AUTOMATED HIGHWAY SYSTEM (AHS)

MILESTONE 2 REPORT

TASK C2: DOWNSELECT SYSTEM CONFIGURATIONS AND WORKSHOP #3

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NAHSC

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Executive Summary

This report documents the completion of Milestone 2 of the NAHSC program plan: *Select Feasible AHS Concepts*. This is the product of work done primarily under Task C2, *Downselect AHS System Configurations*, the second phase of the program's three phase concept development activities. This task was conducted in parallel with other NAHSC efforts to (1) define user needs by reaching out to the AHS stakeholders who will eventually build, own, operate and use the AHS; (2) develop modeling, simulation and evaluation tools; (3) develop critical enabling AHS technologies; (4) address the societal and institutional issues associated with deploying an AHS and (5) prepare for the 1997 demonstration of technical feasibility. Concept definition is an iterative process with all these activities and completing this milestone involved heavy interactions with all of them.

Concept Definition Process

The work plan for this phase of concept development was originally designed to select from the five concept families defined at the conclusion of Task C1, *Develop an Initial Suite of AHS Concepts*, a maximum of three concepts for further development. During the course of this work, it became apparent that the major differences among the five concept families could be reduced to a set of key attributes that distinguish one AHS concept from another. Rather than eliminate certain concepts prematurely on the basis of limited analyses, the Consortium concluded that it would be better to address these key attributes in detail, across the concept families, before selecting a preferred concept. Indeed, inputs from the stakeholder community led the Consortium to a key conclusion:

> *A successful AHS concept must be adaptable to meet the specific transportation needs of different regions, including urban, suburban and rural areas, while maintaining national interoperability.*

This conclusion led the concept definition work to focus on establishing the ranges of specific attributes to include within an "AHS catalog." These ranges could be defined in for each of the six principal technical design attributes:

1. **Traffic Mix** – the issues surrounding the intermixing of automated and manually driven vehicles, including decisions about shared and/or dedicated lanes;
2. **Deployment Sequencing** – the ordering and timing of the steps to advance from the current vehicle-highway system to one which supports automated operation;
3. **Distribution of Intelligence** – the allocation of sensing, computation, communications and decision making responsibilities among individual vehicles, groups of vehicles and the roadway;
4. **Vehicle Separation Policy** – the rules governing the degree of coordination among AHS vehicles: whether they operate in closely coupled platoons, as coordinated "free agent" vehicles or as independent vehicles;

5. **Obstacle Management –** the degree to which the AHS relies on the ability of the vehicles and/or infrastructure to detect roadway obstacles and the ability of the infrastructure to prevent the intrusion of obstacles; and
6. **Driver Role –** the issues associated with the division and exchange of responsibilities between the AHS and the driver, driver comfort and driver alertness.

Only one of these six attributes, distribution of intelligence, differentiated each of the five AHS concept families from the others. This provided further impetus for shifting to the analysis of key attributes.

Concept Analysis

The concept definition work included a range of analyses that provided various perspectives for evaluating the concept attributes:

- *Application Scenarios*
- *Throughput and Travel Time Analyses*
- *Safety Analyses*
- *Civil Infrastructure Cost Analyses*
- *Societal and Institutional Analyses*
- *Dedicated Lane Configuration and Implementation Analyses*
- *Mixed Traffic Operations Analyses*
- *Deployment Approach Analyses*
- *Stakeholder Perspectives*

Application Scenarios

Application scenarios are descriptions of various types of communities and/or regions in which an AHS could be deployed. These scenarios provided a context for the evaluation of the AHS attributes. The specific scenarios used in this phase of concept development are described in Section 3.3 and Appendix F. In summary, they were:

- **Urban Scenario** – represents a heavily congested roadway network encompassing major activity centers with numerous entry and exit points.
- **Inter-City Scenario** – represents an interstate highway connecting two urban centers covering nearly one hundred miles, starting and ending at the suburban edge of each city.
- **Rural Scenario** – a hypothetical highway linking two medium size urban areas that are served primarily by one major highway, covering hundreds of miles.
- **Houston Metro Scenario** – an on-going case study to determine the feasibility of automating travel on the dedicated I-10 Transit-HOV lanes, including automated bus operation.

The evaluation of AHS attributes for each of these application scenarios highlighted the importance of breadth and flexibility in the AHS concept and specifications. These analyses, along with stakeholder feedback, point toward the idea of the AHS specifications as a catalog of options for solving diverse transportation problems. Different parts of that "catalog" might be used at different times and places, and sometimes even in different sequences. Each potential AHS deployer could follow its own decision tree in deciding what aspects of AHS to deploy and when to deploy them, while still maintaining national interoperability through adherence to the AHS system specification. This makes the development process more complicated, but greatly increases the likelihood that AHS will be able to serve a diverse set of needs. The application scenarios validated that AHS technologies can provide benefits in many types of applications.

Throughput and Travel Time Analyses

These analyses used modeling tools developed by the NAHSC to determine the sensitivity of system throughput and travel time to variable AHS characteristics. The models used included the *Pipeline Analysis Model*, the *Travel Time Determination Model*, the *Mixed Traffic Model*, and the *Merge and De-merge Analysis Model*. Throughput for an AHS was compared over ranges of the following parameters:

- *Level of communications among vehicles*
- *Consistency of braking performance among vehicles*
- *Shared knowledge of each vehicle's braking capability*
- *Percentage of heavy vehicles in the traffic stream*
- *Frequency of entries and exits*
- *Merging protocols*
- *Inter-vehicle spacing policies*
- *Whether or not platoons are supported*
- *Number of vehicles in each platoon*
- *Operating speed*

The results of these analyses showed that, ignoring merging and de-merging, the maximum throughput of non-platooned vehicles can vary from 1,500 vehicles per hour per lane (vphpl) (Table 4.1-4, high-speed autonomous vehicles), to over 5,000 vphpl (Table 4.1-8, non-uniform spacing strategy, passenger vehicles only). The maximum throughput of platooned vehicles can vary from 2,300 vphpl (Figure 4.1-4, two-vehicle platoon at 40 m/sec.) to over 11,000 vphpl (Table 4.1-5, 10-vehicle platoons, small differences in braking capability, no trucks). These compare to a nominal maximum throughput of 2200 vplph for non-automated vehicles (no trucks). Mixing automated vehicles in manual traffic produces very little increase in throughput over the nominal value until the proportion of automated vehicles exceeds 50 percent (Figures 4.1-11 and 4.1-12, and Appendix I).

Maximum throughput is not influenced as significantly by the time delays associated with alternate communication, sensing and data processing technologies within reasonable values. For example, increasing the 20 ms inter-vehicle communications delay by 30 ms does not significantly change performance. Increases over 100 ms, however, can have a noticeable effect. The findings in Section 4.1 and Appendices G and H provide guidance regarding these parameters and their effect on maximum throughput.

Safety Analyses

The *Hard Braking Analysis Tool* was used to determine the effect of various AHS characteristics on overall system safety, assessing the probability and severity of vehicle to vehicle rear-end collisions. The analyses were based on a maximum braking scenario where a lead vehicle suddenly fully engages its brakes, and the following vehicle must avoid a collision with it. A hard braking situation would be extremely rare, occurring only as a result of certain AHS malfunctions or system intrusions, and collisions would only occur for a fraction of the hard braking cases.

Calculations were made for a wide variety of assumptions, including the assumption that the following vehicle was manually driven. It was found that AHS vehicles are significantly safer in this situation than are manually driven vehicles. One of the analyses in Section 4.2 (Figure 4.2-6) shows that at 30 m/s an alert driver is over 8 times more likely to have a collision in a maximum braking situation than is a highly-cooperative, non-platooned vehicle; and would experience a 20% higher speed at collision. Another analysis (Figure 4.2-8) shows that the severity of collisions in a maximum braking situation would be an order of magnitude lower for certain platooned vehicles than for a manually driven vehicle with an alert driver, but these minor collisions would be three times more likely to occur. The platooned vehicle analysis addressed only collisions of the first two vehicles. Later analyses will address the dynamics of the complete platoon.

More broadly, the relationship between safety and throughput was investigated. There is a trade-off between throughput and the frequency of collisions (Figure 4.2-11), and another trade-off between the frequency and severity of collisions (Figure 4.2-10). When both frequency and severity of collisions are considered together, it becomes apparent that significant throughput increases can be gained with only relatively minor effects on safety (Figure 4.2-13).

Civil Infrastructure Cost Analyses

A method for costing AHS infrastructure was developed and was applied to the application scenarios in Section 4.3. For the urban scenario, five different variations were estimated.

It was determined that the AHS infrastructure would be very similar to contemporary High Occupancy Vehicle (HOV) lane infrastructure. As with the HOV lanes, the costs of building new AHS infrastructure would vary widely depending on specific local

circumstances. There were, however, some broad conclusions reached as a result of this initial cost analysis:

- *Site-specific characteristics are the biggest determinant of AHS infrastructure cost, as they are for the cost of all highways.*
- *The right of way required for a given maximum throughput is significantly less for a highway that includes automated lanes than with for a highway with only conventional lanes.*
- *In locations that are already heavily congested, AHS vehicles should have separate access and egress ramps in order to avoid the merging conflicts produced by transition lanes.*
- *Even using the most pessimistic assumptions about AHS lane construction costs and a conservative AHS maximum throughput of 4000 vehicles per lane per hour, an urban freeway network with AHS lanes and special AHS-to-AHS freeway interchanges can be built at a cost no greater than expanding the conventional freeway network to have the same maximum throughput.*
- *Increasing the level of intelligence used to coordinate merging of automated traffic streams reduces the length of the merge ramps that are needed.*
- *There are not yet special design standards for AHS infrastructure, so the cost estimates assumed today's design standards. It is likely that AHS-specific infrastructure design could lower the cost per mile for the AHS civil infrastructure because of the precise control of lateral positioning and speed of AHS vehicles.*

Societal and Institutional Analyses

A broad range of societal and institutional factors were addressed in evaluating the key attributes. Specific issues included:

- *Public-private roles in owning and operating an AHS*
- *Responsibility for developing new regulations and standards for AHS*
- *Cost and performance comparisons with conventional highway lanes*
- *Environmental aspects of AHS*
- *Sharing of liability and risk*

These issues are really not very different from those of conventional new highway systems and many of the answers will likely be familiar. During this phase of concept development progress was made in answering these and similar questions. These issues will continue to receive attention as the program proceeds.

Ownership and Operation – This will likely vary by location for the roadway and support infrastructure. Options range from public ownership and operation funded by the highway trust fund or other taxes, through various public-private partnership approaches, to total private ownership and operation funded by tolls. Specifics cannot be resolved until plans are developed for deployment in a given location. This issue is included in the AHS case studies that are underway.

Standards and Regulations – An AHS may require national standards in several areas including:

- *Sensing,*
- *Communications,*
- *Vehicle performance,*
- *Driver interface, and*
- *Periodic vehicle inspections*

It is too early to define all of the areas in which standards will be required and development of AHS standards will not begin for some time. Nevertheless, the NAHSC is working with ITS America and standards organizations on standards in related technologies that will be relevant to AHS. The major short-term goal is to support standards that are consistent with viable AHS designs.

Competitive Cost and Performance – AHS must exhibit economic performance superior to conventional approaches to providing similar levels of safety and capacity or it will not be deployed. As the AHS system concept becomes better defined in the next phase of development, costs and performance can be better assessed. Results in this phase show clearly that an AHS offers superior performance and that the infrastructure costs will be competitive. More accurate projections will be developed shortly.

Environmental Effects – Two studies were carried out to investigate high priority environmental issues:

- *AHS Land Use Panel – This Panel of experts on land use and transportation, convened August, 1996 at CMU, concluded that AHS would have minimal impact on land use since it will be a relatively small part of a well established surface transportation system.*
- *Fuel and Emissions Reduction Study – A study at the University of California at Riverside showed, under defined conditions, that platooned vehicles could reduce emissions and fuel consumption per vehicle-mile-traveled by up to 25%. compared to individual vehicles (Figures 4.4-2, 4.4-3).*

Liability and Risk – The overall losses due to crashes should be significantly less on AHS lanes than on conventional highway lanes with comparable capacity. When crashes do occur, the assignment of liability could be different from today. Drivers will be responsible for ensuring that their vehicles are in sound operating condition but crashes due to driver error will be virtually eliminated. Any AHS crashes that do happen will most likely occur due to system malfunctions or intrusions. Thus while the total liability costs should be much less, the share of liability costs assigned to system developers and operators could increase, while those assigned to drivers would decrease. A two day conference is planned for early 1997 to address this issue.

Dedicated Lane Configuration and Implementation Analyses
A variety of configurations were explored for dedicated AHS lanes. Possible deployment paths were developed for each configuration and analyzed for technical, social and economic feasibility.

The analyses showed that AHS roadway design has many characteristics that are similar to today's HOV lanes. It was concluded that the specifics of an AHS roadway design are very site-specific; this means that the design efforts for the AHS case studies will provide a valuable opportunity to develop designs for different environments and to resolve some of the design issues. The AHS program will not define a single solution or design, but will identify a range of options from among which transportation agencies can select; for example:

- *Roadway alignments*
- *Access and egress ramp locations and configurations*
- *Policies for mixing heavy and light-duty vehicles*
- *Strategies for coordinating AHS with other expressways and surface roadways*
- *Operating policies for safety and throughput.*

The development of design standards for the AHS civil infrastructure will require continued research and development to determine the safety, feasibility and cost of possible AHS-unique characteristics such as narrower lanes, guideway-like designs, special barriers and "sensor-compatible" designs.

Mixed Traffic Operations Analyses
One of the most difficult issues addressed as part of this effort was whether fully automated vehicles could share lanes with manually driven vehicles in "mixed traffic operation." This is an important question because there could be major advantages if this were possible:

- *Transition to fully automated vehicles would be easier, with early customers seeing immediate benefits.*
- *Dedicated lanes would be built only as congestion levels and the number of automated vehicles on the roadway justified them.*

The challenges of mixed traffic operation include:

- *The technical feasibility of operating automated vehicles in an unstructured environment*
- *Significant improvement in maximum lane throughput occurs only when the proportion of automated vehicles exceeds fifty percent*
- *The ability of automated vehicles to respond in a timely way to the uncoordinated actions of manually driven vehicles*

- *The ability of individual automated vehicles to detect obstacles, determine if they must be avoided, and take evasive action in an environment of other potentially non-cooperating vehicles.*

More investigation is needed to determine the feasibility of mixed traffic operation. Because of the deployment advantages of mixed traffic operation, it was concluded that the area should be studied further in the next phase of concept development.

Deployment Approach Analyses

A progressive deployment path for AHS, one that moves in manageable stages from today's vehicles and highways to vehicles and highways that support automated operations, must be:

- *Technically feasible*
- *Socially, institutionally and politically feasible*
- *Capable of providing a satisfactory cost/benefit ratio for all key decision makers at each stage in the path.*

Issues of deployment staging are among the most difficult and controversial ones involving AHS, and are of intense interest to the stakeholder community. Many uncertainties remain around most deployment issues, but the following have been reasonably well established:

- *AHS deployment will not follow a single uniform sequence in all places; rather there will be a diversity of deployment sequences based on local needs, capabilities and decision processes.*
- *The AHS infrastructure development process can be managed in the same ways as conventional infrastructure development projects.*
- *There is a significant step in moving from partial to full automation because of the fundamental change in the role of the driver. This step must be taken before partial automation features lead to a reduction of driver involvement sufficient to detract from driver attentiveness.*
- *The primary technological impediments to full automation in mixed traffic appear to be the lack of comprehensive obstacle/hazard detection and avoidance capabilities and the difficulty of detecting and responding to the wide variety of actions that may be taken by the surrounding manual drivers.*

Stakeholder Perspectives

A *Concept Development Workshop* was held in September, 1996. At the Workshop, program progress, status and concept decisions that were about to be made were presented to a broad range of stakeholders for review and comment.

The stakeholder comments significantly impacted the remainder of the concept development effort. Their identification of special challenges and concerns of their stakeholder communities made it very clear that the AHS must be tailorable to meet regional needs. The stakeholders were also very interested in having the non-technical attributes defined and evaluated, including issues such as: user needs, who will be responsible for each aspect of AHS deployment and operation, how liability will be handled, financing options and other socio-economic considerations. In general, the stakeholders from outside the NAHSC, especially those from state transportation agencies, showed particular interest in:

- *The socio-economic characteristics of the AHS;*
- *Understanding the differences between AHS and conventional transportation alternatives; and*
- *The deployment path to AHS.*

A focus group of stakeholder representatives formulated a set of eight recommendations for the AHS program:

1. *Develop AHS options in a needs-driven, market-responsive process;*
2. *Stress incremental deployment of AHS to facilitate user acceptance, risk management, flexibility, timing, and coordination of all parties concerned;*
3. *Include institutional and legal aspects as AHS concept attributes;*
4. *Evaluate AHS options in terms of real-site case studies, and include interfaces into the existing surface transportation system;*
5. *Consider a broad range of primary benefits, including safety, productivity, and capacity, as well as broader economic, social, and environmental benefits;*
6. *Develop AHS options in the context of other transportation improvement options in the same way they will be evaluated for actual implementation; that is, by comparing with conventional options, within budgetary constraints, as part of the mainstream transportation development process;*
7. *Address liability and risk management as key issues in the development of AHS options; and*
8. *Become a central, proactive agency in standard setting, specifying how and when standards are to be established and implemented.*

Open Issues

Some of the principal constraints and trade-offs among the concept attributes have been defined by the work reported here, significantly increasing our understanding of the feasibility of different alternatives. Many other important issues remain unresolved and will be explored in greater depth in the next phase of concept development in order to lead to an overall AHS architecture and clear guidelines for each of the attributes in the AHS catalog. Chief among these issues are:

- *The absolute level of AHS safety needed and achievable;*
- *Maturity and costs of AHS technologies;*
- *Time phasing of AHS technical capabilities;*
- *Maximum throughput levels needed and achievable while remaining compatible with the rest of the transportation network;*
- *Relationship between public benefit of increased throughput and individual benefit of reduced travel times;*
- *Complete definition of driver capabilities and roles in normal and abnormal conditions;*
- *Deployment sequencing of infrastructure and vehicle capabilities;*
- *Trade-offs between vehicle-vehicle and vehicle-roadside coordination of maneuvering and traffic flow;*
- *Stakeholder decision priorities and willingness to pay for various AHS and pre-AHS services.*

1. Introduction

This report serves as the deliverable to satisfy Milestone 2 of the NAHSC program plan The original stated purpose of the Milestone was to define the selection of three AHS concepts for further development. This is primarily the product of the work done under Task C2 of the NAHSC plan, which is the second phase of the concept definition activities.

1.1 Relationship of Milestone 2 and Task C2 to the Overall NAHSC Workplan

The NAHSC work plan includes multiple parallel paths, as shown in Figure 1.1.

- Societal and Institutional Evaluations (Task B6)
- Enabling Technology Development (Task B3)
- Design and Evaluation Tool Development (Task B5)
- Feasibility Demonstration (Task D2)
- Concept Development (Tasks B1, C1, C2, C3, C4) and Prototype Development (Tasks EX)

The latter form the central thrust of the workplan, leading from the initial definition of AHS goals and objectives to the final definition of the specifications for the AHS. The other tasks generally support the concept and prototype development work by providing the needed input information, tools and technologies.
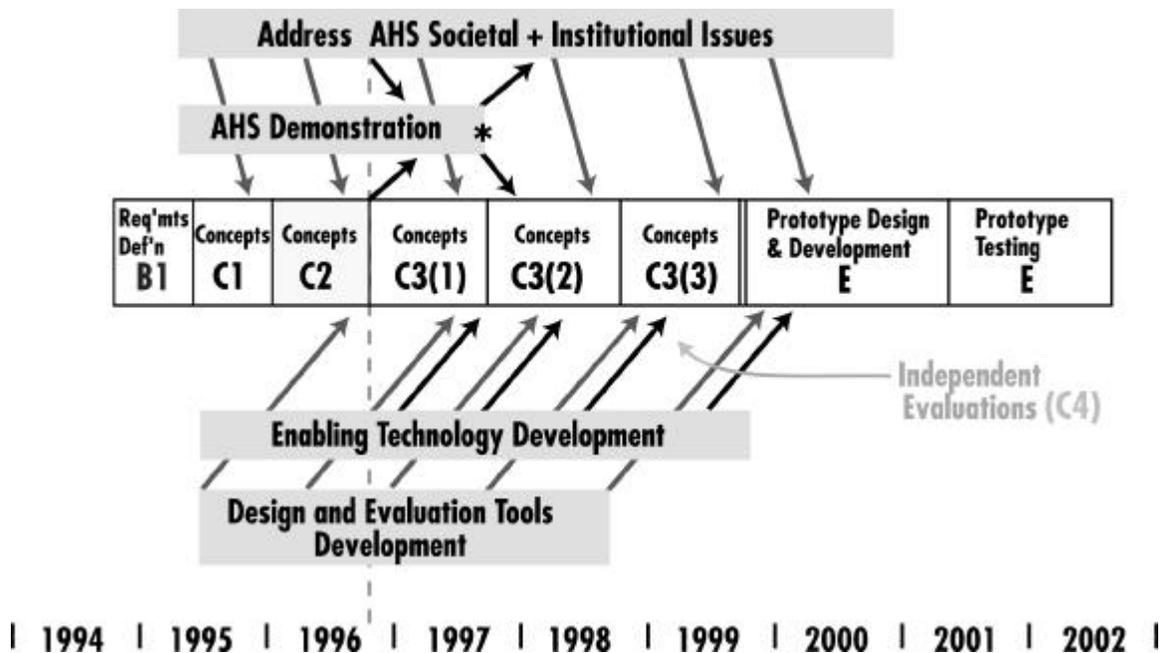
Figure 1.1. Concept Definition in NAHSC

Task B1 led to the generation of the System Objectives and Characteristics Document, describing the broad outlines of what AHS should do and be. Its conclusion corresponded to Milestone 1. Task C1 began with the definition of a very wide range of possible AHS configurations, which were eventually distilled to five concept families for further evaluation during Task C2. The work on concept definition and elimination during Task C1 is described in an extensive report on that Task (Ref. 1-1). The five concept families from Task C1 were the principal inputs to the start of Task C2. Task C3 will pick up from where C2 left off. It will consist of three phases as shown as C3(1), C3(2), and C3(3) on the chart.

1.2 Summary of Task C2 Workplan

The first stage of Task C2 work (Subtask 1) was the refinement of the definitions of the five concept families that were specified at the end of Task C1. Separate teams worked on filling in many of the specifics about each concept family, including the progression of deployment steps that would lead to a full AHS capability for each. The concept descriptions were reviewed by the entire Concepts team, and critical questions were raised about each concept family in order to identify potential weaknesses, as well as to better understand similarities and differences among the concepts. This led to further refinements of the concepts, which all became quite broad and flexible, as well as less dissimilar.

The second stage of work (Subtask 2) was the definition of application scenarios that could serve as the basis for comparative evaluations of concepts. These were designed to represent the diverse environments in which AHS could be applied to improve transportation operations:
- urban highway network
- intercity highway corridor
- rural highway corridor
- urban transit/HOV lane.

The third stage of Task C2 (subtask 3) was focused on a series of cross-cutting studies of key issues for all of the concepts:
- effects of vehicle separation policy on safety and throughput
- infrastructure development costs
- institutional issues related to AHS implementation.

Additional cross-cutting issues were identified but received only limited attention because of limitations of time, staff, relevant available data and resources:
- human factors and driver involvement in AHS operations
- vehicle costs
- customer willingness to pay for AHS products and services
- comparison of technology capabilities to concept needs
- definition of time-staged deployment sequences.

Subtask 4 of Task C2 was the definition of the concept evaluation methods and measures of effectiveness. Methodologies such as generalized cost-benefit analysis, Analytical Hierarchy Process (AHP), Multi-Attribute Utility Theory (MAUT) and Social Decision Analysis (SDA) were considered. The limitations of the available information about AHS made it difficult to apply any of these in a comprehensive fashion, but in the end there was a limited use of SDA to establish the importance of different issues to a focus group of stakeholder representatives.

In the course of the concept evaluation studies, it became apparent that the five discrete concept families would not be the most effective baselines for comparison, so the focus was shifted to the identification of the most fundamental concept-distinguishing attributes. These attributes served as the focus for the main body of the evaluations, because they most clearly indicate the differences among alternative approaches to AHS and their effects can be distinguished most clearly.

The results of the evaluations were presented at AHS Workshop #3 in Minneapolis in September 1996, where they were discussed at length in breakout sessions. These breakout discussions, together with the stakeholder focus group discussions, provided further inputs to the concept definition work that is documented in this report.

1.3 Milestone 2 Accomplishments – Task C2 Completion

The workplan for Task C2 was designed to lead from the five starting concept families to a downselection to at most three concepts for further development work. In the course of the work, it became apparent that the key issues that distinguish one AHS concept from another would be better studied individually rather than having multiple differences in attributes confuse the comparisons of the different concept families. The key attributes for evaluation are:

(a) Fully automated operations in dedicated lanes only, or mixed with manual traffic;
(b) Deployment sequences and timing;
(c) Distribution of intelligence and communication links (primary attribute to distinguish the five concept families);
(d) Operations in tightly-coupled platoons or as loosely-coupled individual vehicles;
(e) Obstacle detection and avoidance or obstacle exclusion;
(f) Driver roles and intervention opportunities.

The primary attribute that distinguishes the five concept families does not stand out from the others in this list, reinforcing the importance of the shift in emphasis to concentrate on the key attributes.

The concept evaluations for the different application scenarios and the inputs from the stakeholder community have highlighted the importance of breadth and flexibility in the definition of AHS. This makes it appear much less likely that the AHS will be a single

narrowly-defined design, but rather leads toward the idea of AHS as more of a catalog of alternatives for solving diverse transportation problems. Different parts of that catalog might be used at different times and places, and sometimes even in different sequences. Each potential AHS deployer could follow its own decision tree in deciding what aspects of AHS to deploy and when to deploy them. This makes the development process more complicated, but appears to greatly increase the likelihood that AHS will be able to serve a diverse set of needs.

The foregoing means that it is no longer appropriate for Task C2 to define a set of three discrete and competing AHS concepts to serve as the basis for a subsequent down-select to choose the "final" concept. Rather, the concept definition task now needs to focus on bounding the range of reasonable attributes to include within the AHS catalog and defining an architecture to support interoperability. These bounds are best defined in terms of the six principal attributes listed above for purposes of technical designs. The stakeholders are also very interested in having the non-technical attributes defined for the toolbox, including issues such as who has responsibility for each aspect of AHS development and operation, means of addressing liability concerns, and financing options.

Some of the principal constraints and trade-offs with respect to the concept attributes have been defined within Task C2, significantly increasing our understanding of the feasibility of different alternatives. However, many important issues remain unresolved and must be studied in greater depth in Task C3 in order to lead to clear definition of each of the dimensions of the AHS catalog.

1.4 Overview of the Remainder of the Report

The remainder of this report documents the accomplishments within Task C2 and some related tasks in each aspect of AHS concept definition. The results and conclusions are reported in the chapters in the main body of the report, while more detailed supporting data are contained in the Appendices.

Chapter 2 – Summary descriptions of the five concept families, with more detailed descriptions in Appendices A-E.

Chapter 3 – Description of the concept analysis process and some of its key issues, such as the selection of evaluation criteria or measures of effectiveness (MOEs); definition of the application scenarios and key concept-distinguishing attributes; and updates to the AHS system requirements based on the knowledge gained during Task C2. More detailed descriptions of the application scenarios are contained in Appendix F and the stakeholder focus group results are described in Appendix Q.

Chapter 4 – Summary of results of most significant cross-cutting analyses, including trade-offs, key issues and constraints. The topics addressed here include the analyses of throughput and travel time trade-offs with safety, the evaluation of infrastructure costs,

and the reviews of human factors, societal, institutional, energy and environmental issues. The more detailed descriptions of analyses, assumptions and comprehensive results to back these up are contained in the Appendices G - M.

Chapter 5 – Review of technology assessments accomplished to date.

Chapter 6 – Identification of issues specific to dedicated-lane AHS operations.

Chapter 7 – Identification of issues specific to automated operations mixed with manual traffic.

Chapter 8 – Definition of alternative approaches to time-staging deployment of AHS.

Chapter 9 – Summary of issues that have been resolved by the work in Task C2 and the issues that remain unresolved.

Chapter 10 – Description of the catalog of concept attributes to continue studying in Task C3.

Chapter 11 – Summary of lessons learned about the AHS concept attributes and the concept definition process.

Chapter 12 – Description of next steps to take in concept definition work.

2. Summary Descriptions of Concept Families

The basis for the first stage of work in Task C2 has been five concept families, which were developed as the principal outputs of Task C1. These concept families primarily differ by their distributions of intelligence among vehicles and roadside infrastructure, but some attributes will be common across all of the concepts, and these differences provided the initial framework for analyzing the effects of concept characteristics on AHS performance, cost and safety.

Each concept family can be customized for a range of applications. In particular, each concept can be adapted to urban, inter-urban, or rural areas, to dedicated transit or commercial trucking lanes or to lanes with mixed classes of vehicles. Each concept offers options for physical infrastructure, which will be a local decision. The following features are common to the five concepts.

- AHS will take full advantage of any deployed ITS services.

- Once the vehicle is in automated mode, the driver will be disengaged from driving tasks.

- Each automated vehicle will be responsible for lane-keeping and maintaining longitudinal separation.

- The automated vehicles will have a manual mode, in which they will operate on any conventional road like other vehicles.

Summary of the Five Concepts

The following is a brief summary of the five concepts, considered in sequence of increasing intelligence assigned to the infrastructure.

Independent Vehicle Concept. This concept is built around the idea that incremental deployment requires vehicles that can be independently upgraded and that can operate automatically when mixed with manual traffic. This requires vehicles to do a high degree of autonomous operation, utilizing on-board sensors and computers. While the vehicle is capable of using data from roadside systems, it does not depend on infrastructure support to operate.

Cooperative Concept. This concept is built around maximizing communication with other AHS-equipped vehicles to achieve the best throughput and safety. It assumes that with the projected growth in computation and communications, vehicles can do everything on-board. This concept is similar to the Independent Vehicle Concept, however, in terms of degree of infrastructure support required for AHS operations.

Infrastructure Supported Concept. The Infrastructure Supported and Infrastructure Assisted concepts require the degree of active infrastructure to greatly improve the quality of AHS services and better integrate AHS with local transportation networks. The Infrastructure Supported Concept envisions automated vehicles on dedicated lanes which can use infrastructure intelligence and global information to support the vehicles' decision-making and operation.

Infrastructure Assisted Concept. This concept goes beyond infrastructure support to a system where two-way communication between an individual vehicle and the highway infrastructure allows the roadside system to assist inter-vehicle coordination during entry, exit, merging and emergencies.

Maximally Adaptable Concept. This concept is built around an AHS that provides a wide range of compatible standards, leaving as many of the architecture decisions as possible as individual stakeholder options. The concept envisions local jurisdictions tailoring vehicle and infrastructure systems from four basic modules or layers to suit their specific needs. To ensure compatibility, standards for system options would be established.

The descriptions of the five concept families that follow include identifications of strengths, weaknesses and deployment sequences based on the inputs from the developer-advocates of each concept. These should <u>not</u> be interpreted as NAHSC conclusions about the respective concept families or AHS in general.

2.1 Independent Vehicle Concept

Concept Vision

The Independent Vehicle Concept is based on fully automated vehicles operating within, and evolving from, the existing manual system. With this concept, autonomous vehicles are deployable on all freeways as soon as the technology is available. Deployment will not be dependent on building new or converting existing infrastructure. Instead, it is based on introducing partial automation capabilities into the existing system and evolving from those capabilities into fully automated systems.

Four key factors motivate this concept:
- The near-exclusive use of existing infrastructure
- No central control and no loss of privacy issues
- Incremental deployment through operations in mixed traffic
- Automation features to provide enhanced safety when used off the highway

Other than ITS services, which may be present in local jurisdictions, the infrastructure has no access to vehicle-specific origin/destination information and no knowledge of who is driving on the roadway. This concept does not provide for vehicle-to-vehicle nor vehicle-

to-infrastructure communication; however, it does support ATIS. Vehicle-to-vehicle communication may become a requirement for emergency situations.

Features and Attributes

The Independent Vehicle Concept suite of equipment includes devices for on-vehicle lane-determination and lane-keeping, longitudinal control, obstacle avoidance, and route determination. The fully autonomous vehicles are capable of driving in and around manually driven vehicles on all freeways, and can employ limited capabilities such as obstacle- and lane departure-warning on arterials and local streets.

Existing infrastructure is used without additional sensors, infrastructure-based communications systems, or new civil infrastructure needed.

Deployment Stages

Initial deployment. In this *Pre-AHS* phase, vehicle capabilities are used for obstacle warning, adaptive cruise control, and lane departure warning. These technologies are not integrated into a fully automated system, and the driver is ultimately responsible for the control of the vehicle.

Early Phase. In the *Early AHS* phase, lateral control, longitudinal control, obstacle avoidance, and lane-determination are integrated to create autonomous vehicles that can operate with existing manual traffic. The driver is fully disengaged. Where ATIS is available, the vehicle will make use of that information for route guidance and planning, while still maintaining privacy about vehicle identity and destination. Privacy is maintained through all stages of deployment and use.

The Early AHS can be broken into two distinct parts, the *Urban AHS* and the *Rural AHS*. This distinction is based on the existing roadway configurations, as the implementation will be different depending on the number of lanes available. On urban freeways where three or more lanes are available, it will be possible to convert the left-most lanes to automated traffic flow. This will only occur where market penetration warrants the "dedication" of an existing lane to AHS use. The remaining lanes will continue to operate with a mix of both automated and manual traffic.

Many rural freeways have only two lanes in each direction, distinguishing them from multi-lane urban freeways. Because manual vehicles will need to retain the ability to pass using the left-most lane, it is impossible to dedicate that lane for automated use only. The rural AHS, therefore, will continue to have a mix of manual and automated vehicles on all lanes.

End State. As more manual vehicles are retired from service, an increase in automation will be seen throughout the nation's freeways. Eventually, this will lead to a fully automated system which can continue to handle manually driven vehicles. This last phase

is known as the *End State AHS*. Automation capabilities will continue to evolve and expand to the side-streets and arterials as the technologies and on-board algorithms progress to handle these types of traffic situations.

Benefits and Limitations

Assuming technical feasibility, this concept is devised to be deployable and marketable without any new infrastructure development, as it would work with mixed traffic. It is also designed to be flexible to accommodate local needs. The benefits relating to deployment and market penetration are listed below.

- Because dedicated lanes are not promoted, the paradigm of building dedicated lanes without vehicle market penetration is eliminated. Likewise, users need not wait for dedicated lanes to be built or set aside before buying automated vehicles. This eliminates the concern that user groups will not be tolerant of congestion on manual lanes if the automated lanes go unused.
- Local and state highway operators can decide when and if to convert lanes based on local needs, impacts, and benefits.
- The trucking industry and passenger vehicles which heavily utilize the rural interstate system will not be limited in their access to the AHS system.
- Transit vehicles will benefit from automated capabilities early in the deployment process.
- "Check-in" and "check-out" procedures involving infrastructure support will not be required.

Key social equity, practical application, and environmental concerns are addressed below.

- The Independent Vehicle Concept's flexibility will be appealing to state and local governments who wish not to build or convert lanes.
- Users will experience benefits without waiting for dedication of lanes. The gradual introduction of automation will foster perception changes that alleviate user fear and lead to wider market acceptance.
- The emphasis on the maintenance of individual privacy will be appealing to many users and advocacy groups.
- The system will be convenient and available to all, regardless of geographical location.
- Rural users will enjoy AHS, as will urban users that travel routes where dedicated lanes are not available.
- There are no new roads to be built to implement this concept. Additionally, there is no encouragement of new development around new entry/exit points.
- This concept makes public financing less of an issue.
- Safety and throughput enhancements are achievable over the current manual system, at higher market penetration levels.

Lastly, it is important to note the constraints and limitations of this concept.

- The Independent Vehicle concept will require more thorough inspections of vehicle than is currently standard.
- This concept is based on the premise that it is technically feasible for automated vehicles to operate within mixed traffic.
- The vehicles will be more complicated and expensive than vehicles that rely on the infrastructure for some functions.
- Throughput is not significantly increased.
- Flow control and the ensuing savings in fuel economy and emissions are not addressed.
- The liability burden shifts from the driver to equipment suppliers and vehicle manufacturing companies.
- The primary mixed traffic issues--obstacle detection and how to handle unpredictable drivers--remain open.

2.2 Cooperative Concept

Concept Vision

In the Cooperative Concept, vehicles use on-board sensors and computers to drive, and share information among other AHS-equipped vehicles to coordinate maneuvers for safety and high throughput.

The first of two major premises of the Cooperative Concept is that AHS vehicles will require sufficient sensors, computers and communications to drive with close headways, to coordinate immediate responses to contingencies as they unfold in congested traffic, and to detect and avoid obstacles. With those capabilities, it is presumed to be a minor extension for the vehicles to do all the necessary decision-making for AHS, thus removing any requirement for roadside infrastructure intelligence. Deployment may unfold much faster since the rate will depend on individual purchase decisions, not infrastructure investments. The Cooperative design does not prohibit infrastructure intelligence as a local option, but does not rely on that option for feasibility.

The second major premise of the Cooperative Concept is that falling costs, especially for computers, will make the necessary sensing, computation, and communications affordable.

The concept expects the final AHS standards will define how vehicles interact. These interactions are primarily defined in the communications protocol. The Cooperative Concept defines how vehicles cooperate and what messages are passed.

Features and Attributes

The following are key features and attributes of the Cooperative Concept.

- The Design-For-Cost target is AHS as a new vehicle option available after 2010 for under $1000 in FY-96 dollars.
- Vehicles will have several on-board sensors (e.g., radar and vision sensors) to "see" the road and what is going on around them.
- Vehicles can use ITS services where available, for example, to obtain real time traffic information about the roadway ahead.
- Vehicles continuously communicate with each other about their actions and with information on the surrounding situation.
    - Vehicles pass information up and down traffic lanes, summarizing as the information travels further away;
    - Vehicles do not repeat information which has already passed through.
- Each vehicle keeps track of what is going on around it, with considerable detail about the immediate area, and decreasing detail further away.
- The national AHS standard will specify how vehicles behave, while leaving internal designs to be decided and improved in the market.
- Operating rules are established to ensure vehicles are coordinated smoothly. For example, if a vehicle asks for a lane change, the rules tell vehicles in the adjacent lane to yield as appropriate.
- The concept facilitates adherence to operating rules, since many vehicles can see what an individual vehicle is doing.
    - For example, if a vehicle is supposed to yield in accordance to AHS protocol and does not, nearby vehicles will be aware that the vehicle is not following established protocol and is possibly malfunctioning. Communication among surrounding vehicles will identify this vehicle so they can stay clear.
- Operating rules lead vehicles to rapidly poll on a joint response to problems, such as failed vehicles or obstacles on the roadway.
- Vehicles can safely drive automatically on regular lanes with regular traffic.
    - Obstacle detection technology is critical in determining when technology has advanced enough to do this.
- On dedicated AHS lanes, cooperative vehicles can drive closely, thereby increasing throughput on lanes.
- The use of platooning is an option for the Cooperative Concept, contingent on safety and throughput requirements.

Deployment Stages and Time Frame

The Cooperative Concept envisions four major time frames, with two parallel tracks running through them. The two tracks are Dedicated Lanes and Mixed with Manual Traffic.

	Prototype & Early Automation	Operational Test & Enhanced Automation	Full AHS	Follow-on AHS
Dedicated Lanes	Prototype testing, Development for Operational Tests	Operational Test of AHS in dedicated lanes	Relieve congestion on very high traffic corridors where appropriate	Option for subsequent development; details TBD until after National Rollout
Mixed with Manual Traffic	Commercially available pre-AHS vehicles and systems	Commercial systems; Possible Operational Test; Full automated driving if privately offered	National AHS on remaining highways; smaller local deployment step	Option for subsequent development; details TBD until after National Rollout

△
National AHS
Rollout

First Phase. The prototype AHS is evaluated, the draft national standard for AHS is refined, and Operational Tests are defined and built. Meanwhile, precursor automation products such as adaptive cruise control and obstacle warning systems are sold in the commercial market.

Second Phase. Operational Tests are conducted, and the results used to finalize the national AHS Standard in support of a national AHS rollout. Meanwhile, the commercial automated precursors will become increasingly sophisticated and robust. The earlier release of a draft national AHS standard will help make vehicle automation upwardly compatible with AHS.

Third Phase. This stage is the full AHS envisioned in the Cooperative Concept, with operation on dedicated lanes where necessary, and operation nationally on ordinary highways once technically feasible.

The Cooperative Concept recognizes that continued increasing AHS functionality is desirable, and explicitly makes provisions to support subsequent phases to be designed and developed after full AHS deployment.

Benefits and Limitations

All the concepts share the generic benefits of being Automated Highway Systems. Benefits of the Cooperative Concept that are not shared with all the other concepts include:

- Allows AHS operations without dedicating a separate AHS-only lane
- Drivers can use Cooperative vehicles for automated driving on any highway
- Supports the local option of dense traffic on dedicated lanes for very high throughput

- Some options, such as having roadside merge control, could be offered, but are not now included
- Vehicles communicate nearby traffic conditions
- Allows detailed maneuver coordination
- Maintains situational awareness in the vehicles at all times
- Helps when driving in manual traffic when another Cooperative vehicle is nearby

Potentially unique disadvantages of Cooperative are:

- May impose some slightly higher lateral control infrastructure standard on all highways, not just dedicated AHS lanes
- May require that vehicles guarantee smaller uncertainty in their braking capabilities.
- Requires significantly higher communication capabilities (and spectrum) than other concepts.
- Assumes technical feasibility of channel hopping coordinated among large numbers of vehicles.

2.3 Infrastructure Supported Concept

Concept Vision

The Infrastructure Supported concept envisions automated vehicles on dedicated lanes. These vehicles use infrastructure intelligence and global information to optimize AHS operations. In its mature deployment, the Infrastructure Supported AHS concept is designed to support fully automated vehicles on dedicated lanes to safely and effectively increase throughput. The concept has special options for congested urban, inter-urban, and rural highways.

This concept proposes that automated vehicle cost, complexity, and development and operational risk be reduced by operation in dedicated lanes, with physical separation from other traffic. The concept also proposes that by coordinating vehicle platoons, throughput can be significantly increased while maintaining safety.

The Infrastructure Supported Concept is designed to:

- Minimize costs of automated vehicles by using relatively mature technologies and carefully controlling the environment in which they operate to make the AHS as predictable as possible.

- Obtain safety, congestion reduction, comfort and convenience of fully automated travel quickly by identifying limited-scale early deployment applications where automated vehicles can be operated in well-structured environments.

- Maximize the safety of AHS travel by isolating automated vehicles from non-automated vehicles and obstacles, thereby eliminating accidents due to manually driven vehicles.

- Seek maximum impact on reducing congestion problems in heavily-traveled urban and intercity corridors by aiming for high throughput while maintaining safety.

- Place more emphasis on eliminating the high-delta-velocity crashes that produce fatalities and serious injuries.

- Provide a distribution of intelligence that makes the system fault tolerant and economical.

- Optimize travel time and reliability, using roadside support to regulate traffic speed and flow in addition to entry and exit rates.

