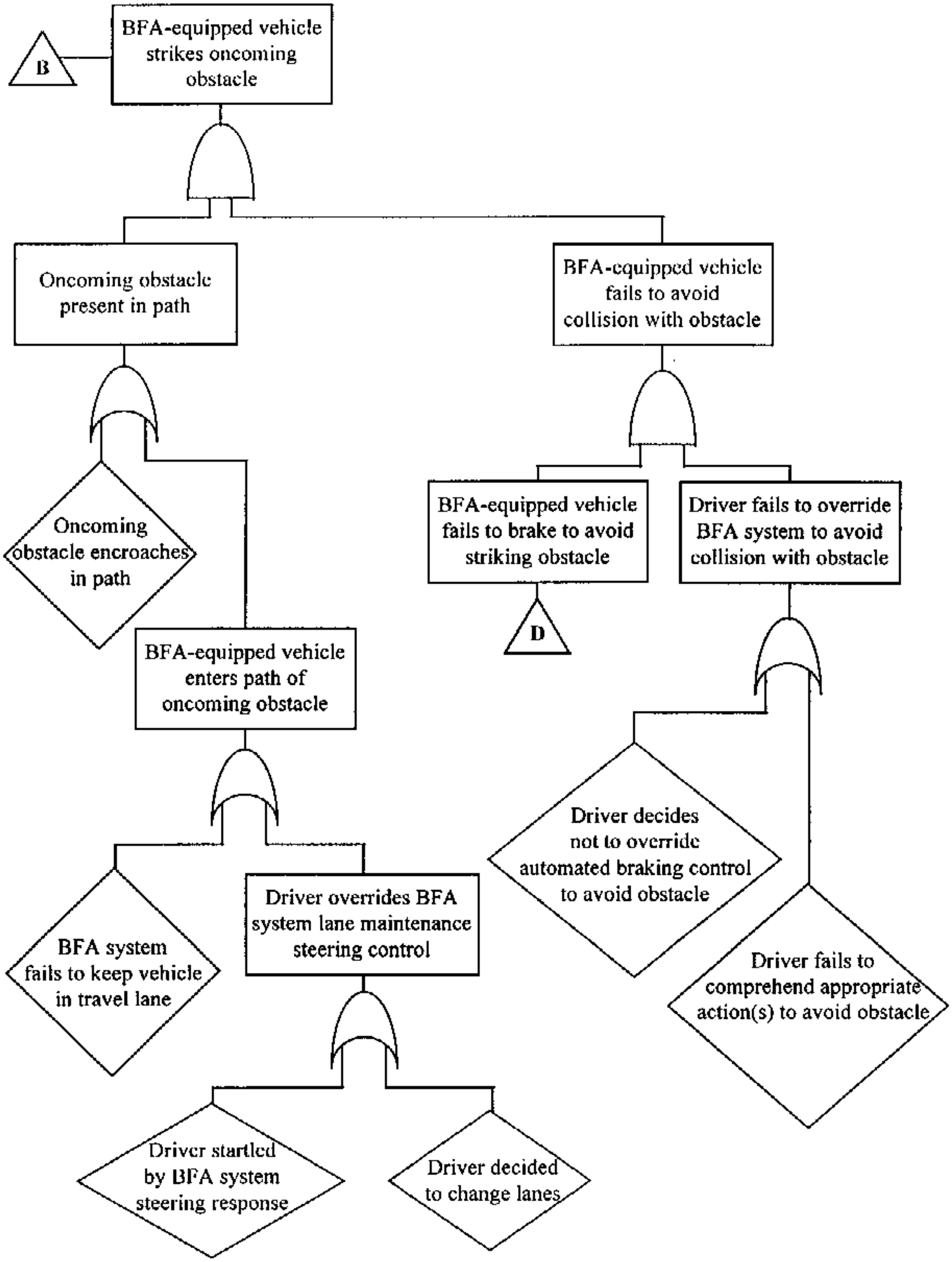
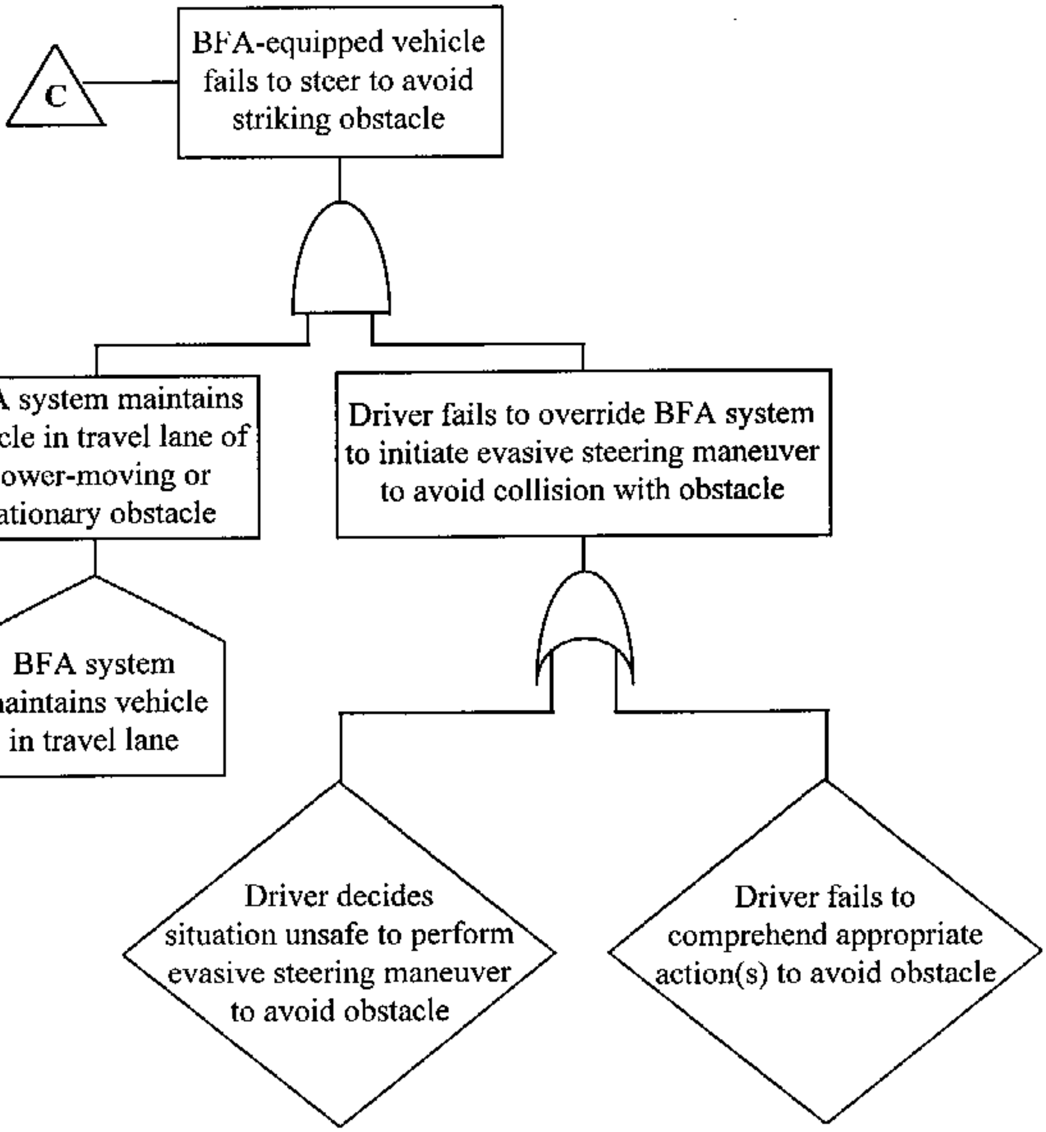
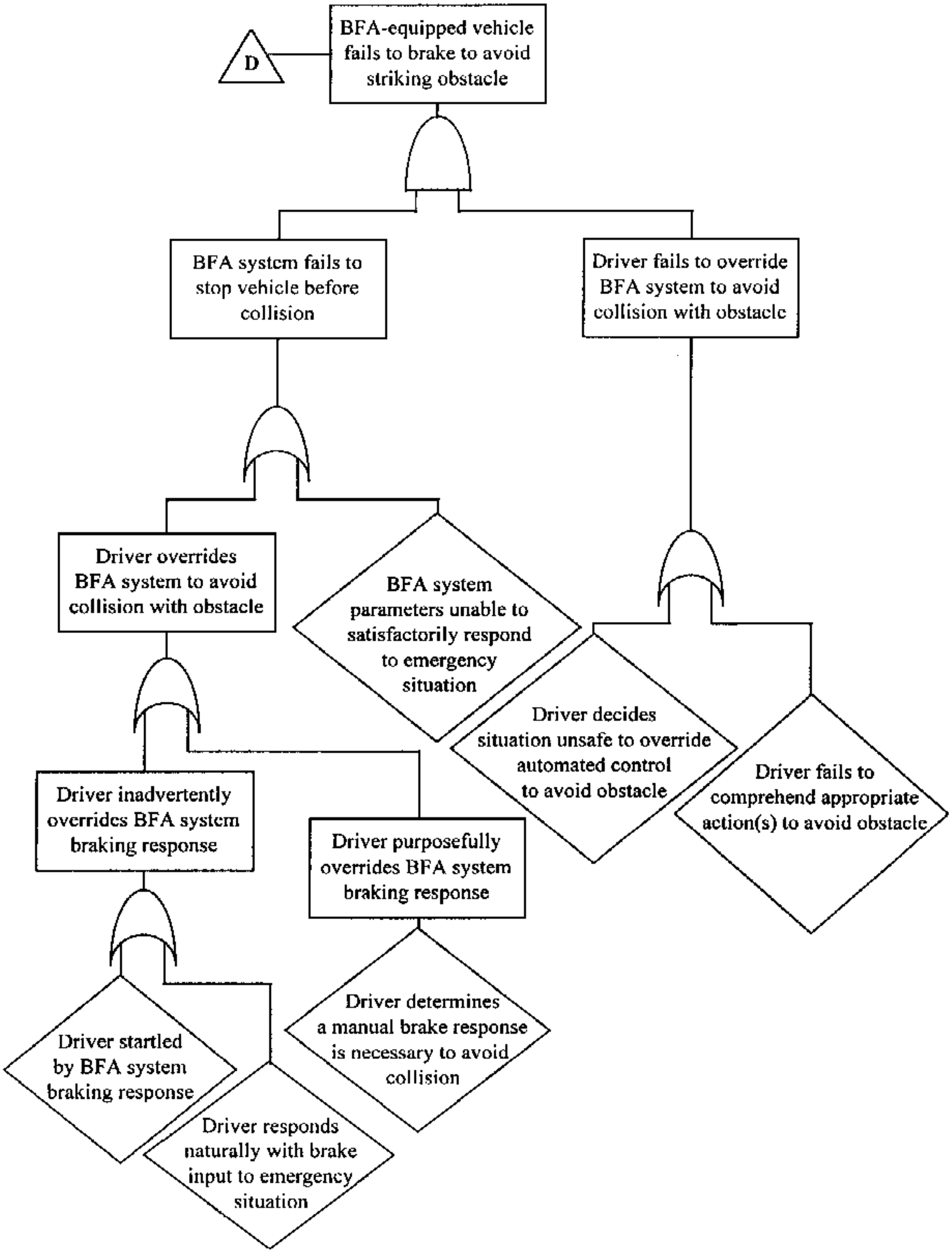
APPENDIX A: FAULT TREE FOR BACKGROUND FREE AGENT SYSTEM