Features and Attributes

The following are some salient features of the Infrastructure Supported Concept:

- Standardized inter-vehicle coordination protocols to guarantee cooperative vehicle behavior (such as in platoon operations) and improve throughput and safety
- Separation of automated vehicles into dedicated lanes
- Degree of infrastructure involvement may be a natural extension of ITS services

The concept ensures that the presence of non-cooperative vehicles, and the associated hazards are rare events. Physical barriers and check-in procedures further reduce the probability of hazards.

At first glance, this concept looks similar to the Infrastructure Assisted Concept (discussed in the next section 2.4, Infrastructure Assisted). The distinction is that the Infrastructure Supported Concept does not employ two-way roadside-to-vehicle communications at the entry/exit and interchange points; it assumes this degree of coordination is not needed. In contrast, the Infrastructure Assisted Concept assumes both implementation of a global flow control and facilitation of specific local flow activities (e.g., entry, merge).

Deployment Stages and Time Frame

The Infrastructure Supported Concept is designed to have several deployment paths that are feasible from the societal and institutional perspective and also with respect to increasing technological maturity. The deployment paths envision incremental growth in vehicle and infrastructure intelligence, and incremental conversion of existing manual highway lanes to automated highway lanes.

A deployment path which relies on applying AHS toward locally tailored congested urban applications relies first on market penetration of certain AHS enabling technologies, then on limited scale civil infrastructure investment to be adopted by other urban networks as benefits are realized. This path would occur in four stages and within the next 20 years as follows:

Stage 1: Three technologies are proven to be reliable: electronic throttle control, electronic power steering, and electronic brake control.

Stage 2: Two pre-AHS services gain sufficient market penetration: adaptive cruise control (ACC) and lane departure warning.

Stage 3: A dedicated, automated lane is built on a highway, initially for special user categories such as buses or high occupancy vehicles (HOVs), and its user services are incrementally expanded to other users, then to include more entry/exit points, extended length, and finally, in-platoon travel.

Stage 4: Automated lanes are expanded to form a network, then multiple lanes, and then begin to expand into other networks.

An alternate deployment path would rely on market penetration of automatic control devices and on the evolving convenience of delegating an increasing set of chores from the driver to the AHS as technologies are made available. It can also be described in four stages to occur within the next 20 years.

Stage 1: Delegation of more and more driving chores, borne from advances in automatic driving technologies (e.g., lane keeping, speed control, lane changing). Technologies are assumed to be usable on all roadways, and no infrastructure modification is needed.

Stage 2: Testbed and showcase of full automation under a controlled, self-contained scenario (e.g., bus platoons in New York's Lincoln Tunnel, the Houston Katy Freeway Corridor).

Stage 3: Segregated and infrastructure supported single-vehicle platoons, or "free agents," with infrastructure-to-vehicle communication and no vehicle-to-vehicle communication, evolving into "free agents" with vehicle-to-vehicle communications.

Stage 4: Segregated and infrastructure supported platooning vehicles.

It is important to note that the Infrastructure Supported Concept supports a variety of locally tailorable deployment options representing different distributions of intelligence between vehicle and infrastructure. The appropriate option can be selected based on local factors, vehicle and infrastructure cost trade-offs or infrastructure cost and social benefit trade-offs. In all options, the degree of infrastructure intelligence is not safety critical. If

the infrastructure fails, the concept is designed to operate safely with reduced level of service.

Benefits and Limitations

Some primary benefits from the Infrastructure Supported Concept are:

• Minimization of vehicle cost and complexity
• Maximized safety by protecting automated vehicles from crashes caused by manual vehicles and obstacles
• Significant throughput increases
• Better local control of system demand and congestion patterns
• Greater system-wide reliability
• Reduced emissions by smoother acceleration and deceleration patterns
• Efficient response to system failures to minimize system-wide delays

This is largely accomplished with infrastructure supported system-wide traffic control – a distinguishing feature of this AHS concept.

Potential limitations are that in its implementation – and to most fully realize its primary benefits – it is assumed that all automated traffic is on dedicated lanes. Within the dedicated lanes, however, there are a number of site-specific civil infrastructure decisions, some of which may require additional highway improvements, such as:

• Single or multiple lanes
• Dedicated or transition lane entry and exit.

2.4 Infrastructure Assisted Concept

Concept Vision

The Infrastructure Assisted Concept offers all the features of the Infrastructure Supported Concept. It is designed to support fully automated vehicles on dedicated lanes to safely and effectively increase throughput. Similar to the Infrastructure Supported Concept, vehicles would receive communications from roadside infrastructure. However, the Infrastructure Assisted Concept envisions direct communication and guidance of individualized vehicles by the infrastructure control system at entry/exit, highway interchange, and other critical flow points.

This concept assumes implementation of <u>both</u> global flow control and the facilitation of specific local flow activities at entries and exits of the AHS. This concept, unlike Infrastructure Supported, employs two-way roadside-to-vehicle communications at the entry/exit and highway interchange points, resulting in a higher degree of coordination within that region and locally around that vehicle. The Infrastructure Assisted concept is

designed to optimize throughput and smooth flow by coordinating movements of individual vehicles at entries and merge points.

Features and Attributes

Two-way roadside-to-vehicle communications at key congestion points (entry/exit and highway interchanges) is the key discriminating feature between this concept and the Infrastructure Supported Concept.

Deployment Stages and Time Frames

The deployment stages for the Infrastructure Assisted Concept are identical to those for the Infrastructure Supported Concept.

Benefits and Limitations

The following benefits and limitations apply specifically to the Infrastructure Assisted Concept (beyond those discussed in the Infrastructure Supported Concept).

- With an "infrastructure assist" at some of the main highway bottlenecks, this concept may realize the greatest throughput benefit of the five concepts, thus greatly reducing urban congestion.
- The same "infrastructure assist" may greatly shorten AHS entry and exit ramps over today's standards.

2.5 Maximally Adaptable Concept

Concept Vision

The Maximally Adaptable Concept envisions a flexible, layered approach to both infrastructure and vehicle automation systems. Local jurisdictions would tailor a mix of "Autonomous," "Cooperative," "Infrastructure Supported," and "Infrastructure Coordinated" layers (or modules) to meet their needs within an overall framework of standardized specifications across the system to ensure compatibility.

A truly National Automated Highway System must meet a wide variety of needs. Urban highways need more roadway capacity, but have limited funds and little available right-of-way. Urban highways need a system that allows dense traffic to be tightly controlled to ensure smooth flow. Rural highways generally do not have congestion problems, but have safety concerns. They need a system that keeps the vehicles safely on the road if the driver becomes inattentive on long stretches. Inter-urban highways can benefit from a system that makes truck operation more efficient. Funding levels vary greatly. A successful AHS system must be flexible enough to meet the needs of all highways. These variations must be fused so that a vehicle can travel in automated mode seamlessly across the country.

The Maximally Adaptable Concept is designed to maximize flexibility and options both in the vehicle and the infrastructure. It ensures compatibility across the country, while allowing communities and vehicle owners to pay for only what they need, adding more capability later. The concept is based on the idea there is no single right answer for AHS, and that allocation of intelligence is a local decision.

The Maximally Adaptable Concept maximizes safety and throughput available during degraded operations by providing underlying layers which can stand alone and provide safety and throughput comparable to an early phase AHS system. The premise that there should be independent, underlying, and active subsystems that will continue safe operation in the case of a failure is central to the Maximally Adaptable Concept.

Features/Attributes

The key characteristics that distinguish the Maximally Adaptable Concept include:

- The concept allows Infrastructure Coordination of incidents and platoon formation. Unlike Infrastructure Supported and Infrastructure Assisted, Infrastructure Coordinated gives the infrastructure the ability to manage traffic flow at any location when needed.
- The concept allows architecturally different solutions for different geographic areas.
- Deployment progressions can be tailored to the needs of different geographic areas.
- The Maximally Adaptable Concept is a toolkit that affords a great variety of applications from four basic modules or layers.

The layers used in a particular installation will depend on local needs, budgets, and systems. In particular, except for the core independent vehicle layer, each layer is built on different levels of communication, so existing communications may facilitate the deployment of one or more layers. Layers can be put together in a variety of configurations to provide different levels of service.

Several Maximally Adaptable Concept *layers* have names and characteristics similar to other AHS *concepts*. However, the Maximally Adaptable Concept is not necessarily a scheme for integrating the other concepts, and its layers are different from the AHS concepts of the same name.

Autonomous Layer

The innermost, or "Autonomous," layer consists of technology located on the vehicle, and contains functions essential to the autonomous operation of the vehicle as part of an AHS system. This is the core of any implementation, and is required in all cases. Autonomous layer functions include:

- Longitudinal position-keeping

- Lane keeping
- Lane changing
- Obstacle detection and avoidance
- Road condition sensing
- Vehicle status monitoring
- Driver status monitoring

Cooperative Layer

The "Cooperative" layer is located in the vehicle. It contains functions which support vehicle-to-vehicle coordination and cooperation. It is built around low-bandwidth vehicle-to-vehicle communications. Cooperative layer functions include:

- Cooperative lane-changing and merging
- Recognition of rogue vehicles
- Local incident warning
- Platoon formation and dispersal

Infrastructure Supported Layer

The "Infrastructure Supported" layer is distributed between roadside processors responsible for segment control, entry, and merging, and the Traffic Operations Center for the region. This layer contains functions which allow the infrastructure to check vehicles in and out of AHS; to broadcast to groups of vehicles; and to receive information that vehicles report back to the infrastructure. The degree of infrastructure support may vary from region to region. If possible, the Infrastructure Supported layer may be "piggybacked" on ITS by using compatible technology.

Infrastructure Supported layer functions include:

- Infrastructure regulation of speed and spacing
- Traffic condition monitoring
- Infrastructure roadway condition monitoring and obstacle detection
- Vehicle check-in/check-out

Infrastructure Coordinated Layer

The "Infrastructure Coordinated" layer is distributed between roadside processors and the Traffic Operations Center. It contains functions which allow the infrastructure to establish two-way communication with individual vehicles, and to order changes in their speed, spacing, routing, or lane use. Infrastructure Coordinated layer functions include:

- Monitoring of vehicle positions and speeds by the infrastructure
- Infrastructure-directed lane changing and merging
- Infrastructure-directed platoon formation

- Emergency response to roadway obstacles and incidents

Deployment Stages

The following describes deployment phases for the Maximally Adaptable Concept.

Phase 0, which could be considered a "pre-AHS" phase, provides automated longitudinal speed and position-keeping along with lane-keeping. The vehicle will drive itself under ordinary circumstances; however, lane changing is done manually, and the driver has the option of taking over control of the vehicle at any time. In this phase, pre-AHS vehicles and manually-driven vehicles mix on AHS-capable lanes; there are no lanes dedicated to AHS vehicles. If the pre-AHS vehicle detects an obstacle or stalled vehicle in the lane ahead, it warns the driver, who may take over control and change lanes or begin braking. If he fails to take over control promptly, the vehicle will begin braking automatically. The vehicle will provide information (from ITS) on choices of routes and which exit to take; the driver is ultimately responsible for getting off at the correct exit, however.

Phase 1 AHS vehicles are truly autonomous in that they can do longitudinal and lateral position-keeping, lane changing, and navigation, all without driver intervention if traffic is light to moderate. As in Phase 0, AHS vehicles and manually-driven vehicles mix on AHS-capable lanes; there are no lanes dedicated to AHS vehicles. Phase 1 AHS vehicles may be unable to change lanes if traffic is heavy; they will recognize that this is the case, remain in their lane, and decrease speed if appropriate. If the AHS vehicle detects an obstacle or stalled vehicle in the lane ahead, it initiates obstacle avoidance and will change lanes (if possible) or begin braking. The driver still has the option of taking over control of the vehicle at any time. Phase 0 and Phase 1 are very similar for urban, rural, and intercity deployments.

The Urban deployment sequence has three phases remaining after Phase 1. The next two phases, Urban Phase 2- and Urban Phase 2+, are designed to be used either sequentially by a single regional traffic authority as AHS market share grows, or at the same time in different geographic areas with different population densities and needs. Urban Phase 2- is infrastructure supported, and is designed for smaller cities with moderate traffic density. Autonomous vehicles are driven on lanes dedicated to AHS. The infrastructure and the vehicles communicate by broadcasting information from short-range beacons to the vehicle and vice-versa. The infrastructure regulates traffic speed and spacing in order to enhance traffic flow, particularly at on-ramps and highway merge points.

Urban Phase 2+, which adds a cooperative capability to Phase 2-, is designed as an intermediate phase for large urban areas with substantial congestion. At on-ramps and merge points, vehicle-to-vehicle communication is used to supplement infrastructure-ordered speed and spacing in matching vehicles in one lane to gaps in the traffic of the other lane. In addition, the cooperative capability makes platooning possible, thereby increasing throughput.

The last phase, Urban Phase 3, is the end state which is described in some detail in Appendix E. Intercity Phase 3, the end state for intercity deployment, is very similar to Urban Phase 3, substituting a dedicated truck lane (where practical) for the dedicated transit lane of Urban Phase.

For rural deployments, Phase 1 (identical to Urban Phase 1) may be the end state for many years in some regions. It is designed to provide substantial AHS benefits to areas which cannot yet justify a dedicated AHS lane. Phase 1 is expected to enhance safety, and requires minimal infrastructure modification. Rural Phase 2 provides rural drivers with a fully automated AHS at the cost of requiring a dedicated AHS lane. This will either necessitate the building of a new lane(s), or the taking of at least one existing lane in each direction on rural interstates, which are mostly two lanes in each direction. This will be practical only once AHS has achieved a high degree of market penetration in a region. Consequently, Rural Phase 2 will be introduced region by region as traffic density and AHS market penetration make it practical.

The deployment phases described above are typical for the Maximally Adaptable Concept. Other deployment paths are possible, based on local needs and legacy systems.

Benefits and Limitations

The following highlights benefits to specific stakeholders that are particular to this concept. These are in addition to the benefits that accrue from any AHS system.

Transportation Users. Users can pay for only what they need on individual vehicles, while multiple layers enhance overall system safety.

Insurance and Financial Industries. Layers of capabilities can increase overall safety and lessen the likelihood of claims.

Transit Operators. The system enables faster, more reliable travel by providing a dedicated transit lane as an option in urban areas.

Vehicle Industry. The range of vehicle capabilities allows penetration of a broader market (not just the higher end market).

Electronics Industry. There would be a broad and diverse potential market characterized by a range of compatible products.

Highway Design Industry. The system allows customization of the AHS to meet local needs.

State Agency and Metropolitan Planning Organizations. An integrated system can be tailored to meet various local needs in a cost-efficient manner.

Local Agency. The system allows agencies to customize the AHS to meet local needs and budget. Agencies can choose a level of control from none to vehicle-by-vehicle. The high-end system provides maximum throughput and safety.

Trucking Industry. The system facilitates faster, safer, more reliable travel by providing a dedicated truck lane as an option in deployments.

The Maximally Adaptable Concept has the following limitations relative to other approaches:

- The variety of local options limits the economy of scale for products.
- A vehicle equipped to operate on all of the various types of automated highways in the nation may be expensive.
- A large number of vehicle and roadway options must be considered in design, adding complexity.
- As many as three different communication types may be needed to support the full range of Adaptable deployment options.

3.   Description of Analysis Plan and Process

This chapter establishes the linkage between the concept families described in Chapter 2 and the analysis results presented in Chapter 4. Much challenging work had to be done and many difficult decisions had to be made before it became possible to develop the results that will lead to the refinement of the AHS concept(s). These "behind the scenes" activities are described here. The overall concept definition process is described in Section 3.1.

Because the AHS is a complicated socio-technical system, with diverse implications, it was important to carefully define the criteria that would be used to evaluate the different AHS options. These criteria and their relative importance for the stakeholder community are important to understand before making choices between the different alternatives. The work on defining these criteria (measures of effectiveness or performance/impact measures) is described in Section 3.2.

AHS alternatives cannot be evaluated in the abstract because their relative advantages and disadvantages are application dependent. This means that it is important to consider a range of representative applications as the basis for comparing alternatives. In order to support a comprehensive and meaningful AHS evaluation, the application scenarios should cover a full range of potential uses of AHS to solve transportation problems. The definition of these application scenarios is described in Section 3.3.

A final product of the NAHSC work will be a system specification for AHS. The early stages of development of that specification have already begun, with the identification of broad system requirements, as described in Section 3.4. These are needed to motivate the decisions that must be made now about the different concept alternatives.

The original idea of selecting the "best" three AHS concepts from among all the possibilities was found to be inappropriate in the course of the concept evaluations. The reasons for this are explained in Section 3.5, where the re-orientation of the work towards a concentration on concept-distinguishing attributes is explained. Those attributes provide the foundation for the subsequent concept definition work.

3.1 Description of Concept Definition Process

The concept definition process that occurred during Task C2 developed in a substantially different direction from what was envisioned at the start of the Task and at the inception of the NAHSC program. This chapter reviews what was done and why it was done that way.

3.1.1 Original Concept Synthesis Process

The concept synthesis process, as originally conceived within the NAHSC work plan, was a series of successive down-selects to an ever-smaller set of reasonable concepts. At the start of Task C1, a long list of concept-distinguishing attributes was developed, and a reasonable number of values was chosen for each. Combining these attributes led to more than 20 million different combinations. Some of the attributes were removed from consideration because they did not seem to be useful or meaningful (such as alternatives based on different propulsion technologies or using pallets to carry vehicles). Some of the combinations of the remaining attributes did not make good engineering sense and were also eliminated, leading to the elimination of all but about 200 "realistic" alternatives.

In the course of the Task C1 studies, emphasis was placed on finding synergistic combinations of attributes to define the preferred concepts. A national solicitation for concepts led to the award of seven contracts for development of specific concepts, which were added to the 22 "best" combinations remaining from the original 20 million. The combined 29 concepts were analyzed from a variety of perspectives and were eventually distilled down to the five most preferred concept families by the end of Task C1.

The five concept families were the starting point for Task C2, and the first activity within this task was to expand on those concept descriptions, filling in enough specifics that they could be subject to more rigorous and thorough analyses. Following those analyses, the plan was to weigh the advantages and disadvantages of each concept family, based on preferences expressed by the stakeholder community, in order to select the "best" three concepts. Those three competing concepts would then serve as the basis for design, limited testing of subsystems, and evaluations during the subsequent three years of Task C3. At the end of that period, supported by a series of broad, independent evaluations, the best of the three, or a synthesis of the best features of the three, would be chosen as the basis for development of a single prototype AHS in Task E.

3.1.2 Motivations for Each of the Five Concept Families

The five concept families were motivated by different assumptions about technology development, institutional settings and the transportation problems to be solved. These differences help explain the wide diversity among the concepts as well as the difficulty of defining how one is "better" than the others in a global sense.

<u>Independent Vehicle</u>

The independent vehicle concept is motivated by the desire to avoid infrastructure investments for AHS by having the fully automated vehicles mix freely with manually driven vehicles. This concept emphasizes widespread use of these vehicles to provide comfort, convenience and safety benefits to their drivers throughout the existing highway network. It assumes that sensor and software technologies will advance rapidly enough to make this capability available within the foreseeable future.

<u>Cooperative Vehicle</u>

The cooperative vehicle concept is motivated by the desire to capitalize on advances in computer power and communications to enable automated vehicles to coordinate their movements without any roadside intelligence. It assumes that the cost effectiveness of computing and communications technology will continue to improve for the next couple of decades at the rates they have improved for the past several decades.

<u>Infrastructure-Supported and Infrastructure-Assisted Vehicles</u>

These two related concepts are motivated by the desire to use a combination of vehicle- and infrastructure-based intelligence to produce substantial increases in highway throughput as well as safety, comfort and convenience. These concepts emphasize the use of dedicated, protected lanes to separate the automated vehicles from manual vehicles in order to achieve increased safety and throughput without imposing technological demands that significantly exceed the present state of the art. They assume that it will be politically and financially feasible to construct dedicated lane facilities analogous to the highway expansion and HOV facility developments that are currently underway.

<u>Maximally Adaptable</u>

The maximally adaptable concept is motivated by the desire to serve as many diverse transportation needs as possible using AHS technology. It is intended to permit variations in functionality and user services over time and by geographic location, and assumes that the incremental cost associated with providing this adaptability (or flexibility) will be justified by the benefits. It provides for the different distributions of intelligence assumed by all of the other concept families, as well as a more infrastructure-intensive option, called "infrastructure-coordinated."

3.1.3   Parallel Cross-Cutting Studies of the Concept Families

The five concept families served as the initial basis for a series of studies of cross-cutting issues that address the benefits and costs associated with each. Several of these studies were able to reach considerable depth and breadth of coverage:

- safety
- throughput
- civil infrastructure designs and costs
- institutional and societal effects.

Other cross-cutting studies that were planned could not be carried out to comparable levels because of limited available information and the inherent difficulty of the issues:

- vehicle and electronic infrastructure costs
- customer willingness to pay
- technological feasibility relative to concept needs
- human factors and driver involvement
- deployment time-staging.

These limitations made it impossible to generate the level of information about costs and benefits associated with each alternative that would be needed to make a meaningful comparison among the five concept families.

3.1.4   Change of Focus to Primary Concept-Distinguishing Attributes

As the concept descriptions were filled in, they became broader and more flexible and began to lose some of their contrasts from each other. The competitive pressures on the concept developers also led them toward more common "middle ground." The cross-cutting analyses of the concepts began to reveal some problems in the way the different concept families were defined, because the combinations of attributes gathered within each concept could not be separated. This meant that it was sometimes hard to tell which attributes were producing desirable or undesirable ratings for each concept. There were some regrets that the concepts could not be redefined in order to re-group the attributes differently. The concepts team was forced to take the "packages" of attributes as they were, rather than being able to select the desirable attributes and discard the ones less desirable. This led to concerns about how to choose the clearly "best" concepts.

Given these problems, the decision was made to rethink the idea of the down-selection of the best from among the set of concept families, and step back to an examination of the most important concept-distinguishing attributes. This enabled the team to more clearly understand the influence that each of these attributes has on the safety, cost and performance of an AHS, so that eventually the best selection of AHS attributes could be made. However, this also meant that it would be impossible to follow the original plan of defining the three preferred AHS concepts at the end of Task C2, so that these could then be refined to compete with each other during Task C3. The "winner" of that competition would then have become the basis for the prototype to be developed in the E tasks.

Rather than following the original plan, the team decided to follow an approach that focuses on the concept-distinguishing attributes. The concept-distinguishing attributes

are associated with a set of key issues that will be studied in greater depth during the first phase of Task C3 in order to develop a more solid basis for choosing which attributes should be favored for the final AHS system. Recent consideration of the diversity of potential AHS applications has also encouraged the idea that the AHS may not be a single uniform concept, but rather a catalog of elements that could be combined as needed to serve different transportation needs.

3.1.5 Processes for Soliciting Stakeholder Involvement

A primary intent of the concept definition effort has been to obtain input from the relevant stakeholder communities to better ensure that the AHS will meet their needs. This is challenging because much of the concept definition work is at an early stage of development, is difficult to understand and communicate, and is focused on technical issues that are not of current interest to the stakeholders. Furthermore, the deployment decisions are not immediate concerns for the stakeholders, but will be arising in the future. Despite these challenges, there have been significant opportunities for stakeholder participation in the concept definition work.

Associate Participants in the NAHSC were provided with the Task C2 statement of work early in the period of performance and were invited to participate in activities of interest to them on a *pro bono* basis. In addition, in May, 1996, the NAHSC held a two-day forum in Boston to stimulate stakeholder involvement in all NAHSC activities. The concept definition work was one of the topics discussed there, and significant inputs were received at that time, indicating the need for more direct involvement and better communication between the stakeholders and the concept team. In that same month, a series of consumer focus groups was held in the San Francisco Bay Area to gauge reactions to AHS and some of the driver warning and control assistance systems that are likely to precede the AHS in the marketplace. These focus groups indicated significant favorable interest in AHS and a substantial willingness to pay for a high level of service.

Recognizing the need for a more structured process for obtaining information about stakeholder preferences, the NAHSC sponsored two two-day focus groups of key stakeholder group representatives to explore AHS issues in greater depth. The results of these groups, which met in September and November 1996, are documented in Reference 3-1. These revealed in particular that the stakeholders were much more concerned about the non-technical issues surrounding the AHS concepts than the technical issues that the NAHSC concept team has emphasized.

The focal point for stakeholder input to the concept definition under the original work plan was AHS Workshop #3, which was held in September 1996 in Minneapolis. This two-day meeting included substantial participation from many of the key stakeholder groups, with three rounds of breakout sessions to stimulate discussion by the attendees. This produced further significant inputs to the concept definition work, including the increased concentration of attention on issues of deployment time-staging and the

definition of the pre-AHS user services of Advanced Vehicle Control and Safety System (AVCSS).

3.1.6 Net Outcome of Concept Definition Work

At the conclusion of Task C2, the concept definition status is considerably different from what was expected at the start of the task. The NAHSC's understanding of the relevant issues is broader than it was then. Rather than having three clearly defined, competing concepts, there is, instead, a single broad concept within which attribute variations will be studied. Thus, the next phase of concept definition work will involve a more focused and unified concept development process than would have been the case with three competing concepts.

The team has identified the key attributes that characterize AHS concepts and the difficult issues that need to be studied in greater depth about each of them in order to understand their advantages and disadvantages. These can all fit within a consistent, broadly defined, conceptual framework with the exception of the dichotomy between operating the automated vehicles in dedicated, protected lanes or mixed with manual traffic. That remains the most fundamental of the contrasts between concepts, and therefore the most difficult to resolve.

The concept definition work has been broadened by the stakeholder inputs within the past year. The non-technical aspects of the concepts are receiving more attention, and the issue of deployment sequencing is now prominent in all concept definition activities. The great diversity of potential AHS applications is also leading attention away from the idea of a single narrowly-defined AHS and toward the idea of a broader and more flexible AHS which might consist of a portfolio of options from which the deployers can choose. The economic and technical feasibility of developing such a flexible portfolio remains to be established.

3.2   Evaluation Criteria / Measures of Effectiveness

The comparison of alternative approaches to AHS must be grounded in specific criteria. Ideally these are quantitative, and have been called measures of effectiveness or MOEs. This is actually a misnomer, since the criteria are much broader than the term suggests. "Measures of performance" or "measures of merit" are sometimes used alternatively to convey the need to address the full range of considerations. Even so, for some of the key considerations such as cost, less is better. Furthermore, as we will discuss below, many of the major criteria are not quantifiable. That being said, we will continue to use the term MOEs for historical reasons.

3.2.1   Introduction

3.2.1.2 The Need for Evaluation Criteria

The comparison of the concepts is based not on the features summarized in Section 2, but on how well each meets the needs of AHS and the level of benefits provided. This means that each must be assessed in terms of its performance. The evaluation criteria are selected to reflect the merit of each alternative, and to cover the considerations that will be used to assess the benefits of the AHS.

3.2.1.3 Techniques for Developing Evaluation Criteria

The Objectives and Characteristics document was the starting point in the development of these criteria. It states the goals and objectives in general terms. In Task C1 there was a Quality Function Deployment (QFD) process to break the twenty-four Goals and Objectives into specific measures of effectiveness in a structured way. The result was an exhaustive list of more than 200 measures, which are listed in Appendix A of the System Objectives and Characteristics document. These reflected the range of considerations that might go into the design of an automated highway system. The list needed to be focused to be usable.

The C2 team set about to produce this more focused set of measures as a basis for further analysis. The following requirements were placed on this more focused list:

•   Reflect all of the MOEs in the Objectives and Characteristics

       These MOEs are to be used to compare alternatives, which is a simpler case than if used to predict concept benefits. With comparisons single measures can stand in for several others that vary in the same way. For example, highway capacity measured in vehicles per lane per hour could be a key measure. From this we can derive such measures as vehicles per travel way width per hour, or cargo per lane per hour (assuming cargo mix is unchanged). If one concept excels in a key measure, it is reasonable to conclude that it will also be better in related measures.

- Be few enough in number that they are not trivialized

  The more than 200 measures that came out of the QFD process cannot be all
  assessed The goal in this task is to limit the number of MOEs to less than 20 key
  parameters so that each can be examined thoroughly.

- Discriminate among concepts

  Following are some of the key discriminators among the concepts that need to be
  reflected in the measures.
  - Separation policy (platoon, free agent, autonomous)
  - Separation distances (may be one for each policy)
  - Merge strategy
  - Obstacle strategy
  - Who knows what when

  This requirement that the measures be used only for concept discrimination allowed
  many measures to not be considered. Many measures depend on design features
  that could be included equally well in all concepts, or that are at a detailed level. It
  is meaningless to evaluate such measures since they will either give the same result
  for each alternative and thus be of no use in down selection, or they are so design-
  specific that they cannot be yet evaluated. Others are outside the control of the
  AHS.

- Be estimable using the tools available

  The parallel NAHSC B5 tools development activity is building analytical and
  simulation tools to support concept development. Each of the measures must be an
  output of one or a combination of these tools, or derivable from an output. Given a
  choice, an MOE that is a direct output of a model is preferred. In some cases the
  tools are still under development and were not available during C2. Even so, for
  each selected MOE, a tool and evaluation technique needs to be identified, for now
  or in C3. This serves as a check on the tools development.

The first step in developing the evaluation criteria was to aggregate the measures
produced by the QFD process. Specifically, key measures were selected that could stand
in for several other related measures. Bob Finkelstein of Robotics Technology Inc., an
NAHSC Associate, performed this task. The product represented all of the over 200
initial measures, either directly or indirectly. These measures were then examined
relative to the alternative concepts and attributes, and those that did not discriminate
among them were eliminated. Finally, a tentative B5 tool and analytical technique was
identified for evaluating each of the measures. The result is shown in Table 3.2-1 below.
Each of these MOEs is discussed in Sections 3.2.2 and 3.2.3.

Table 3.2-1. Key Measures of Effectiveness

MOE	Units	How to Evaluate	Conditions	Tool
Number of collisions	Collisions per vehicle-hour	Failure scenarios and normal traffic	Multiple lanes, multiple vehicle classes	Collision probability tool
Severity of collisions	Average delta v squared	Use above scenarios	Same	Same
Max. number of vehicles/incident	vehicles	Simulation of worst case failure	Worst case relative positions and vehicle mix	Multiple collision analysis tool
Maximum achievable throughput	vplph	Single lane steady state, based on safe spacings	Ideal conditions	Safety eval tools, SmartCap, SmartAHS
Throughput degradation due to entries, exits and lane changes	percentage	Model representative of entries, exits and lane changes	Multiple lanes, typical entries and exits	Analytical model, simple simulations, SmartCap, SmartAHS
System throughput (impact on manual lanes)	vplph	Simulation of corridor, including manual arterials	Typical case studies	SmartCap, SmartAHS, Tactical Reasoning Model
Travel time	minutes	Model representative scenario, including entries and exits	Common representative scenario; mixed classes	SmartCap, SmartAHS
Travel time variance	minutes squared	Same as travel time, probabilistic	Same as travel time, probabilistic scenario	SmartAHS
Vehicle life cycle cost	$ per vehicle	Ongoing cost team analysis	National market, no development costs, cost above manual vehicle	C/B tool
Infrastructure life cycle cost	$	Ongoing cost team analysis	National market, no development costs, cost above traditional road, representative deployment	C/B tool
Fuel consumption/ emissions	Average km/l; total emissions	Initial estimates in the literature	Average mix of vehicles; travel patterns unchanged	Modal emissions/fuel consumption in C3
Qualitative				
Modularity and flexibility	qualitative	Construct reasonable configurations for representative locales	Representative locales, varying vehicle mixes and demands	None
Evolvability	qualitative	Demonstrate feasible evolutionary path	First implementation to national system	None
Development cost and risk	qualitative	Assess technical feasibility	Standard R&D practices	None
Acceptability	qualitative	Societal and institutional assessment currently underway	Equity, urban sprawl, and other issues for non-user	None
Market penetrability	qualitative	Market analysis, focus groups	Future market	None
Response to potential system flaw	qualitative	Fault analysis	Failure conditions	Fault analysis
System dependability	qualitative	Safety and "-ility" analysis	Failure conditions	Safety, "-ility" analyses

It was determined that in the C2 time frame, measuring benefits was not achievable in a meaningful way. The team therefore set a more realistic but still ambitious goal: quantitative MOEs were derived for each major item against evaluatory scenario(s). This emphasis on scenarios or even smaller vignettes (e.g., a large boulder falls on the highway) allowed comparison of the alternatives within a common framework. Overall benefits assessment requires a frequency assessment for all possible situations and an extrapolation of these limited results to these more general situations, and then the (often controversial) step of assigning dollar values. That is not part of this analysis, but the analysis does provide the basis for future benefits assessment.

3.2.1.4 The Importance of Non-Quantifiable Criteria

It may be noted that there are several qualitative criteria in the table above. These are included to ensure that the system is useful under a wide variety of situations and avoids potential "showstoppers." Often in a socio-technical system such as AHS these considerations outweigh any technical performance measures. The qualitative measures will be assessed via rankings, based on stakeholder inputs.

3.2.1.5 Quantifiable Criteria

Fortunately, the key performance measures can be quantified using the NAHSC tools. The major goals of the system are improved safety and highway capacity, each of which can be estimated. Cost, the counterbalance, can also be estimated. There are also models of environmental effects, fuel consumption and emissions.

3.2.1.6 Relationship to the System Specification

Each of these measures raises two questions:

- What is the minimum acceptable value?
- What is the target value?

The minimum acceptable value sets a threshold that must be exceeded if the system is to be acceptable. This could be "at least as good as today." However, there is room for greater performance. A system that is merely as good as today in all dimensions is unacceptable. The tradeoffs – between cost and throughput, cost and safety, safety and throughput – will continue; the results will be reflected in the specification, which is continually updated as the analysis is refined. From this, the criteria will be refined, as will the evaluations and the relative weightings of importance by the stakeholders.

Thus the specification provides a balanced set of requirements, each of which meets the individual minimum acceptable. More detailed specifications are then derived from these.

3.2.2 Qualitative and Feasibility Assessment

The qualitative criteria measure feasibility rather than performance. They reflect aspects of the concepts that affect the viability and acceptability of the system. Examples include:

- Key technologies
- Deployment strategy
- Modularity
- Privacy
- Regulations (entry control, inspections, etc.)

The following MOEs will be evaluated using qualitative ratings rather than models or analysis. "Qualitative" in this sense generally means "subjective rating by experts," rather than the results of analysis modeling the subject. An example question to ask experts (which also defines the scale for the MOE) is given below for each MOE as a point of departure for future work. Their relative importance is envisioned to be determined by the stakeholders. Each MOE is to be rated on a scale of 0 to 5, with 5 being the best.

3.2.2.1 Modularity and Flexibility

Modularity and flexibility is the degree that the architecture consists of a wide variety of separable components, with well defined and standard interfaces, so that it contains discrete and easy building blocks, rather than a compilation of unordered interconnected components. A software analogy would be that well-written object oriented code is modular and can be revised and code written in a poor "spaghetti" style may run but cannot be modified or maintained. In particular, the architecture must be tailorable to meet the needs of urban, rural and interurban regions, and of private and fleet vehicles.

An example measure to discriminate between concepts would be to ask experts:

"Where does this concept fit in the following scale of modularity?

0 = Everything critically depends on everything else
5 = Fully interchangeable and fully stable

"How well does this concept apply to your community and needs?

0 = There is no way to configure it that meets the needs in the least
5 = There is a configuration that meets all the needs exactly"

3.2.2.2 Evolvability

Evolvability is defined as the ability to capitalize on what is currently or presently operational and progress through intermediate steps to a mature AHS. In considering evolvability, it is important to a target AHS deployment in two ways. First, given a concept and an application scenario, is there an achievable deployment sequence to reach

that concept applied to the scenario? Second, once a mature AHS is fielded, how much flexibility, adaptiveness, and ability for future change is there to support further evolution in response to important future issues which we may not even foresee?

3.2.2.2.1 Deployment

To handle the first question of defining a deployment path, an exhaustive way is to evaluate all of the intermediate steps for the concepts on all of the MOEs, and then examine the costs and benefits for each step from the point of view of each stakeholder group. The actual analysis of all intermediate steps for all of the MOEs is overly ambitious in the context of its culminating between concepts.

Alternately one could simply ask experts to rate the apparent deployability of each concept. For each concept the question could be:

"To what extent, is there a deployment path with feasible intermediate steps which leads from now to the full implementation of that concept? Explain the basis for your rating.

0 = No foreseeable deployment path, lack of clear or viable intermediate steps
5 = All feasible paths lead only to this concept"

3.2.2.2.2 Flexibility

One approach would be to ask the following question:

"To what extent would the fully deployed concept provide a basis for further change of AHS in response to future transportation needs?

0 = Dead End, this concept cannot change, adapt or evolve
5 = This concept could change, adapt, or evolve to support new needs"

3.2.2.3 Development Cost and Risk

This is a question of how much will it cost to develop a particular concept, and the chance that the development effort will fail. It includes an assessment of technical feasibility and is tied to the development schedule, as more time could help bring a concept into feasibility.

These could be answered by convening expert panel sessions to elicit answers to the following questions:

"Considering the current technical state of the art, and progress in the state of the art over time. What is the probability that the concept would be technically feasible at a reasonable cost for the following years: 2005, 2010, 2015, 2020, 2025? Please explain your reasoning.

"In your estimation, how much money (in current dollars) must be invested each year, beginning in 1997 to provide a 95% certainty that this concept would be deployed on schedule, if this concept was scheduled to be deployed in the following years: 2005, 2010, 2015, 2020, 2025? Please explain your reasoning."

3.2.2.4 Acceptability

One approach would be to break out the particular sub-issues of acceptability, and rate them separately. A simpler approach would be to ask for an acceptability rating from the stakeholders. This could be done by asking members of each stakeholder group the following:

"For each concept, list potential benefits and difficulties that might arise if it were deployed. Consider issues of equity, privacy, urban sprawl, aesthetics, and any of your own special concerns. How would you feel with the prospect of this AHS concept being deployed in your area?

0 = Would actively oppose deployment
5 = Would vigorously support deployment"

3.2.2.5 Market Penetrability and Deployability

Some issues arising from the joint consideration of these elements include: How long will it take to deploy the system if building new lanes were required? If manual-to-automated lane conversion were required? If no changes were necessary? For each application scenario at each stage of deployment, what percentage of the vehicles could reasonably use an AHS capability?

3.2.2.6 Robustness to Failure or Limitation

An analysis of robustness to failures or limitations requires two steps. First, for each concept, the potential that concept need to be identified. For example, it was suggested that a systemwide loss of communications is a major vulnerability of the Cooperative concept. Deployment of dedicated, fixed lanes might be a limitation; the technical feasibility of obstacle exclusion or obstacle detection is another potential limitation.

One approach would be to explain to the stakeholders the concept, and potential limitations, and then ask:

"Considering both likelihood and severity, how serious to the feasibility of the concept do you consider this limitation?

0 = Very serious
5 = Not serious"

3.2.3   Quantifiable Criteria / Measures of Effectiveness

There are some MOEs that require extensive analysis, since they measure system performance and will be used to evaluate system benefits. The throughput and safety performance comparisons must include considerations such as spacing policy, vehicle coordination, the vehicle/roadside interaction, merge strategy, and obstacle strategy.

3.2.3.1   Safety

At top level, safety refers to the prevention or moderation of hazards which cause vehicle collisions and consequent injuries and property damage. The following concept characteristics have safety implications.
- spacing policy
- obstacle avoidance policy
- emergency control
- degree and accuracy of situation awareness
- failure modes
- level of inter-vehicle coordination

The team determined that most of the original safety MOE's can be represented by the number of collisions and the severity of collisions. Specifically, the first eight MOEs in the SOC can be estimated from these, assuming that given appropriate crash data., collision severity can be translated into injuries and fatalities. Improvement in the following safety categories, will be reflected in an improvement of overall safety: HAZMAT crashes, property loss, property loss per vehicle kilometers traveled (VKT), and infrastructure damage by vehicles. Catastrophic crashes, a key factor in perceived safety, is reflected in the maximum number of vehicles involved in an incident. These safety categories are described by the MOE's elaborated below. The remaining MOEs will need more physical description and so will be evaluated later; these are effects of vandalism and hackers, accident response time, incident clearance time, and time to respond to malfunction.

3.2.3.1.1   Number of collisions

The AHS is required to be collision-free in the absence of malfunctions or system intrusion. This measure addresses how well the system prevents crashes in the event of malfunction. Malfunctions could occur in vehicles, the roadway, electronics, vehicle loads, or the environment. Given a malfunction or hazard severe enough to cause collisions, the number of collisions that would result under one concept versus another is a (negative) measure of safety of the system. This is clearly highly scenario-dependent, so it is essential to use identical scenarios when comparing concepts.

3.2.3.1.2   Severity of collisions

Another aspect of the system response to a hazardous situation is the severity of the collisions. There is a tradeoff between frequency and severity in deciding between platooning or independent vehicles. Typically, platooning has more collisions but they should be considerably less severe.

The number of injuries at each of the Abbreviated Injury Scale (AIS) levels is a common rating of injury severity. While there are AIS models that translate more direct effects such as relative velocities into AIS, they are based on crashes predating deployment of airbags and other automotive safety improvements and, hence, overstate injuries. In any case, the goal here is safety comparison only and not prediction of absolute injury or fatality rates on the AHS; hence, AIS is not necessary at this time.

The measure chosen is the expected values of the square of relative velocity at impact. This was chosen because it can be computed by the models used without assumptions about outside activities, and it is well correlated with the AIS values, especially for fatalities and more severe injuries.

3.2.3.1.3 Maximum number of vehicles involved

This measure is important for perceived safety, which is adversely affected by major crashes that make the news. If a concept allows large pileups, these will adversely affect the public's view of the safety of the system, even if statistically the system is safer per vehicle-mile.

3.2.3.1.4 Hazard scenarios

Clearly, each of the above measures is highly dependent on the evaluation scenario. Hence, the scenarios must be very specific and describable within the evaluation tools. The team agreed to make these as simple and direct as possible, to focus on the response to single representative hazards. Hence, we have identified three representative failure scenarios or hazard vignettes: hard braking, hard steering and obstacles. Originally, communications failure was considered as a hazard scenario, but has been more appropriately made part of the design flaw and system dependability evaluations. This led to the emphasis in the current analysis to be on hard braking and obstacles.

A realistic, multi-lane, mixed traffic vignette is needed for the comparison of all five concepts and (to the extent possible and reasonable) the current manual operations. Multiple lanes are needed to reflect the capability of some concepts to coordinate emergency lane changes. This scenario will probably only need to involve a short road segment and a few vehicles. This comparison should be quantitative, based on models and/or off-line analysis, taking into account the failure response of each. Results may be reduced by the percentage reduction in the occurrence of the failure, if the concept includes preventive measures.

3.2.3.2 Throughput

This is measured in vehicles per hour per some fixed width, such as a lane (primarily in this report), a highway, a right-of-way or a corridor. This is a measure of the efficiency of the highway, and its improvement is one of the major incentives for having an AHS. The traveler, on the other hand, has little interest in throughput, but only in the time it takes him to complete his trip. Hence, there are also measures that reflect travel time. Note that high throughput does not necessarily imply fast travel time, primarily because of potential entry and exit queues. Some of the concept characteristics that impact the throughput measures are:

- Nominal spacing
- Time and space needed for entry
- Time and space needed for merging
- Amount of right of way required for AHS
- Entry delays
- Flow control

Representative scenario vignettes will be developed based on short segments of application scenarios or other relevant scenarios. Each will include an appropriate traffic mix (all transit, etc.) with origins and destinations within or at the edges of the segment. System throughput can be estimated by off-line analyses to assess impact on manual lanes.

The measures described below can stand in for all of the MOEs listed in the SOC. For example, using consistent assumptions, from these we can infer vehicles per travel way width per hour, cargo per lane per hour, and equivalent conventional lanes. Off-line analyses on safety can estimate reduction of throughput resulting from crashes, incidents, local delays, maximum safe speed, vulnerability to single point failure and standard deviation of trip time.

3.2.3.2.1 Maximum achievable throughput

This is a measure of capacity, unhindered by local features such as entries or exits. As such, it is site independent and so provides a neutral basis for comparison of concepts. The scenario is an idealized single lane "pipeline" without bottlenecks at entry or exit or anywhere else. At least two cases should be considered: homogeneous passenger cars (absolute maximum achievable throughput) and a typical vehicle mix.

3.2.3.2.2 Throughput degradation due to entries, exits and lane changes

The preceding measure ignores some important concept-distinguishing issues that have a major impact on throughput on real highways, specifically, how well the concept handles entries, exits, lane changes and merges. This can be initially measured as a percentage degradation in throughput below that on an ideal pipeline. Of course, this is highly dependent on the site. Hence, a well-defined roadway scenario or scenarios, will need to

be defined. The scenario may be a short stretch of multi-lane, including at least one entry, one exit and possibly an interchange.

3.2.3.2.3 Corridor throughput (impact on manual lanes)

The preceding measures ignore the impact on the manual roadways in the corridor. Highway improvements may not improve capacity if the surface streets to which they link cannot handle the traffic. In addition to the considerations mentioned above, the frequency of entries and exits has an impact on this measure. Again, this is very site-specific. The application scenario should include both manual and automated traffic, including surface streets, to estimate the effects of the automated highway drawing traffic off manual roads, and the impact of entries and exits on manual roads.

3.2.3.2.4 Travel time

This measure looks at travel time within the AHS. This is to be estimated relative to representative site scenarios including origin-destination (O-D) pairs on the edges of the AHS. The measure is the distribution of travel time for the vehicles, including entry and exit.

3.2.3.2.5 Travel time variance

This is a negative measure of the trip time reliability and is important to the traveler for two reasons: consistency avoids stress; and it minimizes the time cushion that must be added to the expected travel time in order to ensure arrival on time. The exact measure is the statistical variance. The variance is computed for a particular O-D pair. (Note that origin and destination, as in the previous measure, are within the segment or at its edges, so this will reflect only check-in/out, ramp and mainline times and not surface street times).

3.2.3.3 Cost

Costs can be fit into two broad categories, which are of concern to different stakeholder groups. The vehicle costs are of interest to consumers, automakers and automotive electronics companies. The infrastructure cost is of concern to transportation agencies and advocacy groups. While there are alternatives in which the costs are borne in other ways (e.g., FHWA-subsidized vehicle equipment, toll roads), this breakout is meaningful to most stakeholders, and certainly is more meaningful than a single number in which overall costs are combined.

Since the number is to be used to compare concepts, only the cost of AHS-specific additions are included. In particular, it is assumed that vehicles will have electronically controlled actuators as standard equipment before AHS becomes viable, and so actuators are not included in the costs.

In both cases, we are considering the total cost, specifically the life cycle cost, which includes operations and maintenance. Vehicle life cycle cost analysis should also include an affordability test on vehicle capital equipment, since that may be a deterrent to purchase. Infrastructure costs should estimate capital and O&M costs for representative scenario(s), but also affordability checks need to be applied, especially relative to budgets.

The major concept characteristics that affect cost are:
- Infrastructure
    - Ramps, barriers, entry/exit facilities
    - Sensors
    - Communications
    - Processing

- Vehicles
    - Sensors
    - Communications
    - Processing

3.2.3.4 Environment / Energy

Some of the key concept characteristics that affect fuel consumption and emissions are the smoothness of flow that is maintained, how closely spaced the vehicles are, and how much of the time they are closely spaced. Preliminary analysis indicates that platooning may have significant savings in fuel consumption (see 4.4.9). There are additional effects due to smoother traffic flow, but this will require a micro simulation to verify. The two measures which relate to environment and energy are fuel consumption savings and emissions reduction.

3.2.4 Summary and Next Steps

A reasonable number of MOE's representing those in the SOC have been identified. Firm requirements on these MOEs cannot yet be determined, but are continually being developed based on stakeholder requirements and feasibility assessments, each of which will continue in Task C3.

Most of the evaluations require specific scenarios, which means that the comparisons are relative to specific evaluatory scenarios. Thus, for meaningful results, consistency of assumptions and representative scenarios are essential. In this way, a reasonable quantitative comparison of the concepts may be done, though without a full cost-benefit analysis.

The results of the analyses completed to date appear in subsequent sections. These measures were originally chosen to compare the candidate concepts, but as a result of the

evaluation experience, the emphasis was placed on concept attributes rather than concepts themselves.

The final evaluation of AHS alternatives will depend on a balancing of conflicting needs, such as capacity vs. Cost, or safety vs. capacity. Since these MOE's were defined there have been two stakeholder sessions to define, prioritize and rank them.

3.3 Application Scenario-Description of Analysis Plan and Process

3.3.1 Introduction

This section describes the development of application scenarios that formed the foundation for performing portions of the analysis during the course of C2 work. This introductory section discusses the primary objectives in developing the application scenarios and the scope of work in this development process.

3.3.1.1 Objectives

The objectives for developing application scenarios were to provide the setting in which an analysis of concept attributes would take place. Such an analysis also requires analytical and simulation tools to perform the analysis, as well as measures of effectiveness (MOEs) with which the concept attributes are evaluated. Thus, the work on the C2 task was based on four pillars:
- conceptual attributes to be evaluated,
- tools to perform the evaluation,
- MOEs to provide the means of evaluating one concept attribute against another,
- application scenarios, the contextual environment or setting for the evaluation

The primary objective in developing the application scenarios was to provide the details to this work.

3.3.1.2 Scope of Work

The first step in the development of the application scenarios was to review applicable background material such as results from the Precursor Systems Analyses (PSA) Studies, the NAHSC's System Objectives and Characteristics Document, and pre-C2 discussion within the consortium on scenario development. The next phase was the selection process for the scenarios, including defining scenario characteristics as well as selection criteria. The final area was the description of data requirements to fully flesh-out each scenario.

3.3.2 Method of Approach

3.3.2.1 Compilation of Relevant Background Material

The PSA studies were examined and provided input in the areas of the contextual setting for a scenario (urban, rural, or intercity application), vehicle class (especially transit and commercial vehicle operations) and types of data needed for collection. In some of the PSA studies, detailed site-specific applications were selected for analysis, such as the Long Island Expressway (specifically, roadway deployment and operations and impact on

surrounding non-AHS roadways) and U.S. 101 in Los Angeles (roadway deployment and costs).

The Systems Objectives and Characteristics document, which provides a listing of alternative characteristics for potential application scenarios, was also reviewed. Such characteristics include the contextual setting, vehicle class, network structure, level of congestion, and alternative vehicle propulsion.

Prior to the beginning of the application scenarios subtask, preliminary work was performed with respect to better understanding the terms 'application scenarios,' 'reference sites,' and 'case studies' and their differences. Valuable input was provided as a result of this pre-C2 examination of the issues affecting the development of the application scenarios, including scenario characteristics (See Section F.3) and specific local and/or regional sites to consider in the process of selecting the scenarios for use in addressing the identified key C2 issues.

3.3.2.2 Identification of Scenario Characteristics

The next step in the development of application scenarios was the identification of a set of characteristics or attributes. These characteristics include contextual setting, vehicle class, network structure, level of congestion, weather, air quality, and adjacent land use development.

Contextual setting means the general scenario environment of the scenario, that is, whether it is urban, rural, or intercity. Three vehicle classes were considered during the scenario selection process: light-duty passenger vehicles, transit vehicles, and commercial vehicles. Numerous types of roadway network structure were considered, such as grid-like, linear, and circumferential. The level of congestion is an important characteristic to consider, especially in an urban setting and may be measured by numerous MOEs. A comprehensive range of climate types include dry, wind, dust, rain, snow, fog, cold, and heat. A broad range of site-specific air quality effects was considered because of the strong linkages between transportation (both existing and especially yet to be implemented transportation alternatives such as AHS) and air quality vis-a-vis vehicle emissions and also due to Federal legislation such as the Intermodal Surface Transportation Efficiency Act (ISTEA) and Clean Air Act-Amendments (CAAA). Additional right-of-way may be necessary to accommodate an automated lane(s) whether through manual lane conversion or lane addition; thus, it is important to consider the attributes of adjacent land use development as a characteristic in scenario selection.

3.3.2.3 Development of Criteria for Scenario Selection

The next step in the development of application scenarios was the identification of a set of criteria. These criteria include the degree to which the specific site represents the characteristics of many other potential sites, the availability of data, and institutional support.

A significant amount of data is required to fully develop the application scenarios. These data, primarily geometric characteristics and travel demand information, must be obtained from local and regional transportation and planning organizations within the scenarios' actual reference site locations. Without the data, no evaluation could be performed, thus, data availability would be a significant criterion for selecting an application scenario. The development of application scenarios based on actual data from real reference sites would depend on a substantial amount of interest at each local and regional level, primarily, a willingness to participate, and an interest in ITS and AHS. Thus, each local/regional area would have to provide the institutional support necessary to assist in fully developing their respective application scenario.

3.3.2.4 Selection of Scenarios

At the beginning of work on the C2 Task, the objective was to select application scenarios and appropriately matched specific site locations for which needed data would be obtained. Data sources were Metropolitan Planning Organizations and/or district or state Departments of Transportation. It was decided that four application scenario types would be pursued, urban, rural, inter-city and a transit application. The transit application involved the collaborative effort between the consortium and the Houston Metropolitan Transit Authority (METRO), the first NAHSC-sponsored Case Study (See Section F.5.3.1). Actual site-specific locations were chosen for the urban and rural scenarios, and a process was initiated to obtain the required data.

The tradeoff that exists in working with actual data from specific locations versus representativeness of a site exists. Promising sites of the same type still have differences, i.e., the actual urban site representing all urban sites, and so on. This potential concern was overtaken by the more serious challenge of data acquisition for the application scenarios due to time and resource limitations. Thus, for the urban, rural, and inter-city scenarios, hypothetical or generic scenario sites were used as a way to represent the general features of the highway transportation system for each of these three scenario types. These representative scenario sites are described in Appendix F in sections F.5.2.1, F.5.2.2, and F.5.2.3, respectively. The data, both geometric and travel demand, for these three hypothetical scenarios, while not actual, is characteristic of the three scenario settings.

The method for acquiring the data is described below.

3.3.2.4.1 Estimation and acquisition of data

The estimation and acquisition of data involved a combination of developing hypothetical yet realistic data for the urban, intercity, and rural scenarios and obtaining the required data from the Houston METRO team.

3.3.2.4.1.1 Houston

The scenario was based on actual data from the Houston Katy freeway on I-10 west of the Houston CBD. In early 1996, Houston METRO, an associate participant of the NAHSC, entered into a collaborative effort with the NAHSC to study the potential for AHS implementation on one of the Houston metropolitan area's High Occupancy Vehicle (HOV) corridors, namely, I-10. This HOV corridor is currently part of a Major Investment Study (MIS) in which transportation alternatives are being investigated.

In addition to being chosen as an AHS transit application, the Katy freeway is also a representative urban corridor. Connecting Central Business District at the eastern end, it serves the area along the corridor with employment of several downtowns of mid/small size cities. The corridor carries significant traffic in both eastbound and westbound directions, with demand projected to increase. The Katy freeway HOV Lane has been constructed as a one-way reversible flow lane, separated from mainline traffic by concrete barriers, except for three entry and exit opportunities in each direction. The AHS application scenario on the HOV facility was developed into three subscenario alternatives, which initially use the single reversible HOV lane as the AHS lane for the first subscenario and then expands this to a bi-directional AHS lane for the other alternatives. Complete details for both the existing configuration and the AHS application, with respect to the geometric characteristics and the travel demand data that were obtained from the Houston METRO team are provided in Appendix F – Application Scenario Description. A vehicle class percentage distribution was estimated based on corridor data, namely, 4% bus and 96% light duty passenger vehicle.

3.3.2.4.1.2 Urban

A "typical" urban application scenario was chosen to represent a heavily congested roadway network encompassing major activity centers and numerous entry and exit points such as highway-to-highway interchanges. The implementation of AHS in an urban environment faces challenges because of constraints to potential expansion of the right-of-way. The right-of-way issue is of central importance because of its potential ability to have a beneficial effect on both recurrent and non-recurrent congestion. This is a concern even in cases where manual lanes are converted to automated lanes.

The hypothetical urban application scenario is a 24 mile linear corridor, traveling from the suburban portions of the region through the Central Business District, serving intra-city travel needs, with the number of lanes ranging from 3 to 6 in each direction. The AHS application in this urban corridor is based on converting an existing manual lane into a new AHS lane for each travel direction with dedicated entry and exit facilities from local arterials to the automated lane via an overpass. Complete details are provided in Appendix F – Application Scenario Description for both the existing configuration and the AHS application with respect to the geometric characteristics and the travel demand data. Travel demand data was developed for the baseline or non-automated freeway lanes and for the automated lane during the peak hour of the morning peak period in the peak

direction. Four different levels of travel demand were assumed for purposes of input into the throughput analysis to test the sensitivity of throughput to demand. A vehicle distribution of 93% light-duty passenger vehicles, 1% buses and 6% trucks was applied because it fits a typical vehicle class distribution in urban areas.

3.3.2.4.1.3 Intercity

The hypothetical intercity highway represents an interstate highway. It is a corridor that is heavily used for commercial vehicle travel, recreational needs, as well as commuting. This implementation of AHS in the intercity environment is primarily to ensure the driving safety and convenience over longer distances, but also to relieve congestion at particular locations.

The hypothetical intercity highway connects two urban centers over 74 miles, starting and ending at the suburban edges of distinct urban areas. It consists of a six-lane linear corridor with three lanes for each travel direction. The implementation of AHS in the intercity environment is to build a new automated lane, and there are no dedicated entry/exits for the automated lane; traffic is lower over the corridor and opportunity of access is not as plentiful. Instead, a transition lane is used by converting a manual lane for the transition in/out of the automated lane. Complete details are provided in Appendix F – Application Scenario Description for both the existing configuration and the AHS application, with respect to the geometric characteristics and the travel demand data. Travel demand data was developed for the baseline or non-automated freeway lanes and for the automated lane representing typical hourly volumes per direction. Four different levels of travel demand were developed for purposes of input into the throughput analysis to test the sensitivity of throughput to demand. In the intercity environment light-duty passenger vehicles and trucks are in use, while buses are used at negligible percentage levels. The percentage use for trucks varies widely depending on time-of-day and location.

3.3.2.4.1.4 Rural

The hypothetical rural highway covers a distance of 280 miles, linking two relatively small size urban areas that are served primarily by one major highway (freeway). Safety is the most important issue for the study of AHS implementation in the rural environment.

The implementation of AHS in the rural environment is to build a new automated lane. Non-dedicated entry and exit facilities are part of the physical configuration due to relatively low traffic volumes and to facilitate opportunities for access. A transition lane is used by converting a manual lane for the transition to and from an automated lane. Complete details are provided in Appendix F – Application Scenario Description for both the existing configuration and the AHS application, with respect to the geometric characteristics and the travel demand data. Travel demand data was developed for the baseline case for non-automated freeway lanes and for the automated lane representing

typical hourly volumes per direction. Four different levels of travel demand were developed for purposes of input into the throughput analysis to test the sensitivity of throughput to demand. In the rural environment light-duty passenger vehicles and trucks are in use, while buses are used at negligible percentage levels. The percentage use for trucks varies widely depending on time-of-day and location. The rural scenario is unique in its geometric layout as there are steep grades (6%), structures of mid-length spans and wider shoulders.

3.4 Updated Systems Requirements

In coordination with the C2 effort, Release 1 of the AHS Systems Specification was developed. This section describes the process used in developing Release 1, how the C2 team was involved with its development, and how the Release 1 development efforts affected the C2 work effort.

3.4.1 AHS System Specification Description

The objective of the final AHS System Specification is to describe the AHS approach selected as the best for deployment in the U.S. It will be one of the major deliverables of the consortium work effort. It will encompass all possible AHS implementations, including the functionality and performance of those implementations. The major contents of the specification are as follows:
- System definition, mission, goals, and overview;
- AHS concepts of operation (for all major implementation variations);
- Functional requirements (what will it do?);
- Performance requirements (how well will it perform?);
- Constraints (under what development and operating environments?);
- Subsystems and interfaces (what are the major pieces of the system?);
- Design and construction requirements (how well will it be built?); and
- Test and validation requirements (how will it be tested and validated when it is built?)

Its development will be iterative with the other Consortium activities so that the Specification accurately reflects the research and analyses conducted over the course of the program. Specifically, it will capture findings from a "spiral" iteration among user needs, technology capabilities and system concepts.

3.4.2 Development of Release 1

Because Release 1 is the first iteration of the Specification development spiral, it contains materials that are incomplete, subject to revision and refinement, and not yet agreed to by all parties. However, it does reflect the consortium's efforts to date, and provides a foundation upon which the next iteration (i.e., Release 2) will be based. Contents of Release 1 include:
- System definition, mission, goals, and overview ;
- Initial AHS concept of operation;
- Primary system functions; and
- Initial performance assessments.

The C2 team made the following substantial contributions to Release 1 development:
- C2 team members helped in developing the major AHS functional descriptions;

- Development of the initial AHS performance specifications was coordinated with the development of the Measures of Effectiveness (MOEs) used in C2 to ensure their consistency; and
- Domain experts were assigned to each performance area within the Specification; these Domain Experts were all members of the C2 team, ensuring that the materials used in the Specification were compatible with, and accurately reflect, the C2 analytical work.

3.4.3   Next Steps for Release 1

Release 1 of the System Specification is being used as input to the C3 task; and it will capture the system implications and results from the effort. It will be used to guide the structure and format of C3 technical interchanges. Additionally, feedback from stakeholders and/or users will be used as input in Specification development. Early plans for Release 1 include review by the ITS Architecture's Technical Review Team, and review by a focus group composed of AHS stakeholder representatives. Finally, Release 1 materials will be modified based on results from the Consortium's technology and tool development projects.

3.5   Concept–Distinguishing Attributes

3.5.1   Introduction

Concepts and concept attributes have been central to the development of the AHS. From the beginning of the program, there were two challenges in defining the future AHS. One was to do meaningful comparisons at an appropriately high conceptual level before addressing implementations or other lower-level topics. The other was to ensure that the many AHS alternatives were fully and impartially assessed. The original plan was to select six candidate concepts or approaches, narrow this down to three and then to one.

The first step was to identify the attributes or characteristics that distinguish AHS approaches at the conceptual level. Specifically, these are characterizations that are independent of implementation. Attributes were first analyzed independently, suggesting a refined list of characteristics and alternatives. Since these attributes are closely interrelated, a set of candidate concepts were developed around promising combinations of attributes. The candidate concepts were fleshed out and described in sufficient detail to support evaluation relative to the objectives and characteristics for the AHS. The evaluations suggested the elimination of unpromising alternatives, but more importantly, they yielded new concepts, which were promising combinations of concepts that perform better and provided new issues to be considered. The NAHSC thus developed the five promising concepts in Task C1, which were summarized in Section 2.

3.5.1.1 Concepts and Their Uses and Limitations

These concepts were initially useful in developing, describing and assessing AHS alternatives. They were used as examples for stakeholders and the public of the breadth of the AHS, and they supplied concrete, alternative visions of what the AHS might look like. They were useful within the NAHSC as well to clarify assumptions and alternatives, and they formed the basis for examining alternative deployment strategies, with deployment paths being designed for each.

The concepts were platforms for the exploration of full implications of design choices; for example, concepts were developed around the postulated need for automated vehicles to interoperate with manual vehicles. They provided a context for evaluation, and a consistent framework within which the key issues were considered. Finally, they were test cases for requirements in the AHS System Specification, as each potential requirement was checked for consistency with the various approaches.

Unfortunately, the concepts were not easy to communicate. While they were designed to highlight various attributes, they did not convey these distinctions to the stakeholders. The reason was that as the concepts developed, it became increasingly clear that flexibility needed to be built in to accommodate a range of local needs and growth over time. This made description difficult, since concept particulars depend on the situation. Issues were lost in concept complexity. The Boston forum government agency

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stakeholder group, for example, requested more focus on general AHS issues and less on concepts. They also stated that the concepts were not sufficiently clear to support meaningful feedback or evaluation.

At the same time, the NAHSC was finding that the concepts had limitations in the evaluation effort. Their multiple attributes made them as difficult to evaluate as to describe. In fact, the evaluation teams generally did sensitivity analysis on key individual attributes and then merged these into concept evaluations.

The NAHSC also found that concentrating on the five concepts was limiting. Attributes that are best examined separately tended to become associated with concepts. For example, autonomous vehicles were confused with mixed with manual traffic, although they have application to dedicated lanes as well; additionally, dedicated lanes became associated with platoons. Promising alternatives were not considered, such as an independent vehicles with limited vehicle-to-vehicle communications.

3.5.1.2 The Move Toward Attributes

Hence, the NAHSC adopted a new approach focusing on issues, attributes and options. This options-oriented analysis gives more useful, meaningful results than concepts analysis alone. This is especially true since the developing concepts have a high level of flexibility. Specifically, the questions now asked are, which options make sense and what are the implications of choosing one option or another. This then determines the best options for various situations.

The original goal of the NAHSC team had been to down-select three of the candidate concepts, and then select one. But rather than select a single approach, it soon became clear that the right answer is a combination of the best features of each, with options for tailoring the system to local needs and for growth over time.

Consequently, the NAHSC is moving toward a more flexible concept. It is clear that there is no single right answer for AHS, but that the best concept depends on time frame, budget, congestion levels, legacy systems and many other factors. This was confirmed by the contracted concepts which all defined multiphase AHS. The ongoing case study in Houston also recommended a progressive deployment. Stakeholders repeatedly stated a need for incrementalism. The solution must support local options as well as features to support freight, transit, and private vehicles. The best solution is a combination of all of the concepts. It is not a question of which concept to select, but what the options should be and how one decides which options to choose.

3.5.2 The Key Attributes

The Concepts Team has now selected six key attributes. They were selected based on their meeting the following characteristics:

- The choice of one alternative or the other has far-reaching significance in terms of issues such as who builds, who pays, who operates, who maintains, who enforces, who has liability, and what are the costs and benefits.
- Each alternative has promising applicability in at least some situations
- Further analysis is needed to determine the implications of and the tradeoffs among the options.

Each of the following six attributes is described in subsequent sections:

- Fully automated operations only in dedicated lanes or mixed with manual traffic;
- Alternate deployment sequences and timing;
- Distribution of intelligence and communication links (primary attribute to distinguish the five concept families);
- Operations in tightly-coupled platoons or only as individual vehicles;
- Obstacle detection and avoidance or obstacle exclusion;
- Different levels of driver role and intervention opportunities.

In addition, the stakeholders have suggested that institutional and legal options should be included as concept attributes. Therefore, selected stakeholders and non-technical experts should be involved in further concept generation work. These suggestions are presently being incorporated into the C3 work plan.

3.5.2.1 Dedicated Lanes or Mixed with Manual

Any AHS must support lanes dedicated exclusively to automated use. The biggest issue in the definition of a national AHS is whether or not the automated vehicles can also share the same lanes with manually driven vehicles. If they can, it will avoid common concerns about dedicating lanes or roads exclusively to AHS. Stakeholders, especially DOTs, are concerned about the costs and right-of-way problems involved in either adding a dedicated AHS lane, converting a lane to exclusive AHS use or building a new AHS-only road. It is difficult for local agencies to justify construction if there are few vehicles equipped to use the new roadway.

An AHS built on mixing automated and manual traffic makes any road useable by automated vehicles. For example, this might allow automated operation on long narrow rural roads that could not be cost-effectively widened or converted. As the number of automated vehicles increases it eventually will become cost-effective to convert lanes to the exclusive use of AHS vehicles.

If feasible, mixing with manual traffic would certainly allow a smooth transition from AVCSS technologies, such as adaptive cruise control, currently being developed for use on conventional roads. Basically, the argument for mixing with manual is that it will help alleviate the political, social and implementation issues, which may be the most critical and which may impede the early success of a dedicated-lane system.

The primary issue with this approach is that both longitudinal and lateral control responsibilities are taken from the driver, he or she may not maintain attention well enough to respond to emergencies. To counter this vigilance issue, full automated emergency response will need to be provided before moment-by-moment control is taken from the driver. This emergency control in manual traffic is expected to be extremely difficult due to anomalous driver behavior, since many of these behaviors do not now cause accidents and are not well understood.

The argument for dedicated lanes is that the technical issues related to safe operation among unpredictable manual vehicles are not solvable within the foreseeable future. The dedicated lane environment allows full and consistent control of all vehicles, including entry control. It also allows configuring the infrastructure specifically to support AHS, for example with infrastructure communications and barriers to preclude obstacles and unauthorized vehicles. This level of control and uniformity facilitates platooning.

The figure below illustrates the two options. The jagged line separating them indicates that there are other choices in between, such as to designate lanes for automated and appropriately equipped manual vehicles, possibly with help from the infrastructure in functions such as obstacle detection and communications.
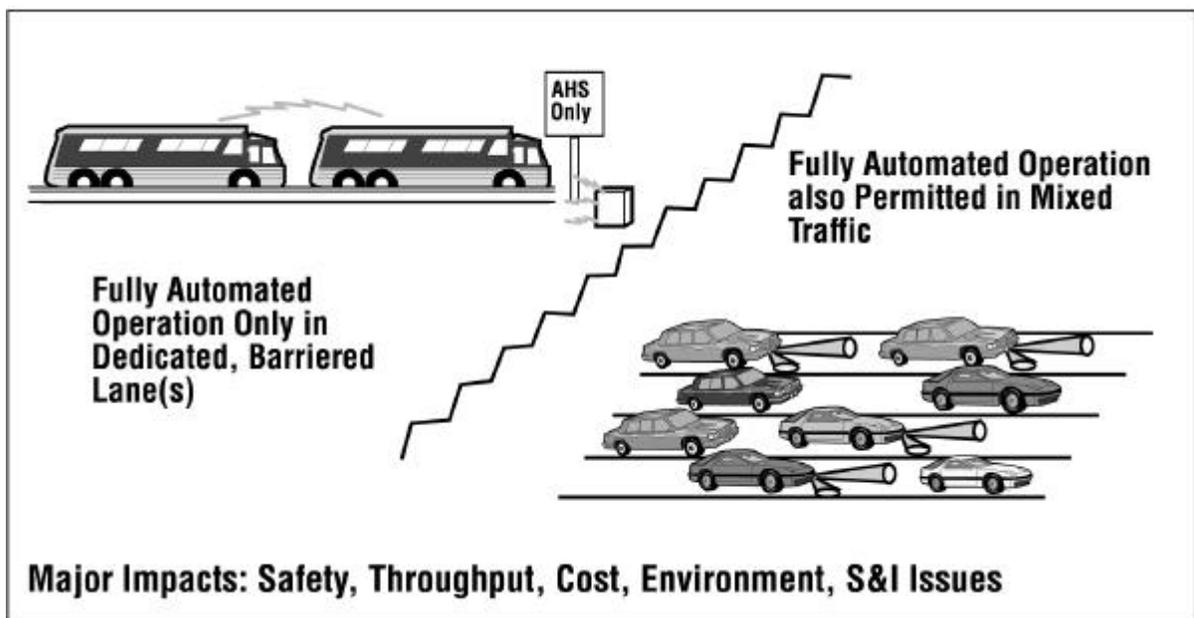
Figure 3.5-1. Dedicated Lanes or Mixed with Manual?

3.5.2.2 Deployment Sequences and Timing

It is not sufficient to define the final AHS. There must be defined pathways to get from current vehicles to this final system within credible market and deployment structures. The stakeholders have repeatedly stressed the importance of incrementalism, and the need

to grow the AHS in manageable-size steps. A major activity by the Concept Team is to define and evaluate several such progressive deployment paths. The assessment is based on market, organizational, technical and social feasibility, among other considerations.

Automakers and their suppliers are currently developing products that are promising steps toward AHS, including adaptive cruise control, lane departure warning and the ability of vehicles to communicate their position and speed information. Ideally such driving aids could be further developed to give fully automated vehicles, thus giving a market-driven deployment. The role and level of involvement of the driver must be carefully considered in this progression, as discussed in the previous section. A policy-driven alternative starts the process by building some dedicated AHS lanes to speed progress. Another alternative is to start with dedicated lanes for semi-automated vehicles. Some stakeholders at the Workshop #3 suggested an approach with multiple paths. Further discussion of deployment sequencing may be found in Chapter 8.

The primary deployment issue is the "chicken or egg" problem of equipping vehicles before there are roadways or equipping roadways before there are vehicles. Getting the process to move along requires public and private partnerships and cooperation. If at any step the benefits to any vital player do not outweigh the costs, the process will cease.

The major impacts and issues of the progressive deployment are the role of the various stakeholders, specifically the federal government, the public sector, and the private market. Also important are the constraints imposed by technology development, costs and a range of societal and institutional issues.

3.5.2.3 Distribution of Intelligence

At the heart of AHS is the intelligence to control the vehicles and the overall system. Is the decision-making primarily in the vehicle or in the roadway or some of each? The answer has profound implications for design of sensing and communications, who pays the costs and how the automated highway develops. This is so central that it formed the basis of the five concepts. Specifically, they were based on four alternative distributions of intelligence, with the fifth concept accommodating combinations of all four. Now, the NAHSC is focusing on variations on these four, plus an additional low communications level cooperative approach that has been shown to be promising in the analyses so far. The five alternatives are illustrated in the diagram below. The balloons indicate examples of the decisions being made and information being communicated.

The *autonomous* approach is based on the premise that automated vehicles will need the capability to operate mixed with manual traffic to get the market-driven evolution started and to support rural areas. This approach is centered on the individual vehicle. The vehicle senses its surroundings, including adjacent vehicles and lane boundaries but does not communicate with the infrastructure except possibly to exchange information with the Intelligent Transportation System (ITS). It also does not communicate with other vehicles. The infrastructure does not support vehicle control, but may provide some

means for the vehicle to sense the lane boundaries such as magnetic markers or roadway striping that can be detected by a sensor on the vehicle, or global positioning system (GPS) data that can be used by the vehicle to ascertain its location.
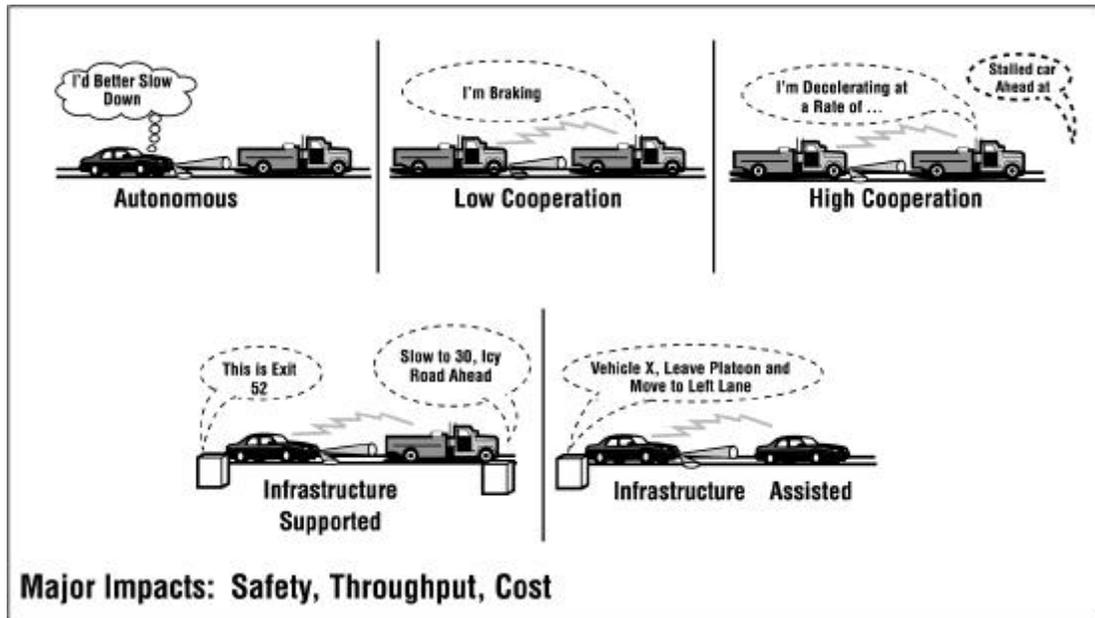
Figure 3.5-2. Distribution of Intelligence.

The *low cooperation* option is similar to the autonomous concept, but adds vehicle-to-vehicle communications to improve inter-vehicle coordination for merging, lane changes and hazard warnings. Other infrastructure support is the same as in the previous alternative. Lane changes are initiated by the vehicle wishing to change lanes. It sends messages to the surrounding vehicles asking them to back off or speed up to open a gap. Merges are handled similarly. This facilitates lane changes and merges in relatively dense traffic. This basic cooperative approach uses local, short-range communications for maneuver coordination among immediate neighbors. There may be passing of information vehicle-to-vehicle or platoon-to-platoon, for example in an emergency, but the vehicles do not routinely act as conduits for information transmission.

The *high cooperation* approach pushes this approach further by the use of longer range and higher bandwidth communications. This allows the collection and distribution of intelligence among the vehicles on the roadway, without requiring any infrastructure involvement. The vehicles continuously share specific information such as their positions, speeds and acceleration and braking rates. This allows synchronized braking, which is an integral part of platooning (see 3.5.2.4). A platooning option would use high cooperation within the platoon but only needs low cooperation between platoons.

The *infrastructure supported* approach supplements the simple vehicle-to-vehicle coordination of low cooperation with a more global view from the infrastructure. Here the cooperating vehicles are given location-specific information by the infrastructure that is monitoring the global traffic flow and trouble spots. The information is not specific to any one vehicle or platoon, though it may be lane-specific. For example, through infrastructure-to-vehicle communications, local information such as desired speed and intervehicle spacing, and global information such as the location of congestion are passed to vehicles. Static information is provided as well, such as exit signs. The vehicles concentrate on the local scene that includes themselves and the surrounding vehicles, and the infrastructure concentrates on the global view. Some entry-exit flow control is possible by monitoring the ramp and main-line flows and adjusting speed, spacing and entry rate parameters for all vehicles in the vicinity.

Infrastructure assisted is similar, but it manages the coordination of maneuvering by individual vehicles at points that benefit from greater control, such as fixed entry, exit and merge points. For example, by combining infrastructure sensing and two-way vehicle/roadside communications, entering vehicles can be matched to gaps in the mainline AHS traffic. The merge assistance allows the use of shorter ramps and merge areas.

3.5.2.4 Separation Policy

There are two approaches to the separation of vehicles in a lane. Ordinary manually-driven vehicles operate as individual vehicles, each keeping a following distance that the driver feels is safe. The automated highways can perform this safe car following function as well, and sensing and communications technologies can maintain the proper distance precisely. This distance is very dependent on relative braking capabilities of the two vehicles, since it must guarantee no collision if the front vehicle brakes suddenly. This means that if the vehicles can communicate their braking capabilities, tighter spacings can be achieved than if they had to assume worst case. Also, the response time to braking affects the spacing, so that communication of braking rate allows closer spacing.

The other approach builds on the fast reactions possible with vehicle-to-vehicle sensing and communications. This allow several vehicles to follow each other very closely and synchronize their accelerations and decelerations. Rather than spacing them so that emergency braking causes no collision, the close spacing ensures that if there is a collision resulting from a malfunction, the relative velocities are small, and so there is minimal effect.

Groups of coordinated vehicles are called platoons. Each has a leader, the first vehicle in the platoon, in communication with the others. A typical platoon will use high cooperation communication within the platoon and low cooperation with other platoons. A platoon typically consists of up to ten vehicles that might be spaced as close as 2 to 4 meters apart. Each platoon maintains a large enough distance from the platoon ahead of

it to preclude collision. Platoons provide very high throughput, but require a somewhat more complex control system.
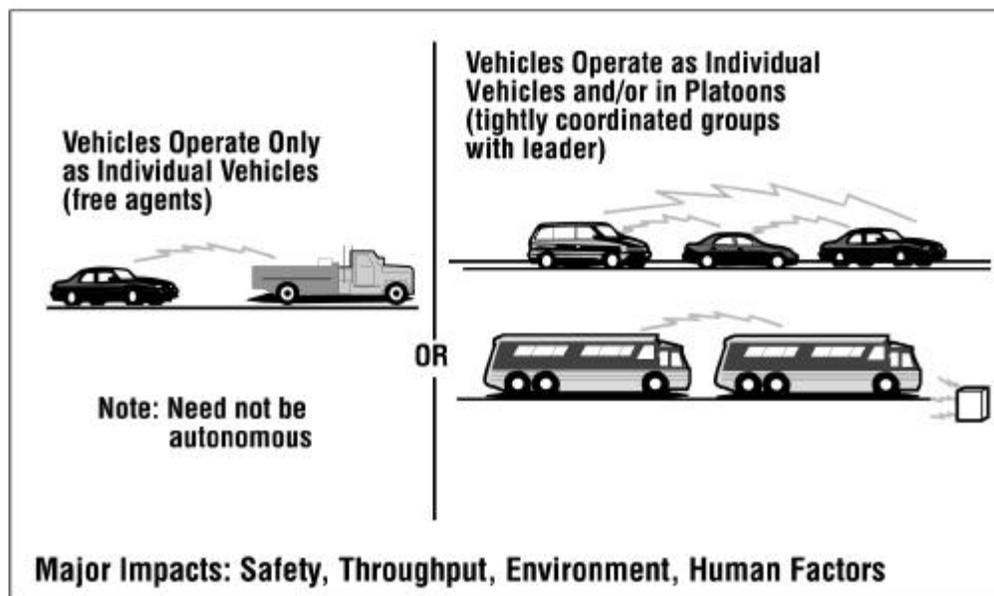
Figure 3.5-3. Should Vehicles Be Grouped or Separated?

3.5.2.5 Obstacle Avoidance or Exclusion

One of the most difficult problems for the automated highway is preventing crashes with obstacles. Obstacles are present in any highway system. They come from the surrounding environment, such as boulders or animals, or from vehicles, such as tire treads or dropped cargo. Failed vehicles in the roadway are themselves obstacles. In a fully automated system, the AHS must ensure that the vehicles do not hit obstacles of large enough size or mass to cause a crash.

One approach uses physical means such as barriers and check-in to exclude obstacles. The idea is to keep obstacles off the road rather than to respond to them. For dedicated lanes, barriers keep manual vehicles from drifting or swerving in from adjacent lanes. Fences and possibly overhead netting keep out environmental obstacles. Check-in at entry ensures that the vehicles are properly equipped and not carrying loose cargo.

The other approach is to equip the vehicles and/or the roadway to sense, identify and avoid obstacles. The assumption here is that obstacles cannot be completely precluded, and so the AHS must be able to detect, recognize and respond to them. The vehicle or the infrastructure or both will have sensors to detect hazards and logic to assess whether or not they are a hazard that requires action, and if so what that action should be.

The jagged line in the diagram indicates that the right answer may be somewhere in between, some combination of exclusion and avoidance. Physical means would limit the frequency of obstacles on the roadway, but the system would properly react to those that do get through. For fully automated vehicles operating mixed with manual traffic, obstacle exclusion cannot be relied upon, so the vehicles must be able to detect, recognize and respond to all obstacles.
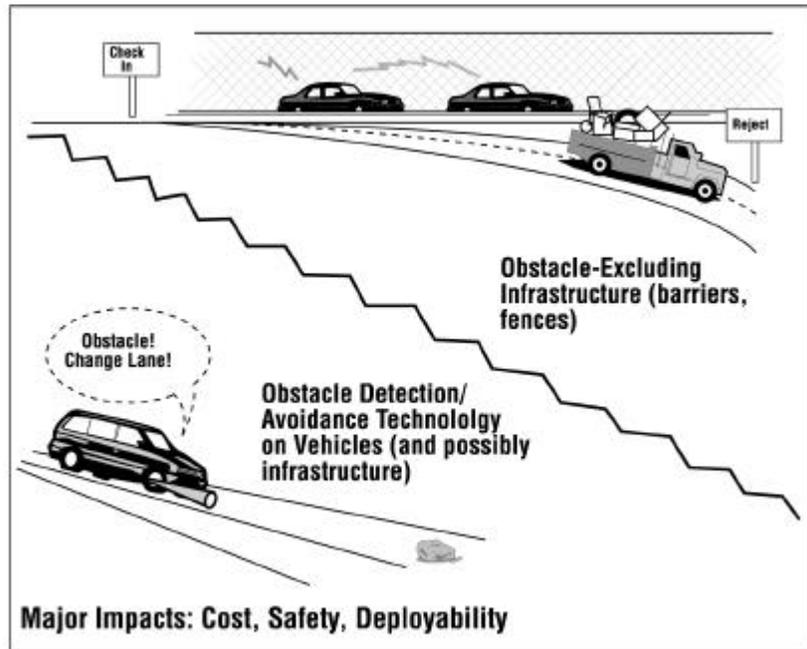
Figure 3.5-4. Obstacle Avoidance or Exclusion?

3.5.2.6 Driver Role

There are two questions related to the driver. What can the AHS rely on the driver to do? What must the AHS allow the driver to do?

One of the conclusions of the mixed with manual analysis (Section 7) is that once moment-by-moment control is taken from the driver, the system cannot rely on him to monitor the situation and respond to anomalies. But this does not say that all control will be taken from the driver. Humans generally demand override capability for automated systems. In fact, there may be situations in which the human can respond better than automation, due to abilities in situation interpretation.

The problem with human intervention is that a highly efficient automated highway system is designed around the precision and fast reaction of automation. For example, typical humans cannot manually maintain the tight spacings required for platooning, at least not consistently and safely. This means that a tightly optimized AHS cannot safely allow human override.

The trade-off is in safety. There are situations in which it is safer for the automation to maintain control and those in which it is safer for the human to take over. For example, full override would allow the driver to override automated control at any time that it be deemed necessary. This means that the system must be designed for safe operation in the face of a driver's panic response. In particular, this means that human intervention during platooning will not be feasible. Since human intervention is disruptive, there should be severe penalties for frivolous use of the override.