Accident while under BFA control
BFA-equipped vehicle strikes an obstacle
BFA-equipped vehicle leaves road surface
A
BFA-equipped vehicle strikes slower-moving or stationary obstacle
BFA-equipped vehicle strikes oncoming obstacle
B
Slower-moving or stationary obstacle present in path
BFA-equipped vehicle fails to avoid collision with obstacle
Obstacle present in path
BFA-equipped vehicle fails to steer to avoid striking obstacle
BFA-equipped vehicle fails to brake to avoid striking obstacle
C
D

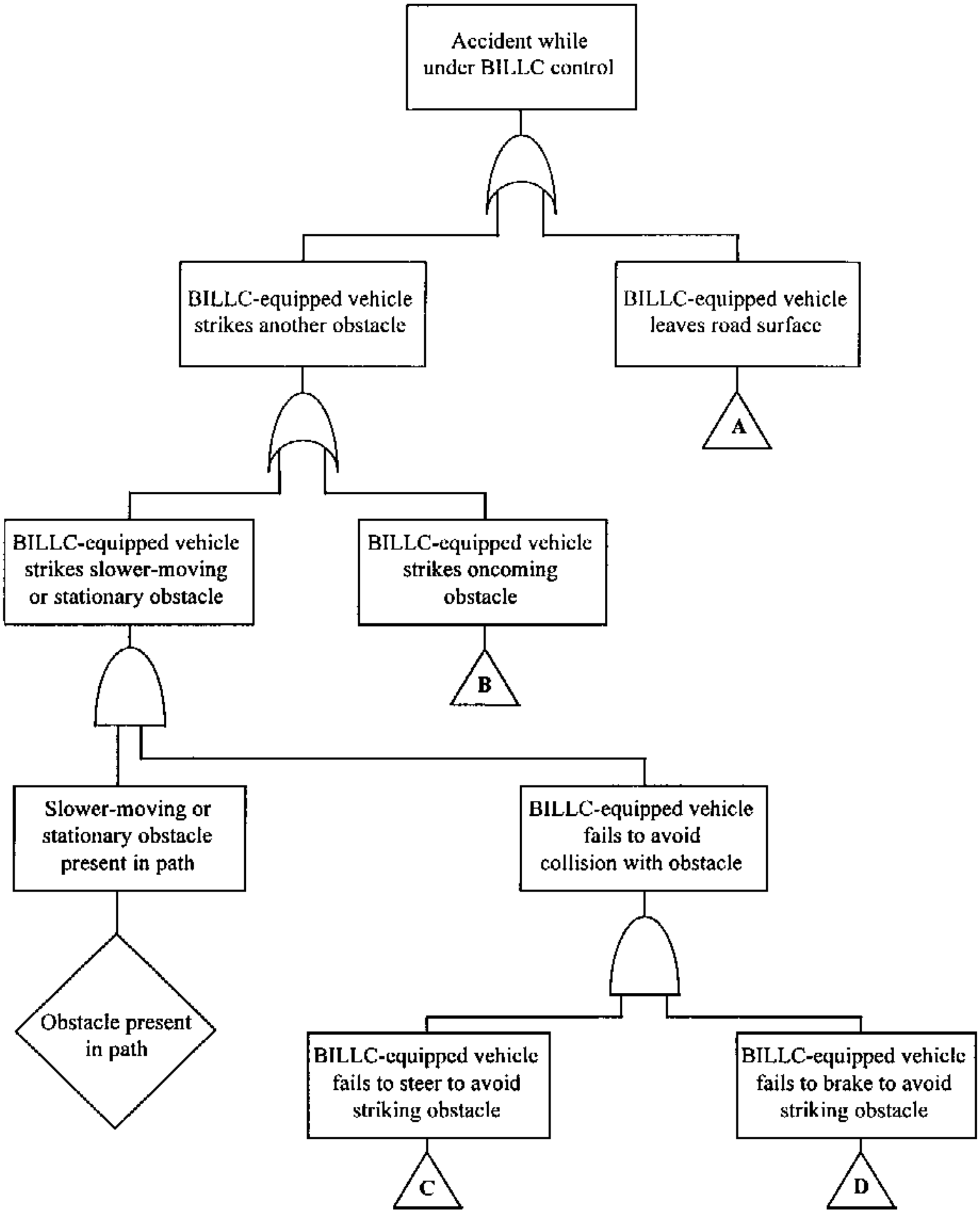

A
BFA-equipped vehicle leaves road surface
BFA system fails to keep vehicle in travel lane
Driver fails to perform appropriate action(s) to maintain vehicle on the road
Driver unaware vehicle has left/is leaving road until too late
Driver fails to comprehend appropriate action(s) to return vehicle to safe lane position
Driver believes BFA system will return vehicle to safe lane position

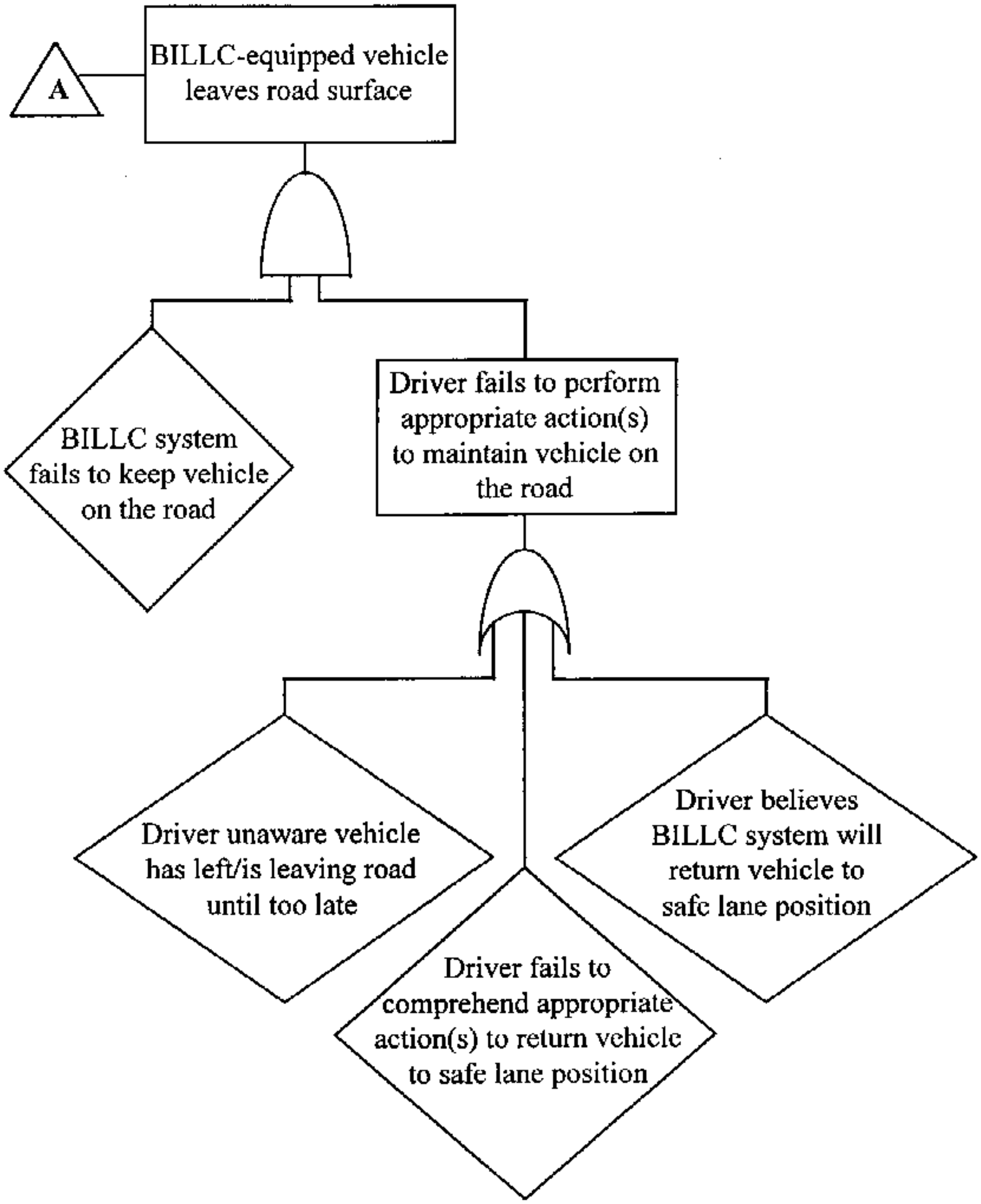

B
BFA-equipped vehicle strikes oncoming obstacle
Oncoming obstacle present in path
BFA-equipped vehicle fails to avoid collision with obstacle
Oncoming obstacle encroaches in path
BFA-equipped vehicle enters path of oncoming obstacle
BFA-equipped vehicle fails to brake to avoid striking obstacle
Driver fails to override BFA system to avoid collision with obstacle
D
BFA system fails to keep vehicle in travel lane
Driver overrides BFA system lane maintenance steering control
Driver decides not to override automated braking control to avoid obstacle
Driver fails to comprehend appropriate action(s) to avoid obstacle
Driver startled by BFA system steering response
Driver decided to change lanes