Another option is to allow the driver to override only in those circumstances in which it can be done safely. In this case, the driver's request for control would be granted by the system only after the system determined that it was safe. An AHS system operating with very close tolerances would need to prevent driver intervention except in the most extreme situations, and then it would be through a "panic button" that would safely bring the vehicle and all following vehicles to a stop.
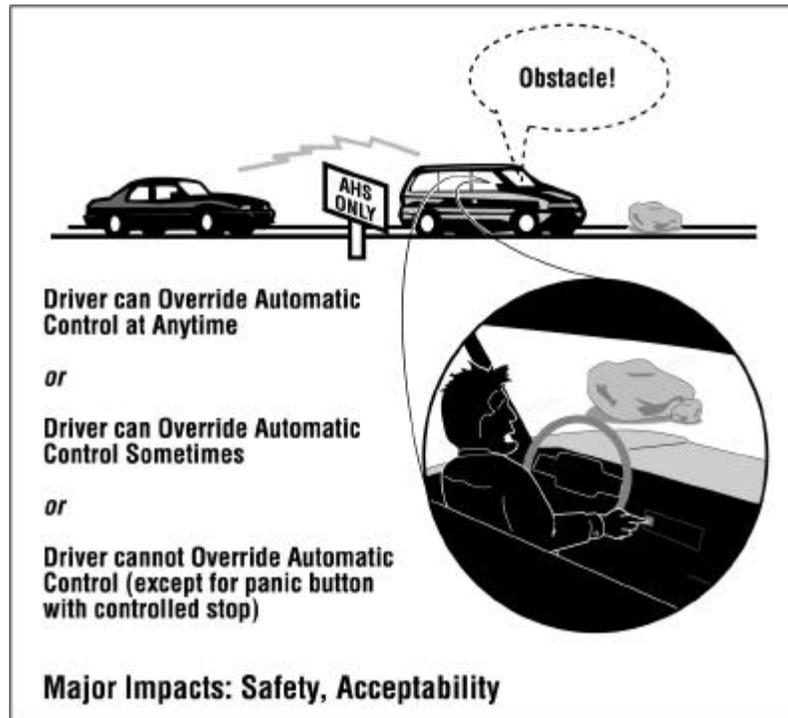
Figure 3.5-5. What is the Role of the Driver?

3.5.3 Next Steps

The NAHSC's goal in concept development has shifted from selecting the one best concept to describing the tool kit and how the pieces are best used. Much of the activity of Task C3 will be analyzing the choices for each of the attributes. Should there be one choice? If so, which one should it be? It may be that the best choice is something in between the options described or some variation on one of them. Or should it be a local

option? If so, which choices should be available? The analysis will describe what impact the choice has and under what conditions should each option be chosen. This will be a continuing effort through Task C3.

4.1 Throughput and Travel Time

4.1.1 Introduction

This section describes the throughput and travel time analyses performed during Task C2 to differentiate among AHS concept attributes. Detailed descriptions of the mathematical models and parameter value selection may be found in Appendices G, H and I. The Appendices also contain results derived for a much larger variety of assumptions (parameter values) than reported here.

4.1.1.1 Objective

The objective is to understand the effect of key AHS attributes on throughput and travel time so that detailed design can be carried out during Task C3 in an informed manner. This analysis focuses only on the AHS and is performed by considering the AHS in isolation from the rest of the transportation system. A complete travel time and throughput analysis would also consider interactions between AHS and its local environment, such as the non-AHS highways and the local street network that AHS would interact with, as well as the effect of AHS on the entire regional transportation network. Such analysis would require detailed AHS designs for throughput evaluation, and will be carried out during the next phase of concept development.

4.1.1.2 Concept Distinguishing Attributes for Throughput-Travel Time Analysis

During the course of work on Task C2, AHS concepts were studied to differentiate among them with respect to a variety of measures of effectiveness, including throughput, travel time, safety, and highway-related costs. As explained in Section 3.5, the alternative concepts vary in the following six primary attributes:
- Fully automated operations only in dedicated lanes only or mixed in lanes with manual traffic
- Deployment sequence and timing
- Distribution of intelligence and communication links
- Operations in platoons or as individual vehicles
- Obstacle detection or exclusion
- Driver roles and intervention opportunities.

This analysis assumes fully automated vehicle operation without driver intervention and does not consider effects of obstacles on throughput and travel time; those issues are studied as part of the human factors and safety analyses respectively. Dedicated lane and mixed traffic AHS are analyzed separately.

The dedicated lane analysis is aligned with the following concept distinguishing attributes:
- Autonomous individual vehicle operation: vehicles do not communicate with each other and do not form platoons.

- Cooperative individual vehicles: vehicles operate individually and inter-vehicle communication at two levels is assumed:
  – Low cooperation: vehicles communicate only during maneuver coordination and emergencies
  – High cooperation: vehicles continuously exchange state information such as vehicle speed and acceleration, in addition to maneuver coordination messages and emergency warnings.
- Platoons: vehicles travel in clusters, or "platoons;" there is high cooperation among vehicles within the same platoon; there is low cooperation between adjacent platoons. It was assumed that all vehicles in a platoon belong to the same class--trucks, buses or light duty passenger vehicles (LDPVs).

In the mixed traffic AHS, automated vehicles are assumed to operate as autonomous individual vehicles on lanes intermixed with manually driven vehicles. No cooperation was assumed among the AHS vehicles, and no communication was assumed between the AHS vehicles and the manually driven vehicles.

4.1.1.3 Application Scenarios

The throughput analysis was performed in the context of the following scenarios:
- Single dedicated lane urban AHS
- Mixed traffic AHS
- Houston transit/HOV case study

The first and third scenarios are described in Section 3.3 and in Appendix F while a detailed write-up of the second scenario may be found later in this section as well as in Appendix J.

(a)   The single dedicated lane urban AHS scenario was formulated from hypothetical yet realistic travel demand and highway geometric characteristic data. This urban AHS corridor was approximately 25 miles in length with dedicated and separate entry and exit facilities each for manual and automated vehicular traffic.

(b)   The mixed traffic AHS scenario consists of manual and automated light-duty vehicles sharing the same facility. Automated vehicle intelligence is concentrated within the vehicle and there is no cooperation among vehicles, that is, no communication of information with one another. Other assumptions are made regarding the operating speeds on the AHS and the spacings between vehicles. No additional information with respect to the physical configuration of the mixed traffic setup is specified.

(c)   The Houston Case Study is an on-going collaborative project between the NAHSC and the Houston Metropolitan Transit Authority to perform an initial investigation of the potential for implementing an AHS on the 12-mile single reversible HOV lane on the Katy Freeway (I-10) west of downtown Houston. This facility is barrier-

separated from the adjacent manual freeway lanes except in two locations to allow for access to and egress from the HOV facility via a slip ramp and a park-and-ride facility.

It should be noted that most of the analysis was performed for a single lane AHS without considering the effect of vehicle malfunctions, obstacle avoidance, crashes, or flow control on the automated highway. Evaluation of these effects will be the subject of further study.

4.1.2 Dedicated Lane AHS Analysis

Three steps were followed in this analysis. First, the maximum achievable per lane capacity (called pipeline capacity) is determined without lateral flow disturbances resulting from lane-changes, entries and exits. This is based on the calculation of minimum safe longitudinal vehicle following distance so as to reduce the probability of inter-vehicle rear-end collisions compared to today's driving situations. The same calculation is also used to determine requirements for safe lane changes, which in turn would provide highway space-time resources needed for lateral flow.

The merging disturbance at the entry ramps is then introduced to obtain the throughput of a single lane AHS. The merging analysis calculates reductions in pipeline capacity due to lateral flow of entering vehicles. This throughput is compared with the throughput of a typical present-day manual highway. The throughput analysis is followed by the benefit assessment of AHS to individual travelers, namely travel time savings.

4.1.2.1 Pipeline Analysis

For the details of the mathematical models and explanations of the reasons for the selection of the parameter values that were used, see Appendix G.

The objective of the pipeline analysis is to derive the (theoretical) capacity of the single lane AHS pipe without any lateral flow due to lane changes, entrances and exits. The pipeline capacity is determined by the longitudinal vehicle following distance. If vehicles follow each other at close distances, capacity is maximized. We use the following safety criterion to determine minimum allowable vehicle following distances:

The hard braking scenario is used to determine following distances because it can be shown (see Reference [4.1-3]) that in a single lane AHS, hard braking by a vehicle is the "worst" disturbance that it can generate for the following vehicles. It is also shown that the optimum action by the follower to avoid colliding with the preceding vehicle is also to apply maximum braking, when following at the minimum safe spacing. Using this principle, the minimum safe vehicle following distance is calculated as a function of the braking capabilities of the leading and following vehicle, the operating speed, initial speed differential and delays or lags encountered during sensing, actuation and processing. A computer program was developed to obtain the boundary between safe and

unsafe states (minimum following distances for different speeds, relative velocities and accelerations) as a function of system parameters. For the pipeline analysis, inaccuracies or noise associated with sensing and actuation are not modeled. Table 4.1-1 contains the nominal parameter values and parameter ranges, in brackets, used in the analysis.

Table 4.1-1. Nominal Parameter Values [and Parameter Ranges].

Parameter Name	LDPV*	Bus	Truck
Vehicle length (m)	5	12	20
Operating Speed (m/s)	30	30	30
Max & Min braking rates for individual vehicles (g)	0.54, 0.86 [See Figure 4.1.3.2 for the entire range]	0.20, 0.43	0.26, 0.54
Max & Min braking rates for platoons (g)	0.45, 0.98 [Figure 4.1.3.2]	0.20, 0.43	0.26, 0.54
Maximum Jerk (g/s)	7.5 [2, 10]	5	3
Comm delay - low cooperative (msec)	50 [20, 500]	50 [20, 500]	50 [20, 500]
Comm delay - high cooperative (msec)	20 [10, 100]	20 [10, 100]	20 [10, 100]
Sensing Lag (msec)	200 [0, 1000]	200 [0, 1000]	200 [0, 1000]
Actuation lag (msec)	100	1000	1000
Platoon size	10 [1, 10]	3	2
Speed tracking error (%)	1.5 [1, 1.5]	1.5 [1,1.5]	1.5 [1, 1.5]

*LDPV = Light-Duty Passenger Vehicles

Although the spacing is determined based on a worst-case disturbance, the results are both necessary and sufficient for no-collision in the following sense. If a vehicle follows the preceding vehicle at a distance greater than or equal to the minimum safe separation, then there exists a control strategy (in particular, application of hard braking at the boundary of safe and unsafe states) so as to avoid colliding with the vehicle ahead. If the preceding vehicle does not apply maximum braking (operates in a normal mode), then the following vehicle can apply a comfortable and efficient control law so long as its state does not cross into the unsafe region (follow too close to the vehicle ahead). On the other hand, if a vehicle follows at an unsafe distance, there exists a worst-case strategy or disturbance for the leading vehicle such that the two vehicles cannot avoid having a collision.

4.1.2.1.1 Coordinated braking of platoons

In Reference [4.1-4] a coordinated braking strategy was derived for platooning in order to achieve collision-free operation in the absence of malfunctions or system intrusions. This strategy requires the followers within a platoon to apply larger brake torque than the leader. The ratio of the maximum braking force needed by any follower to the lead

vehicle braking force is called braking amplification factor a. Therefore, intra-platoon collisions can be avoided if the followers in a platoon are capable of braking at ($a \times$ a_lead) where a_lead is the deceleration applied by the platoon leader. Based on the control law of [4.1-4] and the parameter values given above, we calculate intra-platoon separation and braking amplification factor so as to attenuate the disturbance generated by the platoon leader along the length of the platoon, in the absence of malfunction. The braking amplification factor is used to derate the braking capability of the platoon leader for purposes of deriving the inter-platoon spacing, leading to longer spacings between platoons than between individual vehicles.

The last vehicle of the leading platoon is assumed to exert maximum braking force whereas the leader of the following platoon is only capable of applying minimum braking force given by the braking distribution. Note that although this is sufficient to avoid any inter-platoon collisions under the given set of assumptions, intra-platoon collisions could arise in the following platoon due to the hard braking disturbance created by the preceding platoon. To eliminate such intra-platoon collisions, the braking rate of the leader of the platoon has to be further derated by the brake amplification factor, thereby increasing the inter-platoon separation. The safety implications of these design choices are further investigated in Section 4.2.

Figure 4.1-1 shows plots of inter-vehicle spacing error and decelerations applied by vehicles within a platoon of light duty passenger vehicles as a response to the platoon leader applying sudden braking at the rate of 8.5 m/s/s. We use the nominal values of sensing and actuation lags and communication delays in this calculation and assume identical braking capabilities by all vehicles. From these plots, the maximum spacing error between any two vehicles in a platoon never exceeds 0.5 m and the braking amplification factor is given by 11/8.5 = 1.3 (the ratio of the maximum deceleration by the responding vehicles to the deceleration rate of the leader). If a malfunction or system intrusion causes the platoon leader to apply maximum hard braking, some low-impact-velocity intra-platoon collisions are still likely to occur.

Such plots were generated for platoons of trucks, buses and passenger vehicles with nominal parameter values to obtain maximum spacing error and the braking amplification factor. The intra-platoon separation for each type of platoon was then chosen to be larger than the maximum spacing error. Table 4.1-2 summarizes these results.

4.1.2.1.2 Individual vehicle pipeline analysis

Minimum safe spacing between two platoons and two individual vehicles is calculated using the no-collision safety criterion. To begin with, vehicles are assumed to not know their own braking capabilities. In this case, for a no-collision design, it is necessary to assume for the spacing calculation that the preceding vehicle has the maximum braking

capability while the following vehicle has the least braking capability. This results in a true worst-case design. Given the fact that the braking capabilities of vehicles that are currently on the road are distributed over a wide range, as shown in Figure 4.1-2, a worst-case design would result in very conservative spacing and low pipeline capacity (no higher than today's manual traffic). To make the design less conservative, nominal braking rates for the front and back vehicle
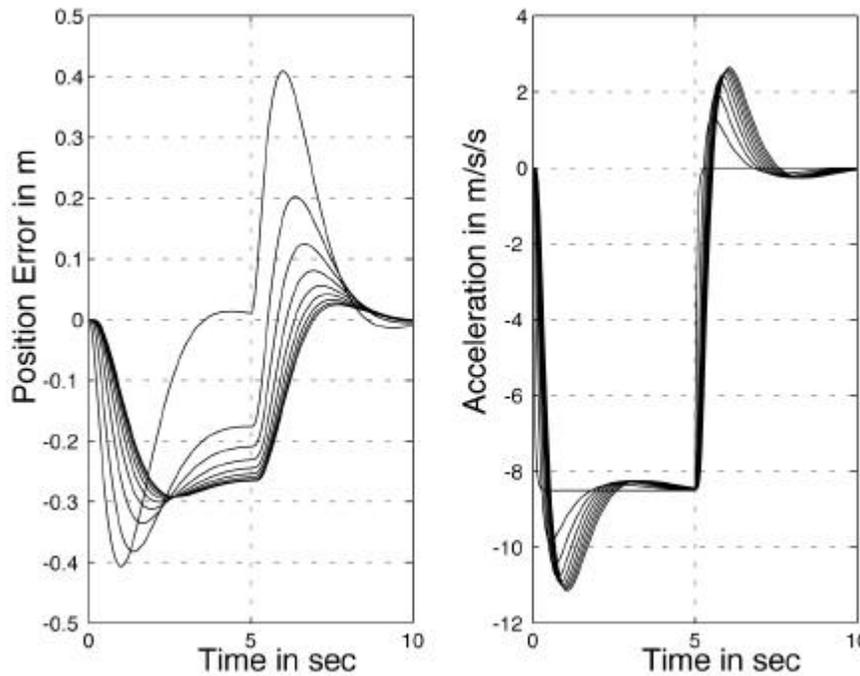
Figure 4.1-1. Platoon Response to Hard Braking Malfunction of Leader.

Table 4.1-2. Intra-Platoon Spacings to Avoid Collisions in the
Absence of Malfunctions or System Intrusions.

	LDPV platoon	Bus platoon	Truck platoon
Intra-platoon spacing (m)	2	8	8
Brake amplification factor	1.3	1.5	1.5

from Table 4.1-1, which cover 93% of the vehicle population described by the braking distribution of Figure 4.1-2, are used.

The braking distribution shown in Figure 4.1-2 is based on maximum braking rates for new 1995 model year light-duty passenger vehicles, given dry and good pavement conditions. The rationale for this is that these are the conditions for which we could find braking data in the literature. We match the North American production figures for each model for the time period January 1 through April 15, 1995—as reported in *Automotive News*—to create a braking rate distribution of light-duty passenger vehicles. We validate

the reasonableness of the braking rate values using the stopping distance requirements mandated in the *Federal Motor Vehicle Safety Standard Number 105: Hydraulic Brake Systems* and through consultation with the National Highway Traffic Safety Administration's (NHTSA) Office of Crash Avoidance Research. We use a derating factor of ten percent to account for the degradation of light-duty passenger vehicle braking performance (i.e., due to physical wear and tear) as the vehicle ages.
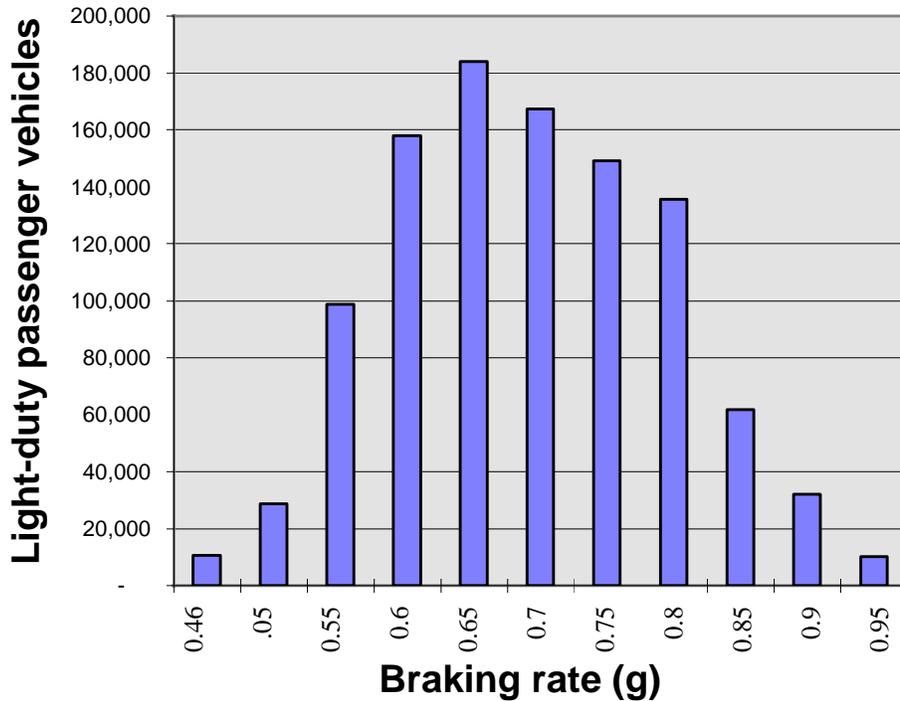
Figure 4.1-2. Light Duty Passenger Vehicle Braking Distribution,
As Derived in Appendix G.

We base our choice of maximum braking rates for full-size transit buses on the braking rates specified in the American Public Transit Association (APTA) document titled *Baseline Advanced Design Transit Coach Specifications: A Guideline for New 35- and 40-Foot Coach Designs*. The maximum heavy articulated truck braking rates used for analysis purposes are based on a synthesis of test track results published by NHTSA's Vehicle Test Center. We use the worst-case braking rates, for both buses and trucks, since the throughput analyses are coupled to the safety analyses.

4.1.2.1.3 Results

Figure 4.1-3 contains a plot showing the output of the spacing design tool in case of light duty passenger vehicles following each other. The inter-vehicle spacings for different classes of vehicles following each other at a nominal speed of 30 m/s are shown in Table 4.1-3. Figure 4.1-4 converts these spacing values into pipeline capacity for a typical

urban vehicle mix of 93% light-duty passenger vehicles, 6% trucks and 1% buses. Random ordering of vehicles (platoons) of different classes is assumed to generate this plot.
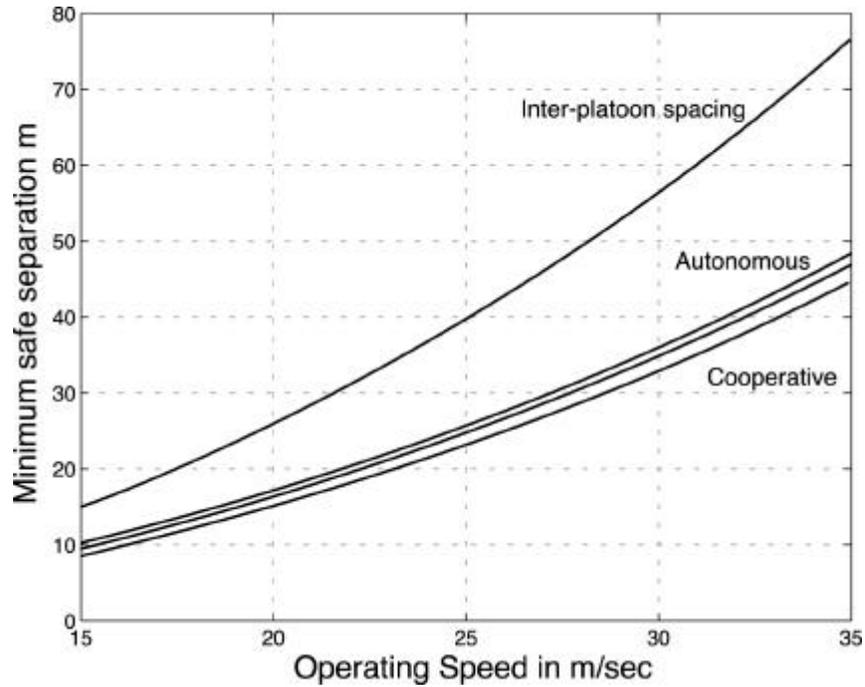
Figure 4.1-3. Minimum Safe Spacings for LDPV Following LDPV.
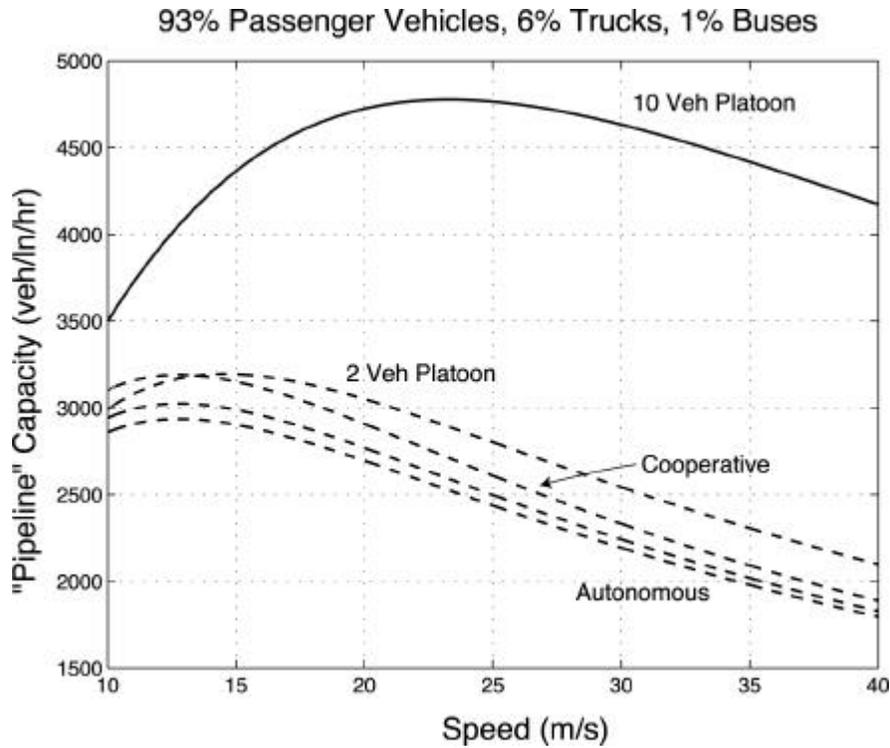
Figure 4.1-4. Pipeline Capacity for Urban Vehicle Fleet Mix, Uniform Spacing Design.

Table 4.1-3. Minimum Vehicle Following Distances (m) at 30 m/sec
for Nominal Performance Assumptions of Table 4.1-1.

Following Vehicle	Leading Vehicle	Autonomous	Low Cooperative	High Cooperative	Inter-platoon spacing
LDPV	LDPV	36	35	33	56
Bus	Bus	129	128	127	128
Truck	Truck	101	100	98	100
Bus	LDPV	182	182	180	188
Truck	LDPV	133	132	130	139
Truck	Bus	79	78	77	79
Bus	Truck	151	150	148	150
LDPV	Bus	15	15	15	15
LDPV	Truck	20	20	20	20

As the nominal braking rate of a LDPV is much larger than that of a truck or a bus, it can follow the truck or the bus at a very close spacing. Such close following may not be very robust or comfortable. We therefore impose a lower limit of 15m when a LDPV is following a bus and 20m when a LDPV is following a truck at nominal speed of 30 m/sec.

Pipeline capacity is sensitive to the ratio of heavy trucks to light-duty passenger vehicles. Table 4.1-4 summarizes the pipeline capacities corresponding to combinations of distribution of intelligence and ratios of heavy trucks to light-duty passenger vehicles, computed for a speed of 30 m/s; the results for a wider range of speeds and vehicle-class ratios are shown in Appendix G. The results are based on a uniform spacing policy.

For the individual vehicle cases, there is a decline in pipeline capacity of between 17 and 19 percent as the ratio of heavy trucks to light-duty passenger vehicles increases from zero to 1:9. In contrast, the 55 percent decline in pipeline capacity for the platoon case is much greater than that of the individual vehicle cases. The increase in space-utilization requirements for separation of platoons of different classes of vehicles accounts for the large difference in percentage decline in pipeline capacity between the individual vehicle and platoon cases – all other things being equal, the braking capability of a platoon of heavy trucks is much less than that of a platoon of light-duty passenger vehicles. In Appendix G, the plots of pipeline capacity versus vehicle-class ratio show that the rate of decline in pipeline capacity decreases as the percentage of trucks increases from zero to 100.

Table 4.1-4. Pipeline Capacity at 30 m/s for Combinations of Distribution of Intelligence and Ratios of Heavy Articulated Trucks to Light-Duty Passenger Vehicles.

| | Pipeline Capacity (veh/ln/hr) | | |
| | Ratio of Heavy Articulated Trucks to Light-Duty Passenger Vehicles | | |
Distribution of Intelligence	0	1:19	1:9
Autonomous individual vehicle	2527	2290	2096
Low-cooperative individual vehicle	2600	2345	2138
High-cooperative individual vehicle	2731	2446	2218
Platoon	8615	5399	3984

Pipeline capacity is also sensitive to the absolute value of the difference between the lowest and highest vehicle deceleration rates for the population of vehicles permitted to enter and travel on the AHS lanes. The results from the analysis of the sensitivity of pipeline capacity to minimum check-in thresholds for braking rates, in terms of maximum achievable vehicle deceleration, are shown in Table 4.1-5. The results for a wider range of vehicle speeds are shown in Appendix G.

Table 4.1-5. Pipeline Capacity at 30 m/s for Different Assumptions About the Rigor of Braking Performance Check-In Requirement.

Distribution of Intelligence	Pipeline Capacity (veh/ln/hr)				
	Percentage of vehicle braking distribution permitted by check-in, as measured from the right tail to the left				
	100%	99%	96%	87%	71%
Autonomous individual vehicle	1702	1939	2270	2644	3069
Low-cooperative individual vehicle	1732	1980	2329	2728	3188
High-cooperative individual vehicle	1795	2064	2447	2892	3415
Platoon	8615	9189	9875	10527	11148

The percentages refer to the percentage of the area under the braking rate distribution curve (Figure 4.1-2), measured from the right-hand tail of the distribution. For example, seventy-one percent refers to the portion of the vehicle-braking distribution which corresponds to a minimum check-in braking rate threshold of 0.65 g and a maximum braking rate of 0.95 g (i.e., the value located at the right tail end of the distribution), representing a variation between the lowest and highest braking rates of approximately 34 percent. The range and variation in braking rates are shown in Table 4.1-6. The baseline case for the majority of the results in this report is 93% of the braking distribution.

Table 4.1-6. Percentage Difference in Low and High Braking Rates for Each Percentage of the Light-Duty Passenger Vehicle Braking Distribution, Permitted by Check-In, From the Right Tail to the Left.

Percentage of vehicle braking distribution, permitted by check-in, as measured from the right tail to the left	Lowest braking rate (g), light-duty passenger vehicle	Highest braking rate (g), light-duty passenger vehicle	Percentage difference
71	0.65	0.98	34
87	0.60	0.98	38
93	0.54	0.98	42
96	0.55	0.98	43
99	0.50	0.98	50
100	0.46	0.98	53

As the strictness of the minimum braking-rate check-in policy increases (i.e., from allowing all vehicles within the distribution entry to a policy of disallowing vehicles on the left tail of the distribution from entering the AHS lanes), the pipeline capacity increases. The magnitude of the increase varies between 45 and 47 percent for the individual vehicle cases, while the increase for the platoon case is 23 percent.

Different levels of cooperation among individual vehicles differ in the values for sensing delays. All of them are assumed to have a nominal actuation delay of 100 msec.

Autonomous individual vehicles are modeled with a sensing delay of 200 msec as they have to sense the emergency deceleration of the preceding vehicle. Individual vehicles with low cooperation can issue an emergency warning to the followers with a delay of 50 msec, whereas individual vehicles with high cooperation are assumed to exchange continuous state information every 20msec. Thus the combined sensing and actuation delay for the three kinds of individual vehicle following concept attributes is given by 300, 150 and 120 msec respectively. In addition, vehicle following with high cooperation is assumed to have access to acceleration of the preceding vehicle (via communication), whereas vehicle following with other two concept attributes requires reconstruction of such acceleration information using sensor readings of relative position and velocity.

In this analysis the brake response of the lead car is modeled by a step function, and that of the following car is modeled by the step response of a first order system.

The brake response of the following car is delayed with respect to the step function representing the braking behavior of the lead car by the sensing or communication delays shown in Table 4.1-7. The majority of the analyses that follow were based on the total lumped lag values in the table, but sensitivity studies were performed to assess the effect of overlapping the actuation time with communication time.

Table 4.1-7. Combination of Lag Times.

Attribute	Sensing delay	Communication delay	Actuation delay	Lumped lag	Lag if actuation were fully overlapped
Autonomous	200 ms	--	100 ms	300 ms	300 ms
Low Cooperative	--	50 ms	100 ms	150 ms	50 ms
High Cooperative	--	20 ms	100 ms	120 ms	20 ms
Platoon Leader	--	50 ms	100 ms	150 ms	50 ms

The model's approximations are illustrated with an example. The actual brake response of a vehicle may be modeled as a dead time in series with a first order lag, based on experimental data derived from testing of two different fast acting brake actuators developed and tested by PATH. The brake dead times, lag times and saturation levels for the leading and following cars in this example are:

	lead	trail
dead time	40 ms	60ms
first-order lag	40ms	60ms
saturation level	0.8g	0.5g

The model approximations are shown together with the actual braking trajectories in Figure 4.1-5 for the low cooperative case. Note that the brake response of the following car is delayed by 150ms as expected.

If the deviations from the nominal values of the actuator lags and the communication latencies are not too high, then the step approximations lead to lower pipeline capacities than would be obtained by higher fidelity modeling. This is mainly because the lead car brake response is significantly slower than the step function modeling it. However, for the following car the approximation does not seem quite so conservative.

In addition to showing that pipeline capacity is sensitive to vehicle speed, Figure 4.1-6 shows the effect of varying the lag of the following individual vehicle braking response with respect to the initiation of braking by the preceding individual vehicle, for lags of 20 to 120 ms and light-duty passenger vehicles. The figure shows that pipeline capacity, which is a function of inter-vehicle spacing, changes approximately 7.5 percent between the lowest and highest lags at 30 m/s. This indicates that pipeline capacity is relatively
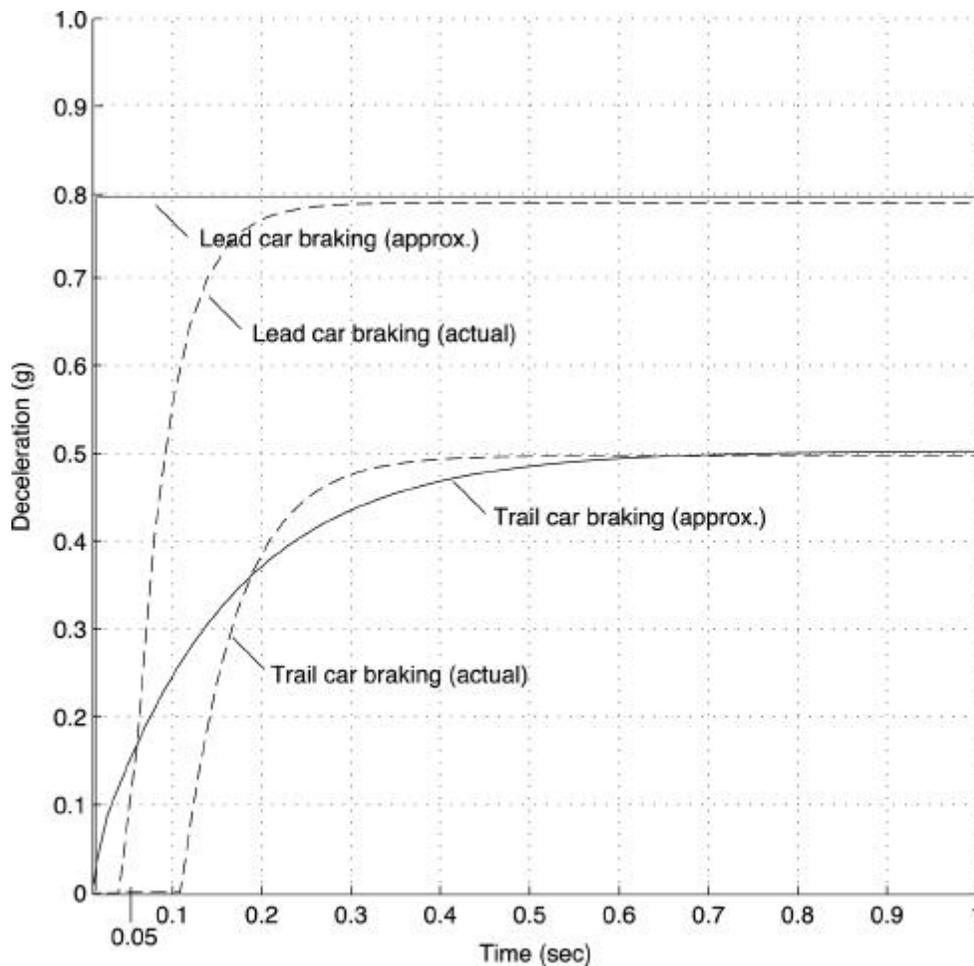
Figure 4.1-5. Approximation of Leading and Following Car Braking.
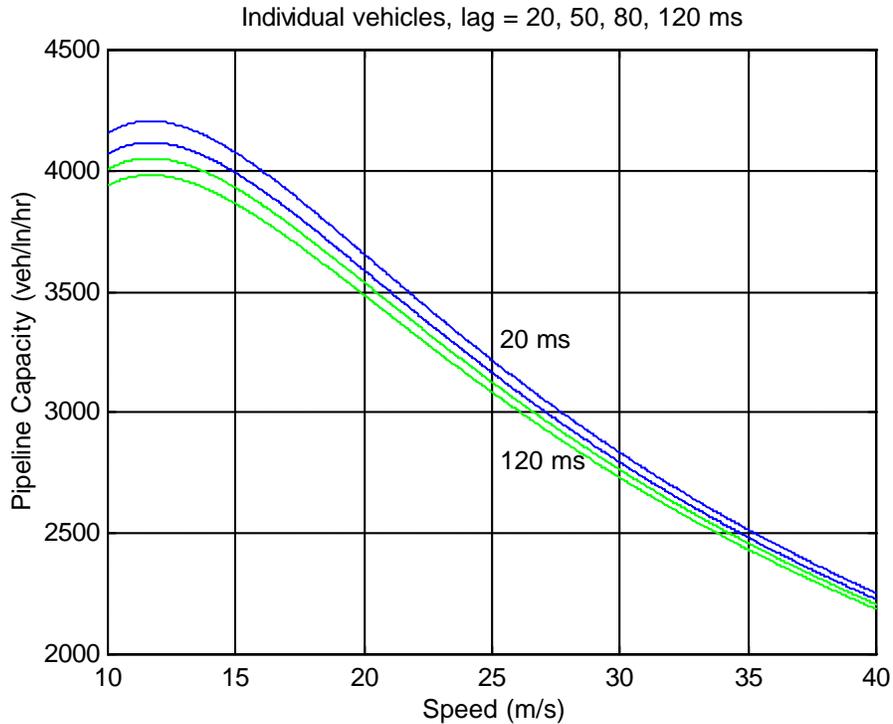
Figure 4.1-6. Pipeline Capacity Versus Speed for Four Different Closed-Loop Lumped Lags, Light-Duty Passenger Individual Vehicles.

insensitive to lags for the range of values shown in Table 4.1-4, assuming either lumped lags or overlapping actuations, at the high cooperative level (from 20 ms to 120 ms).

The spacing design tool was also used to obtain sensitivity of minimum separation to system parameters. The spacing, and pipeline capacity in turn, is highly sensitive to the differences in braking capability and operating speed of the two vehicles. It is insensitive to changes in the sensing, actuation and communication delays within the range assumed here. This implies that to improve capacity, the automatic speed tracking function should be carried out with high accuracy and the braking rates of the vehicles on the highway should not differ widely. The vehicle braking rate distribution can be modified by denying access to vehicles with poor braking performance at the check-in to the AHS. Alternatively, if each vehicle can monitor its own braking capability, it can follow at an appropriate, and less conservative, spacing thereby increasing capacity. If the preceding vehicle communicates its own braking capability, the two vehicles can operate at an even tighter spacing. This spacing design is called non-uniform spacing, as each vehicle follows at a possibly different spacing depending on the information available about braking capabilities of the two vehicles. In the same spirit, the previous design is called uniform spacing design. Figure 4.1-7 illustrates the capacity benefits of acquiring the braking capability information.
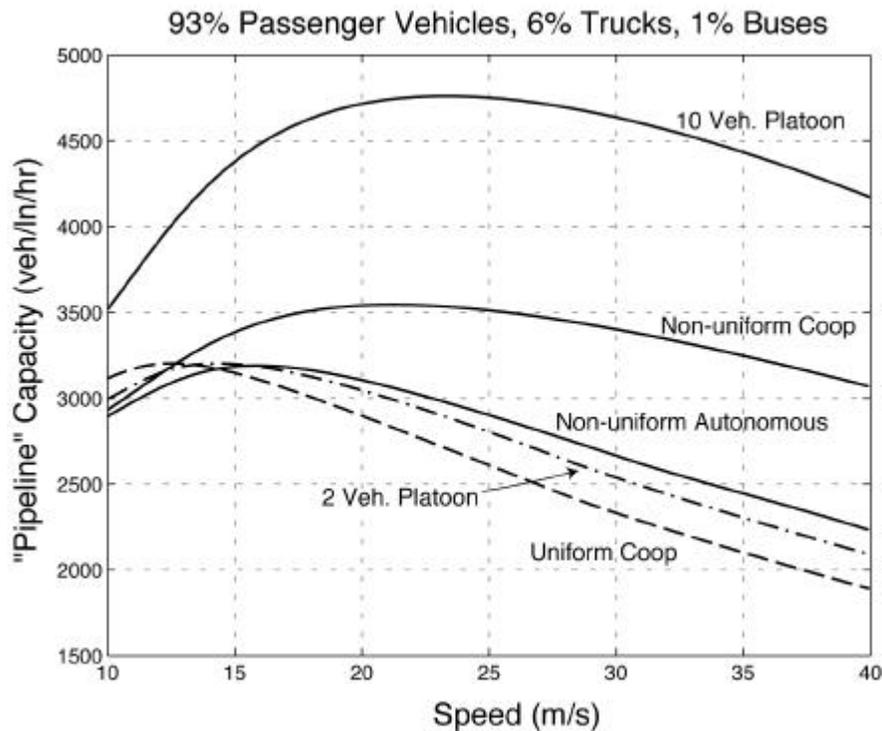
Figure 4.1-7. Pipeline Capacity Including Non-Uniform Spacing Designs.

Cooperative vehicles communicate their own braking information to the vehicles behind, thereby allowing the spacing design to be based on the braking capabilities of both vehicles. The autonomous vehicles, on the other hand, cannot obtain braking capability of the preceding vehicle and therefore assume that the vehicle ahead can brake at the maximum rate. The knowledge of one's own braking capability still results in a substantial advantage over not knowing it.

Non-uniform spacing design is used when light duty passenger vehicles follow each other and communicate. Vehicle following for all other combinations of communicating vehicle classes is carried out using the uniform spacing values as obtained before. Non-uniform inter-platoon spacing design would be difficult to implement as the platoons would need to be sorted according to their braking capability (i.e., all vehicles in a platoon having similar capability) in order to maximize the capacity benefits. For the above non-uniform spacing design, the light duty passenger vehicle braking distribution was discretized into 11 uniform classes thereby applying the assumption that the braking capability identification system should have an accuracy of 0.5 m/s/s. The spacings are based on relative braking capabilities of each pair of consecutive vehicles. The spacing distribution is bounded from below at a 0.5 sec headway, to avoid having extremely short spacings when a vehicle with a high braking capability follows one with a significantly lower braking capability.

Combining the effects of non-uniform spacing design with overlapping of brake actuation times and narrowing the range of braking capabilities in the AHS vehicle population provides some increase in throughput, as shown in Figure 4.1-8. Note that the effects of these three capacity-enhancing assumptions are not additive because the harmonization of braking capabilities means that the non-uniform spacing design offers less of an advantage relative to uniform spacing design. Figure 4.1-8 shows that the capacity is very insensitive to the variation between 50 and 150 ms in the total lag, representing the difference between whether or not braking time is overlapped with communication time.

100% light-duty passenger vehicles

Non-uniform (0.65,0.98,50ms)
Non-uniform (0.46,0.98,150ms)
Uniform (0.65,0.98,150ms)
Uniform (0.54,0.86,50ms)
Uniform (0.54,0.86,150ms)
Uniform (0.46,0.98,150ms)
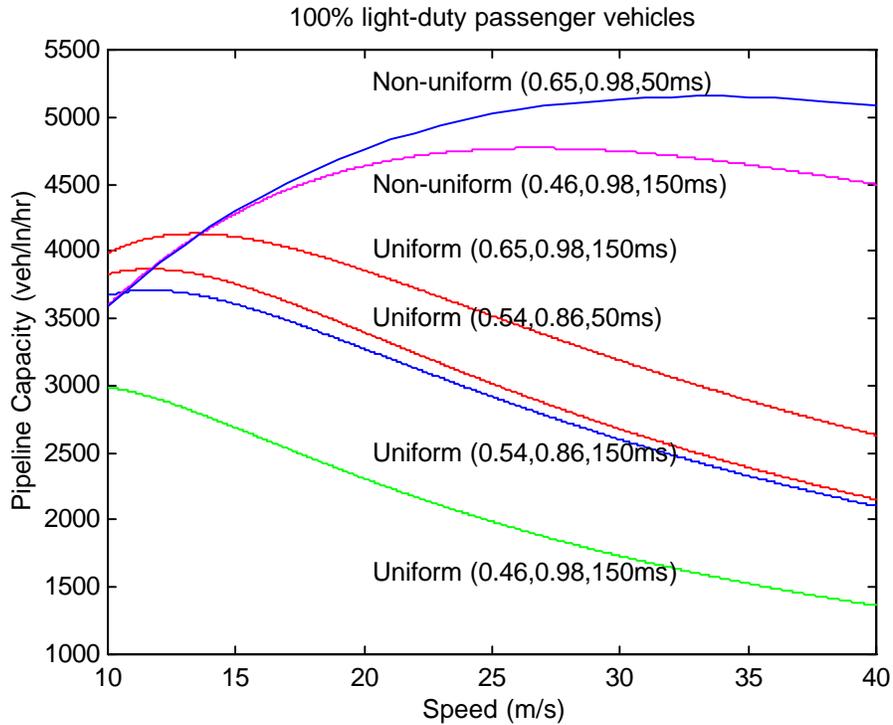
Figure 4.1-8. Pipeline Capacities for Individual Light-Duty Passenger Vehicles Given Non-Uniform and Uniform Spacing Policies and 50 and 150 ms Lumped Lags.