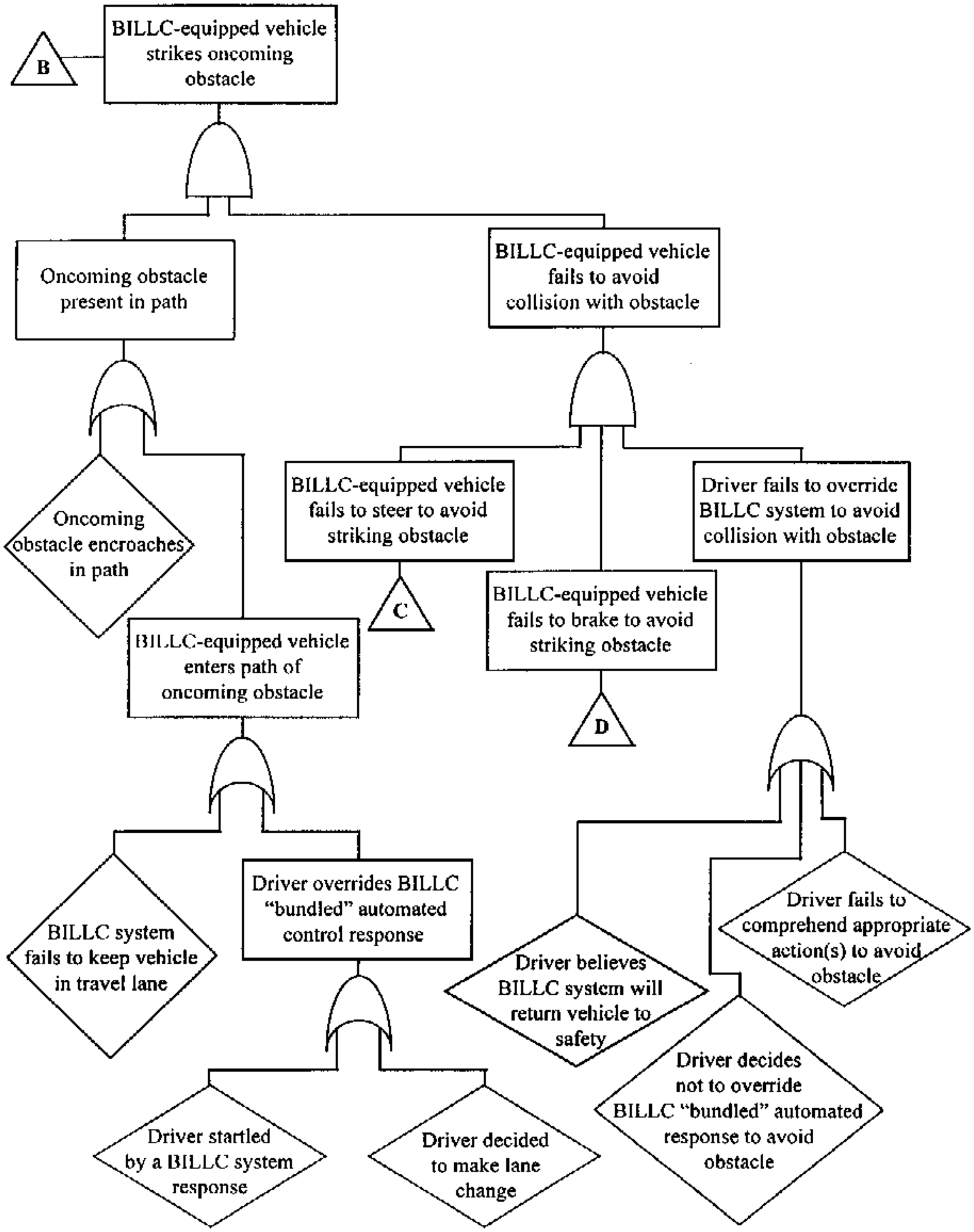
C
BFA-equipped vehicle fails to steer to avoid striking obstacle
BFA system maintains vehicle in travel lane of slower-moving or stationary obstacle
Driver fails to override BFA system to initiate evasive steering maneuver to avoid collision with obstacle
BFA system maintains vehicle in travel lane
Driver decides situation unsafe to perform evasive steering maneuver to avoid obstacle
Driver fails to comprehend appropriate action(s) to avoid obstacle

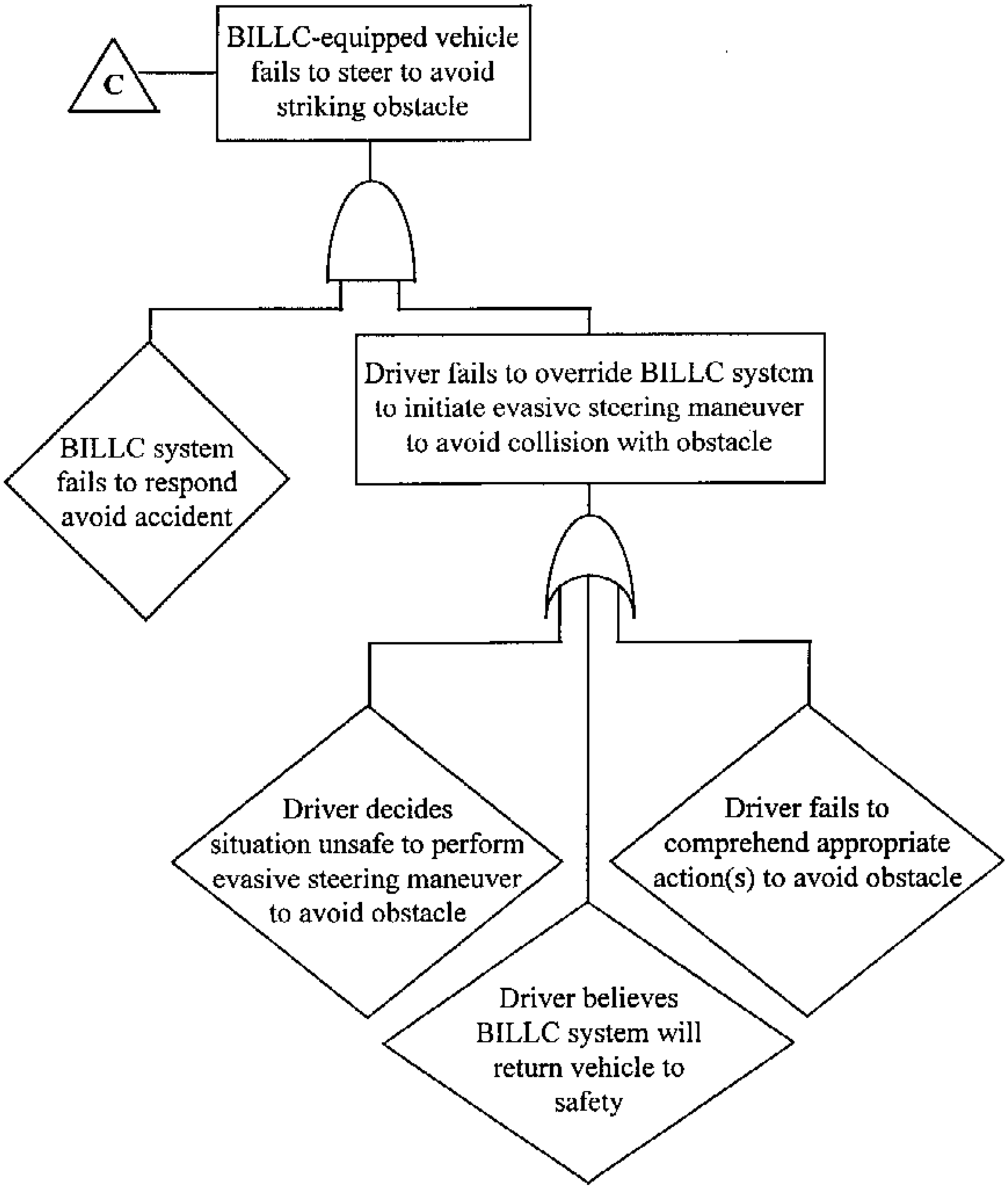

D
BFA-equipped vehicle fails to brake to avoid striking obstacle
BFA system fails to stop vehicle before collision
Driver fails to override BFA system to avoid collision with obstacle
Driver overrides BFA system to avoid collision with obstacle
BFA system parameters unable to satisfactorily respond to emergency situation
Driver decides situation unsafe to override automated control to avoid obstacle
Driver fails to comprehend appropriate action(s) to avoid obstacle
Driver inadvertently overrides BFA system braking response
Driver purposefully overrides BFA system braking response
Driver determines a manual brake response is necessary to avoid collision
Driver startled by BFA system braking response
Driver responds naturally with brake input to emergency situation

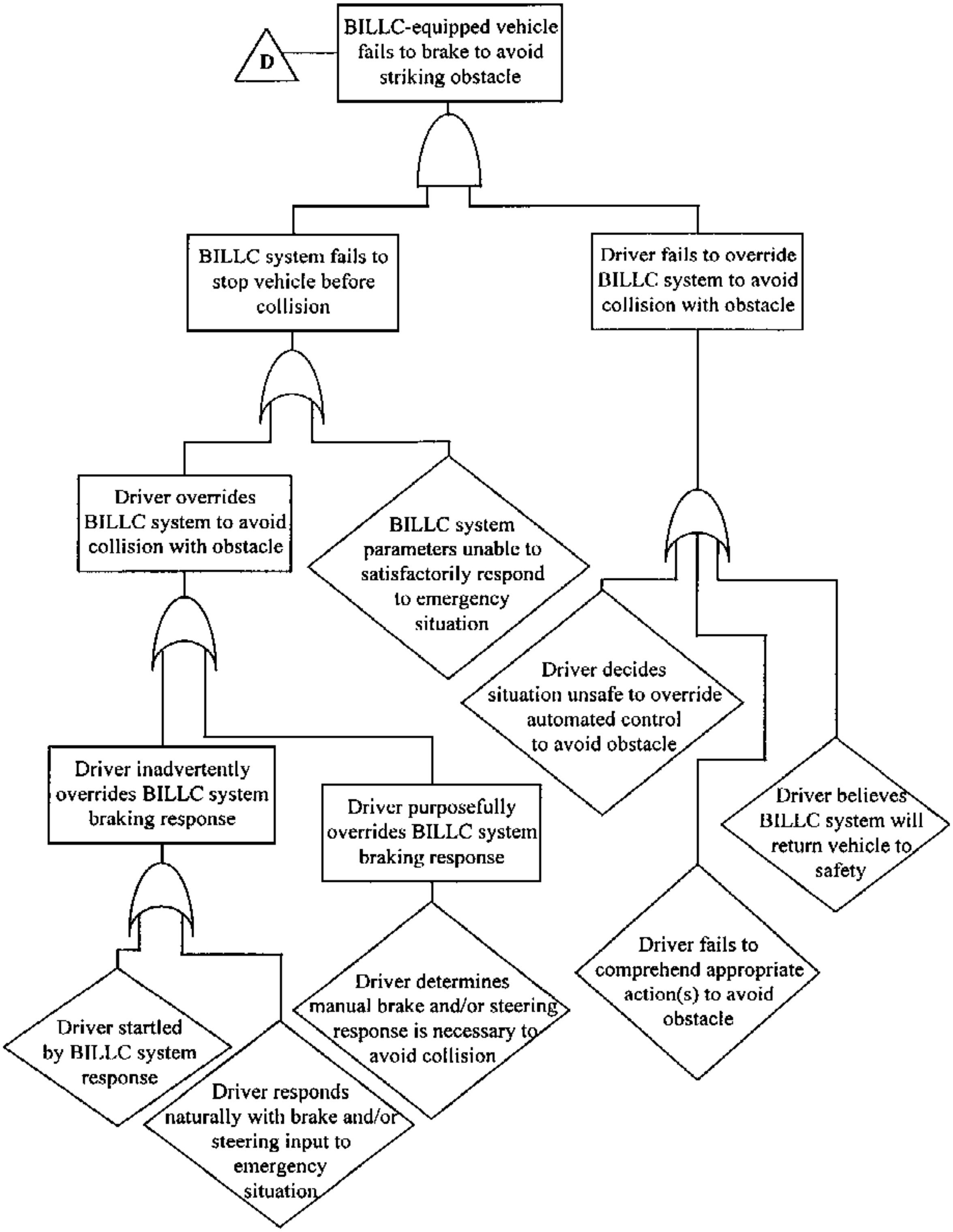
APPENDIX B: FAULT TREE FOR BACKGROUND INTEGRATED LONGITUDINAL AND LATERAL CONTROL SYSTEM


Accident while under BILLC control
BILLC-equipped vehicle strikes another obstacle
BILLC-equipped vehicle leaves road surface
A
BILLC-equipped vehicle strikes slower-moving or stationary obstacle
BILLC-equipped vehicle strikes oncoming obstacle
B
Slower-moving or stationary obstacle present in path
BILLC-equipped vehicle fails to avoid collision with obstacle
Obstacle present in path
BILLC-equipped vehicle fails to steer to avoid striking obstacle
BILLC-equipped vehicle fails to brake to avoid striking obstacle
C
D


A
BILLC-equipped vehicle leaves road surface
BILLC system fails to keep vehicle on the road
Driver fails to perform appropriate action(s) to maintain vehicle on the road
Driver unaware vehicle has left/is leaving road until too late
Driver fails to comprehend appropriate action(s) to return vehicle to safe lane position
Driver believes BILLC system will return vehicle to safe lane position


B
BILLC-equipped vehicle strikes oncoming obstacle
Oncoming obstacle present in path
BILLC-equipped vehicle fails to avoid collision with obstacle
Oncoming obstacle encroaches in path
BILLC-equipped vehicle enters path of oncoming obstacle
BILLC-equipped vehicle fails to steer to avoid striking obstacle
C
BILLC-equipped vehicle fails to brake to avoid striking obstacle
D
Driver fails to override BILLC system to avoid collision with obstacle
BILLC system fails to keep vehicle in travel lane
Driver overrides BILLC "bundled" automated control response
Driver startled by a BILLC system response
Driver decided to make lane change
Driver believes BILLC system will return vehicle to safety
Driver decides not to override BILLC "bundled" automated response to avoid obstacle
Driver fails to comprehend appropriate action(s) to avoid obstacle


C
BILLC-equipped vehicle fails to steer to avoid striking obstacle
BILLC system fails to respond avoid accident
Driver fails to override BILLC system to initiate evasive steering maneuver to avoid collision with obstacle
Driver decides situation unsafe to perform evasive steering maneuver to avoid obstacle
Driver believes BILLC system will return vehicle to safety
Driver fails to comprehend appropriate action(s) to avoid obstacle


D
BILLC-equipped vehicle fails to brake to avoid striking obstacle
BILLC system fails to stop vehicle before collision
Driver fails to override BILLC system to avoid collision with obstacle
Driver overrides BILLC system to avoid collision with obstacle
BILLC system parameters unable to satisfactorily respond to emergency situation
Driver decides situation unsafe to override automated control to avoid obstacle
Driver inadvertently overrides BILLC system braking response
Driver purposefully overrides BILLC system braking response
Driver believes BILLC system will return vehicle to safety
Driver fails to comprehend appropriate action(s) to avoid obstacle
Driver determines manual brake and/or steering response is necessary to avoid collision
Driver startled by BILLC system response
Driver responds naturally with brake and/or steering input to emergency situation

C3 Interim Report

10.4.5 Appendix C - Literature Review on Human Factors Issues in Automated and Partially Automated Intelligent Highway Vehicle Systems

NAHSC

LITERATURE REVIEW ON HUMAN FACTORS ISSUES IN AUTOMATED AND PARTIALLY AUTOMATED INTELLIGENT HIGHWAY VEHICLE SYSTEMS

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INTRODUCTION

This literature review addresses five human performance questions that have become the focus of recent interest. All five questions are interrelated and all have serious safety implications. These five questions are: 1) Should collision avoidance be separate from collision warning? 2) Should a vehicle be configured so that the driver can override automatic control in one dimension but not in the other to avoid a collision? 3) Should the driver be permitted to operate longitudinal and lateral control separately if both are available? 4) What characteristics should a collision warning system in an intelligent vehicle have? 5) Can fallback schemes where higher levels of automation are replaced by lower levels function effectively? It is imperative that answers to these questions be found, for, as noted by Herridge and Pittenger (1996), "The occurrence of one or two 10 or 20 vehicle accidents in the early stages of AHS introduction would devastate public confidence in system safety and reliability; probably delaying widespread introduction for decades (pg. 34)."

Assumptions

Much of the information used to address the issues described above is concerned with human response times. Thus, any assumptions about the design and use of the intelligent vehicle highway system (IVHS) that limit the time available to the driver to respond must be stated. The primary assumption made in this paper is that intelligent vehicles will operate in dedicated lanes. This assumption corresponds to that used by Dickerson et al. (1994) in the development of all five representative configuration systems. Given this assumption, four parameters of the IVHS appear to have a major influence on the available response time. The first of these is the speed of the vehicles. Herridge and Pittenger (1996) state that the vehicles in an IVHS will be traveling between today's standard speed (55 mph) and 80 mph. Plocher and DeMers (1994) modeled driver performance capabilities using vehicle speeds from 55 mph to 95 mph. This range is consistent with those examined by Bloomfield et al. (1995) in their studies. The second parameter of interest is the gap between vehicles. Herridge and Pittenger (1996), Tsao, Hall, Shaldover, Plocher, and Levitan (1994), and Dickerson et al. (1994) indicate that gaps as small as 1 m are possible. The third is the lane width. Herridge and Pittenger (1996) and Plocher and DeMers (1994) assumed lane widths from 8.5 ft to 12 ft. The fourth parameter concerns traffic density. Although the exact percentage increase in traffic density of the IVHS is not known, the system will carry more traffic than the current highway system. Tsao et al. (1994) indicate that smaller than usual lateral separations are being considered. Bloomfield, Buck, Christensen, and Yenamandra (1995) indicate that the capacity could be over three times that of a current highway.

Thus, for the purposes of this review, intelligent vehicles will be assumed to operate in dedicated lanes at speeds of at least at 55 mph, the lane width will remain approximately the same as that of current highways, the gap between vehicles will be considerably less than current following distances, and the lateral separation between vehicles will decrease. The decreased gap and decreased lateral separation both serve to decrease the time available to the driver to make a response.

COLLISION WARNING AND COLLISION AVOIDANCE

One IVHS human factors issue concerns the relation between collision avoidance and collision warning. Specifically, should the functions of warning and of control for crash avoidance be available separately to the driver? If, for example, collision avoidance is technologically feasible in both longitudinal and lateral dimensions, should a vehicle be allowed to operate with collision warnings in both dimensions but collision avoidance in only one? Riley (1994) advocates not allowing the warning and avoidance functions of an intelligent vehicle to be decoupled because drivers may forget that they do not have automatic collision avoidance in one dimension. An additional argument against decoupling these functions in the assumed high speed, high density environment can be made by examining drivers' response times to unanticipated events. If human response times are too slow to avoid collisions, the separation of collision warning from collision avoidance cannot be allowed.