On the other hand, the capacity is very sensitive to the variability in the braking capabilities of the two vehicles, particularly when uniform spacings are applied. If the entire braking rate distribution is permitted (0.46 g for follower and 0.98 g for leader), the pipeline capacity at 30 m/s is only 1700 vehicles per hour. When this distribution is truncated from both ends (0.54 g for follower and 0.86 g for leader), that increases to about 2600 and if it is further truncated at the low end, by imposing strict check-in requirements that will disqualify more vehicles from entering, (0.65 g for follower and 0.98 g for leader) it increases to about 3200.

Cooperative non-uniform spacing can permit significantly higher capacities than uniform spacing, but the advantage decreases as the braking distribution is truncated. If the

complete braking distribution is permitted, non-uniform spacing permits a 180 percent capacity increase at 30 m/s, but if the narrowest of the three braking distributions is used, this increase is only about 60 percent (but relative to a much larger starting value).

4.1.2.1.3 Summary of pipeline capacity analysis

We can summarize the results of spacing design and sensitivity analysis as follows:
- As the level of cooperation increases (from autonomous to low cooperative to high cooperative), the spacing requirement decreases and the pipeline capacity increases.
- Knowledge of braking capability significantly increases the pipeline capacity of individual vehicle operation.
- Platooning (with platoon size above 5) provides highest pipeline capacity.
- Pipeline capacity decreases at higher speeds (above the current highway speed of 65 mph)
- Limiting the range of AHS vehicle braking capabilities (for example by strict check-in criteria) increases pipeline capacity.

For further details, refer to Appendix G.

4.1.2.2 Merging Analysis

The definition of capacity and its calculation for AHS with traffic needing no lane changing or merging, i.e., the pipeline capacity, has been the subject of Section 4.1.2.1. An AHS would probably be implemented with 2 or more lanes, and with frequent entry and exit points.

Lane-changing and merging will cause disturbance to AHS traffic flow; hence the actual capacity of each lane on an AHS highway will be less than the pipeline capacity of an individual lane. Since merging can be viewed as location-constrained lane-changing, it imposes more impediment to the longitudinal flow and more severely reduces traffic flow from the pipeline capacity than lane-changing. It is presumed that in most cases, the system would not conduct lane changes unless they would not impede, or would even increase, overall AHS lane throughput. This subsection describes the impact of merging into an AHS lane on the pipeline capacity. Merging at highway-to-highway interchanges where the traffic from one highway to a crossing highway is not first stopped is beyond the scope of the present study. Merging at a location where two mainline lanes merge into one and merging with the AHS traffic at the end of the transition lane are also beyond the scope of the present study.

Entering vehicles merge with the mainline traffic after being checked in. For some cases, the vehicles may first be stopped at the on-ramp for metering and/or waiting for merging opportunities.

To simplify the analysis, it was assumed that the on-ramp will merge into an AHS with one single mainline lane. The degradation of AHS capacity from its pipeline capacity in a

single lane configuration will be higher than the degradation for a multiple-lane AHS, so this analysis represents something of a "worst case."

4.1.2.2.1 Problem formulation

Three basic vehicle-following concepts were analyzed for merging: autonomous individual vehicles, cooperative individual vehicles and platoons. Autonomous individual vehicles are not equipped with any capability of electronic communication, although they may still be able to cooperate with one another through non-electronic means. Cooperative individual vehicles use vehicle-to-vehicle communication and hence support real-time cooperation among vehicles. In platoons, vehicles not only can electronically communicate with one another but also have tight coordination of maneuvering with their neighbors within the platoon.

The merging disciplines considered are as follows. None of the disciplines calls for any conditioning of the mainline traffic (e.g., gap management) except that all the disciplines for the autonomous individual vehicle concept call for the closing of useless (small) gaps to save space for merging maneuvers.

Merging disciplines for the autonomous individual vehicles assume a dedicated lane with all automated autonomous vehicles on it. Several different disciplines are considered. They include:

(i)   Non-Cooperative with Conventional Metering
   - no mainline slowdown (100% mainline right-of-way),
   - conventional metering at on-ramp (to smooth out burstiness of the arrival stream),
   - on-ramp vehicle (after release by metering) traveling on an extended merge lane that is parallel to the mainline lane,
   - entering vehicle waiting for a sufficiently large gap between two mainline vehicles; entering vehicle merging into mainline traffic by changing lanes into the gap on the mainline lane,
   - a positive and constant speed differential between the mainline lane and the parallel merge lane, with the mainline traffic being faster

(ii)   Non-Cooperative with Microscopic Metering
   - same as (i) except that microscopic metering is supported, where the infrastructure monitors the position of gaps and vehicles and releases on-ramp vehicles accordingly so as to align the entering vehicle with a gap at the merge point,
   - microscopic metering is subject to monitoring inaccuracy; due to inaccuracy, the entering vehicle and the intended gap may not be exactly aligned when the entering vehicle reaches the merge point; in such a case, the entering vehicle uses its sensors to identify the location of the gap and adjusts its speed to reach the gap

(iii)   Cooperation by Yielding
  • same as (i) except that a mainline vehicle is required to slow down to accommodate an entering vehicle if the size of the gap between the mainline vehicle and its immediate predecessor is larger than a specified threshold and if the entering vehicle is next to the gap.

Merging disciplines for the cooperative individual vehicle assume a dedicated lane with all cooperative individual vehicles on it. The analysis assumed the merging discipline of "release to gap." Release-to-gap is made possible by cooperation among vehicles at or near the merge point through vehicle-to-vehicle communication or by vehicle / infrastructure coordination. When the entering vehicle reaches the merge point, the intended gap also reaches the merge point so that the entering vehicle and the gap are properly aligned at the merge point.

Merging disciplines for platooning assume a dedicated lane where all vehicles are traveling in platoons. Three different disciplines are considered:

(i)   release-to-gap (as defined earlier),
(ii)   preplatooning, i.e., on-ramp vehicles forming into platoons while they are stopped at the metering light, and
(iii)   "release to tag," i.e., releasing a vehicle or a platoon so that when it reaches the merge point, it is at the tail end of a platoon on the mainline. The entering vehicle or platoon tags along the mainline vehicle or platoon upon reaching the merge point and joins at the tail end of the mainline platoon.

Measures of Effectiveness: The following measures of effectiveness have been chosen for this study:

MOE1   total throughput downstream of merge point, i.e., the combined flow from mainline upstream and from on-ramp
MOE2   length of the parallel merge lane required for (virtually) all vehicles merging (at least 95 percentile)
MOE3   wait time or queue length at on-ramp, and
MOE4   disturbance to mainline traffic, particularly the number of vehicles slowing down for a merging maneuver and the reduction of mainline speed.

4.1.2.2.2 Simulation and modeling approach

Probabilistic simulation and analytical models have been developed to study the effect of merging on the pipeline throughput for the following concept/merging-discipline combinations: autonomous individual vehicle concept/ non-cooperative with conventional metering, cooperative individual vehicle concept/ release-to-gap and cooperative platooning concept/ all disciplines. Simulation results obtained for the

combination of cooperative individual vehicle concept/release-to-gap will be used as an input to the analysis of the combination of non-cooperative with microscopic metering. Unlike the previous concept/merging-discipline combinations, autonomous individual vehicle/cooperation by yielding will be studied with an analytical model. Details about the methodology will be discussed next, together with the discussion of assumptions.

The simulation model assumes that the mainline traffic moves at a constant velocity, the entering traffic moves at a constant velocity after it has reached the merge point, and there is a constant speed differential between the two traffic streams with the mainline traffic moving faster. It also assumes that it is undesirable to disrupt the flow of mainline traffic during the merge process.

The simulation model has four basic components:
1) arrival generator for mainline traffic,
2) arrival generator for on-ramp traffic,
3) ramp meter for releasing vehicles from ramp, and
4) ramp/mainline merge.

The model is fundamentally a single server queuing system, with the merge point acting as the server (or, with metering, two servers in series).

The model is designed to represent two physical configurations: the cooperative configuration and the non-cooperative configuration. The cooperative configuration is one in which traffic is released precisely to coincide with the arrival of the intended merging position in the mainline, e.g., a sufficiently large gap, the end of a platoon, etc. This case requires communicating the precise intended merging position on the mainline to the vehicles on the on-ramp prior to their release. It also implies a pre-specified acceleration and merge profile. In the non-cooperative configuration, intended merging position on the mainline is not defined and the positions of the gaps are not communicated to the vehicles on the on-ramps. In this configuration, the on-ramp vehicles are released from the ramp meter at a regulated rate and then, upon arrival at the mainline, sense the location of nearby vehicles. If a gap is immediately adjacent on the mainline, then the vehicle immediately moves into position. Otherwise, the entering vehicle travels along a parallel merge lane until it locates a gap and then moves over. In this case, the entering vehicle is assumed to travel at a lower but constant velocity than the mainline traffic. With this lower speed, the vehicle waits for a gap while in motion along the parallel merge lane. For more detail about the simulation model, the reader is referred to Appendix H.

To use the simulator for estimating the capacity reduction of an AHS lane due to on-ramp merging, the upstream flow and the on-ramp flow are varied. Given the speed and the safety spacing numbers provided by the Safety Evaluation Team and stated in Subsection 4.1.3 and Section 4.2, a flow level is translated into density.

For the non-cooperative configuration, the length of the parallel merge ramp required to ensure 95% of the entering vehicles to merge into the mainline (by lane-changing) is the primary inhibitor for the capacity. When the length required for a particular combination of the mainline/on-ramp traffic flows exceeds 1.5 km, the combination is assumed to be non-sustainable and the capacity must therefore be less than this combined flow. Note that the parallel merge ramp does not include the on-ramp. In other words, the on-ramp is the portion that extends to the merge point from the entrance of the on-ramp while the parallel merge ramp includes only the portion that extends beyond the merge point.

For the cooperative configuration, the length of the parallel merge ramp is no longer used as the primary indicator because, with the cooperation, no such parallel merge ramp is needed. Rather, the wait time on the on-ramp is the primary inhibitor. Similar to the non-cooperative configuration, the mainline and on-ramp flows are varied to estimate the capacity reduction due to merging.

A particular flow combination is considered to be beyond the capacity of an AHS lane if the 95 percentile of the wait time distribution exceeds 2 minutes. Before reporting the results, note these threshold values, e.g., the 1.5 km for the merge ramp length and 2 minutes for the wait time, should be treated as worst-case values, rather than average values. Also, experience shows that the capacity is not very sensitive to moderate variation of the threshold values.

As mentioned earlier, simulation results obtained for the combination of cooperative individual vehicle concept/release-to-gap will be used as an input to the analysis of the combination of non-cooperative/microscopic-metering. The consequence of a particular flow combination is captured by two measures: the length of the parallel merge ramp and the wait time. The simulation result for the cooperative individual vehicle concept/release-to-gap produces the wait time while the monitoring inaccuracy (for mainline gaps) together with the speed differential between the two lanes determine the required length of the parallel merge ramp. Due to lack of clear justifiable trade-off between the wait time and the length of the parallel merge ramp, definite conclusions are not drawn about the capacity of an AHS lane for this concept/discipline combination.

An analytical model has been developed to study the autonomous individual vehicle concept with the cooperation-by-yielding discipline. Given the speed, the safety spacing calculated by the Safety Evaluation Team and a given flow level on the mainline, a probability distribution for the physical distribution of vehicles and gaps on the mainline is first estimated. Consider the entry of a particular vehicle from the on-ramp. Since the vehicle has no knowledge of the positions of the vehicles and gaps on the mainline, the entering vehicle, upon arrival at the merge point, begins to look for a sufficiently large gap (catching up from behind) in the mainline lane while traveling at a constant speed. Without any cooperation from the mainline vehicles, the entering vehicle must wait for a gap that is longer than the sum of the length of a vehicle, the required safety spacing and a maneuvering space for adjusting the speed of the entering vehicle (to the speed of the faster traffic on the mainline). This severely limits the amount of traffic that can enter the

mainline, i.e., throughput of the AHS lane. Note that this represents the case of complete mainline right-of-way. On the other extreme is complete on-ramp right-of-way, which stipulates that the mainline traffic has to yield to the entering vehicle whenever there is a vehicle wanting to enter the mainline. This discipline is equivalent to one that calls for creating a gap for the entering vehicle no matter how small the gap is between the mainline vehicle and its immediate predecessor.

Between these two extremes are many possible intermediate policies. This motivated the idea of yielding threshold. When a mainline vehicle detects the presence of a vehicle on the parallel merge lane, if the gap between itself and its immediate predecessor is larger than the threshold value, then it should create a gap to accommodate the entering vehicle into the mainline. Note that the gap refers to space that is not occupied by vehicles and does not contain any part of the safety spacings reserved for safety purposes. In fact, through the use of the yielding threshold, the two extremes are connected by a continuum of yielding policies. When the threshold is set at 0, it represents the policy of complete on-ramp right of way. When the threshold is set at the sum of the length of a vehicle, the required safety spacing and a maneuvering space for adjusting the speed of the entering vehicle, then this threshold value represents the policy of complete mainline right-of-way. Half of that sum is used in this subsection and Appendix H for easier demonstration of the effectiveness of yielding.

Associated with a threshold value is the number of vehicles slowing down to accommodate the merging of an on-ramp vehicle. A limit of 10 is imposed on the maximum number of vehicles (95 percentile) that need to slow down to accommodate such a merging maneuver. Also, the on-ramp traffic is metered so that no single mainline vehicle would need to slow down more than once so as to accommodate multiple merging maneuvers per on-ramp. Any combination of mainline and on-ramp flows that can satisfy these constraints is considered a feasible throughput for the merge. The least upper bound of these feasible flows is then designated as the capacity of the AHS lane.

4.1.2.2.3 Parameter values and results

The parameters used in the study and the corresponding results are:

Autonomous Individual Vehicles: safety spacings: 20 m at 20 m/s; 41 m at 30 m/s; 69m at 40 m/s.

> Results: net throughput less than 50% of pipeline capacity

Note: A major contribution to the throughput reduction is the phenomenon of First-In-Last-Out, in terms of the queuing theory. After an entering vehicle (vehicle A) has reached the merge point, the best the vehicle can hope for is to merge into the next available gap upstream on the mainline lane. However, that gap may actually be encountered and used by a trailing vehicle (vehicle B) on the on-ramp. When this

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happens, vehicle A would have to wait for a gap further upstream, which would take a long time to catch up with vehicle A, if at all.

Cooperative Individual Vehicles: safety spacings: 20m at 20 m/s; 40m at 30 m/s; 68m at 40 m/s.

Results: net throughput 70-75% of pipeline capacity

Platoons: safety spacings: 27m at 20 m/s; 58m at 30 m/s; 101m at 40 m/s.

Results: net throughput as percentages of pipeline capacity:
- with "release to gap" "preplatooning", and "release to tag": 75%;
- without "release to tag" (at 30 m/s): 60%
- without "preplatooning" and "release to tag": 30%.

Autonomous Individual Vehicle with Mainline Slowdown: safety spacing = 41m at 30 m/s, with a yielding threshold of 20m.

Results: net throughput 75% of pipeline capacity

The safety spacings used here are similar, but not identical, to those reported in Section 4.1.3. The differences are attributable to small refinements in the analyses, and the results reported here are not sensitive to such small changes.

4.1.2.2.4 Summary of results

- High reduction from the "pipeline" capacity will result, if merging is not performed efficiently.
- Without some form of coordination, e.g., yielding, for the autonomous individual vehicle concept, capacity reduction due to merging could be drastic, e.g., 50%+. Reasons include the First-In Last-Out phenomenon.
- With yielding, autonomous individual vehicle capacity can be much improved to 75% of the pipeline capacity with negligible disturbance to the mainline traffic (at most 2% reduction in average speed).
  Note that all other merging disciplines assume no mainline slowdown, i.e., no yielding by any mainline vehicles.
- Cooperative individual vehicle concept with release-to-gap provides 75% of the pipeline capacity.
- Microscopic metering also works well for the autonomous individual vehicle concept (without mainline slowdown), at 75% of the pipeline capacity, but with the need for some short parallel merge lane, roadside intelligence for accurate detection of gaps on the mainline, and roadside-to vehicle communication.
- Preplatooning together with release-to-gap lead to throughput of 60% of the pipeline capacity for cooperative platooning.

- Release-to-tag adds significant amount of efficiency for platooning, providing 75% of the pipeline capacity.
- Without release-to-tag and preplatooning, i.e., with only release-to-gap and single-vehicle release, less than 30% of the pipeline capacity has been achieved.
- For all three vehicle-following concepts, merging disciplines have been identified that can provide throughputs of 75% of the pipeline capacity.
- Merging at highway-to-highway interchange, at locations where one lane is being dropped, and merging at end of transition lane (without stopping vehicles on the transition lane prior to "release") is more difficult, in terms of traffic management and model development.

4.1.2.3 Travel-Time Analysis

4.1.2.3.1 Problem formulation

While throughput is an important measure of effectiveness, especially for highway operators, travel time is a significant measure of effectiveness for the driving public who are especially concerned about levels of traffic congestion. This section presents the results of an analysis to estimate travel time as a function of the level of demand and the sensitivity of travel time to throughput.

While the analysis performed focuses on travel on an automated highway facility and so by its very nature is limited in scope, it does provide initial insights into travel time for an automated highway system compared to an all manual highway as well as the differences in travel time across different throughput levels.

An analysis that is regional in scope which encompasses travel activity not only on the automated lanes and adjacent manual lanes but includes neighboring arterials, access and egress points, will be investigated within the next stage of the consortium's concept analysis work, within Task C3.

4.1.2.3.2 Assumptions

As previously mentioned, a very limited and focused scenario was developed for purposes of the travel time analysis. Travel activity is assumed to occur on a ten mile segment of a three lane highway in which one lane has been converted to automated traffic use. Hourly lane capacity for manual lanes is 2,000 vehicles and free-flow speed on manual lanes is 100 km/hr. Automated lane free-flow speeds are assumed to be 100 and 130 km/hr for all throughput volumes, up to total capacity.

4.1.2.3.3 Methodology

The general methodology to convert throughput into travel time is basically to convert speed into time for a given level of aggregate travel demand. The development of a travel time estimate for manual lane traffic is based on data from the Highway Capacity Manual

which indicates that for throughput up to approximately 1500 vehicles per hour per lane (vphpl), vehicles travel at approximately free flow speeds, i.e. 100 km/hr. For throughput between 1500 vphpl and 2000 vphpl, speeds decrease to about 55 km/hr. The onset of unstable traffic conditions generally begins at 2000 vphpl. Thus travel time for manual traffic no greater than 1500 vphpl to travel the 16 km (10 mile) segment is 10 minutes. As throughput increases from 1500 vphpl to 2000 vphpl and speeds decrease from 100 km/hr to 55 km/hr, travel times increase from 10 minutes to approximately 17 minutes for the 16 km segment. While there is no unique functional relationship between travel demand and travel time for these throughput values, as site-specific data will inevitably lead to different travel time growth patterns as throughput increases from 1500 to 2000 vphpl, a relationship that is monotonically increasing and approximately quadratic in nature is assumed.

For any of the automated travel cases, travel time is calculated for the automated lane (depending on its speed) and for the remaining two manual lanes separately and then a weighted average of these two travel times is calculated. Travel on the automated lane is always at free-flow speeds and travel on each of the two remaining manual lanes will be at free-flow speed for manual lane volumes less than or equal to 1500 vphpl. Then speeds on each manual lane will decrease from free-flow to approximately 35 mph as throughput increases to 2000 vphpl.

For example, if the automated lane throughput is 3000 vphpl and free-flow speed is 100 km/hr, then speed on the automated lane is 100 km/hr for travel volumes up to this throughput level and speeds on each of the manual lanes are 100 km/hr for throughput up to 1500 vehicles. Thus, for an aggregate demand level of 6000 vehicles over the three lanes where the travel volume on the automated lane is 3000 and 1500 vehicles are on each of the two manual lanes, average vehicle travel time over the 16 km segment is 10 minutes. At the onset of unstable traffic conditions, total aggregate demand is 7000 vehicles (3000 automated vehicles and 2000 manual vehicles on each manual lane), at which the weighted average vehicle travel time over the 16 km segment is approximately 14.1 minutes. This was calculated from the following expression:

weighted average vehicle travel time $= ((3000/7000)*(1/100) + (4000/7000)*(1/55))*16*60$

The growth in travel time between total aggregate demand of 6000 and 7000 is monotonically increasing and generally quadratic. Analogous calculations are made for other automated lane throughput levels.

Another area of investigation was the possibility of having a free-flow speed on the automated lane greater than the free-flow speed (100 km/hr) on the manual lanes. In this case, automated lane free-flow speed is assigned a value of 130 km/hr and manual lane free-flow speed remains 100 km/hr. For low volume, i.e. uncongested driving conditions on the manual lanes, the driver of an automated vehicle may choose to drive at 100 km/hr on the manual lane rather than 130 km/hr on the automated lane, especially if, for example, the automated lane is a toll lane. Of all the ways in which the automated and manual lanes are populated with vehicles, two different ways are highlighted to show the possible differences in travel time when free-flow speeds on the automated and manual

lanes are not equal. The first way the lanes are populated is called "AHS First" in which the automated lane fills up first before the two manual lanes. The second method is called "Proportional to capacity" in which both the automated and manual lanes fill up in tandem in proportion to their capacities. The general method for calculating travel times is the same as previously described.

4.1.2.3.4 Results

In Figure 4.1-9, for a given level of aggregate demand, higher levels of AHS throughput correspond to lower travel times. In Figure 4.1-10, higher AHS speed results in lower travel time. As AHS throughput increases, the level of aggregate demand at which unstable traffic conditions begin increases and the number of vehicles traveling under free-flow conditions increases. It is assumed that the throughput on the AHS lane is 4000 vphpl.
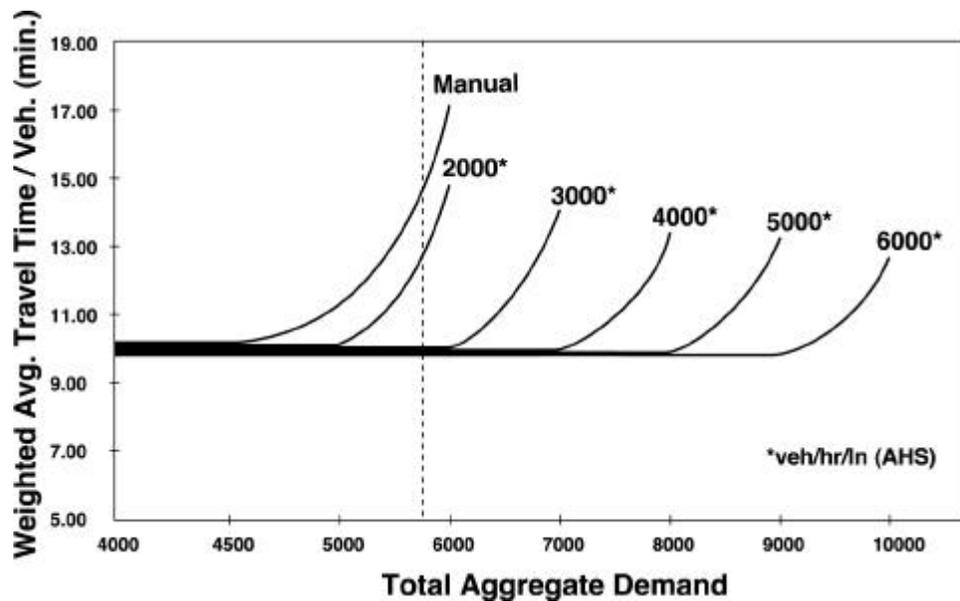
Figure 4.1-9. Example of Travel Time Benefits with Increased AHS Lane Throughput.
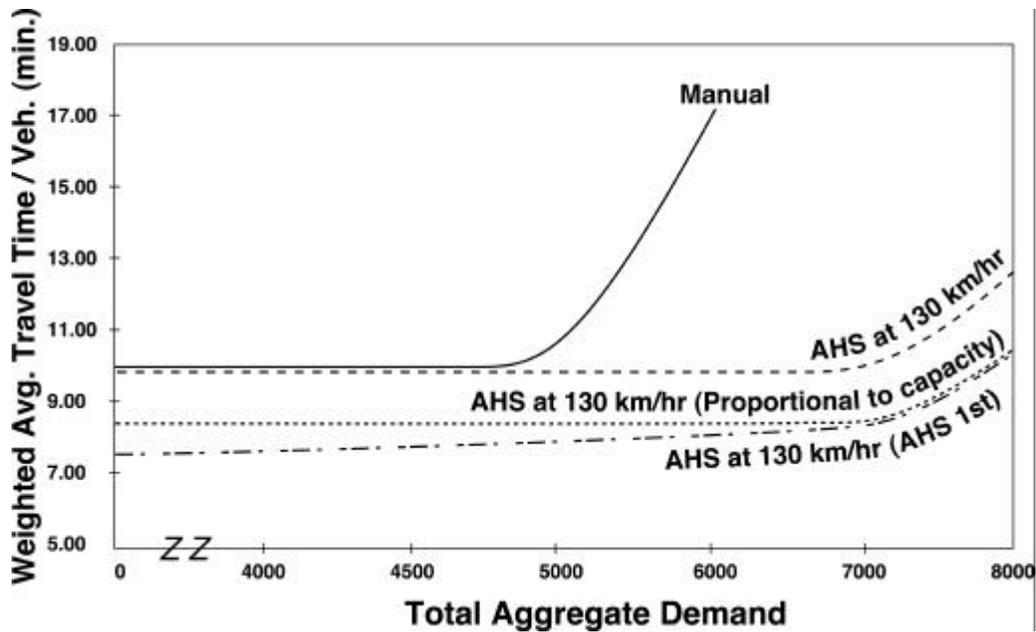
Figure 4.1-10. Travel Time: Sensitivity to AHS Operating Speed.

4.1.3 Mixed Traffic AHS Analysis

4.1.3.1 Problem Formulation

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, throughput estimates for mixed traffic operations were derived.

4.1.3.2 Modeling Assumptions

It is assumed that all the automated vehicle intelligence is concentrated within the vehicle and there is no cooperation among vehicles, that is, no communication of information with one another. It is assumed that manual driving behavior is unchanged from that of today with the analysis carried out for light-duty vehicles only, which are approximately five meters long. It is assumed that the sequencing of manual and automated vehicles in the lane is random, requiring a derivation of the likelihood of occurrence of the four possible pairs of manual/automated vehicle relative roadway positions.

Operating speeds of 20 and 30 meters per second were used in the analysis. The following values for the merge derating factor (a percentage to represent the potential reduction in throughput experienced due to merging and lane changing) were used: 15%, 25%, and 35%.

It is assumed that a manual vehicle will follow an automated vehicle at the same distance that it would follow another manual vehicle. It is assumed that an automated vehicle would follow a manual vehicle at the same distance that it would follow another automated vehicle.

Whether to assume that an automated vehicle would follow a manual vehicle closer than a manual vehicle would follow another manual vehicle was considered for reasons of potential tailgating. 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? Based on data used for the analysis in [4.1-1], the answer to this question is no and 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.

Inter-vehicle safe spacing design and its dependence on the braking capabilities for the two automated vehicles allowed for two types of following distance designs: Uniform or fixed and dynamically changing or non-uniform spacing. With the latter, inter-vehicle spacing may be reduced and thus result in a capacity improvement. For non-uniform spacing, it is assumed that each vehicle has the ability to identify its own braking capability on-line and adjust its spacing accordingly. Since the automated vehicle is assumed to be autonomous in this analysis, it cannot communicate this information to any other vehicle. If cooperative automated vehicles were assumed, they could exchange braking information and thereby operate at potentially smaller spacings.

4.1.3.3 Methodology

The derivation of all-manual throughput was based on data available from a recently completed work [4.1-1] as well as from [4.1-2]. For the case of vehicles traveling at 20m/s, data available from [4.1-2] yields a throughput of approximately 1900 vehicles/hour, which translates into a spacing of 38 meters (including vehicle length).

Reference [4.1-1] provided data on average speeds and spacings of vehicles in light to moderately congested manual traffic. Under manual control, the average speed traveled for all drivers was 30m/s. The average spacing between vehicles, including a 5 meter vehicle length, was 67 meters, which yields an average throughput of 1600 vehicles/hour.

With respect to the random sequencing of manual and automated vehicles, four combinations of vehicle-to-vehicle pair positions are possible since each of the two vehicles of any pair may be automated or manual. A simple probability calculation is used to estimate the likelihood that each of these four outcomes will occur, which lead to

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an expression for throughput as a function of automated vehicle market penetration. Let the market penetration of automated vehicles be expressed as α. Then the probability of any individual vehicle being automated is α and manual is $1-\alpha$.

Let the probability of

an automated vehicle followed by an automated vehicle $= P(A,A) = \alpha*\alpha$
an automated vehicle followed by a manual vehicle $= P(A,M) = \alpha*(1-\alpha)$
a manual vehicle followed by an automated vehicle $= P(M,A) = (1-\alpha)*\alpha$
a manual vehicle followed by a manual vehicle $= P(M,M) = (1-\alpha)*(1-\alpha)$

Throughput may therefore be expressed in terms of α as follows:
Throughput $= 3600*v/(\alpha*\alpha*S(A,A) + (1-\alpha)*(1-\alpha)*S(M,M) + \alpha*(1-\alpha)*(S(A,M)+S(M,A)))$,

where (1) throughput is expressed in vehicles per hour per lane, (2) v equals the velocity expressed in meters per second, and (3) the spacing in meters for

an automated vehicle followed by an automated vehicle $= S(A,A)$
an automated vehicle followed by a manual vehicle $= S(A,M)$
a manual vehicle followed by an automated vehicle $= S(M,A)$
a manual vehicle followed by a manual vehicle $= S(M,M)$

Values for S(. , .) are provided in Tables 4.1-8, 4.1-9 and 4.1-10. The values for S(A,M), S(M,A), and S(M,M) are based on the inter-vehicle spacing assumptions and methodology previously discussed. The values for S(A,A) are based on work documented in Appendix G and presented in Table 4.1-3 for the case of autonomous automated vehicles for a light-duty passenger vehicle following another such vehicle.

Table 4.1-8. Inter-Vehicle Spacing Values for 25% Merge Derating Factor & Uniform Spacing, Including Vehicle Length.

Alternative Operating Speed Values	S(A,A)	S(A,M)	S(M,A)	S(M,M)
20m/s	30.0	38.0	30.0	38.0
30m/s	57.1	67.0	57.1	67.0

Table 4.1-9. Inter-Vehicle Spacing Values for 30m/s Operating Speed & Uniform Spacing, Including Vehicle Length.

Alternative Merge Derating Factor Values	S(A,A)	S(A,M)	S(M,A)	S(M,M)
15%	50.4	67.0	50.4	67.0
25%	57.1	67.0	57.1	67.0
35%	65.9	67.0	65.9	67.0

Table 4.1-10. Inter-Vehicle Spacing Values for 25% Merge Derating Factor & 30m/s Operating Speed, Including Vehicle Length.

Alternative Inter-Vehicle Spacings Values	S(A,A)	S(A,M)	S(M,A)	S(M,M)
Uniform Spacing	57.1	67.0	57.1	67.0
Non-Uniform Spacing	42.4	67.0	42.4	67.0

4.1.3.4 Results

Results show the relationship between throughput and automated vehicle market penetration as parameters such as maximum operating speed, merge derating factor for the automated vehicles, and spacing are allowed to vary in value. Two values for cruising speeds were used, 20m/s and 30m/s. Three values of the merge derating factor were used, 15%, 25%, and 35%. Alternative spacings between automated vehicles are used identifying both uniform and non-uniform spacing designs.

Figures 4.1-11 through 4.1-13 show results of the sensitivity analyses. Figure 4.1-11 displays throughput as a function of market penetration and its sensitivity to vehicle operating speed, with fixed merge derating factor of 25% and uniform inter-vehicle spacing. Throughput varies with increasing market penetration with considerably larger throughput changes for the operating speed of 20m/s. Throughput is sensitive to changes in operating speed throughout the entire range of market penetration percentages. A slight initial decrease in throughput occurs for small values of α. Note that even at a market penetration of 50%, the throughput increases are only 11.1% and 8.0% over the all-manual base case for the speeds of 20m/s and 30m/s, respectively.
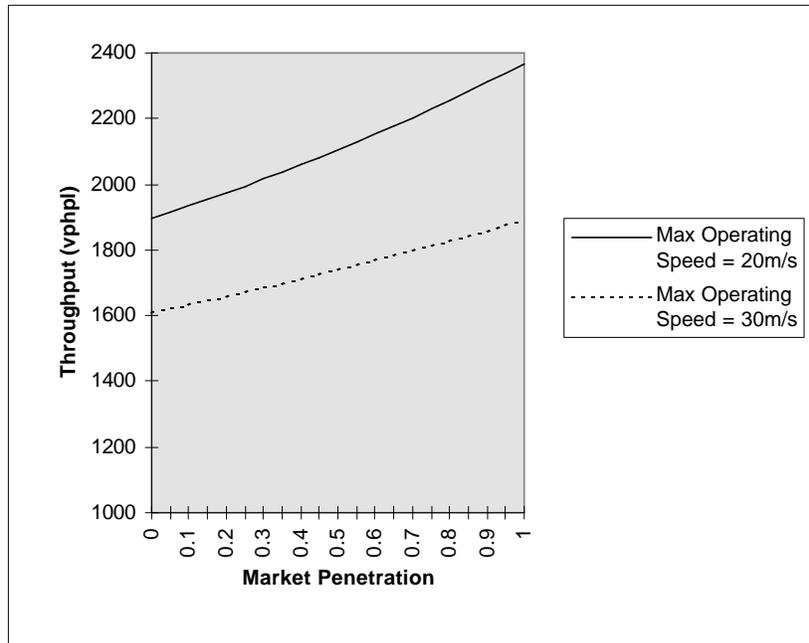
Figure 4.1-11. Throughput vs. Market Penetration
Merge Derating Factor = 25% & Uniform Spacing.
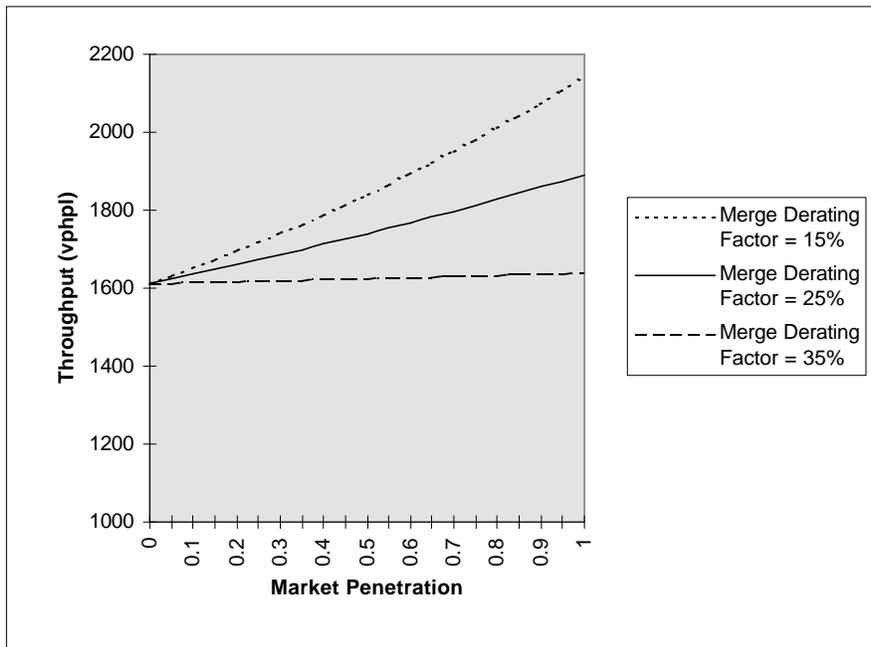
Figure 4.1-12. Throughput vs. Market Penetration
Maximum Operating Speed = 30m/s & Uniform Spacing.

Figure 4.1-12 displays throughput as a function of market penetration and its sensitivity to changes in the merge derating factor for the automated vehicles with a fixed operating speed of 30m/s and uniform inter-vehicle spacing. Throughput increases with increasing market penetration with considerably larger throughput increases corresponding to smaller values of the merge derating factor. Throughput is sensitive to changes in merge derating factor throughout the entire range of market penetration percentages and this sensitivity grows with market penetration because the merge derating only applies to the automated vehicles (spacing for merging already being included in manual driving throughput estimates). Note that even at a market penetration of 50%, for the derating factor of 15%, only a 14.1% throughput increase is produced compared to the all-manual driving base case.

Figure 4.1-13 displays throughput as a function of market penetration and its sensitivity to changes in the inter-vehicle spacing, with a fixed operating speed of 30m/s and merge derating factor of 25%. The non-uniform spacing approach, in which the automated vehicle chooses its spacing based on its own braking capability, permits significantly higher throughput than the uniform spacing case. Note that even at a market penetration of 50%, and with non-uniform inter-vehicle spacing, only a 22.5% throughput increase is produced compared to the all-manual driving base case.
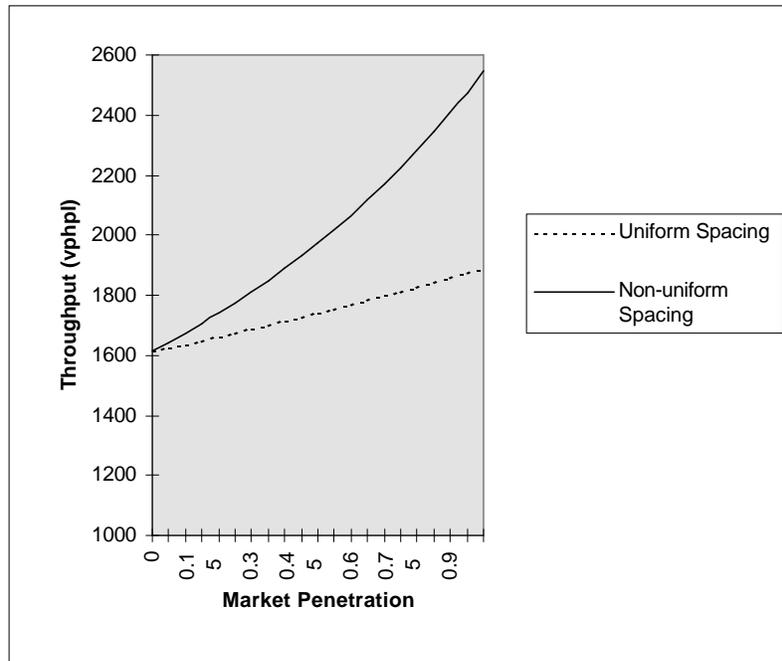
Figure 4.1-13. Throughput vs. Market Penetration
Maximum Operating Speed = 30m/s & Merge Derating Factor = 25%.

The throughput analysis results generally indicate that throughput modestly increases with increasing market penetration, however, at different rates of increase. The two

primary parameters for which the sensitivity analysis was performed, speed and merge derating factor, showed some sensitivity. For relatively small values of α, changes in throughput are small. Based on this analysis, a substantial market penetration of automated vehicles is required before appreciable throughput increases can be achieved.

4.1.4 Conclusions

The comparison of different AHS attributes from the throughput and travel time perspective can be summarized as follows:

- Most of the AHS attribute combinations considered in the analyses result in increased throughput and reduced travel time on dedicated lane AHS as compared to the existing highway system.
- AHS throughput increases with increases in the level of cooperation among automated vehicles.
- This implies that automated vehicles on dedicated lanes should cooperate with each other during maneuver coordination (including emergency maneuvers).
- Limiting the range of AHS vehicle braking capability (such as by applying strict check-in criteria to exclude low-capability vehicles) can significantly increase throughput.
- Knowledge of braking capability significantly increases the throughput of individual vehicle operation.
- AHS throughput decreases at operating speeds higher than today's highway operating speeds of about 30 m/s.
- Platooning provides highest throughput among dedicated lane AHS attribute combinations considered in the analysis.
- In the mixed traffic environment, AHS throughput might increase beyond current highway levels when the market penetration of automated vehicles reaches a high percentage.

It should be noted that the above analysis did not consider multi-lane AHS, effects of active flow control on AHS, interaction of AHS with non-AHS highways and city street networks, and effects of increases in safety (reduction of crashes and resulting congestion) on throughput and travel time. These will be the subject of further study during Task C3.

4.2   Safety Analyses

4.2.1   Hard Braking Safety Analysis Method and Results

This section summarizes the safety analysis of the key AHS concept distinguishing attributes. For a full development refer to Appendix J. In any kind of AHS, it is important to maintain passenger safety at a reasonable level of highway utility. In this analysis, one utility measure is considered, i.e., capacity in vehicles per hour per lane (*vphpl*). Safety is measured by two metrics that quantify collision frequency and collision severity. The methods and data presented here can be used to compare the safety levels associated with different attributes at a fixed capacity, or the capacity levels associated with different attributes at a fixed safety level. We have also derived baseline values for the safety metrics. The baseline is intended to represent current highway driving in certain specific circumstances. This analysis is the first step in the long term AHS safety analysis workplan.

Below, the assumptions made and the studies performed are given, and the procedures used in this analysis are described, including the hard braking modeling process and the methods for generating the collision velocity distributions. The parameters that can be varied in the hard braking model are also described. The process of finding or generating that data is described in Section 4.2.1.4, and the results of the studies outlined in the introduction are presented in Section 4.2.1.5.

4.2.1.1   Assumptions

Safety Metrics. Vehicle safety on an AHS can be quantified by the frequency and severity of collisions between vehicles on the highway. More specifically, we calculate the *total probability of collision given the occurrence of a hard braking malfunction* (described below), and the *expected value of the square of the relative velocity at impact*, which is related to the energy dissipated at impact. These two safety metrics are derived from a *collision velocity distribution:* a probability density function of the relative velocity at impact of two hard braking vehicles in the same AHS lane. This distribution is calculated as shown in Section 4.2.1.3.

The focus of this analyses is the first longitudinal collision after the onset of the hard braking malfunction. Other forms of collision analyses are left for later study. We do not estimate the probability of its occurrence, but instead, the conditional probability of collision is calculated *given* the occurrence of hard braking. Therefore, in making comparisons between the frequency of collision on different automated highway systems, we assume that the probability of the onset of hard braking is the same in each system.

Hard Braking Scenario. There are a large number of possible vehicle responses to a hazardous event. This study focuses on those hazardous events in which the AHS response is to brake the vehicle as hard as it can. Other types of evasive action such as swerving, accelerating, or perhaps sending distress signals to a threatening vehicle may

also be possible depending upon the vehicle/highway configuration. Such responses are not considered in this study.

The safety evaluation scenario is as follows. An AHS vehicle brakes at its maximum capability until it comes to a stop. The hard braking may be due to an obstacle in the vehicle's lane, or an onboard system failure that erroneously invokes hard braking but it should not occur during normal operations (i.e., in the absence of malfunctions or system intrusions). The vehicle behind the hard braking vehicle in the same lane must respond in order to ensure its own safety. In order to minimize the possible impact velocity, the following vehicle brakes at its maximum capability as soon as it detects the hard braking of the front vehicle. This sequence of actions is called the hard braking scenario in this analysis. The hard braking scenario is chosen to represent a plausible emergency condition on the highway, even though it does not represent the worst-case disturbance to the following vehicle; the worst case would occur if the front vehicle hit a brick wall and stopped immediately.