Some concerns may be raised by using data obtained in today's vehicles to approximate data from intelligent vehicles. Drivers today must detect a potential collision, select an avoidance response, and execute the response. In a vehicle equipped with a collision warning system, the driver must process the warning, select an avoidance response, and execute the response. The driver may also attempt to assess the situation before selecting the response. Thus, the response times of drivers of vehicles with collision warning systems may be no faster than those of drivers of vehicles without warnings although drivers of vehicles with warning systems may have a higher probability of detecting an imminent collision.

Because drivers can avoid some collisions either by braking or by changing the path of the vehicle, steering times for lateral incursions, braking times for lateral incursions, and braking times for rear end collision avoidance will be examined. As noted in the introduction, this section assumes that the intelligent vehicles operate in a high speed, dense traffic environment, on dedicated lanes.

Braking Response Time—Rear End Collision Avoidance

A number of studies of braking time for rear end collision avoidance have been reported in the human factors literature. Two representative studies, an earlier one and a more recent one, were selected for review. A third study (Lings, 1991) is also described because it includes data from drivers with paraparesis inferior(a mild, partial paralysis of the extremities).

The first study (Olson and Sivak, 1986) is of particular interest because it involved actual highway driving. Subjects drove a car on a two-lane highway in a rural area. A foam rubber object was placed near the crest of the highway in such a position that the driver first saw the object on average when it was 46 m in front of the vehicle. After the initial test run involving the unanticipated appearance of the object, each subject made five more runs during which he/she was told the approximate location of the object. The subject then performed a series of "brake" trials in which a light attached to the front of the hood illuminated periodically. The subject stepped on the brake as soon as she/he saw the light.

For the 49 young subjects (ages 18 to 40), the average response time for the brake trials was approximately .6 s. The average response time to the unanticipated object was 1.1 s. When the object was anticipated, the average response time was .7 s. The corresponding values for the 15 older subjects (ages 50 to 84) were approximately .6 s, 1.1 s, and .7 s, respectively. The 95th percentile response time for the subjects as a whole to the unanticipated object was approximately 1.6 s.

Broen and Chiang (1996) had 50 male and 50 female subjects perform a simulated task involving driving around a suburban neighborhood. The study was designed to investigate the effect of age, gender, and pedal configuration on braking response time. Each subject drove around the neighborhood a total of 21 times. During one trip, the subject saw an unexpected obstacle and was required to stop as quickly as possible.

Subjects were placed into one of three age groups: 18 to 30, 31 to 50, and 51 years and older. Age was found to have a significant effect on response time. The average response time ranged from 1.27 s for the youngest group to 1.46 s for the oldest group. Neither gender nor pedal configuration had a significant effect on response time.

Lings (1991) had 109 healthy individuals and 52 individuals with paraparesis inferior perform several driving tasks in a simulator. Forty-seven of the 52 individuals with paraparesis inferior had a driver's license. None were taking any medications that might affect their reaction times.

A standard traffic light placed in front of the simulator was used to present braking and acceleration signals to the subject. When a green light was illuminated, the subject moved his/her foot from the brake to the accelerator as quickly as possible. Similarly, when a red light was illuminated, the subject moved his/her foot as quickly as possible from the accelerator to the brake. The traffic light also displayed green arrows. When an arrow was displayed, the subject turned the steering wheel as quickly as possible in the direction of the arrow. Both the time to begin turning the wheel and the direction of the turn were recorded. On any given trial, any one of the four types of stimuli could be presented.

For the healthy group, the average braking time (the sum of the reaction time--the time between the onset of the stimulus and the removal of the foot from the accelerator--and the movement time) was .76 s. The paraparesis group differed from the healthy group primarily in the speed of the movement time but not in the reaction time. The difference in movement time was approximately .14 s. Lings found that age increased response time but no specific values were reported.

In these three studies, drivers knew they were participating in a study. Thus, response times reported in these studies may be optimistic. In Olson and Sivak (1986), the difference in response time between the anticipated and the unanticipated appearance of the object was approximately .4 s. In Maeda, Irie, Hidaka, and Nisimura (1977), which will be discussed in detail in the following section, the corresponding reduction in initial response time for at least some of the drivers was approximately .5. Thus, the reported braking times for articles reported in this section may underestimate road performance by at least .4 to .5 s. Response times reported by Lings (1991) may be particularly short because the subjects did not have an actual driving task to perform.

Braking Response Time—Lateral Incursions

Hankey, McGehee, Dingus, Mazzae, and Garrott (1996) examined response times to intersection incursions using a motion-based driving simulator. As subjects approached an intersection, a car moved into the intersection and stopped. In one condition, the incursion occurred sufficiently early to allow the subjects to brake to avoid the car. All of the 96 subjects were licensed drivers between the ages of 30 and 50 and half were women. Hankey et al. recorded the initial reaction time, which was measured from the time at which the incurring vehicle passed a point 48 ft. in front of the stop line until the subject released the accelerator. The average initial reaction time was .96 s.

Steering Response Time

Only two studies recorded steering response time. In the Lings (1991) study, the average reaction time for the healthy group to begin turning the steering wheel was approximately .3 s. No steering reaction time measures were obtained from the paraparesis inferior group. Again, Lings noted that age increased the steering response time but reported no specific values.

Maeda, Irie, Hidaka, and Nisimura (1977) studied drivers' steering responses to two types of sudden, unanticipated events. In the first type of event, the "emergency avoidance test," the subjects were told that an object suddenly would move in front of their vehicle as they drove down a track. The investigators told the subjects that they were to change lanes when the object appeared. The subjects were specifically instructed not to brake to avoid the object. In the "surprise test", the subjects were not told that an object would appear and were given no steering or braking instructions to avoid objects. In the emergency avoidance test, the object was triggered to appear 1.3 s before the car would collide with it. In the surprise test, the object was triggered to appear 1.8 s before the car would collide with it. After the first trial of the surprise test, the subjects were asked to repeat the test run. They apparently were not told the exact location of the object in the subsequent trial.

A detailed analysis of the eye movements of subjects in the emergency avoidance test indicated that the subjects did not acquire the object until .3 to .4 s after the appearance of the object. After the object was acquired, the drivers required approximately .1 s to begin turning the steering wheel. All 20 of the drivers in the surprise test collided with the object during the first test run. Detailed analysis of the steering wheel motion indicated that none of the drivers began turning the steering wheel in less than 1 s. During the second run, the three fastest subjects began turning the steering wheel approximately .5 s after the appearance of the object.

Comparisons

Required braking response times for rear end collision avoidance depend on the distance between the front and the rear of the two vehicles and their absolute speed. The average braking times found by Olson and Sivak (1986) for speeds of approximately 30 mph and by Broen and Chiang (1996) for speeds of 25 mph give rise to concerns that in an high density, high velocity IVHS situation, drivers may not be able to brake quickly enough to avoid collisions.

Lings' (1991) data on drivers with mild paralysis confirms that such drivers will have slightly longer braking times than healthy drivers.

Direct estimates for steering response times and braking response times to lateral incursions other than at intersections were not found. However, the required times for certain types of lateral incursions may be estimated using values from Plocher and DeMers (1994), who calculated lane crossing times for vehicles experiencing various types of automatic failures. The times for the vehicles to cross their lanes may be used as estimates of the amount of time a driver in an adjacent lane has to respond to an incursion. In some cases, these estimates may be optimistic; the driver of a vehicle in an adjacent lane that is even with or slightly ahead of the incurring vehicle may not perceive a lane incursion until the incurring vehicle is within a few inches of the lane line. Drivers following further behind will have more time to respond because the movement of the incurring vehicle will be visible earlier.

Plocher and DeMers (1994) performed a computer simulation of three scenarios involving steering failures for an intelligent vehicle. A failure was complete when the simulated vehicle crossed into an adjacent lane. Two lane widths, 8.5 ft. and 12 ft, and four speeds--55 mph, 65 mph, 75 mph, and 95 mph-- were included in the simulation. Two of the scenarios involving hardover steering failures produced estimated times to lane crossing that ranged from 0.4s to 0.85 s. The third scenario (lane following on a curved roadway with a neutral steering failure) produced lane crossing times that ranged from 0.6 s to 3.0 s although the simulations at 55 mph did not produce a lane crossing.

A comparison of the data obtained by Maeda et al. (1997) and Hankey et al. (1996) with predictions obtained by Plocher and DeMers (1994) indicates that drivers may not be able to avoid colliding with a vehicle with a hardover steering failure. They may have time, however, to respond to a neutral steering failure. The steering data from Lings (1991) are not comparable because the subjects were not required to perform any type of driving task during data collection.

Summary

Some discussion has concerned the possible decoupling of collision warning and collision avoidance systems. The most persuasive reason for not permitting such a decoupling concerns the driver's ability to avoid collisions in an IVHS. Several studies were reviewed that obtained human steering response times and human braking response times to both lateral incursions and potential rear end collisions. No estimates were found of the response times required to avoid collisions in an IVHS. Consequently, data from Plocher and DeMers (1994) on the time to a lane excursion for vehicles experiencing various types of automatic failures were used to estimate the time available to a driver in an adjacent lane to respond to an incursion. Drivers' response times are too slow to avoid collisions in many of these potential scenarios.

Conclusion

Although collision warning systems sometimes may decrease the response times, drivers still will respond too slowly in a dense, high-speed IVHS environment to avoid many types of collisions. If collision avoidance systems are technically feasible, vehicles using the IVHS should be equipped with them and drivers should be required to use them. A warning system without a collision avoidance system may provide little additional protection for the driver beyond that of the unaided driver.

OVERRIDE CAPABILITIES FOR COLLISION AVOIDANCE SYSTEMS

One evolutionary representative system configuration proposed by Dickerson et al. (1994) provides rear end collision avoidance and steering assistance on dedicated lanes. Rear end collision avoidance is provided by automatic throttle control and automatic brake control, neither of which can be overridden by the driver. During hard braking, the driver may have to steer the vehicle out of the lane to avoid a collision.

Serious questions have been raised about the ability of a driver to avoid a collision by maneuvering only in the lateral direction. No vehicle data are generally available from comparable systems to answer these questions. Nevertheless, if the rear end collision avoidance and steering assistance of this configuration are sufficient to provide a high speed, high density environment than the drivers' steering response times may not be adequate to avoid collisions.