The effects of secondary longitudinal and lateral collisions are left for future study with due caution, understanding that these may have a significant effect on the overall safety picture. Finally, in the hard braking scenario, we only consider situations in which the initial collision is between vehicles, rather than between a vehicle and a foreign object. Thus, there are no sudden changes in the vehicles' velocities prior to the initial collision. Similarly, the safety effects of transient vehicle behavior such as entry, exit, and lane changing should be considered in the future.

Capacity. It is assumed that the AHS has a specified minimum inter-vehicle spacing at any particular operating speed. In calculating capacity at a speed, it is assumed that all vehicles are at the specified minimum spacing, i.e. the highway is at maximum density for the given speed. Capacity is simply the product of the speed and corresponding maximum density. Any variations in vehicle velocities due to controller performance are assumed to be small enough not to affect the overall capacity of the highway. Thus, the evaluation of safety described in this report assumes that the highway is operating at its full capacity.

4.2.1.2   Summary of Studies Performed

Four AHS attribute combinations are evaluated:

1. *Autonomous Individual Vehicles*. For this attribute combination, each vehicle determines its own behavior based on its environment. Each vehicle is equipped with range and range-rate sensors which it uses to sense the behavior of the vehicle in front. When autonomous vehicles' safety is evaluated in the hard braking scenario, the reaction time of the following vehicle includes the time to detect hard braking of the vehicle in front via these sensors. Thus, hard braking detection times are relatively high.

2. *Low Cooperative Individual Vehicles.* Individual vehicles with low cooperation determine their own behavior as in the autonomous vehicle case. Here, however, each vehicle transmits a signal to warn the vehicle behind when it brakes hard. Thus, the time needed for the following vehicle to become aware of an emergency condition is less than in the Autonomous case.

3. *High Cooperative Individual Vehicles.* Individual vehicles with high cooperation transmit their acceleration to the vehicle behind via a high bandwidth communications link. In the hard braking scenario, the reaction delay is therefore further reduced.

4. *Platooned Vehicles.* Platooned vehicles set their following distance based on their status as a platoon leader or a platoon follower. As the first vehicle in a platoon, the platoon leader keeps a large (inter-platoon) spacing from the platoon ahead to guarantee that there will be no platoon-platoon collisions under hard braking. The rest of the vehicles in the platoon, called platoon followers, maintain a very small (intra-platoon) spacing to avoid high relative velocity collisions. Platoon followers react to hard braking by the vehicle in front with the same delay as high cooperative individual vehicles. Platoon leaders react to hard braking by the platoon in front with the same delay as low cooperative individual vehicles.

In addition to the AHS attributes described above, a baseline evaluation of human driving on today's highways is performed. Data on highway spacings and speeds, together with driver reaction time data are used to compare the AHS attributes to manual driving by using the same hard braking scenario to evaluate them. Thus, the performance of an AHS attribute can be compared to a baseline of common experience.

The results that are shown are of four types. First, safety comparisons show a benefit of highway system automation over a manual driving baseline. Second, we compare the four AHS attribute combinations with each other. Third, parameter variation (sensitivity) studies show how the performance of AHS attribute combinations changes with AHS operating speed and intra-platoon spacing. Fourth, safety metric comparisons show the relationship between the two measures of safety (probability and severity) for two attribute combinations. Finally, safety-capacity relationships show how the safety of an attribute combination can change as the system is forced to increase the capacity that it provides.

4.2.1.3   Analytical Process Description

The behavior of the two vehicles in the hard braking scenario is modeled by the list of seven parameters described below. The vehicles are considered to be second order systems with a pure time delay, in the same lane, with no lateral motion. No jerk constraints are imposed on either vehicle.

d_B   *Lumped Reaction Delay sec*

This represents the total reaction delay (sensing + computing + actuating) of the back vehicle. If the front vehicle brakes at its maximum capability, the back vehicle is able to brake at its maximum capability after this delay. For manual driving evaluation, this is the driver reaction time plus the braking actuation delay.

✦$_x$ *Inter-vehicle Spacing m*
This is the distance between the rear bumper of the front vehicle and the forward bumper of the following vehicle. For automated vehicle following, this corresponds to the gap between vehicles.

v_B *Back Vehicle Velocity m/s*
The absolute velocity of the following vehicle. For AHS concepts, this parameter models the AHS operating speed.

✦$_v$ *Relative Velocity m/s*
The velocity of the front vehicle relative to the following vehicle (v_F - v_B). For automated vehicle following, this parameter is associated with the range-rate or velocity tracking error.

$a_{max,B}$ *Maximum Back Vehicle Acceleration m/s^2*
The maximum acceleration (throttle) of the following vehicle.

$a_{min,B}$ *Minimum Back Vehicle Acceleration m/s^2*
The minimum acceleration (maximum braking capability) of the following vehicle This is a negative number.

$a_{min,F}$ *Minimum Front Vehicle Acceleration m/s^2*
The minimum acceleration (maximum braking capability) of the front vehicle This is a negative number.

It is assumed that the front vehicle brakes at its maximum capability at time **0**. The back vehicle begins braking at its maximum capability at time d_B. For this study of vehicle following at maximum highway speed, the back vehicle's acceleration during the delay is zero, and fluctuations in velocity due to controller performance limitations are taken into account by the velocity tracking error. The collision velocity can be calculated kinematically by determining the applicable collision case scenario from among the following:

Collision occurs...

>   1. ...before the following vehicle reacts, before the front vehicle stops.
>   2. ...after the following vehicle reacts, before the front vehicle stops.
>   3. ...before the following vehicle reacts, after the front vehicle stops.

4. ...after the following vehicle reacts, after the front vehicle stops.
5. ...never. The following vehicle stops in time.

The system is required to have no collisions in the absence of malfunctions or system intrusions; however, it is possible to postulate a system design, using the seven parameters, that is free of collisions even in the hard braking scenario caused by some malfunctions or system intrusions. The safe spacing for such a system (Δ_{xsafe}) would be calculated for each vehicle-following pair using the extremum values of each parameter. Thus, Δ_{xsafe} would be a function of $max(d_B)$, $max(\mathbf{n}_B)$, $min(\Delta\mathbf{n})$, $max(a_{max,B})$, $max(a_{min,B})$, and $min(a_{min,F})$. If the parameter values for conservative vehicle performance (described in Section 4.2.1.4) were used in this calculation, the AHS would be extremely safe but the capacity would be unacceptably low – below what would be expected for manual driving. This demonstrates that a balance must be achieved between safety and throughput. It also demonstrates that an AHS designer could improve performance for the same safety level by designing a system that has higher performance than defined in Section 4.2.1.4. For example, a system could be designed to reduce d_B , reduce Δ_v, and minimize the difference between a_{maxa} and a_{minb}, but each of these imposes additional costs. The vehicle spacings calculated in this section are less stringent than those needed for no collision in hard braking, but more stringent than would be needed to meet the basic requirement of no collision in absence of malfunction or system intrusion.

The collision velocity distribution is calculated as follows. Since each hard braking modeling parameter is a random variable, the collision velocity will also be a random variable. In order to calculate this collision velocity distribution, the vehicle parameter distributions are first discretized. For every combination of these discrete parameter values, a collision velocity is calculated. The probability of that collision velocity is incremented by the probability of the corresponding parameter value combination. Notice that parameters can also be modeled as deterministic values while calculating the collision velocity distribution.

We describe next the calculation of highway capacity. If the inter-vehicle spacings are known, it is easy to calculate the capacity of the highway by one of the following formulae:

Individual Vehicles:

(4.2.1)

$$C = 3600 \cdot \frac{V}{(\Delta X + L)}$$

Platoons:

(4.2.2)

$$C = 3600 \cdot \frac{(v \cdot N)}{((L \cdot N) + i \, (N - 1) + I)}$$

where:

> C   Highway Capacity *vphpl*
> L   Vehicle Length *m*
> N   Number of Vehicles in a Platoon
> i   Spacing Between Vehicles in a Platoon (Intra-Platoon Spacing) *m*
> I   Spacing Between Platoons (Inter-Platoon spacing) *m*

Thus, given inter-vehicle spacings and AHS operating speed we can compute capacity. Alternatively, given capacity and speed, the we can use Equation 4.2.1 to get ✦x and Equation 4.2.2 to get *i* or **N**. Then we can use the methods already described to analyze safety.

4.2.1.4   Parameter Modeling

Values or distributions must be selected for each of the seven parameters. Depending on the AHS attributes under evaluation, parameters may have different values or distributions. For AHS, parameters are determined by the capabilities of automated vehicle components (i.e., sensors, computers, actuators) and the automated highway parameters (i.e., operating speed, spacing policy). For manually driven vehicles, parameters are determined by the capabilities of the manual vehicle and the driver's performance.

For each of the four AHS attribute combinations, the hard braking scenario is modeled using the set of seven parameters described. The values of these parameters for each attribute combination are explained in the following paragraphs.

4.2.1.4.1 Automated vehicle parameter values

The physical system parameters describe the aggregate capabilities of the automated vehicle's sensors, transceivers, onboard computers, and actuators. Various longitudinal control laws may be used on a single automated vehicle, but these parameters would not change since they are determined by the hardware constraints.

Lumped Reaction Delay. For automated vehicles, this lumped value is potentially the sum of sensing, computing, communicating, and actuating delay. Each component of the delay is described as follows:

$t_{sen,no}$ 200 *ms*
        This delay is the sensing and computation time needed to discern that the vehicle ahead is applying emergency braking. The vehicle ahead does not communicate an emergency message during hard braking. Thus hard braking detection is by range and range-rate sensors. The value of 200 *ms* allows acceleration estimation of the vehicle in front using 10 sensor readings at the 20 *ms* loop time reported in [4.2-4].

$t_{com,lo}$ 50 *ms*

This delay is the communication and computation time needed to discern that the vehicle ahead is applying emergency braking, assuming that the vehicle ahead communicates its *onset of emergency braking*, and hence that there is Low Cooperation between individual vehicles. A 50 *ms* communication link loop time is verified for four-vehicle platoons in [4.2-4].

t$_{com,hi}$ 20 *ms*

This delay is the communication and computation time needed to discern that the vehicle ahead is applying emergency braking, assuming that the vehicle ahead communicates its *onset of emergency braking* on a high bandwidth communication channel, and hence that there is High Cooperation between individual vehicles.

t$_{act}$ 100 *ms*

This delay is the actuation time between the initial hard braking command signal and when the vehicle actually achieves maximum deceleration. This value is consistent with brake actuator tests, and is feasible as shown in [4.2-10], although faster than current-day production brake systems.

The alternative approaches for combining these delays were already listed in Table 4.1-7, which showed different results for combinations with and without overlapping of communication times with brake actuation times. In these analyses, the actuation times were not assumed to be overlapped for most of the cases studied.

The transient brake response of the vehicles is modeled by step functions. The step function representing the braking behavior of the following car is delayed with respect to the step function representing the braking behavior of the lead car by the amounts shown immediately above. The approximations made by the step response model are illustrated with an example. The actual brake response of a vehicle may be modeled as a dead time in series with a first order lag, which is compared with the step response approximation in Figure 4.2-1. The results shown in the figure are based on actual experimental responses of two different fast-acting automatic brake actuators developed and tested at PATH.

The brake dead times, lag times and saturation levels for the leading and following vehicles in this example are:

	leader	follower
dead time	40 ms	60ms
first-order lag	40ms	60ms
saturation level	0.8g	0.5g

The step responses are shown for the low cooperative case. Note that the step response of the following vehicle is delayed by a total of 150 ms compared to the leader, as assumed in the simplified lumped-delay model of the low cooperative case.
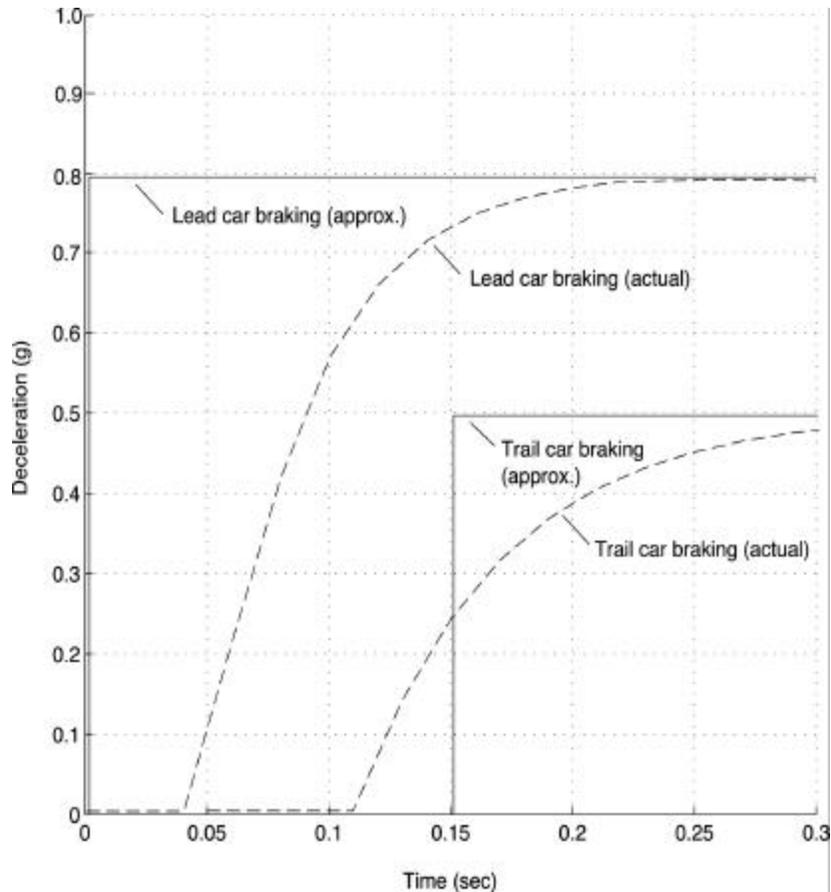
Figure 4.2-1. Approximation of Leading and Following Car Braking.

If the deviations from the nominal values of the actuator lags and the communication latencies are not too high, then these step approximations yield higher collision probability and severity estimates than would be obtained by higher fidelity modeling. This is mainly because the lead car brake response is significantly slower than the step functions modeling it. However, for the following car the approximation is not quite as conservative.

Relative Velocity. In vehicle following, the desired relative velocity between any two vehicles is zero. However, in any vehicle following control system, there will be fluctuation about the desired velocity. The *velocity tracking error* parameter accounts for this fluctuation. For each automated vehicle design, a velocity tracking error of 1.5% was used. This value is consistent with test results for an actual vehicle follower control system [4.2-1].

Maximum Acceleration. This parameter corresponds to the maximum acceleration that the back vehicle may have during the delay d_B between the braking of the front car and

the braking of itself. Since all vehicles are assumed to be approximately at the maximum allowable operating velocity, this parameter is set to 0 m/s^2. Future analysis of other maneuvers which involve acceleration of the back vehicle would require the acceleration saturation limit represented by this parameter to be changed.

Minimum Back/Front Acceleration. The braking capabilities of the AHS vehicle population are modeled by using data on the maximum deceleration on dry pavement of new light duty passenger vehicles as compiled in [4.2-2]. The proportion of each type of vehicle on the highway is derived from the North American production figures in [4.2-3]. In order to account for wear, we assume a 10% derating factor applies to the vehicle's maximum deceleration. This data yielded the histogram shown in Figure 4.1-2. We fit a truncated Gaussian distribution to this data, yielding the smooth distribution shown in Figure 4.2-2, which was used for the safety analyses. The gaussian is clipped at -10 and -4 m/s^2, has a mean of -7.01 m/s^2, and a standard deviation of 1.01 m/s^2.

4.2.1.4.2 Automated highway parameter values

The AHS sets the highway operating speed and spacing. Speed and spacing determine capacity and maximum density.

AHS Operating Speed. Since all vehicles are assumed to be traveling at approximately the system's determined operating speed, the following vehicle's velocity is fixed at that operating speed. The front vehicle speed is assumed to be slightly lower as determined by the velocity tracking error. The AHS operating speeds investigated in this section are 20, 30, and 40 m/s (45, 67, and 89 mph).

Inter-Vehicle Spacing. This study evaluates the performance of AHS attribute combinations at highway capacities between 500 and 8000 $vphpl$ at the AHS operation speeds mentioned above. Thus, Individual Vehicle spacings are calculated from highway capacity and speed using equation 4.2.1 to be from 4 to 280 m. For vehicles traveling in platoons, the inter-platoon spacing is set to guarantee that no platoon-platoon collisions occur in the hard braking scenario. Thus, the inter-platoon spacing varies over the above AHS speeds within the range of 42 to 163 m. In order to investigate changes in capacity at a fixed speed for platooned vehicles, the number of vehicles in a platoon and the intra-platoon spacing were varied; the inter-platoon spacing was not varied. Intra-platoon spacing is small so that high relative velocity collisions can be avoided [4.2-9]. This section considers intra-platoon spacings between 1 and 10 m.
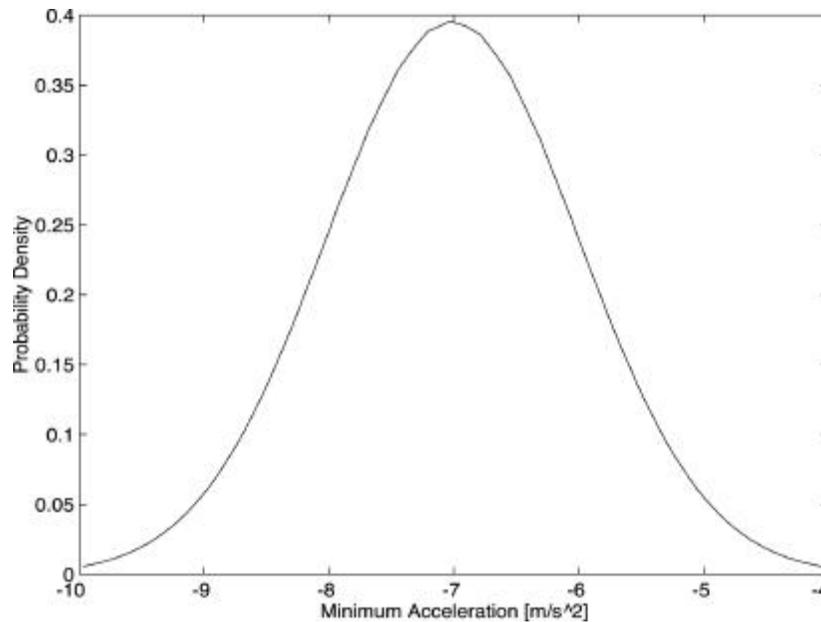
Figure 4.2-2. Estimated Distribution of Braking Capabilities for all Automated Vehicles.

4.2.1.4.3 Manual vehicle/driver parameter values

Just as an AHS was decomposed into a vehicle and an AHS system, a manual highway system can be decomposed into a vehicle and the driver behavior. Each parameter is evaluated based upon the performance of these two components.

The maximum acceleration of the following vehicle and the braking capabilities of the vehicle population are the same as those described above for automated vehicles. The lumped delay described above must now change since only the actuator delay applies to the physical system. All of the delays associated with computing and sensing hardware are replaced by delays associated with the driver performing these functions. The portion of the lumped reaction delay that originates from the brake actuation system is the same as that for the automated vehicles. Thus, $t_{act} = 100$ *ms*.

The parameters which depend on the behavior of a human driver are described next. The parameters are estimated based upon data taken under highway driving conditions.

Lumped Reaction Delay: Driver Reaction Time. The total lumped delay is composed of a braking actuator delay in series with a driver reaction delay. An estimate of the distribution of driver reaction times for highway driving was obtained by fitting a lognormal distribution to reaction time data collected by Michael Sivak as detailed in [4.2-6]. The data was collected by measuring brake reaction times of unalert drivers at highway speeds up to about 20 *m/s*. The lognormal distribution is fixed with median $\lambda = 1.07$ *s*, mean $\mu = 1.21$ *s*, standard deviation $\sigma = 0.63$ *s*, and dispersion parameter $\zeta = 0.49$. This reaction time distribution was discretized as shown in Figure 4.2-3 to calculate the collision velocity distribution.
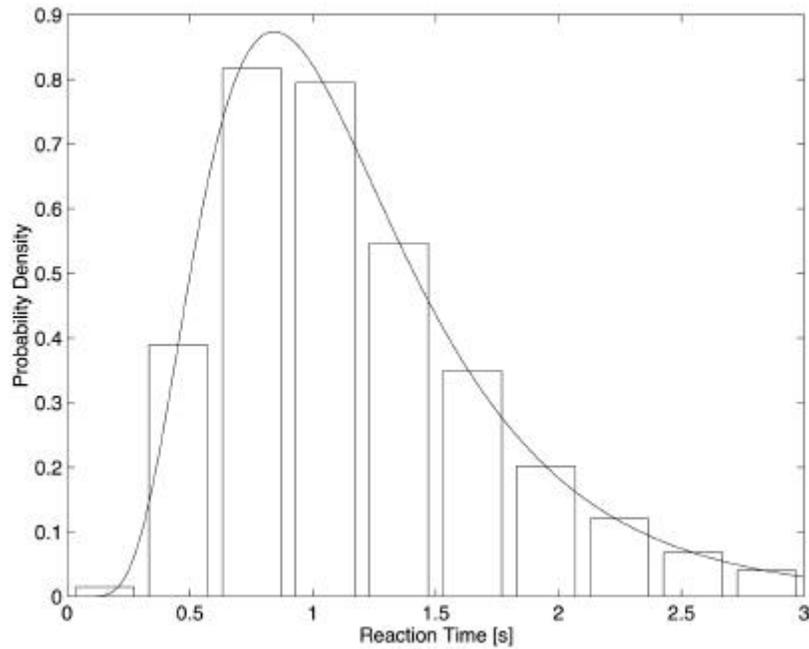
Figure 4.2-3. Reaction Time of a Typical Unalert Driver.

Inter-Vehicle Spacing/Relative Velocity. An infra-red sensor measured the inter-vehicle distance and the correlated relative velocity during vehicle following for a sample of 36 drivers in a study conducted by researchers at the University of Michigan Transportation Research Institute. This data was collected on a 55 *mi* sequence of highways in Ann Arbor and the Metropolitan Detroit area [4.2-7]. We used a probability distribution of the correlated range and range-rate from this data as shown in Figure 4.2-4.

Back Vehicle Velocity. In actuality, the velocity of the back vehicle is correlated to the spacing and relative velocity distribution described above. However, the velocity data was recorded independently of range and range rate. In order to estimate the collision velocity distribution under hard braking for manual driving, we assumed that the velocity of the back vehicle was the mean of the velocity distribution in [4.2-7]. The mean of the velocity distribution is $\mathbf{v_{mean}} = 29.3$ *m/s*.

4.2.1.5 Results

Figure 4.2-5 contains three collision velocity distributions derived as detailed above. They show how the safety of automated vehicles compares to the manual driving baseline at an AHS operating speed of 30 *m/s*. The spacing of the autonomous vehicles was
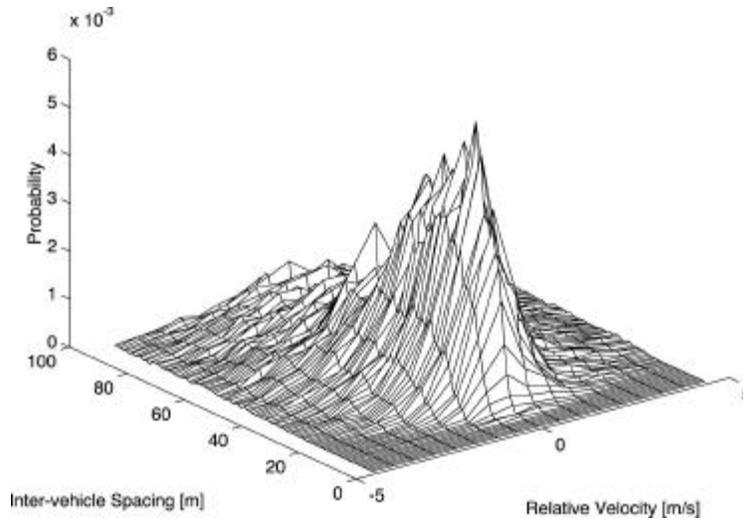
Figure 4.2-4. Highway Vehicle Following for a Typical Manual Driver.
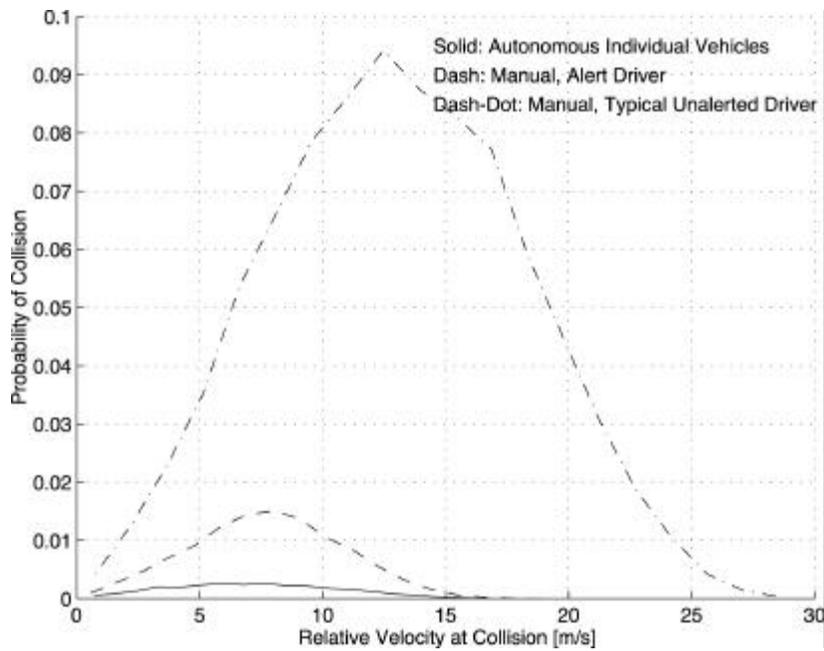
Attribute	Capacity	Total Prob of Collision	Expected $\cdot v^2_{coll}$
AHS Autonomous	2500 *vphpl*	0.028	64.1 m^2/s^2
Manual Alert	< 1500 *vphpl*	0.11	69.5 m^2/s^2
Manual Typical	< 1500 *vphpl*	0.87	195 m^2/s^2

Figure 4.2-5.   Safety Comparison between Manual and Automated Vehicles.

chosen to give an AHS capacity of 2500 *vphpl*, assuming that all vehicles in the lane are automated. The manual driving data from [4.2-7] was collected under non-rush-hour conditions along a route whose average volume was less than 1500 *vphpl*. Thus the demonstration of the increased safety of the automated vehicles over the manual baseline is even stronger, since the level of utility provided by the automated system is also higher than the manual baseline. The two collision velocity distributions shown for the manual baseline reflect two possible assumptions about the driver reaction delay. The curve representing an "alert" driver was derived assuming a reaction time of 0.5 *s*, which is near the minimum delay reported in [4.2-6]. The remaining curve was derived using the full reaction delay distribution described above for unalert highway drivers. Thus, these two distributions form a reasonable range for the safety of manual driving under the hard braking scenario. If driver reaction delay data existed that was correlated to vehicle following range and range-rate, then the true collision velocity distribution would likely fall between the two derived bounds. The table accompanying Figure 4.2-5 provides some statistics about these collision velocity distributions. Both frequency and severity safety metrics indicate the benefit of automation.

Adding cooperation between vehicles can increase safety as shown in Figure 4.2-6. The alert manual driver baseline from Figure 4.2-5 is included for comparison. Again, the table accompanying Figure 4.2-6 quantifies the benefit of decreasing the hard braking delay by increasing cooperation between vehicles. The low cooperative vehicles are much more safe than the autonomous vehicles because of the significant shortening of the hard braking delay (from 300 *ms* to 150 *ms*). The safety gain between the high cooperative and low cooperative individual vehicles is relatively small. It results from the slight shortening of the hard braking delay (from 150 *ms* to 120 *ms*). As before, the automated vehicle evaluations are done at 30 *m/s* and 2500 *vphpl*, while the manual baseline is near the same speed, but at less than 1500 *vphpl*.

The next two results show the variation of safety at a fixed capacity as AHS operating speed increases. Figure 4.2-7 shows this relationship for low cooperative individual vehicles, and Figure 4.2-8 shows the same result for cooperative platooned vehicles. The other individual vehicle cases are similar to the low cooperative individual vehicle. Both individual vehicles and platoons are safer at lower speeds, though the safety of platoons is less sensitive to changes in speed at a fixed capacity (2500 *vphpl*). To keep a constant capacity at higher speeds, the individual vehicles travel at larger spacings. This larger spacing allows for a larger relative velocity build up during the time until collision in the hard braking emergency scenario. Therefore, the severity of individual vehicle collisions increases significantly with speed. To keep a constant capacity for platoons at a fixed intra-platoon spacing while increasing AHS operating speed, each platoon must contain fewer vehicles. But since the intra-platoon spacing is always small, the collision severity remains low for all three speeds. This seeming benefit of platooning should be reevaluated to account for the effects of secondary collisions that are not studied here. The intra-platoon spacing affects safety as shown in Figure 4.2-9. As the spacing increases within the 1 to 10 *m* range, the probability of collision decreases. This is
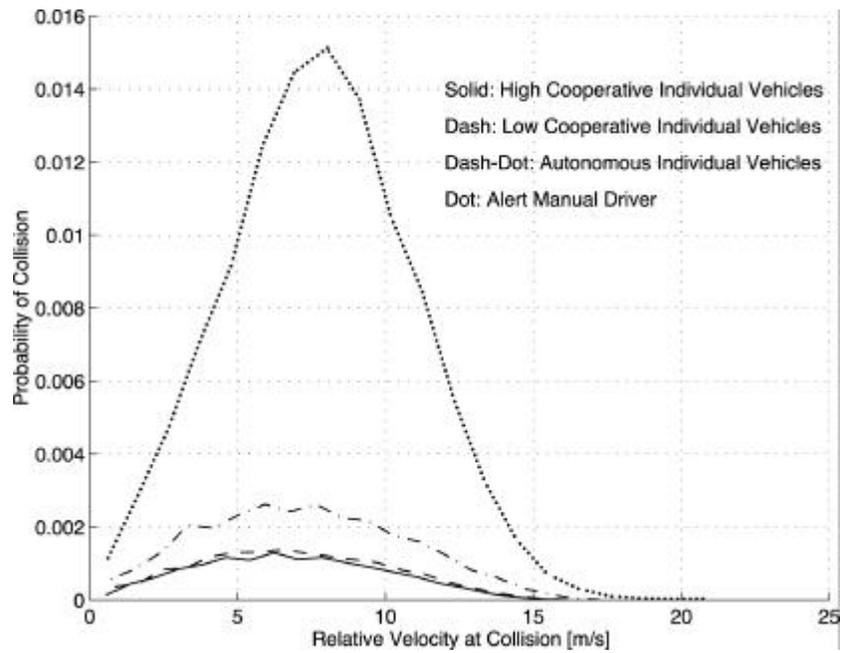
AHS Attribute	Capacity	Total Prob of Collision	Expected $\blacklozenge\,v\,^2_{coll}$
Autonomous	2500 *vphpl*	0.028	64.1 m^2/s^2
Low Cooperative	2500 *vphpl*	0.015	58.2 m^2/s^2
High Cooperative	2500 *vphpl*	0.013	56.9 m^2/s^2
Manual Alert	< 1500 *vphpl*	0.11	69.5 m^2/s^2

Figure 4.2-6. Safety Comparison at Different Levels of Cooperation.
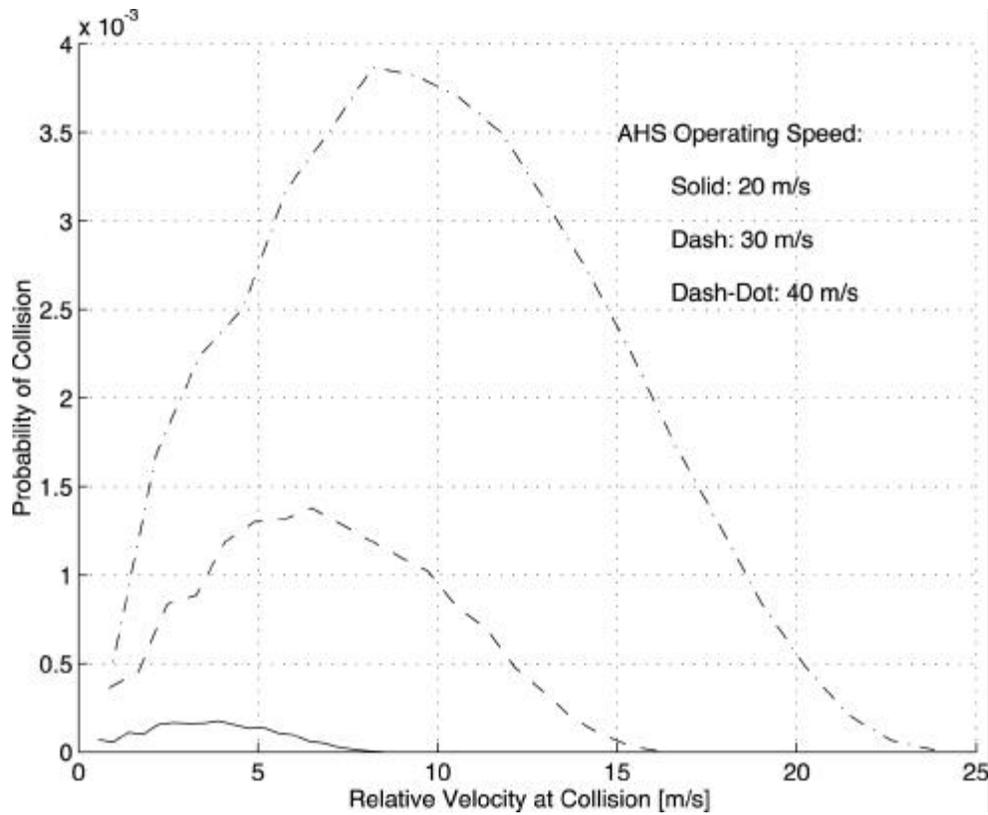
AHS Speed	Capacity	Total Prob of Collision	Expected ✦ v $^2_{coll}$	Nominal Spacing
20 *m/s* 45 mph	2500 *vphpl*	0.002	16.8 *m²/s²*	24 *m*
30 *m/s* 67 mph	2500 *vphpl*	0.015	58.2 *m²/s²*	38 *m*
40 *m/s* 90 mph	2500 *vphpl*	0.041	121 *m²/s²*	53 *m*

Figure 4.2-7. Low Cooperative Individual Vehicle Safety at Different AHS Speeds.
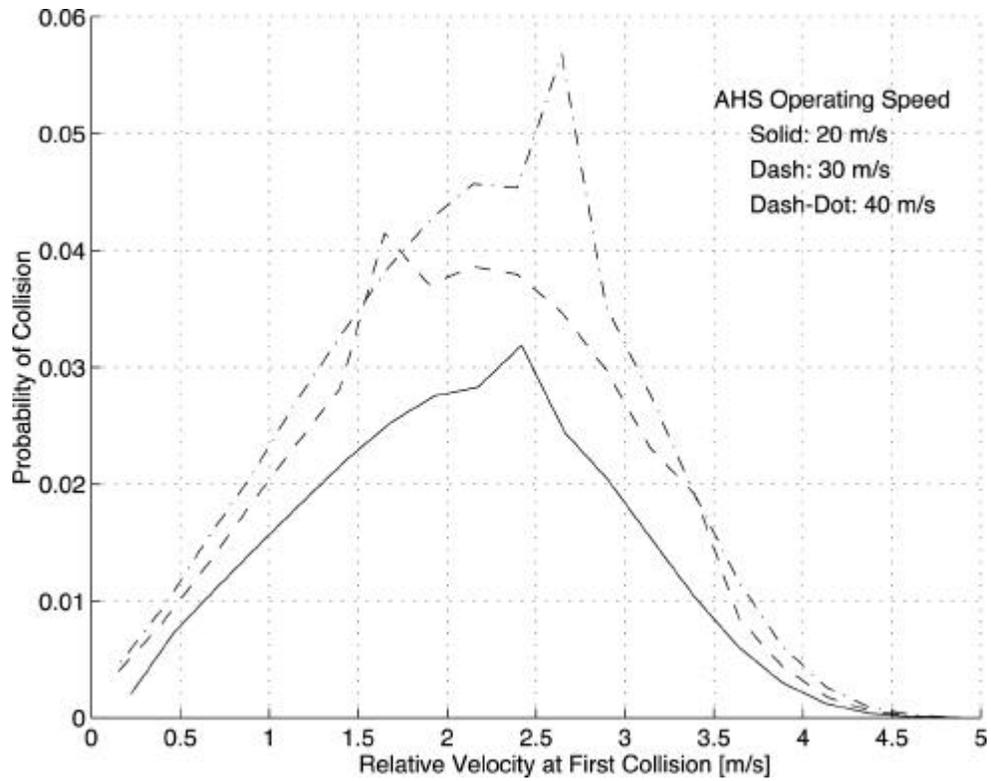
AHS Speed	Capacity	Total Prob of Collision	Expected Δv^2_{coll} [*]
20 *m/s*	2500 *vphpl*	0.27	5.03 m^2/s^2
30 *m/s*	2500 *vphpl*	0.37	5.13 m^2/s^2
40 *m/s*	2500 *vphpl*	0.44	5.29 m^2/s^2

Figure 4.2-8. Platoon Safety at Different AHS Speeds.

[*]This is for the first pair of vehicles. The Δv *for other vehicles in the platoon was not calculated.*
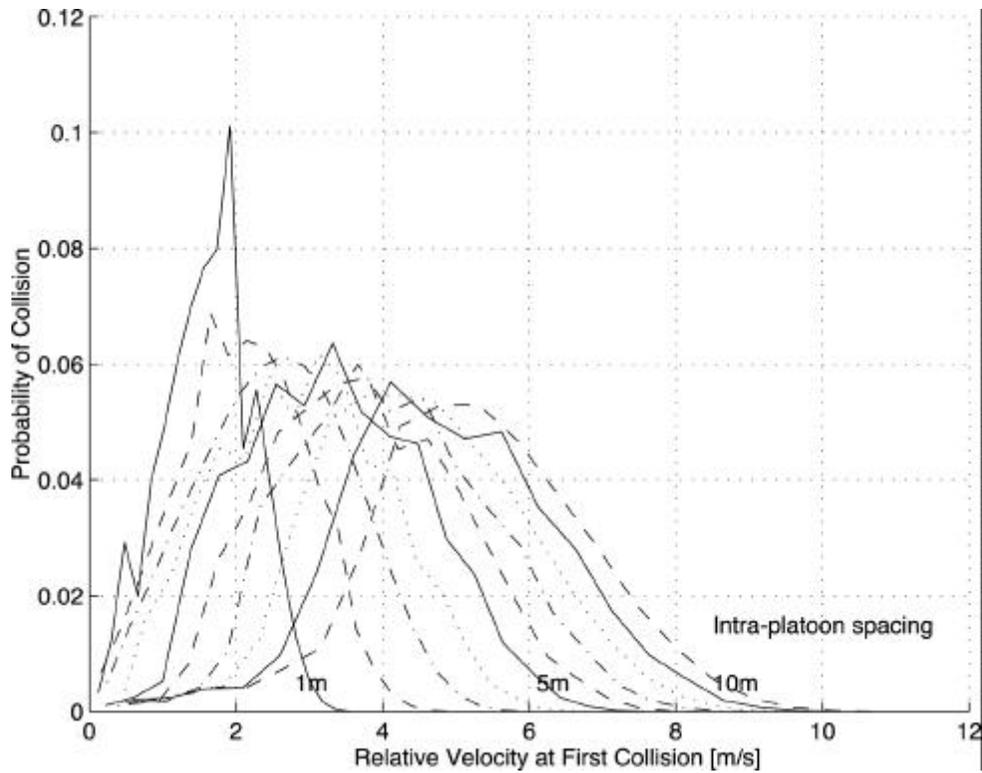
Intra-Platoon Spc	Total Prob of Collision	Expected Δv^2_{coll}*
1 *m*	0.73	2.94 m^2/s^2
2 *m*	0.62	5.13 m^2/s^2
3 *m*	0.58	7.38 m^2/s^2
4 *m*	0.54	9.87 m^2/s^2
5 *m*	0.51	12.6 m^2/s^2
6 *m*	0.48	15.6 m^2/s^2
7 *m*	0.45	18.9 m^2/s^2
8 *m*	0.42	22.4 m^2/s^2
9 *m*	0.39	26.2 m^2/s^2
10 *m*	0.36	30.2 m^2/s^2

Figure 4.2-9. Platoon Safety at Different Intra-platoon Spacings.

*This is for the first pair of vehicles. The Δv *for other vehicles in the platoon was not calculated.*

because there are a few more possible combinations of favorable braking rates which result in avoiding a collision at such small spacings. In many cases however, the vehicle pair still collides, and at larger intra-platoon spacings, the severity of the collisions steadily increases. This result demonstrates the advantage of minimizing intra-platoon spacing to reduce the risk of high severity collisions.

The next result quantifies the differences in frequency and severity of collisions for low cooperative individual vehicles and platooned vehicles. Specifically, these two AHS attributes are shown to achieve safety by reducing a different one of the two safety metrics. In Figure 4.2-10, platoons have a high total probability of collision for any speed, but the expected severity of the collisions is low. In interpreting these probabilities it should be noted that these are conditional probabilities given the occurrence of the hard braking emergency. In any mature AHS, the hard braking emergency is expected to be a very low probability event. For low cooperative individual vehicles, the probability of collisions is lower, but those collisions that do occur are much more severe. Again, this result is at a constant capacity of 2500 *vphpl*.

The remaining set of results show the relationship between safety and capacity for each of the attribute combinations studied. Figures 4.2-11 and 4.2-12 plot the two safety metrics defined earlier against AHS capacity at 30 *m/s*. The y-axis of each plot is defined such that increased safety is in the +y direction. Thus, in Figure 4.2-11, the y-axis represents the probability that a collision is avoided, and in Figure 4.2-12, it represents the negative of the expected square of the collision velocity. Curves are shown for individual vehicles, platoons at constant intra-platoon spacing, and platoons of constant size at intra-platoon spacings of from 1 to 10m in 1m increments (indicated by hash marks on platoon curves). In order to best understand the safety-capacity relationship for each AHS attribute, we examine the frequency and severity safety metrics in conjunction.