Because driver response times are, for the most part, inadequate for steering or braking responsibilities in a high speed, high density IVHS environment, is there any reason to provide the driver with the capability to override the automatic lateral and longitudinal control systems? One reason for providing such a capability concerns objects on or near the roadway that the automatic systems may not be able to detect or correctly classify, such as animals that may stray in front of the vehicle or objects with low radar returns. Conceivably, a driver may be able to detect these objects sufficiently far ahead to allow him/her to override the automatic control system usefully.

The second reason for providing an override capability concerns failures of the automatic system itself. In these scenarios, the driver is responsible for detecting failures of the automatic system, overriding the affected system, and resuming control of the vehicle. The major question here again concerns response time. Can a driver detect a failure, override an automatic system, and resume control in time to avoid a collision?

Fortunately, data are available to answer this question; failure detection in continuous control tasks has been studied since the 1970's. In these studies some element of the control system fails, and the operator is required to detect the failure as quickly as possible. All of these studies sought to identify the factors that affected 1) the probability that the human operator would detect the failure and 2) the time required to resume control of the system. The relevant literature will be reviewed below.

Failure Detection

A few failure detection studies used a one-dimensional (single-axis) tracking task. Most used a two-dimensional (dual-axis) tracking task or a "flying task, " which is typically performed in an aircraft simulator. All of the tracking studies discussed below included at least two conditions: a passive monitoring condition in which the operator simply observed the functioning of the automatic control system and a manual control condition in which the operator controlled the system. Few of the studies using aircraft simulators included the passive monitoring condition.

Tracking tasks can be performed with or without a secondary task, which is used to manipulate workload. Tracking performed without a secondary task is referred to as "single-task" tracking. Tracking performed with a secondary task generally is referred to as "dual-task" tracking. The exception to this nomenclature concerns flying. Because of the number of concurrent tasks involved in flying, performance in an aircraft or in a flight simulator is referred to as "multi-task" performance regardless of the presence of an artificial secondary task.

Single-axis tracking tasks are typically performed with a one-dimensional control stick; dual-axis, with a two-dimensional control stick. The control stick usually is manipulated with the operator's dominant hand. Multi-axis tracking, particular in aircraft simulators, is usually performed with two input devices, typically foot pedals and a yoke or a two-axis control stick. In some studies, such as the Wickens and Kessel (1979, 1980) articles discussed below, the subjects indicated a detection of a failure by pressing a button on the control stick. In other tracking studies, the subject pressed another button placed nearby. In studies using aircraft simulators, the subjects typically pushed a button on the control yoke to indicate a failure.

Single-axis tracking. Ephrath and Young (1981) had subjects detect two types of sudden onset failures involving the control order of the system during single-axis tracking. They found that direct manual control of the tracking task resulted in faster detection times (approximately 1 s) than passive monitoring (approximately 3 to 5 s). Kessel and Wickens (1982) also found faster mean reaction times with the manual mode as compared with the passive mode (approximately 2.3 s versus 3.6 s, respectively). Additionally, Kessel and Wickens found that subjects in the manual control group had a higher probability of detecting a failure than subjects in the passive monitoring group.

Dual-Axis Tracking. Wickens and Kessel (1980) had subjects perform a two-dimension tracking task with and without a secondary task. Two different secondary tasks were used, a tracking task and a mental arithmetic task, and were selected to use different cognitive resources. Again, under single-task conditions, manual control resulted in better detection performance and faster mean response times (2.36 s versus 3.37 s) than passive monitoring. Under dual-task conditions, mean response latency for manual control increased when critical tracking was the secondary task and decreased when mental arithmetic was the secondary task (2.75 s versus 2.30 s) . The mean response latency for passive monitoring showed the same pattern of results (3.56 s for critical tracking and 3.27 s for mental arithmetic). The accuracy of detection of both control modes decreased under dual- as compared to single-task conditions. Thus, the manual control mode maintained its superiority under dual-task conditions relative to the passive monitoring mode. Wickens and Kessel (1979) found essentially the same pattern of single- and dual-task results although their data showed little difference in accuracy between the two control modes under single-task conditions.

Aircraft Simulations. Gai and Curry (1975) simulated a Boeing 707 for a study of failure detection during automatic landings. Two pilots performed the last 5 minutes of an automated approach to landing. Failures occurred in either the glideslope indicator or in the airspeed indicator. All failures were sudden-onset failures that affected the mean value presented on the instrument (prior to the failure, both the glideslope indicator and the airspeed indicator displayed an approximately constant value). Four levels of the magnitude of failure (change in the mean value of the instrument) were used and a failure occurred on 90% of the trials. The data indicated that the greater the magnitude of the failure, the faster the pilots detected the failure, and that failures of the glideslope indicator were detected more rapidly than failures of the airspeed indicator. Mean detection times ranged from 25.4 s for lowest magnitude failure of the airspeed indicator to 5.0 s for the largest magnitude failure of the glideslope indicator.

Ephrath and Curry (1977) had experienced airline pilots perform a simulated aircraft control task involving multi-axis tracking and a secondary task. This experiment had four conditions: manual control of both axes, manual control of heading only, manual control of the pitch axis only, and passive monitoring. The secondary task was present under all conditions. Failures could occur in only one axis in a given trial and involved a subtle autopilot failure that resulted in the aircraft drifting off course. Failures that occurred on an axis that was passively monitored were detected faster and more accurately than failures that occurred on an axis that was actively controlled. Additionally, the subjects detected failures in the pitch axis more quickly than those of heading.

Van de Graaff and Wewerinke (1983) had experienced airline pilots perform an automatic approach to landing in a simulator configured as a medium weight jet transport. On some of the approaches the pilots experienced either a wind shear or a failure of the autopilot. Both of these failures could result in either heading or pitch deviations from the standardized approach and both were gradual onset failures. The pilots monitored the approach and disengaged the autopilot as soon as the deviations were recognized. The time from the beginning of the event (wind shear or autopilot failure) until the pilot disconnected the autopilot was the dependent measure.

Two findings are of interest from this study. First, the between-subject differences were larger for the wind shear detection task than for the autopilot failure detection task; the mean detection time for the wind shear on the pitch axis ranged from 13.7 s to 34.2 s. In contrast the mean detection time for an autopilot failure on the pitch axis ranged from 17.1 s to 21.6 s. Second, the mean detection time of heading failures were significantly longer than detection of pitch failures (approximately 22.5 s versus 20 s)

As part of a study on the use of voice recognition in aircraft, Bortolussi and Vidulich (1987) had pilots hover a simulated helicopter. The hover maneuver could be accomplished manually or by using an automatic altitude-hold function. During the hover, the pilot transmitted a report and waited for confirmation that the report had been received. During some of the hover maneuvers, a wind shear occurred that disrupted the attitude of the helicopter. The time from the onset of the wind shear until the pilot moved the controls properly to recover from the unusual attitude was recorded. The data revealed significantly longer response times under the automatic altitude-hold condition as compared with the manual condition (approximately 830 ms versus 730 ms).

More recently, Beringer (1996) examined four types of autopilot failure in a simulated general aviation aircraft. Two of the autopilot failures were sudden onset, supra threshold failures; two were subtle failures. The dependent variable was the time from the onset of the failure until the subjects, who were all pilots, took corrective action by either manually overriding the autopilot or disconnecting the autopilot. Data were taken during a realistic scenario in a medium fidelity flight simulator that was configured to represent a complex, single-engine general aviation aircraft.

Several findings are of interest. First, there were large individual differences in response times, ranging from 1.8 s to 107.1 s. Second, sudden onset, supra threshold failures were responded to more quickly than subtle failures (mean response time of approximately 8 s versus 15 s). Third, for each type of failure, some of the subjects responded by manually overriding the autopilot whereas others disconnected the autopilot. Fourth, despite the fact that all of the subjects were licensed pilots with a valid medical certificate, two of the pilots never heard the 77 dB aural warning associated with one of the failures because of hearing loss. Fifth, some of the pilots never detected one type of subtle failure. These results, including the lack of effect of the aural warning, were essentially replicated in a second study (Beringer, in press).

Summary

Some questions exist about including an override capability in intelligent vehicles. One reason to include such a capability is to allow the driver to avoid obstacles that the automatic system may not be able to detect. A second reason is to allow the driver to resume control of the vehicle when some component of the automatic control system fails. The problem with allowing the driver to override a failed automatic control system concerns the time available to detect the failure, override the system, and resume control of the vehicle.

The failure detection literature that used single-axis tracking tasks, dual-axis tracking tasks, and aircraft simulations was reviewed. The single- and dual-task tracking studies showed that individuals detect failures more quickly when they are actively controlling the system. The data from the aircraft simulation studies generally showed longer mean response times than the tracking studies and large differences in reaction times between individuals. The data also indicated that the type of failure affected the response time; sudden onset failures were detected more rapidly than slow onset failures.

Conclusions

An override capability will not aid in collision avoidance in many instances because of the length of human response times. Automatic systems should be used for collision avoidance. Nevertheless, an override capability should be included in intelligent vehicles to permit the driver to resume control of the vehicle under certain circumstances, i.e., the presence of objects that the automatic systems cannot detect. This capability should not be used as a backup system for failures of components of the automatic systems; human failure detection times are too long to avoid many types of collisions that may result from the failure of a component of an automatic system.

SEPARATION OF LATERAL AND LONGITUDINAL CONTROL

One major human factors issue that must be confronted during the design of the IVHS concerns the separability of lateral and longitudinal control. Specifically, assuming that both automatic longitudinal and lateral control are available, should the driver be allowed to operate the vehicle manually in one dimension while using automatic control in the second? Initially, the answer to this question seems evident; drivers today use cruise control, which provides some level of automatic longitudinal control, without using any form of lateral control. However, basing a decision on today's highway system may be misleading; if both lateral and longitudinal control are available, the IVHS may be in a mature configuration with greater vehicle density than the present system and possibly with vehicles traveling at higher speeds. Additionally, some drivers will elect to use automatic control in both dimensions. Given this environment, should drivers be allowed to use automatic control in only one dimension?