For platooned vehicles, we see in Figure 4.2-11 that collisions are avoided entirely at capacities below about 1200 *vphpl*. This is due to the zero collision assumption between platoons. At these low capacity levels, the demand can be satisfied by 1 car platoons traveling at very large spacings. As capacity increases at a constant intra-platoon spacing however, more followers are added to the platoons. They are not able to completely avoid hard braking collisions, and the probability of avoiding a collision drops off sharply at 1200 *vphpl* as the first followers are added, and then flattens out at high capacities. This flattening is a result of the proportion of followers within a platoon. To find the probability of collision for platoons of N vehicles in which the leader maintains a safe spacing from the platoon in front, the probability of collision for a follower is multiplied by (N-1)/N. For large platoons, (N-1)/N approaches one asymptotically, and hence the probability of collision within a platoon asymptotically approaches the probability of collision of a single follower. Looking to Figure 4.2-12, we see that the collision severity at constant speed and intra-platoon spacing shows no dependence on capacity. This is consistent with the restriction of studying only the first longitudinal collision in the hard braking scenario. The severity of the first longitudinal collision depends only on the two
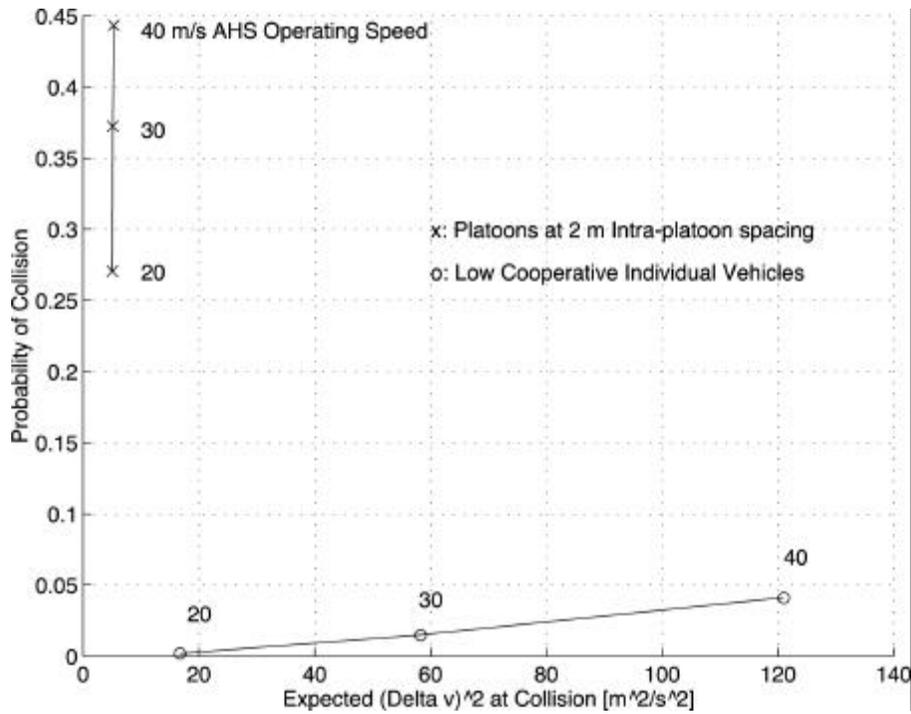
Low Cooperative Individual Vehicles

AHS Speed	Capacity	Total Prob of Collision	Expected Δv^2_{coll}
20 *m/s*	2500 *vphpl*	0.002	16.8 m^2/s^2
30 *m/s*	2500 *vphpl*	0.015	58.2 m^2/s^2
40 *m/s*	2500 *vphpl*	0.041	121 m^2/s^2

Platooned Vehicles

AHS Speed	Capacity	Total Prob of Collision	Expected Δv^2_{coll} *
20 *m/s*	2500 *vphpl*	0.27	5.03 m^2/s^2
30 *m/s*	2500 *vphpl*	0.37	5.13 m^2/s^2
40 *m/s*	2500 *vphpl*	0.44	5.29 m^2/s^2

Figure 4.2-10. The Probability/Severity Safety Trade-Off.

*This is for the first pair of vehicles. The Δv *for other vehicles in the platoon was not calculated.*
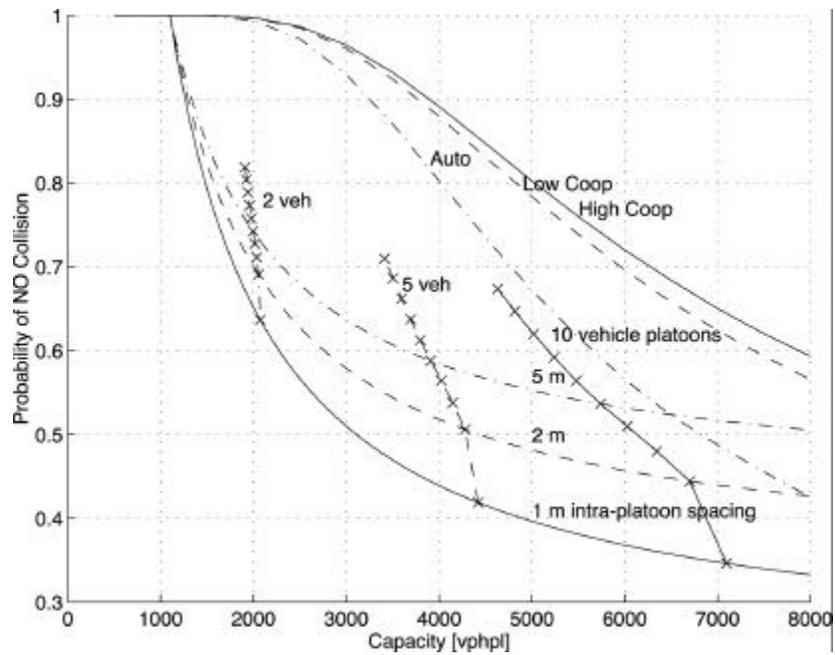
Figure 4.2-11. The Safety/Capacity Relationship for all
Attribute Combinations: Frequency Metric.
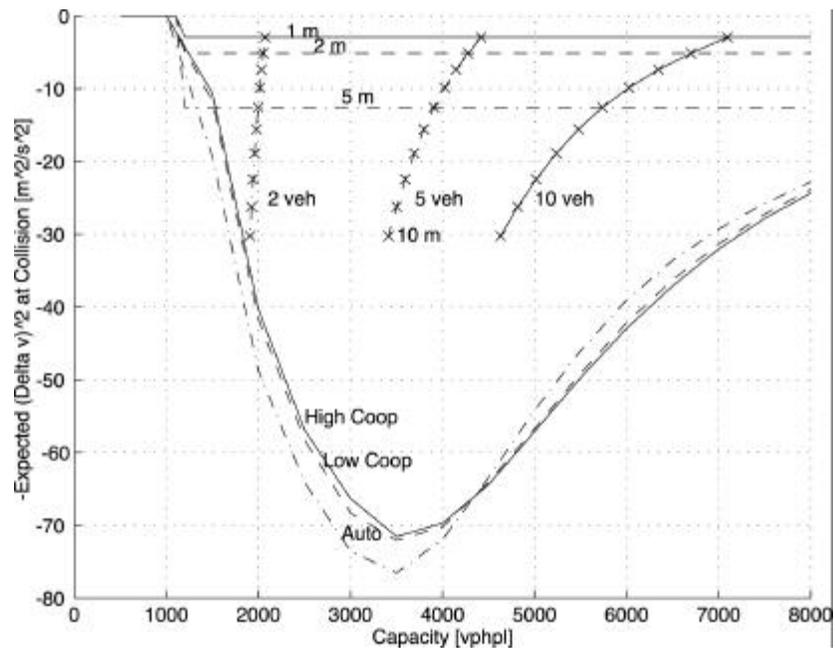
Figure 4.2-12. The Safety/Capacity Relationship for all
Attribute Combinations: Severity Metric.

vehicles involved, and not the other potential followers needed to reach the given capacity.

Turning to the individual vehicle results, we see in Figure 4.2-11 that individual vehicles at all levels of cooperation are less likely to collide than platoons at all but very high capacity levels. Increasing cooperation between vehicles reduces the probability of collision at any capacity. The advantage of individual vehicles over platoons is reversed in Figure 4.2-12. There we see that individual vehicle collisions at moderate capacities are more severe than for any of the platooning cases. It is interesting to note in Figure 4.2-12 that at capacities between 4500 *vphpl* and 9000 *vphpl*, the expected severity of collisions is actually *worse* for individual vehicles with more cooperation. The collision severity decreases for all of the individual vehicle cases at the higher capacities (above about 3500 vehicles per lane per hour) because at these capacities the spacings between vehicles become short enough that the collision impact speeds are reduced. It is important to remember that this expected severity is for the entire vehicle *population*. For a single vehicle pair colliding in the hard braking scenario, decreasing the delay d_B will always *reduce* the severity of that collision. However, the expected severity of collision for the vehicle population is influenced by the shape of the hard braking parameter distributions as well as the kinematic calculations. The crossover region in Figure 4.2-12 can be explained by looking at the parameter distributions used in this study in more detail (refer to Appendix J).

The last result shown in Figure 4.2-13 demonstrates the safety-capacity relationship by combining the measure of frequency and severity to evaluate overall safety. The composite safety metric is the expected square of the collision velocity, not conditioned on the occurrence of the collision. It can be derived from the previously defined safety metrics by simply multiplying the expected square of the collision velocity (severity metric) by the total probability of collision (frequency metric). Therefore, if vehicles have rare, more severe collisions or frequent light collisions, the composite safety metric will indicate that the system is more safe than an AHS with frequent severe collisions. Using this composite safety metric, we continue to see the advantage of increasing inter-vehicle cooperation for improving the safety of the individual vehicle AHS attribute. For the platooning attribute, it is advantageous to minimize the intra-platoon spacing. The safety of a platooning system does not seem to be sensitive to increasing the number of vehicles within a platoon in this analysis, but this will change when secondary collisions are considered. Finally, if this safety metric is used, we see that the safety-capacity curves for individual vehicles and platoons intersect. For instance, highly cooperative individual vehicles and platoons with 2 *m* intra-platoon spacing are equally safe at just under 3000 *vphpl*. At higher capacities, platoons appear to be much safer, but this depends on the composite measure of safety used and the limitation to analysis of the first forward collision. A different composite measure could also produce different results by changing the weighting of the two safety metrics.

4.2.1.6   Summary and Future Work

We have analyzed the safety of four different kinds of AHS, i.e., Autonomous Individual Vehicles, Low Cooperative Individual Vehicles, High Cooperative Individual Vehicles, and Platoons. The study helps quantify the impact of inter-vehicle cooperation on AHS safety. It also helps to compare and contrast the safety characteristics of an individual vehicle AHS with a platooned AHS. In all cases we have restricted our attention to safety under the hard braking scenario, i.e., the vehicle in front of the subject vehicle brakes hard until it comes to rest. This is a severe disturbance that serves well to elicit differences between the different kinds of AHS. It is arguably not the most dangerous hazard for which AHS safety systems have to be designed.
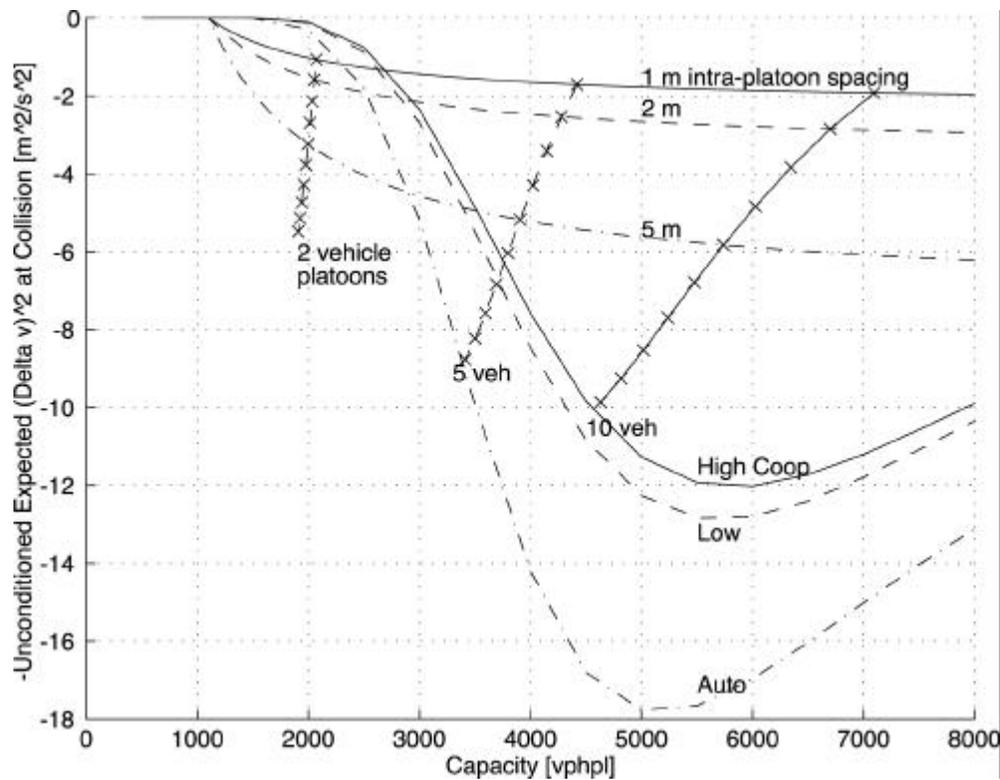
Figure 4.2-13. The Safety/Capacity Relationship for all
Attribute Combinations: Composite Metric.

We are interested in both the frequency and the severity of collisions. Frequency is quantified by the total collision probability given the occurrence of hard braking, and severity by the mean square collision velocity given the occurrence of a collision. Note that we restrict our attention to the first forward collision. Multiple collisions are not considered in this study. We estimate safety as a function of automated vehicle capabilities and automated highway parameters. There may be large variations in the

capabilities of automated vehicles. Such variations are modeled by probability distributions. The equations of motion are used to map the deterministic and stochastic vehicle and highway parameters to collision velocity distributions. The collision frequency and severity metrics are computed by post-processing these distributions.

The extent of variation in vehicle braking capabilities is such that even within the limited context of the hard braking scenario, zero-collision inter-vehicle spacings result in much lower capacities. Thus, for higher capacities, collisions occur with a non-zero probability. We provide a context to the collision probability numbers by relating them to two automated highway operating parameters, capacity and AHS operating speed. We also provide a baseline, computed to model present-day highway driving as a point of comparison.

The analyses show several interesting results. At a speed of 30 m/s (67 *mph*) all four kinds of AHS compare favorably with the manual driving baseline. For a given set of automated vehicle capabilities and AHS capacity, higher speeds reduce safety. There is a significant improvement in safety as one goes from no inter-vehicle cooperation (i.e., autonomous) to low inter-vehicle cooperation. The safety improvements from low to high cooperation are not quite so dramatic. These findings are predicated on assumptions about varying capabilities of sensing and communication systems. Two-vehicle platoons have comparable safety characteristics to Low Cooperative Individual Vehicles at capacities of approximately 3000 *vplph*. However, platoons do better in terms of the severity metric whereas the Low Cooperative Individual Vehicles do better in terms of the frequency metric.

We have several ideas for future work that will broaden the scope of this AHS safety analysis. This analysis considers only the first collision between vehicles on a highway. We propose to analyze the safety impacts of secondary collisions, which could change the results significantly. We are also interested in broadening the range of evaluation scenarios to include obstacles, lane-keeping failures and other likely crash scenarios.

4.2.2 Obstacle Avoidance Safety Analysis Method and Results

4.2.2.1 Overview

Here we consider a different kind of abnormal operating condition. This analysis addresses the sudden appearance of a dangerous obstacle, which can be avoided by hard braking or a lane-change maneuver. The purpose of this analysis is to determine the effect of increased vehicle cooperation on obstacle avoidance performance. The safety of two lane change techniques, one more and one less complex, as well as hard braking, is examined under three different AHS architectures. The performance of the three techniques is analyzed as a function of speed and range to the obstacle. A qualitative assessment of the communication bandwidth required to support the different obstacle avoidance techniques is also made.

In this analysis, AHS architectures are associated with obstacle avoidance techniques using best engineering judgment, that is to say, the most capable obstacle avoidance technique which the architecture is capable of supporting is designated as the primary technique for that architecture. A quantitative analysis of the data rate supported by the different architectures, and the data rates required by the different obstacle avoidance techniques is deferred for follow-on study.

All three architectures are assumed to have the capability to evaluate the different obstacle avoidance techniques and to choose in real time among those which are feasible for that architecture. The different obstacle avoidance strategies are evaluated based on range to the obstacle, relative position of right and left lane vehicles, and obstacle position and size (see Appendix K for more details). Following are the three architectures, listed with their primary obstacle avoidance technique. These techniques will be described in Section 4.2.2.3.

High Cooperative/Full Lane Change

The full lane change technique is expected to require large amounts of data to be transmitted very rapidly from vehicle to vehicle and vehicle to infrastructure (if any). It is also the technique best suited for use by an AHS with an infrastructure which guides individual actions during an incident. Since high cooperative is the architecture with the highest data rates and the one most likely to have an infrastructure capable of directing individual vehicles, full lane change was associated with high cooperative.

Low Cooperative/Hybrid Lane Change

The low cooperative architecture will have limited data exchange capabilities and the infrastructure will probably not be capable of directing individual vehicles. The hybrid lane change obstacle avoidance technique is well suited to such an architecture, since the vehicles need to know only their distance to the obstacle, and the position of the other vehicles around them.

Independent Vehicle/Autonomous Full Lane Change

Independent vehicle braking is similar to other architectures. With lane changing, however, the left lane vehicles maintain speed and spacing, and the right lane (lead) vehicle must do gap alignment and merging without their cooperation. Furthermore, since the vehicle sensing the obstacle cannot warn the vehicles behind it, each vehicle cannot begin its obstacle avoidance strategy until it has line-of-sight (LOS) to the obstacle.

4.2.2.2 Obstacle Avoidance Scenario

The scenario which was chosen to evaluate obstacle avoidance strategies has two dedicated lanes with individual vehicles moving in the same direction. Traffic in the left lane moves 2.2 meters per second (5 mph) faster than that in the right lane due to vehicles entering into and exiting from the right lane. The AHS lanes are assumed to be operating at near capacity, with vehicles in both lanes separated by the minimum safe spacing for braking, given the lane speed. Relative position of the vehicles in the right and left lanes, an important consideration for lane changing, is regarded probabilistically, with all geometries taken as equally likely. This is based on the assumption that the two lanes cannot be kept aligned due to the speed differential.

The obstacle is assumed to be stationary, with a specified diameter and mass. The relationship between size and mass is set by assuming that the obstacle is roughly spherical and composed of granite. It is assumed to be located in the right lane.

All vehicles are assumed to have forward-looking sensors capable of detecting a 0.3 meter (12 in) diameter obstacle at 100 meters (330 ft), and measuring range to the obstacle, azimuth of the obstacle, and size of the obstacle. All vehicles are assumed to have accurate position information on all nearby vehicles, either from on-board sensors, or communicated from the infrastructure, or communicated directly from the other vehicles.

4.2.2.3 Obstacle Avoidance Building Blocks

The three obstacle avoidance strategies discussed later in this paper have in common certain elements which might be thought of as "building blocks." This section introduces these elements, which are central to constructing an obstacle avoidance strategy for the AHS.

Two levels (or ranges) of braking are assumed to be available for obstacle avoidance. The first, referred to as "hard braking," is the maximum longitudinal deceleration of which the vehicle is capable, consistent with any lateral acceleration or deceleration which is required at the time. This typically ranges from 70% to 100% of the vehicle's maximum capability in the absence of lateral acceleration or deceleration. The second level of braking is referred to as "light braking." It is used when there is substantial uncertainty about whether the obstacle is in the path of the vehicle. Its purpose is to reduce vehicle speed in preparation for hard braking, while minimizing the discomfort to the passengers and the effect on throughput.

Gap alignment is the first phase of a lane change. It is done by the right lane vehicles accelerating or decelerating longitudinally, depending on whether they lead or lag the left lane vehicles, and the left lane vehicles either doing the opposite or maintaining speed. Gap alignment ends when the two vehicles are separated longitudinally by the minimum safe distance, or MSD (see Figure 4.2-14). This minimum safe longitudinal distance is
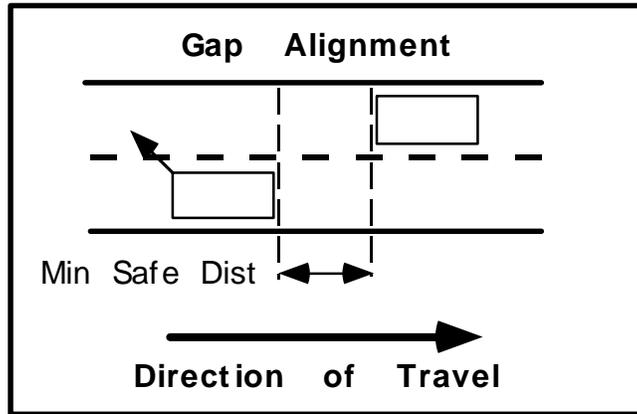
Figure 4.2-14. Gap Alignment.

the smallest separation which is acceptable during an emergency maneuver, and is assumed to be much smaller than the headway required for safe braking during routine operation. If the vehicle in the right lane happens to be alongside a gap in the left lane when the maneuver starts, then gap alignment is already completed. Merging is the second phase of a lane change. Merging begins while gap alignment is still taking place, and is timed so that gap alignment achieves the minimum safe distance between vehicles just as overlap occurs. Overlap is when the left edge of the right lane vehicle lines up with the right edge of the left lane vehicle (see Figure 4.2-15). The merge phase ends when the left and right edges of the vehicles are aligned. Vehicle separation, however, is monitored in the model until the speed of the vehicle merged in from the right lane is the same as that of the left lane vehicles.
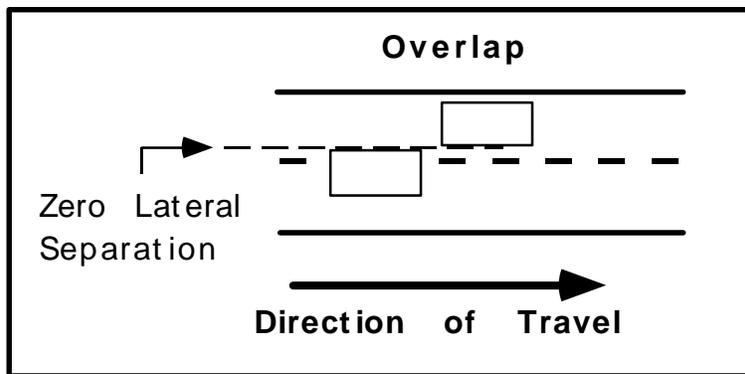
Figure 4.2-15. Overlap.

Lane changes are referred to as Case 1 or Case 2, depending on whether gap alignment is achieved by the right lane vehicles decelerating or accelerating (see Figures 4.2.-16 and 4.2-17, respectively). The arrows on the vehicles in the diagrams indicate movement relative to the normal traffic flow. Case 1 is the more conservative maneuver if substantial uncertainty about obstacle position exists, since the right lane vehicles reduce speed, decreasing the ΔV of a collision should the maneuver fail. However, at most speeds and spacings a Case 1 lane change is not possible from all right/left lane geometries, so Case 2 must be used also. Whether Case 1 or Case 2 maneuvers predominate will depend on the relative speed of the two lanes in which the maneuver starts and finishes.
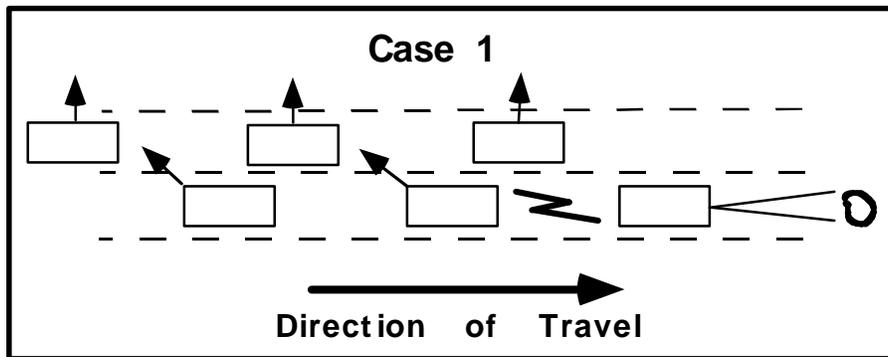
Figure 4.2-16. Geometry of Case 1 Lane Change.
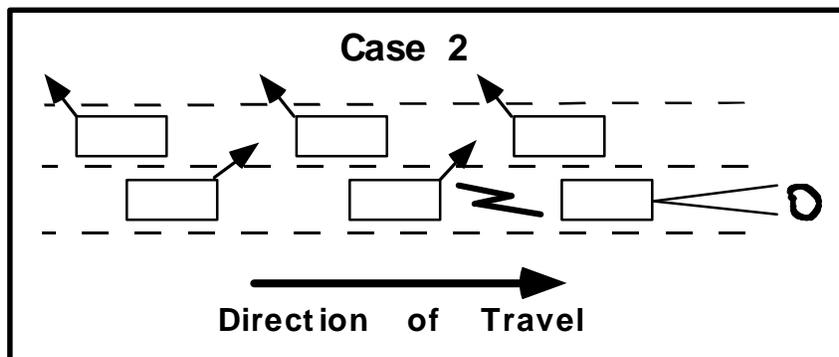
Figure 4.2-17. Geometry of Case 2 Lane Change.

The differences between the independent vehicle and the two other architectures are driven by the fact that independent vehicles cannot communicate. For braking, this increases the lag only slightly, since the second vehicle senses the deceleration of the first

relatively quickly, and then begins braking. For lane changing, however, the second vehicle must have line-of-sight to the obstacle, and this does not occur until the first vehicle has moved a substantial distance to the left (see Figure 4.2-18). The exact delay depends on obstacle position and size. Such a delay may be as much as 1 1/2 seconds, which for lower speeds may require that independent vehicle spacing be increased above the distance required for hard braking.
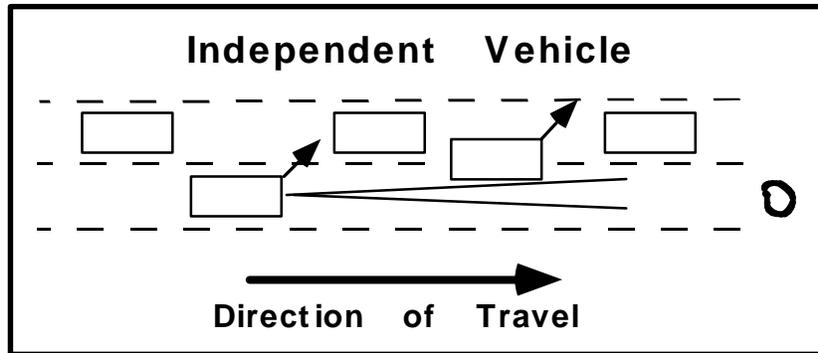
Figure 4.2-18. Autonomous Lane Change.

4.2.2.4 Obstacle Avoidance Strategies

Using the obstacle avoidance "building blocks" discussed in Section 4.2.2.3, a set of three obstacle avoidance strategies was assembled for analysis. These range from full lane change, with relatively high coordination and data exchange between vehicles, to braking, where the vehicles can operate autonomously if needed.

"Full lane change" is a combination of Case 1 and Case 2 lane changes. In order for full lane change to be feasible at a specified range to the obstacle, it must be possible to do either a Case 1 or a Case 2 lane change from any right/left lane vehicle geometry (Figure 4.2-19, dark shading). If, for any given speed/spacing combination, there are ranges to the obstacle at which lane changing can be done from only a subset of vehicle geometries (Figure 4.2-19 lightest shading), then the obstacle avoidance function will select hybrid lane changing as the obstacle avoidance strategy.
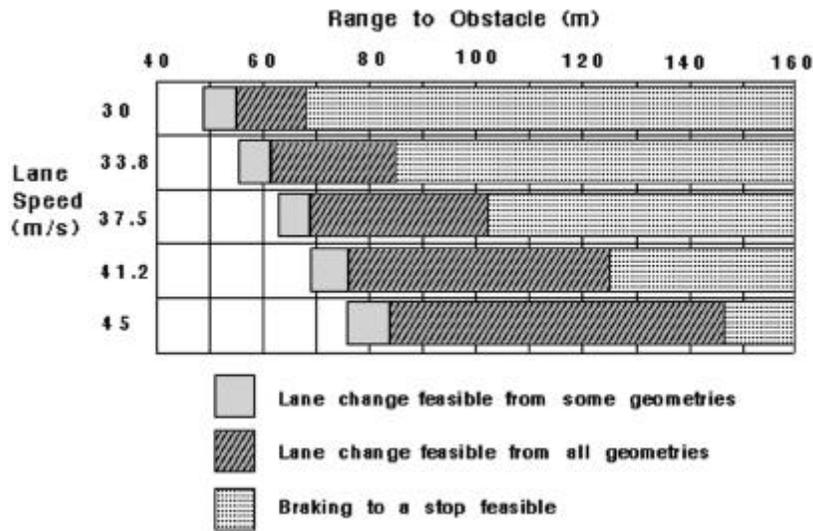
Figure 4.2-19. Feasible Ranges for Lane Changing and Braking.

For most speeds and spacings, both Case 1 and Case 2 lane changes are needed to cover lane changing from all right/left lane geometries. When both are feasible, the system chooses the one with the lower expected $\mathcal{D}V$.

Full lane change can require coordination and real-time decision-making among as many as seven vehicles – a maximum of three in the right lane executing the avoidance maneuver, and a maximum of four in the left lane being merged into. Obstacle position, vehicle positions, speeds, maximum acceleration and deceleration capabilities, and messages assigning and confirming each participant's role must be passed among vehicles and to/from the infrastructure, if it takes part, very quickly. Consequently, full lane change has the highest bandwidth requirements of the three obstacle avoidance techniques discussed here.

Braking is the simplest of the obstacle avoidance techniques. It requires no knowledge of adjacent vehicle positions and only limited coordination with other vehicles in the same lane. It is also less sensitive than lane changing to knowledge of obstacle position. Braking is also the most effective technique for reducing collision $\mathcal{D}V$ at ranges so short there is insufficient distance either to change lanes or to brake to a stop.

"Hybrid lane change" uses a combination of Case 1 lane changing and braking, providing an alternative to a braking-only strategy for obstacle avoidance in AHS architectures which support low data rates. Since there may be insufficient distance to complete a Case 1 lane change, hard braking is done when it will result in a lower expected $\mathcal{D}V$.

Hybrid lane changing requires only that vehicles know the position of other nearby vehicles and the range to the obstacle. The position of nearby vehicles is expected to be available from on-board sensors. Since a maximum of three right lane vehicles are expected to be involved, it is expected that each vehicle can receive the "range to

obstacle" message sent by the prior vehicle, add its forward spacing, and rebroadcast the message without excessive delay. Because hybrid lane changing is not required to succeed from all right/left lane geometries in order to be considered feasible at a given range, it can be the strategy of choice at slightly shorter ranges than full lane changing.

4.2.2.5 Results

This section presents the results of modeling runs showing the performance of the three obstacle avoidance strategies. The model is described in Appendix K. Values of the input parameters most critical to the modeling are given in Table 4.2-1, with the names of dependent parameters listed in italics. The nominal values of parameters which were varied as part of this analysis appear in Table 4.2-1 in bold type.

Because the resulting performance values will vary with changes in the scenario and assumptions, the conclusions accompanying each run are phrased in qualitative rather than quantitative terms to the extent possible. They necessarily remain somewhat dependent on the choice of scenario and on the assumptions chosen for this study, however.

Table 4.2-1. Important Modeling Parameters

Parameter Name	Units English (metric)	Value in English Units	Value in Metric Units
Right lane speed	mph (m/s)	**67** to 100	30 to 45
Left lane speed	mph (m/s)	right lane + 5	right lane + 2.2
Spacing	ft (m)	**54** to 110 **	16.5 to 33.5
Throughput	veh/lane/hr	4600 to 5600	same
Range to obstacle	ft (m)	**180** to 492 **	55 to 150
Max. long. decel	g's	.75	same
Max. lateral accel.	g's	.3	same
Max. lateral decel.	g's	.3	same
Max. long. accel.	g's	.1 to .15 **	same
Long. decel. for "light braking"	g's	.2	same
Vehicle mass	lbs (kg)	4405	2000
Obstacle diameter	in (m)	**12** to 22	0.3 to .55
Obstacle mass	lbs (kg)	88 to 517	38 to 235
Sensor update rate	msec	25 to 150 (**50**)	same
Sensor range standard deviation	percent	1.0	same
Sensor azimuth standard deviation	degrees	0.5	same

** Varies with speed

4.2.2.5.1 Performance vs. speed

Figure 4.2-20 shows the obstacle avoidance performance of the three AHS architectures as a function of speed. The x-axis (forward) is the speed of the right lane; the left lane is 2.2 meters per second (5 mph) faster. The z-axis (vertical) is the expected severity of collisions in the obstacle scenario described above expressed as delta-v squared; less is safer. The y-axis (right) lists the three architectures. The delta-v squared numbers are very small because they include the probability that no crash occurred. The delta-v's are uniformly near zero at 20 meters per second because braking is the preferred strategy for all three architectures here, and because it can almost stop the vehicles at this speed before they hit the obstacle. One can immediately draw two conclusions from this plot – 1) obstacle avoidance is safer at lower speeds (not surprisingly); 2) the more intelligent architectures using more sophisticated obstacle avoidance strategies are safer. Note that the latter conclusion is true for 30 meters per second and up, the range of speeds in which the AHS is expected to operate most of the time.
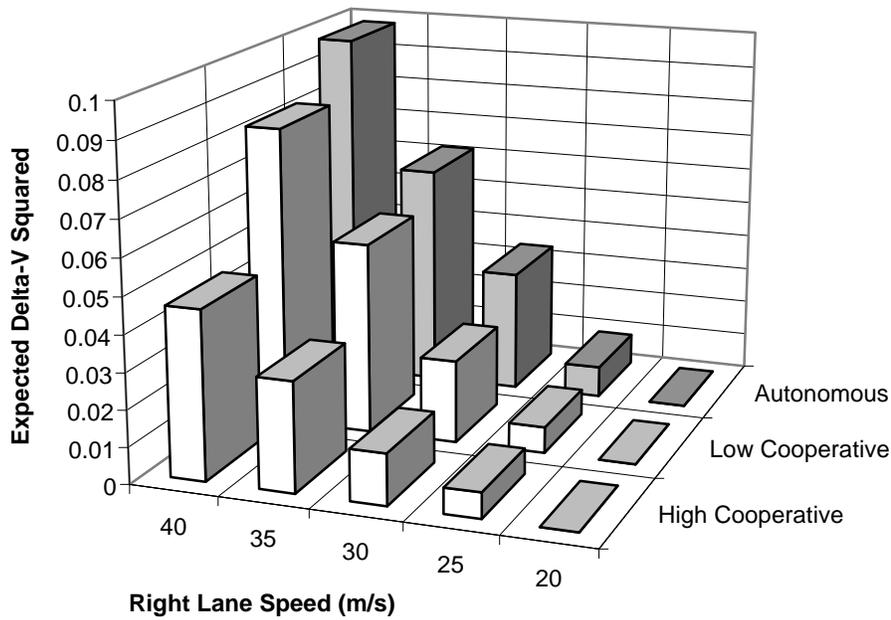
Figure 4.2-20. Obstacle Avoidance Performance vs. Speed.

4.2.2.5.2 Performance vs. range

Figure 4.2-21 shows the obstacle avoidance performance of the three AHS architectures as a function of range to the obstacle. The x-axis (forward) is the range to the obstacle. The z-axis (vertical) is the expected severity of collisions in the obstacle scenario described above expressed as delta-v squared; less is safer. The y-axis (right) lists the three architectures. The delta-v squared numbers are very small because they include the probability that no crash occurred. At 45 meters, there is insufficient distance for either hybrid or full lane-changing; consequently, all three architectures use braking. At 50 meters, both cooperative architectures use hybrid lane changing (there is insufficient distance for a full lane change). The autonomous architecture uses braking since autonomous lane changing requires considerably more distance than under the two architectures with communication. The delta-v's are uniformly zero at 70 meters because braking is the preferred strategy for all three architectures here, and because this is sufficient range to stop the vehicles before they hit the obstacle. One can conclude from this plot that the ability to choose among all three obstacle avoidance strategies makes the high cooperative architecture the safest.
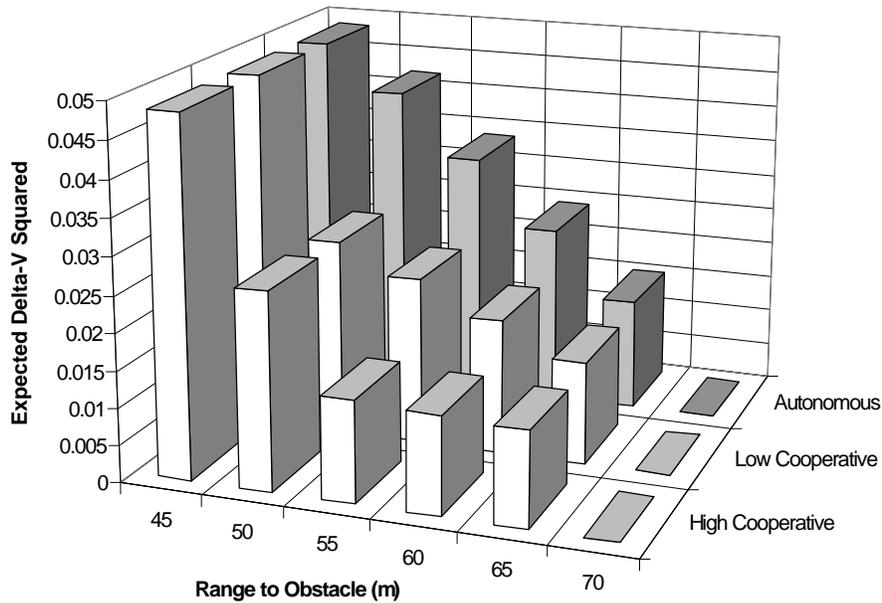
Figure 4.2-21. Obstacle Avoidance Performance vs. Range to Obstacle.

4.2.2.6 Conclusions

The optimal choice of obstacle avoidance strategy for the Automated Highway System depends on speed, right/left lane geometry, range to obstacle, and other scenario-specific conditions. An obstacle avoidance function which is able to choose among full lane changing, hybrid lane changing, and hard braking in real time will be safer (have a lower expected ☺V) than one which is limited to a subset of these strategies.

One can also draw some general conclusions from these results and others discussed in Appendix K about the strengths of the three obstacle avoidance techniques that were analyzed:

Full lane changing is a good choice for obstacle avoidance
• against medium to large obstacles (or)
• at medium to high speeds (or)
• with more accurate sensing.

Hybrid lane changing is a good choice for obstacle avoidance
• at ranges too short for full lane changing (or)
• in architectures where communication capability is limited.

Hard braking is a good choice for obstacle avoidance

- against small obstacles (and)
- with less accurate sensing (and)
- at low speeds (and)
- at ranges to the obstacle too short for other techniques.

4.3 Civil Infrastructure Cost

4.3.1 Introduction

This section summarizes the methodology and findings of civil infrastructure cost estimates for AHS-dedicated lane operations. The objective of this C2 subtask was to develop a general order-of-magnitude cost estimate for the implementation of a dedicated AHS lane on an existing freeway infrastructure. Assessments were performed for generic application scenarios for AHS operation in the urban, inter-city, and rural environments.

A detailed report for this task can be found in Appendix L of this report.

4.3.2 Cost Estimating Premises

The scope of the analyses centers around the AHS application scenarios that were created for three operating environments--urban, inter-city, and rural. Cost estimates were generated for each application scenario and include only standard civil and structural construction costs. Right-of-way (ROW) costs are also included. However, these estimates do not include any systems infrastructure, communications, or control systems costs, nor do they include operations and maintenance costs, which will be addressed in later phases of the program. For each scenario, base case conditions were established. Dedicated AHS lane operations were then applied to these base cases.

4.3.2.1 Application Scenarios

Hypothetical application scenarios were created instead of using "real world" cases due to the short timeframe given to gather real site data. However, these hypothetical cases are based upon prevalent characteristics of "real world" environments in several regions across the country.

In the urban scenario, a 25-mile (40 km) corridor is used. This corridor travels through a medium-dense urban environment providing four lanes in each direction, 21 arterial interchanges, and two regional (freeway-to-freeway) interchanges.

For the inter-city environment, a 74-mile (119 km) interstate corridor which links two major urban centers is used. This heavily traveled facility provides three lanes in each direction, 20 arterial interchanges, and two freeway-to-freeway interchanges.

The rural operating environment consists of a 296-mile (476 km) rural interstate highway with 20 interchanges.

4.3.2.2 Adaptation to AHS Operations

Various configuration cases were generated for the urban operating environment while a single case was developed for each of the inter-city and rural environments. These highway geometric configurations and their AHS adaptation are based on current design standards. It is realized that AHS-specific roadway designs (following new standards) might be more economical and/or use less right-of-way. Those AHS-specific designs are beyond the scope of this analysis. The following paragraphs briefly describe these cases. A more detailed discussion, along with figures depicting these configurations, can be found in Appendix L.

4.3.2.2.1 Urban application

For the urban environment, five cases for applying dedicated AHS lane operation on the base case configuration were considered:

- **Urban Case 1:** Convert one manual lane in each direction to an AHS-dedicated lane to be fed through seven new dedicated interchanges, with average spacing of 3.6 miles (5.7 km). An 8-foot breakdown lane (shoulder) is provided for each direction.

- **Urban Case 2:** Convert one manual lane in each direction into an AHS-dedicated lane to be fed through seven new dedicated interchanges, with average spacing of 3.6 miles (5.7 km). Provide a shared 12-foot breakdown lane in the median between the two AHS lanes. A variable barrier is used to separate the two opposing directions of travel.

- **Urban Case 3:** Convert one manual lane in each direction to an AHS-dedicated lane where access is gained via existing interchanges and ramps, and use a dedicated "transition" lane between the manual and automated traffic. In addition, one 8-foot breakdown lane has been added in each direction to serve the AHS-dedicated lane. For access to another highway, special by-pass ramps are utilized prior to freeway-to-freeway interchanges (see Figure L-4, Appendix L) to accommodate the transition.

- **Urban Case 4:** Add one dedicated AHS lane in each direction to the four manual lanes. Access is gained through seven dedicated interchanges at an average spacing of 3.6 miles (5.7 km). An 8-foot shoulder is also provided for each direction of travel. Access to another freeway is gained via dedicated ramps through regional interchanges.

- **Urban Case 5:** This is the same as Case 4 with the exception that a 10-foot shoulder is provided on either side of the dedicated AHS lane to serve AHS traffic. Similarly, a 10-foot shoulder is constructed on both sides of the manual traffic lanes to serve non-AHS vehicles. Once again, access is gained through 7 dedicated interchanges at an average spacing of 3.6 miles (5.7 km). An 8-foot shoulder for breakdowns is also provided for each direction of travel. Access to another freeway is gained via dedicated ramps through regional interchanges.

4.3.2.2.2 Inter-city application

For the inter-city operating environment, one dedicated AHS lane is added without taking away an existing manual traffic lane. Access is gained using existing manual traffic interchanges and ramps. One dedicated "transition" lane is provided between manual and AHS operation for entry and exit.

4.3.2.2.3 Rural application

In the rural environment, again, the case for the addition of an AHS lane without taking away an existing manual traffic lane is employed. Access to this facility is the same as above.

4.3.3 Cost Estimating Approach

The Timberline© cost estimating and modeling software was acquired, adapted, and used as the tool for the order-of-magnitude cost assessment for the above AHS application cases.

The purpose of this tool was to generate preliminary cost estimates (rough order-of-magnitude costs) based on the definition of each of the hypothetical cases. The tool provided a modular, building block approach which accommodated the various permutations of each case.