The answer to this question rests critically on human response time and assumptions about the availability of automatic collision avoidance systems. As noted in the two preceding sections, human response time is too slow to avoid many types of collisions. Thus, for safety reasons, drivers should not be permitted to operate vehicles in a mature IVHS environment without taking full advantage of all of the available features, including automatic lateral and longitudinal control and automatic collision avoidance.

Two other topics pertaining to human motor cross talk and driver-vehicle interface problems are presented below to argue against separating longitudinal and lateral control.

Human Motor Cross Talk

One issue that appears to be underappreciated in arguments about the separability of control concerns motor "cross talk". Motor cross talk occurs when motor control impulses directed to one limb are transmitted to another limb. Although the impulses arriving at the unintended limb are attenuated compared to those received by the intended limb, they are still of a magnitude sufficient to affect performance.

Motor cross talk between hands was demonstrated in Damos and Wickens (1980), using two one-dimensional tracking tasks. The inputs to the two tasks were independent, and the subject used left-right movements of two identical control sticks to track the cursors, which moved horizontally. The subject tracked the display presented on the right portion of the screen with her right hand and the display on the left portion with her left hand. Fourier analysis was used to examine the relation between the movement of the cursor and the movement of the control stick. The analysis showed a low, but non zero, relation between cursor movement on one display and stick movement by the contralateral hand. This finding indicates that motor control impulses designated for the right hand were sent to left hand and vice versa and provides evidence of cross talk.

A form of cross talk can also occur within a limb performing a two-dimensional tracking task. An example of this phenomenon occurs in Navon, Gopher, Chillag, and Spitz (1984, Experiment 3). Subjects performed a pursuit tracking task in which the target and the cursor were rectangles that moved in two dimensions. In the two conditions of interest, the subjects were told to track in one dimension and "not to attempt to control" the second dimension. However, movements of the control stick in the second dimension affected the position of the cursor in the corresponding dimension. Navon et al. noticed that the subjects did tracking on the second axis; the average error score on the second axis was less than in test trials where no human inputs were made.

Although the findings by Damos and Wickens (1980) and Navon et al. (1984) by themselves might have few implications for the design of an intelligent vehicle, those of Lings (1991) (described earlier) have more direct applicability. Lings noted that subjects had a tendency to turn the steering wheel while braking. Although most of the turns were small (less than 25°), one turn of 280° was recorded. Lings also recorded instances in which the subject applied the brake while turning. These results are particularly interesting because none of the experimental tasks required concurrent activation of the controls and because no visual driving stimuli were provided except the stop light, i.e. no visual simulation of a highway environment was provided.

The results of these three studies imply that drivers may accidentally disengage automatic control of one dimension when responding in the second dimension. For example, assume the driver is controlling the position of the vehicle longitudinally and that the lateral position of the vehicle is under automatic control. If the driver has to brake relatively quickly, he/she may accidentally turn the steering wheel. The effect of this motion on the lateral automatic control will depend on how the disengagement function has been implemented. If lateral disengagement occurs when the steering wheel is turned more than a set number of degrees, the driver may unintentionally disconnect lateral control.

Design Issues

If lateral and longitudinal control can be operated separately, then controls and displays must be designed that permit safe and efficient operation of automatic control in each dimension independently. Problems associated with designing such controls and displays for intelligent vehicles do not seem to have been addressed. Currently, two problems can be identified that must be resolved before lateral and longitudinal control can be operated separately. These concern how to design controls and displays that 1) allow rapid and accurate engagement/disengagement of automatic control in the desired dimension without accidentally either engaging or disengaging control in the other dimension and 2) minimize any confusion about the status (on/off) of the automatic control in each dimension. Both of these problems will be discussed in turn.

Engagement/disengagement. Fitts and Jones (1961/1947) studied the problems of accidental activation/deactivation (i.e., bumping) and confusion (deliberate activation of the wrong control) to reduce the number of aircraft accidents caused by incorrect control activations by experienced pilots. The authors identified three primary design flaws that were the source of the control confusion and accidental activation/deactivation of controls: Different aircraft had the controls for the same function located in different places, the controls were placed too close together, and the controls could not be adequately identified by touch alone. After the publication of this 1947 report, aircraft manufacturers standardized the position of all controls, adopted and standardized shape coding for the different types of controls, and separated the controls sufficiently to avoid accidental activation/deactivation of the controls. As a consequence, accidental activation/deactivation of controls and deliberate activation of the wrong control (confusion) were greatly reduced in aircraft and still remain of little concern in modern, propeller-driven aircraft.

The solutions to the problem of accidental activation/deactivation and control confusion in aircraft can be used in intelligent vehicles. However, designing to support independent operation of automatic lateral and longitudinal control presents at least four problems not encountered in aircraft design. First, the space available in intelligent vehicles for two new controls may actually be less than in two-man cockpits. Thus, the designer may not have sufficient space to separate the longitudinal and lateral controls sufficiently to avoid accidental activation/deactivation. Second, shape coding, such as occurs in aircraft, may not be feasible in highway vehicles because the shapes tend to protrude into the operator's space, increasing the likelihood of an injury during a collision. Third, drivers compose an essentially unselected population. Consequently, the interface designer for an intelligent vehicle must accommodate a far greater range of body shapes, reach envelopes, manual strengths, and tactile sensitivity than for a selected population such as pilots while observing the potential limitations in space and control construction mentioned above. Designing to accommodate such a diverse population is a challenging task. Fourth, drivers may have less time on average to respond to confusions or accidental activations/deactivations than pilots. Thus, the limited available response time will restrict further the possible design solutions.

Confusion. Driver-vehicle interface designers must ensure that drivers can ascertain unambiguously which dimensions are under automatic control. Several methods for providing this information have been used in modern jet aircraft, none completely successfully. Indeed, Sarter and Woods (1992) attribute some of the pilots' lack of understanding of the automated flight system to poor status display indications. As noted above, any technique selected for an intelligent vehicle must work with the essentially unselected population that constitutes U.S. drivers.

Summary

Resolution of the issue concerning separability of longitudinal and lateral control should rest primarily on the ability of the driver to control the vehicle to the required tolerances and avoid collisions when separate control is used. Two potential problems—human motor cross talk and the driver-interface design—must be taken into account before automatic longitudinal and lateral control can be exercised separately.

Conclusions

The response data from the previous sections provide a serious argument against allowing drivers to operate in an IVHS without automatic control in both dimensions.

Human motor cross talk may cause inadvertent disengagement problems regardless of the separability of the dimensions unless automatic collision avoidance in both dimensions is available. Developing a driver-vehicle interface to support separable dimensional control may be difficult. Design strategies used in aviation may not be applicable to an intelligent vehicle because of differences in the nature of the population, the space available for new controls and displays, and the limited available response time. All of these problems suggest strongly that drivers should not be permitted to operate a vehicle in an IVHS using automatic control in one dimension if two-dimensional control is available.

FALLBACK SCHEMES

Before discussing problems associated with various fallback schemes, the term "fallback" must be clarified. A fallback occurs when a system reverts from a higher level of automation to a lower level of automation. Fallbacks typically occur in response to a system failure although not all failures cause a fallback. For example, Dickerson et al. (1994, p. 56) noted that the failure of the blind spot warning system would not cause a fallback in an intelligent vehicle. Instead, the driver would be warned of the failure and the vehicle operations would continue. Additionally, fallbacks may be initiated by the human operator although they are typically initiated automatically by the system itself. In a fallback, a system may revert to the next less sophisticated level of automation or to a much simpler level of automation. In some instances, the system may revert to manual control, bypassing several levels of automatic control.

Fallback schemes have serious safety implications; an improper fallback scheme may result in an accident. Several authors have noted problems with fallback schemes that revert to manual control. For example, Riley (1994, p. 35) observed that fallback schemes that revert to manual control may be inappropriate in situations where the driver is uncomfortable (high speeds) or unable (icing or low visibility) to resume control of the vehicle. Dickerson et al. (1994, p. 32) noted that the driver must be warned of the failure in time to recover from potentially dangerous situations. When dense traffic is moving at high speeds, the available time may be less than sufficient for a reversion to manual control.

Although some of the problems with fallback schemes that revert to manual control have been identified and discussed, two major classes of problems appear to have received little attention. One of these concerns fallback schemes that revert to manual control and that are caused by failures that affect the lateral or longitudinal control dynamics of the vehicle. The second is associated with fallback schemes that revert to lower levels of automation automatically. Each of these will be discussed in turn.

Fallback to Manual Control Caused by Failures of Vehicle Control Dynamics

Steer-by-wire and brake-by-wire systems have been mentioned as possible control systems for intelligent vehicles. Such systems are analogous to fly-by-wire systems in modern jet aircraft. A problem with these systems is that certain types of failures alter the vehicle dynamics in such a manner that the dynamics in one dimension are different from the dynamics in the other dimension(s). Thus, the human operator is suddenly required to perform a tracking task with different control dynamics in the different dimensions.

Human performance using different control dynamics in each dimension was initially studied by Chernikoff and his colleagues (Chernikoff, Duey, and Taylor, 1960; Chernikoff and LeMay, 1963) using two-dimensional tracking tasks. The first experiment (Chernikoff et al., 1960) had subjects perform a two-dimensional compensatory tracking task. The control dynamics of each axis could be manipulated independently, allowing the investigators to examine all possible combinations of position, velocity, and acceleration control. Conditions that used the same order of control dynamics on both axis (i.e., position-position) had significantly better performance than combinations with mixed dynamics (i.e., position-rate) in all cases except acceleration-acceleration control versus acceleration-rate control. This comparison did not reach statistical significance although the acceleration-acceleration control combination resulted in better performance than the acceleration-rate control combination.

These results were essentially replicated in Chernikoff and LeMay (1963), who found that mixed control dynamics (position-acceleration) resulted in poorer dual-axis tracking performance than same-order control dynamics (acceleration-acceleration and position-position). In this study Chernikoff and LeMay examined the effects of using one versus two control sticks. The data from this study clearly demonstrate that using two input devices to control a system with different dynamics in each axis resulted in better performance than using one input device.

Because of the clarity of the results of the studies by Chernikoff and his colleagues, only two studies addressing the issue of mixed control dynamics have been conducted recently. The first (Fracker and Wickens, 1989) has data that appear to conflict with that of Chernikoff and his colleagues; their data seem to demonstrate that tracking with a velocity-acceleration combination results in better performance than tracking with acceleration dynamics on both axes. However, no single-task data are reported and the dual-task data are actually decrement scores (the difference between single- and dual-task performance) rather than raw scores. Because no raw data are reported, the relative performance of mixed versus consistent dynamics cannot be determined from the information reported in the study. The second study (Goettl, 1991) showed poorer performance when mixed control dynamics (velocity and acceleration) are used as compared with identical dynamics (velocity on both axes). Thus, Goettl's results support those of Chernikoff and his colleagues.

Automatic Fallback to Lower Levels of Automation

Although fallback schemes involving reversions from a higher level of automation to a lower level do not appear to have been extensively examined in the context of intelligent vehicles, they have been the object of extensive study in aviation. (Appendix A describes the automated flight system of a modern commercial aircraft for the interested reader.) Possible problems in the design of intelligent vehicles may be averted by examining the schemes used in airliners and understanding the shortcomings associated with these schemes.

Modern commercial jet airliners have multiple fallback schemes involving several levels of automation. The fallback schemes involving automatic transitions from higher to lower levels of automation are called "automatic mode transitions." During flight with any level of automation engaged (except manual control), three modes typically are active at any given time. One mode controls the thrust of the aircraft, one controls the lateral movement, and one, the vertical movement. During an automatic mode transition, the aircraft senses the need for a change, makes the reversion automatically, and advises the pilot that the change has been completed. One, two, or three of the modes may change during an automatic transition.

Automatic mode transitions have been the subject of considerable study over the last 8 years. Although Wiener (1989) may have been the first to identify some of the problems associated with automatic mode transitions, Sarter and Woods (1992) have studied the problem most extensively. Because of liability issues, no data have been obtained in flight. However, Sarter and Woods conducted surveys and experiments and performed observations during simulator training sessions. One of the most distressing findings of Sarter and Woods' (1992) survey was that, despite having an average of over 900 hours of flight time in the Boeing 737-300, captains still did not understand the conditions under which automatic mode reversions occurred. This finding was supported by observations during simulator training of crews transitioning to the Boeing 737-300. Sarter and Woods attributed this lack of understanding in part to poor feedback from the displays concerning the active modes and in part to the complexity of the algorithms controlling the transitions.

In a second study, Sarter and Woods (1994) found that both experienced pilots (over 1000 hours of flight time in the aircraft of interest) and pilots just completing training had difficulty anticipating automatic mode transitions; they did not understand the conditions under which a transition could occur and could not predict the resulting modes. Sarter and Woods reported that most of these problems appear to occur under time-critical situations. Such events are infrequently encountered because they usually involve some type of system failure. Sarter and Woods also attributed these problems to the large number of possible automatic mode transitions; one modern jet airliner has over 20 automatic mode transitions.

Summary

Fallback schemes that involve transitions to manual control have two possible problems. First, as noted by Riley (1994) the driver may be unwilling or unable to resume control when necessary. Second, research on mixed control dynamics demonstrated that subjects tracked more poorly with mixed dynamics than with identical control dynamics. This result was obtained when the subjects used one control stick to control a cursor that moved in two dimensions as well as when two control sticks were used, each controlling movement in one of the two dimensions. However, no studies were found involving tracking with a hand and a foot.

Some indications about the problems that may occur with fallback schemes involving automatic reversions to lower levels of automation were obtained by examining an analogous system in commercial airliners. Pilots of these systems have problems understanding when the transitions will occur and predicting which level of automation will be active after the transition. These problems were attributed to the complexity of the algorithms governing the transitions, the number of possible transitions, and the infrequency with which certain transitions are encountered.

Conclusions

Given the operating speeds and density of traffic in a mature IVHS, fallback schemes that involve reversions to manual control after a failure of the control system of the vehicle may be implausible; the driver may be unable to control the vehicle sufficiently to maintain lane keeping and spacing. Fallback schemes involving automatic reversions to lower levels of automation are difficult to implement well. As suggested by Dickerson et al. (1994, p. 205), the number of such reversion paths should be kept to a minimum to avoid confusing the driver.

COLLISION WARNING SYSTEM DESIGN

Currently, individuals involved with designing the IVHS seem to be very concerned with the collision warning systems. The goal of any warning is to present the recipient with information to change his/her behavior. In a dynamic environment, this information must be presented in a timely manner, i.e. the recipient must have sufficient time to process and respond to the message. If the recipient has no means to respond to the message or insufficient time to respond, then the message may simply contribute to the recipient's information overload.

IVHS designers can draw several useful lessons from the design of warning systems for commercial airliners. As Billings (1997) notes, by the mid-1960's, many commercial aircraft had several hundred warnings. One crash was attributed in part to the overwhelming number of warnings presented to the pilots. After this accident, aircraft manufacturers began to rethink the design of warning systems, especially in terms of the prioritization of messages. One major aircraft manufacturer recently has gone to the extent of automatically correcting any minor malfunctions that occur. An alerting message is sent to a pilot's display, which he/she may read at any time. This system greatly reduces the number of warnings the pilot must deal with at any given time.

Much has been written about the problems of false alarms from an abstract viewpoint, i.e. Parasuraman, Hancock, and Olofinboba (1997). The practical effects of false alarms are discussed in a recent article by Carbaugh and Cooper (1996). This article documents failures of airline pilots to respond adequately to ground proximity warnings and suggests possible reasons for the poor response. In some cases, the crew turned off the warning because, based on its prior history of false alarms, they believed it was malfunctioning. In other cases, the crew did not respond quickly enough because, again, they believed it was a false alarm. Similar response failures may be anticipated on the part of drivers of intelligent vehicles.

Summary

Commercial aircraft manufacturers have attempted to reduce the number of warnings presented to pilots to reduce information overload at critical times. Several factors may affect an operator's willingness to respond to a warning, include the device's history of false alarms.

Conclusion

Given the density and the velocity of traffic in a mature IVHS, collisions probably will happen rapidly. Vehicle occupants may have little opportunity to take evasive action. Multiple collision warnings may serve only to overload the driver.

RECOMMENDATIONS

Collision Warning and Collision Avoidance

1. Collision warning systems should not be operated without collision avoidance systems if they are available.

Override Capabilities for Collision Avoidance

1. The driver should be given the capability to override the automatic lateral and longitudinal control systems to avoid objects the automatic systems may be unable to detect and to resume control of the vehicle when some element of the automatic control system fails. However, the driver should not be relied on to detect a failure of the automatic systems, override the system, and resume control of the vehicle in sufficient time to avoid collisions. Automatic systems should be used for collision avoidance.

Separation of Lateral and Longitudinal Control

1. Lateral and longitudinal control should not be operated separately, particularly if automatic collision avoidance systems are available.

Collision Warning System Design

1. Designers should use the fewest possible number of warnings. Warnings should only be presented when the driver has sufficient time to respond effectively.

Fallback Schemes

1. Fallback schemes involving reversion to manual control after a failure of the control dynamics of the vehicle should be avoided if the vehicle will have different control dynamics in the lateral and longitudinal dimensions.
2. The number of different fallback schemes involving reversion to lower levels of automation should be minimized

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APPENDIX

THE AUTOMATED FLIGHT SYSTEM OF COMMERCIAL AIRCRAFT

Because this review refers to many features of automated aircraft, a brief description of the automated flight system of a commercial jet aircraft is provided below. The purpose of this information is to allow the reader to draw informed analogies between automated aircraft and proposed versions of intelligent vehicles. The information below describes a large (100,000 lbs or more maximum gross weight), post-1980 commercial jet aircraft made by an American manufacturer.

The automated control system of a commercial aircraft fitting the description given above consists of an automated thrust (speed) control system and an autopilot system plus several other components. The thrust control system is managed by a dedicated computer. The autopilot has three levels of automation. The most computationally sophisticated level is run by one computer; the two less sophisticated levels are run by the second computer. Pilots may communicate with the computer controlling the most sophisticated level of automation by typing commands on a keypad or by dialing the appropriate numbers on a control panel located under the windscreen. The pilot communicates with the computer controlling the less sophisticated levels of automation only through the control panel.

The most sophisticated and the least sophisticated levels of automation each have one lateral and one vertical mode of operation. The intermediate level has two lateral modes and four vertical modes. Almost any combination of lateral and vertical modes may be engaged after take off. By allowing this flexibility, two different autopilot computers may be engaged in controlling the aircraft at any given time, one controlling the lateral dimension of flight and one controlling the vertical dimension. Additionally, the pilot may choose to fly semi-manually in the vertical dimension while having the autopilot retain control of the lateral mode or vice versa.

Two methods are used to indicate to the pilot which mode(s) are active. One method displays the name of the engaged mode on the primary attitude instrument. This instrument is located below the normal line of sight, and the pilot must look slightly downward to see the instrument. The second method involves illuminating the push button on the control panel that is used to engage the mode. The push buttons are located on the control panel just below the windscreen and are easy to see when the pilots are looking outside of the aircraft.

Mode changes, either within or between levels of automation, occur in two different ways. First, the pilot may choose to change one or more modes. Depending on which computer is controlling the mode of interest, the pilot may make the change by typing commands using the keypad or by pressing the push buttons and setting values on the control panel.

All major airlines train their pilots to use mode combinations that involve different levels of autopilot control (automation), and these combinations are used routinely in line flying. Older aircraft allowed manual control of the vertical dimension with autopilot control of the lateral dimension although the reverse situation was not permitted. More modern aircraft require the autopilot to be engaged in both a lateral and a vertical mode if it is engaged. However, apparently no rationale for this change has been provided.

Different methods are used to warn the pilots about failures of components of the automated flight system. Dedicated (specific) aural warnings are used to alert pilots to the failure of the most critical components. Failures of important components are usually signaled by the illumination of a centrally placed master warning light and the appearance of a written description of the failure on one of the instrument display screens. Failures of the least critical components are announced solely by a written description.