The basic structure of any cost estimate is that of a quantity multiplied by its unit cost. Developing the quantities to be used in a given estimate is usually the most time-consuming and tedious task involved in preparing the estimate. The cost estimating tool is structured to allow the estimator to choose from three mechanisms for quantity input, depending on the circumstances. This flexibility makes the estimating process much more efficient and accurate, and the sophistication of the software allows this to be done without any loss of estimate detail. The quantity input may be in the form of: 1) items, 2) work packages, or 3) models. A detailed description of these elements can be found in Section L.3.2 of Appendix L.

4.3.4 Assumptions

Several assumptions were made concerning the physical modification of the existing freeways to accommodate the addition of the AHS civil infrastructure. Examples of these geometric characteristics include lane widths, shoulder widths, ramp lengths and widths, barrier requirements, interchange requirements, etc.

The second set of assumptions used in this order-of-magnitude cost assessment are subject to engineering judgment, experience, and interpretations. Some examples include:

- Extent of ROW acquisition
- ROW acquisition cost
- Unit construction cost rates
- Planning, design, construction, construction management, and administrative costs
- Lump sum allowances for freeway-to-freeway interchanges
- Contingency allowance

The assumptions used here were quite conservative (for example, assuming that all right-of-way must be purchased and more is already available), making these estimates closer to "worst case" than "best case" conditions.

4.3.5   Results

This section details the results of each case for each of the three operating environments. As noted earlier, these costs are only capital costs for civil infrastructure and <u>do not include</u> costs for vehicle or infrastructure systems nor operations and maintenance costs for the facility or equipment. The cost per mile and per kilometer are for both directions of the highway segment.

4.3.5.1 Urban Cases

Urban Case 1

The total cost for this case is $37.71 million per two-way lane mile ($23.57 million per km), based on:

- Replacing one manual lane with one dedicated AHS lane, fed by seven dedicated interchanges at 3.6 miles (5.7 km) average spacing
- Separate breakdown lane per direction
- Length of merge lane assumed at 1,400 ft (425 m), exit lane at 500 ft (150m)
- Carry AHS lanes over dedicated ramps through regional interchanges
- Lump sum cost assumption for regional interchanges: $350 million for 4-leg and $125 million for 3-leg
- 100% ROW acquisition at $15 per square foot

Urban Case 2

The total cost for this case is $36.24 million per two-way lane mile ($22.65 million per km), based on:

- Replacing one manual lane with one dedicated AHS lane, fed by 7 dedicated interchanges at 3.6 miles (5.7 km) average spacing

- Case 2 assumes a shared breakdown lane (modified variable barrier) for two opposing AHS directions
- Length of merge lane assumed at 1,400 ft (425 m), exit lane at 500 ft (150m)
- Carrying AHS lanes over dedicated ramps through regional interchanges
- Lump sum cost assumption for regional interchanges: $350 million for 4-leg and $125 million for 3-leg
- 100% ROW acquisition at $15 per square foot

Urban Case 3

The total cost for this case is $31.35 million per two-way lane mile ($19.59 million per km), based on:

- Replacing one manual lane with one dedicated AHS lane fed by common entry/exit ramps and a dedicated continuous transition lane
- Barriers with gaps assumed between manual and transition lanes as well as between transition and AHS lanes
- Flexible placement of entrance / exit gaps for transition and AHS lanes on basis of local conditions
- Special by-pass ramp arrangement at freeway-to-freeway interchanges
- Need for local widening of manual lanes to accommodate weaving traffic
- 100% ROW acquisition at $15 per square foot

Urban Case 4

The total cost for this case is $45.50 million per two-way lane mile ($28.44 million per km), based on:

- Adding one dedicated AHS lane (without taking away a lane), fed by 7 dedicated interchanges at 3.6 miles (5.7 km) average spacing
- Separate breakdown lane per direction
- Length of merge lane assumed at 1,400 ft (425 m), exit lane at 500 ft (150m)
- Carrying AHS lanes over dedicated ramps through regional interchanges
- 100% ROW acquisition at $15 per square foot

Urban Case 5

The total cost for this case is $49.85 million per two-way lane mile ($31.17 million per km), based on:

- Adding one dedicated AHS lane (without taking away a lane), fed by 7 dedicated interchanges at 3.6 miles (5.7 km) average spacing

- Separate breakdown lane per direction
- Length of merge lane assumed at 1,400 ft (425 m), exit lane at 500 ft (150m)
- Maintaining 10-foot shoulders on both sides of both the manual and AHS traffic lanes
- Carrying AHS lanes over dedicated ramps through regional interchanges
- 100% ROW acquisition at $15 per square foot

Analysis of Urban Cases Cost Estimates

From these estimates, it can be concluded that changes in highway geometrics greatly affect construction and ROW cost as a percentage of total cost; this is true for both AHS and non-AHS roadways. For example, in Urban Case 2, where a shared breakdown area is utilized between both directions of AHS travel, ROW cost is significantly reduced (almost half the cost of Case 1), while construction costs are maintained.

In Urban Case 3, although there is substantial savings in construction costs, the ROW costs are almost double those in cases 1 and 2. The rationale is that in this case, a transition lane is required next to the dedicated AHS lane and thus results in two lanes dedicated for AHS use only. In this case, construction costs are lower since there are no dedicated entry/exit ramps and the total cost per mile of highway is 17 percent lower than the previous two cases.

In Urban Case 4, where the number of existing manual traffic lanes are maintained, extra ROW is necessary to accommodate a new lane for AHS use and Construction costs are higher as compared to all the three previous cases.   The total cost per mile is 20 percent higher than the previous three cases.

The most expensive configuration among these studies is in the last case, Urban Case 5, where full 10-foot shoulder widths are maintained for both AHS and manual operations.

The least expensive case, in terms of civil infrastructure only, is Case 3; this case depends upon the capabilities of AHS technologies to perform in these conditions. At this point in the program, it is too early to establish civil infrastructure design standards. The configuration is dependent on the results of the technological characteristics and needs of the final AHS concept which are still under investigation.

4.3.5.2 Inter-City Case

The total cost for the inter-city case is $6.63 million per two-way lane mile ($4.12 million per km), based on:

- 74 miles (119 km) inter-city freeway, three lanes each direction, 20 normal interchanges, and two freeway-to-freeway interchanges
- Adding one dedicated AHS lane fed through common ramps via a localized transition lane

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- Assuming a 50% new ROW acquisition at $7.50 per square foot

4.3.5.3 Rural Case

For the rural case, total cost is $3.29 million per two-way lane mile ($2.05 million per km), based on:

- 296 miles (476 km) rural freeway, 2 lanes each direction, 20 normal interchanges and 2 freeway-to-freeway interchanges
- Adding a dedicated AHS lane fed through common ramps via localized transition lanes
- No ROW acquisition required in this case

4.3.6 Recent Highway Cost Experience

Appendix L lists examples of recent highway retrofitting cost experience in California. The cost per lane-mile ranges between $3.3 million to $29 million.

4.3.7 High Occupancy Vehicle Lane Cost Experience from Other U.S. Regions

Over the past 10 to 15 years, several urban regions in the United States have embarked on the addition of a high occupancy vehicle (HOV) lane along their freeways.

Figure L-12 in Appendix L lists various examples of these types of projects dating from 1986 to 1993. Costs range from $2.5 million per mile to $49.5 million per mile. These figures have not been escalated to today's dollars and detailed descriptions were not available at the time of data collection. Additionally, cost elements vary from project to project. Thus, no detailed comparative assessment or conclusion, relating to the AHS costs presented in this report could be drawn.

4.3.8 Conclusions

This task only provided order-of-magnitude cost estimates for hypothetical cases for the urban, inter-city, and rural environments. In the urban environment, if ROW is not available, a dedicated AHS lane for both directions of a roadway may cost up to $50 million per mile. For the inter-city application, the cost is estimated at approximately $7 million per mile. In the rural environment, the cost is almost $3.5 million per mile. These costs are comparable to current HOV lane construction costs.

At this stage of the program, there are no design standards for a dedicated AHS civil infrastructure. Assumptions employed as a basis for these cost estimates reflect existing highway design and construction standards and practices. Although highway configuration is independent of most concept attributes, it is mostly dependent on characteristics of a site-specific application as well as the technologies. AHS configurations can be further refined once AHS technological characteristics are better

understood and a real site can be modeled. It is important to keep in mind that site-specific AHS applications may result in substantial reductions or increases to the cost estimates presented in this report.

The most critical factor in calculating the cost of adding a dedicated AHS lane(s) to existing highways, especially in urban environments, is the required AHS highway geometrics or configuration. A discussion of highway configuration issues can be found in Section 7.0 of this report. Some of the outstanding issues include the dimensions of lanes, ramps, shoulders, breakdown areas, etc.

The next phase of the AHS program will take these steps further. Case studies are being identified. As the AHS concept and its systems characteristics are defined and developed during the next few years, a better understanding of highway geometric characteristics and operations and maintenance issues will be gained. This will then provide a better basis for estimating the cost of civil infrastructure needs for the AHS.

4.4   Societal and Institutional Considerations

It will also need to be accepted by consumers in the marketplace and by society at-large. Some of the issues that need to be addressed include:
- assignment of institutional responsibilities
- decisionmaking process
- investment analysis
- environmental review
- liability and risk minimization
- potential effects on land use

These institutional considerations are formidable, but by no means insurmountable. The building of the original interstate highway system required a number of significant changes to the way our agencies do business, particularly in the roles for the federal government. These highways also helped accelerate the suburbanization of American society and fundamentally altered our landscape and travel behavior. An AHS that profoundly changes automobile travel by reducing travel times and releasing the driver to do other things during the trip may justify the institutional changes that it will require.

4.4.1   Institutional Responsibilities

The assignment of responsibility for the various components of an AHS has been a fundamental concern for many potential stakeholders. The "Five Whos;" who owns, who pays, who operates, who maintains, and who regulates and enforces, need to be answered before many institutions will decide whether they wish to participate in the deployment of a system.

Ownership: An AHS will probably include three basic components; the roadway infrastructure (including electronic infrastructure), the vehicle, and a portion of radio spectrum. Most of today's expressways are owned by states under the jurisdiction of their highway or transportation departments. Some are owned and operated by semi-autonomous authorities. Recently, some states have begun to develop highways with private partners who share an equity stake in the investment. An AHS that includes an infrastructure improvement could be owned and operated by any of these actors.

Most of today's light duty vehicle drivers own their own vehicles; however, there are significant numbers of leased vehicles and flat vehicles. Assuming that the equipment to be mounted on the vehicle is affordable, there is no reason for this to change. Some after-market vehicle equipment such as cellular phones or toll tags may be leased, but AHS equipment will need to be factory installed and integrated. If the equipment is not affordable to individuals, then the market may be limited to fleet operators, including bus systems and freight haulers.

Radio frequency channels have become a scarce resource as the number of potential users has increased, particularly in the private sector. The FCC is currently exploring options to have narrower bandwidths, which would allow for more channels, and it has also begun to auction those channels. An AHS operator, probably the infrastructure operator (who may or may not be the owner), will need to bid for and reserve those channels, based on use of national standards. An alternative would be for the FCC to reserve a part of the radio spectrum for AHS use.

Payment: An AHS will need to be funded for both capital and operating costs. Vehicle owners would in all likelihood bear the costs for AHS equipment through purchase or lease. The costs for the construction, operation and maintenance of infrastructure will be borne by a taxing authority and/or the agency (or partnership) that owns and/or operates the system. These funds may come from general government coffers, or special-purpose bonds, or they may be raised by charging tolls or other user fees to those who wish to use the system. This choice will have fundamental impacts on the way the system develops. A system that relies on user fees may be slower to achieve full market penetration, and may not achieve it at all. This would limit the potential societal benefits from the system.

Operations and Maintenance: For the most part, operations and maintenance are owner responsibilities (for infrastructure and for vehicles) and this may continue to be the case. However, the same trend that has led to some public-private partnerships has also led some agencies to contract out responsibility to build and/or operate highway and transit systems. These arrangements are generally limited to toll roads, which provide a discrete source for operating and/or capital funds.

Regulation and Enforcement: The institutions that currently promulgate and enforce standards for highway design and construction include the Federal Highway Administration (FHWA), and the American Association of State Highway and Transportation Officials (AASHTO). They will continue to be responsible, although they will need to develop new standards for AHS systems. The National Highway Traffic Safety Administration (NHTSA) oversees vehicle equipment standards. However, individual manufacturers are responsible for ensuring their compliance with these standards. The standards and procedures for the periodic inspection of vehicles varies from state to state.

Police and highway patrol agencies will continue to be responsible for enforcing traffic laws and regulations. Some of the traffic laws may change, depending on the type of AHS system that is deployed.

4.4.2   Decision Making

Each state can be expected to tailor the decision making process leading to AHS deployment to meet its own needs. A flexible decision-tree paradigm, called the Reactive Adaptive Management Portfolio (RAMP) has been suggested as a way to maintain some

common system elements. RAMP assumes several common decision points on the path to system deployment. Each of these points will come with several options.

The first is the decision to accept the idea of AHS. A political decision is needed on whether a state or other jurisdiction wants to allow and encourage AHS. The answer will be based on whether such a system is compatible with the state's overall transportation goals and whether it threatens any potentially sacred cows. Assuming that an AHS is desirable, the states must then decide whether they want to establish interoperability standards.

The next decision point relates to the specification of system requirements. At this point modifications to enabling legislation and regulations may be required to allow for such elements as private participation, charging of tolls, dedication of lanes, and a host of specific system elements. A state may choose to support a single type of system, that assumes operation in mixed traffic or on dedicated lanes, with or without infrastructure support. It may also choose to allow more than one type of system, provided that they maintain interoperability according to a set of national standards.

Once the systematic ground rules are laid out, then the actual deployment decisions will be made on a case-by-case basis. These decisions will require an investment analysis and an environmental review that are common to all major transportation improvements.

4.4.3   Investment Analysis

The current procedure for analyzing the merits of major transportation investments that involve federal funds for construction is a Major Investment Study (MIS). MISs focus on transportation corridors and their mobility problems before specific transportation modes are selected. They must consider all reasonable alternatives, including those that make use of more than one transportation mode. Potential AHS alternatives may range from Transportation System Management (TSM) -type improvements to support independent vehicle operations in mixed traffic, to an additional lane to an existing highway that is set aside for automated use, or to a completely segregated AHS facility with its own entry and exit points. These alternatives are evaluated against a set of criteria that address the study's goals and objectives. The recommendation that emerges from the study may draw upon the best elements of each alternative.

The specific investment criteria cover a range of effectiveness, financial, environmental, and community issues. Obviously, a system should result in improved mobility, which may take the form of reduced travel time or improved access to locations within and beyond a corridor. A successful system will provide these benefits at a reasonable capital and operations/maintenance cost. It should not result in significant negative impacts to the environment, and it should be acceptable to the communities it affects.

4.4.4 Environmental Review

An investment will also require environmental clearance under the National Environmental Policy Act (NEPA) or under similar state-level environmental regulations. The type of review required will depend on the level of investment to be made. Low level investments that are not expected to have environmental impacts may qualify as categorical exclusions. High level investments, including most systems that will require major infrastructure investments, which are likely to have environmental impacts, require an Environmental Impact Statement (EIS). An EIS is prepared under strict guidelines and must identify expected impacts, consider alternatives that would avoid those impacts, and if impacts are unavoidable, identify strategies for their mitigation. When an agency is unsure of a project's impacts, it must complete an Environmental Assessment (EA), which investigates potential impacts. If an impact is identified, then an EIS must be initiated.

4.4.5 Liability / Risk

The assignment of liability for the failure of system component(s), particularly when a collision might be involved, is a crucial issue to determining the deployability of any AHS system. Key to any consideration of liability is the reasonable expectation of system performance held by each involved party. Liability generally arises when performance does not meet reasonable expectations.

The current vehicle/highway system assigns most of the liability to the driver(s). A system that removes vehicle control from the driver will clearly shift that liability to those parties assuming control, such as vehicle manufacturers and infrastructure owners/operators. Offsetting this increased liability for some parties is the potential reduction in collisions and collision severity creating a potential overall risk reduction to each party.

The issue may become more complicated for highway agencies, where sovereign immunity applies to many states. If this immunity is extended to infrastructure-based AHS systems, then the potential liability burden could only fall upon vehicle manufacturers and drivers, and by extension, their insurers. This may be unacceptable to those parties, thereby creating a hindrance to the production of technologies necessary for an AHS.

A potential solution may exist in the form of private operation of the AHS in which the contractors operating the AHS facility could assume liability and factor the costs related to their risk into the tolls or other fees that they charge users. An alternate solution may involve a general fund into which all users pay and from which injured parties may recover damages.

4.4.6   User Needs / Market Analysis

Because consumers do not respond reliably to product concepts with which they have had little or no previous experience; the primary way to measure consumer need for and acceptance of AHS is to introduce it from the perspective of familiar highway driving. To begin to identify the public's preferences among AHS and AHS-related technologies, a self-administered survey was conducted on the Internet during May and June 1996. Just under five hundred self-selected individuals participated in this survey. The survey measured attitudes towards present highway driving, current use of cruise control, and interest in future technologies, specifically Adaptive Cruise Control, Collision Warning Systems, Automatic Steering, and AHS.

A large proportion of respondents would like to see improvements in driving stress, environmental impact of driving, congestion, and safety, and believe that technology, including AHS, can meet their needs. Conditions necessary for public acceptance of AHS include high levels of (perceived) system safety, reliability, and benefit/cost ratio, and minimum driving-induced stress. Collision Warning Systems may satisfy drivers' needs for safety if human factors issues can be adequately addressed. This survey's results implied that when developing different potential AHS concepts, major consideration should be assigned, in this order, to: *driving-induced stress, system safety, system cost, effect on environment,* and *effect on congestion.*

In order to get more in-depth inputs from a more limited sample of consumers, a series of six focus groups was held in May 1996 in the San Francisco Bay Area to gauge consumer reactions to AHS and AVCSS user services. These consumers were most concerned about problems of traffic congestion, driving stress and the compromise of safety because of the rudeness and inattentiveness of other drivers, and looked favorably on solutions to these problems.

Adaptive Cruise Control was viewed favorably by about half of the consumers, particularly the older ones, who were typically willing to pay between $250 and $500 for this service. Collision avoidance systems that included the computer taking over control of brakes and steering were less favorably received because of doubts about whether the systems could be made safe enough.

AHS, with fully automated driving in dedicated lanes separated from the manual traffic was viewed favorably because of that separation, which would provide protection from the bad actions of other drivers. People liked the safety, convenience, stress reduction and opportunity to do other things while traveling, but had concerns about the reliability and the need to take back control in an emergency. They were interested in AHS for both daily commuter and long-distance driving, and were willing to pay prices in the range of $2000 to $5000 for this capability on their vehicles.

4.4.7 Costs / Benefits / Tradeoffs by Stakeholder Group

The issue of differentiating among different types of customers and stakeholders is important as it influences the point of view from which the analysis of alternatives is carried out and how many of which type of customers will experience particular benefits and costs, as different customers will value costs and benefits differently.

AHS ultimately has to meet the needs of travelers. These come in a variety of forms each with its own needs, concerns and requirements. Stakeholders include these customers but also includes vendors and regulators. We must be careful not to design a system that does not meet real needs. While stakeholders have a vested interest in AHS, customers are purchasing a product, in this case an automated highway system. Stakeholders who influence financing and implementation are also the customers of the AHS program, and in turn, their customers will buy AHS from them.

In the case of users versus non-users, a benefit to a user may be a cost to a non-user or vice versa. For example, a more convenient, faster route to work for a commuter may disrupt a residential neighborhood. Similarly, inter-generational issues are important when looking at different stakeholders.

It is important to note that the stakeholder groups are not unique. An organization or an individual could be a member of one or more stakeholder groups. The general stakeholder/customer categories are:

Users. The ability to differentiate among different types of users (peak vs. off-peak, work related and commuting trips vs. recreational, single and multiple occupant vehicles) is critical for a cost-benefit analysis. The drivers of trucks and transit vehicles are a category of users that are of particular interest.

Facility owners. Includes two stakeholder groups, government organizations and transit and commercial vehicle owners.

Government organizations and other agencies. Includes state DOT's, local government, metropolitan planning agencies, and turnpike and toll authorities.

Transit and commercial vehicle. The operators, owners and providers of the services.

Private sector interests. These include the four stakeholder groups of "vehicle manufacturers," "vehicle electronics industry," "highway construction industry" and the "insurance industry." Their interests in AHS relate to opportunities for making profit. These industries may be involved in and impacted by the terms of their role as responsible corporate citizens.

<u>Non-user</u>. Includes environmental stakeholders. This is broadly defined to embrace interests and concerns related to sustainability, neighborhoods, emissions, noise and energy use.

In representing benefits and costs there is considerable confusion between benefits and measures of effectiveness and attributes of the system. For example, "user friendly displays, controls, and operations" are not benefits but attributes of the system. Improved throughput is a benefit, while the MOE measures the extent of the benefit. Therefore, some general classes of benefits and costs represented by the attributes – performance (throughput or capacity), safety, reliability, economic, environmental and technical – have been developed. Within these general groupings of attributes are sub-categories of benefits that can be estimated or measured. Some of these measures are part of a cost-benefit tool under development.

In looking at the relationships between stakeholders and costs, one can see the potential for double counting unless the point of view of the analysis is explicitly considered, transfer payments are recognized as such, and cost reductions that have already been included as benefits are not included again. For example, the vehicle purchase cost is a cost for a user but a benefit for the vehicle manufacturer. As another example, consider a toll. From the point of view of the automobile user, a toll is a real cost, but to society as a whole it is a transfer payment as it is cost to the motorist and income to the agency or institution running the AHS. Similarly, if reductions in accidents are included as a benefit, they cannot be counted again as a (reduced) cost (with a negative sign). The costs and benefits to society as a whole are represented by the union of the other stakeholders' costs and benefits. That is, costs and benefits accrued to society are the sum of all the costs and benefits for the other stakeholder groups assuming that non-user interests are adequately represented by the environmental stakeholders.

4.4.8   Land Use and Sprawl

The link between land use and transportation is one that is both commonly recognized and frequently misunderstood. Access is one of the key factors in determining property value. However, there are a number of other factors that contribute to the shape and type of development that will take place in a given area, including zoning, geology and topography, environmental issues, proximity to metropolitan areas, economic conditions and other socio-economic and demographic factors.

AHS, like any major transportation improvement, raises some concerns about land use on a number of levels. There are concerns about the effects of taking land for right-of-way purposes. There are concerns about developmental impacts at a local level. Finally, there are concerns about "sprawl," the decentralization of urban form. In each case, the influence of a major transportation investment is manifest. However, the other factors listed above, particularly zoning and land use policies, are often just as, if not more, influential.

Eventually, the NAHSC intends to use whatever modeling tools are available or can be developed to analyze the effects of AHS in regard to land use. However, Christine Johnson, Director of USDOT's ITS Joint Program Office, suggested that the NAHSC not rely solely on models, but rather seek the "best thinking" of those with expertise in the area of transportation-land use impacts.

Accordingly, a panel of such experts was selected to represent a broad range of interests and previously-published conclusions regarding the transportation-land use relationship. The panelists were charged with preparing background papers summarizing their reactions to the concept of AHS as defined in materials that had been developed to date by the NAHSC, and to convene on August 1, 1996, at Carnegie Mellon University in Pittsburgh, Pennsylvania, to present their papers and discuss their thoughts with each other.

The moderator of the August 1 session, and author of background papers on the history of transportation and land use and the differences among cities with different prevailing community cultures, was Sam Seskin, Parsons Brinckerhoff. The expert panel participants were: Edward Beimborn, University of Wisconsin; Anthony Downs, The Brookings Institute; Genevieve Giuliano, University of Southern California; John D. Landis, University of California-Berkeley; and G. Scott Rutherford, University of Washington. The papers are scheduled for publication by the NAHSC in early 1997.

One of the most significant outcomes of this effort was a concurrence among more than one of the experts on several of the potential impacts of an AHS deployment. [The experts generally saw their role as a broad analysis of land use patterns in general (and not intersection-specific or land use category-specific)]. The first and perhaps the most important of their concurrent opinions was the general feeling that AHS by itself would have minimal land use impacts. It is widely accepted that there are other – and, perhaps, greater – influences than transportation improvements in defining land use, including political, economic, and cultural trends. Although the opinions of these experts differed as to the relative influence of transportation improvements on land use in the past, they generally foresaw the result of the interaction of transportation with these trends in the future to be complementary, without dramatic alterations. Transportation improvements are expected to provide only incremental changes in accessibility, which are necessary but are not sufficient for land use changes. Specifically, the deployment of an AHS is expected to have minimal impact in changing current land use trends, which do not currently encourage centralization.

On the other hand, several experts expressed the possibility that an AHS could be implemented as a tool to assist planners in improving current land use patterns. A transit/high occupancy vehicle (HOV) application was one alternative noted that could realize this potential.

In addition to these impacts, many of the authors noted repeatedly that our fastest growing population group is the elderly. The subtle importance of this consensus lies in some of

the general characteristics of this group. On a general level, they are drivers who have driven their entire adult lives, prefer suburban locations, and will most likely move further out of the metropolitan areas after retirement. Technologies that can prolong this lifestyle would be the most successful and marketable.

Local Land Use Impacts

Anyone who has seen an office park or mall spring up adjacent to a new arterial highway or expressway interchange will understand that highway access opens up a range of land use opportunities in previously undeveloped areas. Development brings economic activity and improves a community's ratable base. However, it also brings costs; environmental impacts, infrastructure needs, policing, etc. In a growing area without land use or zoning regulations, such developments near highways are predictable. However, much of the developed areas, and even undeveloped areas, do regulate land use, and therefore can shape induced development so that it does not disrupt tax base or infrastructure needs.

Regional Land Use

Sprawl, a pejorative term that refers to the decentralization of traditionally urban land uses, including office, commercial/retail, industrial, and residential, is driven by a number of factors, transportation-related and otherwise. In the nineteenth and early twentieth centuries, these uses were largely concentrated in cities. The advent of the freeway made it possible to relocate these uses to the suburbs during the 1950's, 60's, 70's and 80's. However, improvements in building technology, changes in land use planning and policy, real estate pricing, and the current problems of congestion tend to slow down the sprawl that these highways encouraged. Many of our large metropolitan areas have now developed as far out as one can expect to drive in an hour. In many areas, transportation planning and investment is shifting from radial access to/from the center city toward connecting already dispersed activity centers within a metropolitan area.

On the other hand, some areas, particularly in the south and west, are still booming, and continue to see untrammeled growth. Land use experts generally agree that a transportation improvement, such as AHS, that reduces travel time, will give people the opportunity to seek lower cost (outlying) real estate, that is still within an hour's (or whatever their tolerable travel time is) travel from wherever else they want to go. However, other forces that discourage sprawl will have greater influence in the future than they had during the Interstate Highway building years.

Communities hold the power to establish comprehensive plans and zoning. If they choose to, they can develop plans that encourage "livable communities" with good pedestrian links and access to community services. On the other hand they can chase ratables and permit sprawling subdivisions that generate high numbers of auto trips. Any major new transportation investment in a corridor, including AHS, makes sprawling development possible. A community must take positive action, by allowing sewer and

utility improvements, and through their comprehensive plan and zoning, in order for it to happen.

Communities that are concerned about sprawl will need to deal with AHS in the same ways that they deal with other highway or transportation improvements. As with other transportation improvements, investment in AHS can be made to encourage growth where desired and discourage growth elsewhere. Investment in a network of AHS facilities could help to distribute growth where desired. Areas that do not wish to grow and develop will enact zoning and other land use restrictions that discourage it.

4.4.9 Effects on Fuel Consumption and Emissions Per VMT

Although the net environmental effects of AHS are quite difficult to assess because of diverse uncertainties about traveler behavior and land use changes, beneficial effects in terms of fuel consumption and emissions per VMT appear to be very likely based on available data and models. It is well known that vehicles cruising at a constant speed consume less fuel and emit substantially lower tailpipe emissions than vehicles engaged in stop-and-go driving. The acceleration and deceleration cycles, particularly if they are abrupt, can be extremely unfavorable to the environment. If, as expected, the AHS can smooth out these driving cycles by means of automatic control of speeds and increased throughput to relieve congestion, driving conditions will be much closer to constant-speed cruising for the AHS vehicles.

If the AHS operates using platoons at close spacings (of a vehicle length or less), the aerodynamic drag can be reduced substantially. This phenomenon of "drafting" is well known to racers, and has been explored in wind-tunnel experiments by Prof. Frederick Browand at USC. His experiments show that drag can be reduced by about 20% when vehicles operate at spacings of a vehicle length, and that reduction can approach 50% as the spacings approach zero, as shown in Figure 4.4.1, where the vertical axis represents the ratio of the drag on the platooned vehicles to the drag on an individual vehicle. The effect of this drag reduction on fuel economy and emissions depends on driving speed. For normal highway speeds, Browand and his colleagues have estimated these to translate into fuel economy improvements in the range of 15% to 25% for spacings of a vehicle length or less, as shown in Figure 4.4.2. These are substantial improvements compared to the other improvements that are being made to today's already-efficient vehicles.

The aerodynamic drag and fuel economy improvements can be translated into effects on the production of running emissions. Prof. Matthew Barth of U.C. Riverside has been using a modal emission model to predict these effects. Figure 4.4.3 shows his model's prediction of the effects on CO emissions of platooned operations at 1 m and 3 m spacings, as compared to individual vehicle driving, for speeds up to 120 km/h. The benefits are larger at the higher speeds because the aerodynamic drag represents a larger fraction of the resistance to vehicle motion. Similar-shape curves have also been developed for HC and NOx emissions. These indicate the potential for significant emissions reductions per VMT for closely-spaced platoons operating at highway speeds.
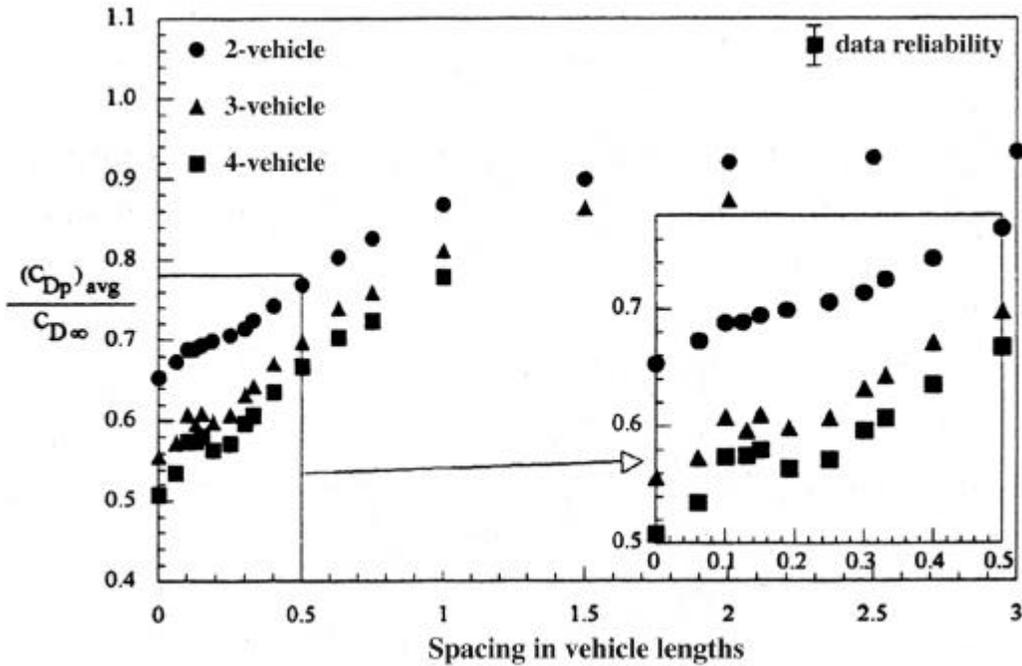
Figure 4.4-1. Ratio of average aerodynamic drag for platoons to drag for individual vehicles. (Ref.: Zabat, Stabile, and Browand, "Estimates of Fuel Savings from Platooning," Proc. of ITS America Annual Meeting, March 1995, pp. 1203-1208.
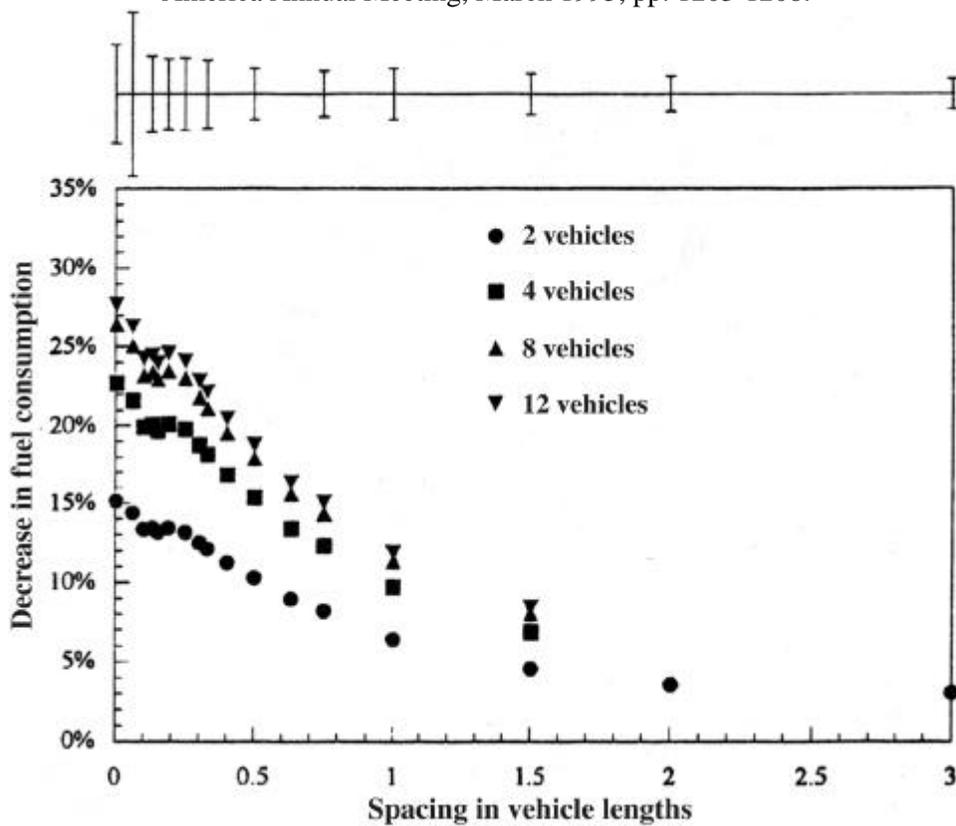
Figure 4.4-2. Average decrease in fuel consumption for platoon vehicles at highway speeds, as compared to individual vehicles. (Ref: Zabat, Stabile, and Browand, "Estimates of Fuel Savings from Platooning," Proc. of ITS America Annual Meeting, March 1995, pp. 1203-1208.
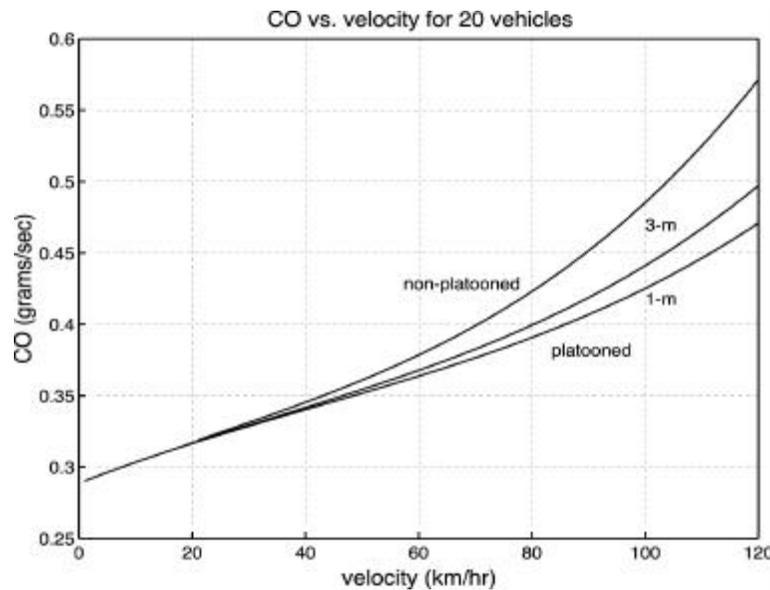
Figure 4.4-3. Estimated carbon monoxide emission rates per second for 20-vehicle platoons at
1m and 3m spacings and individual vehicles, all at constant speed.

4.4.10 Conclusions

Development and deployment of an automated highway system will test the capacity of
our society and institutions to adapt to progress and change. If a system offers substantial
improvements in mobility, safety and convenience and comfort at a reasonable cost; and
can do so without additional harm to the environment, then there will be support for
policy changes. By the same token, a system that fails to deliver on any of those
attributes will likely encounter opposition. In fact, the system and the policy framework
that is developed to support it, should be crafted in a way to ensure that all interested
parties; drivers and passengers, manufacturers and vendors, insurance, and roadway
providers; benefit from each major increment of the system. Otherwise, the disappointed
stakeholder group is likely to block implementation, by refusing to build, insure, develop
or buy key system components.

Key issues described in this section include:

- assignment of responsibilities for ownership and operation of system components,
  including infrastructure, vehicles, and radio frequencies
- development of new standards and regulations to deal with the new technology and
  changes in operational responsibilities.
- development of a system that can compete, on the basis of cost and performance,
  with conventional highway systems
- environmental review of proposed facilities
- fair and equitable assignment of liability and risk

- interoperability of a variety of system architectures, ranging from those with independent vehicles operating in mixed traffic to those with infrastructure support on dedicated lanes.
- coordination with local land use planning to prevent adverse impacts.

The list of such issues may appear daunting, but only to someone who has never tried to deploy a major transportation improvement. In the cases of infrastructure operations, insurance policy, and the development of new traffic regulations, a new paradigm will be needed. Most of the other issues are already faced by state DOTs on their major highway and transit projects. It would be unrealistic to expect AHS to avoid them. Many projects get stopped, because they are weak in one or more areas. The strong projects survive and are implemented. An AHS with proven technology, that is cost-effective, and that offers real benefits, will survive and reach implementation.

4.5   Human Factors

4.5.1 Introduction / Background

It has long been recognized that human factors issues play a significant role in automotive safety. So-called "driver error" associated with such factors as inattention or fatigue constitutes the major causal factor associated with crashes. Although the driver may have a substantially reduced role while interacting with the AHS, many similar issues must be addressed. Researchers have made significant progress in the development of in-vehicle controls and displays that improve the driver's performance. Human factors research for the AHS will utilize the results of past driver performance evaluations; however, since the AHS will combine new and innovative technologies into an environment that will be unfamiliar to the driver in many ways, new slants on traditional human factors issues will require that a new era of in-vehicle and on-the-road evaluations be undertaken.

Consider the following variable AHS characteristics:

- Lane types - automated, transition, manual
- Automated entrances and exits - yes or no
- Metered entry - yes or no
- Vehicles enter/exit automated lanes as individuals or groups
- Lane selection by driver or system
- Lane changes automated or manual
- Maneuvers as individuals or groups

A number of human factors issues associated with each of these characteristics require consideration to determine which AHS characteristics will allow the definition and optimization of an AHS in terms of driver safety, usability and acceptance.

4.5.2 Summary of Work in Progress

Initial NAHSC human factors efforts have concentrated on assessing the state of knowledge of relevant AHS human factors research and to identify critical human factors issues yet to be addressed in the design of the Automated Highway System.

Research recently conducted for the NAHSC includes:

- Subcontract with Virginia Polytechnic Institute, under the direction of Dr. Thomas Dingus
- Various AHS human factors studies under development by the Netherlands' Ministry of Transport, Public Works and Water Management

In addition, research on driver roles in AHS is to be conducted in Task C3; this is described in Section 4.5.5.

Each of the two current efforts is further described below.

4.5.2.1 Research at Virginia Tech

A draft final report "*Human Factors Analysis and Design Support for the NAHSC*" has been prepared by Dr. Thomas Dingus and the staff at Virginia Tech. [Ref. 4.5-1] Specifically, the goal of the report was to identify the most critical human factors issues yet to be addressed in the design of automated highways by determining the state of relevant human factors knowledge with respect to automated highways, related ITS work such as crash avoidance research, and comparable systems research such as automated aircraft systems. In addition, the scope of work included an analysis of the information collected to determine the most critical human factors issues relevant to AHS design. The following three tasks were conducted:

Task 1. Conduct a Literature Review. This task compiled past research recommendations regarding AHS, related ITS, and comparable semi-automated systems. The review included literature addressing the psychology of automation, and aircraft auto-pilot studies, as well as a variety of semi-automated tasks (e.g., cruise control, adaptive cruise control, collision avoidance systems).

Task 2. Review the Honeywell/University of Iowa AHS Studies. Honeywell and the University of Iowa are conducting several human factors studies under the sponsorship of the Federal Highway Administration. The program consists of two parallel and interweaving approaches, one analytical and one experimental. The experimental portion of the program is being conducted at the University of Iowa Driving Simulator. These studies were reviewed and provided unique insight into AHS issues.

Task 3. Identify Critical Human Factors Issues. This task summarized the findings of Tasks 1 and 2 in the form of issue identification, description, and prioritization relevant to the AHS.

A summary of the report findings and recommendations is included in Section 4.5.4.

4.5.2.2 Research by the Netherlands' Ministry of Transport, Public Works and Water Management

The Dutch transport ministry is an Associate Participant of the NAHSC. The Dutch have conducted considerable human factors research for ITS systems currently in use in the Netherlands, and are planning future research efforts to address human factors issues associated specifically with AHS. They are supporting NAHSC research requirements and have three studies underway. The research areas address:

- User's Perception of AHS - Find what users want AHS to do for them

- Human Control in AHS Emergencies - Find if and how humans can take over control in AHS systems
- User's Perception of Car Behavior - Find what effect tactile information has in AHS

4.5.3 Recommendations from Stakeholders

Stakeholder feedback has consistently identified the need to consider human factors in tandem with analyses and deliberations of technical and institutional aspects of an AHS. Observations made during the AHS workshop in Minneapolis include the following:

- The Consortium should take a more proactive stance in addressing human factors issues. Human factors experts should be involved in the design process on an on-going basis. Human factors requirements must be evaluated and integrated into system requirements as the AHS develops.
- Care should be taken not to duplicate human factors research that is currently being conducted for ITS technologies (such as Adaptive Cruise Control) and to allow some human factors issues to be resolved during the natural development of technologies currently being introduced into the market.
- From a human factors perspective, the key step in the advance from partial to fully automated systems will occur with the introduction of automated lateral guidance systems, when used in conjunction with automated longitudinal controls. At this point the driver will no longer need to be involved in moment-to-moment lateral or longitudinal control, but could still be asked to perform a monitoring role.

These and other issues discussed during the workshop are consistent with the results of the research conducted by Dr. Dingus at Virginia Tech, and are discussed further in the following sections.

4.5.4 Summary of Virginia Tech Research Results

The Human Factors literature survey conducted by Virginia Tech provided a valuable resource for the NAHSC to develop future human factors research and work plans. In addition to providing the state of knowledge of relevant AHS issues available in existing non-NAHSC literature, it offers insight into general human factors concerns with partially automated systems, AHS concepts; and the major AHS attributes recently identified by the NAHSC.

The literature review did not answer questions or resolve specific issues identified in the PSAs. The conclusions do, however, provide sound recommendations for future analysis that should be undertaken by human factors experts as part of the ongoing design process.

Highlights of the report [Ref. 4.5-1] are provided below.

4.5.4.1 General Human Factors Concerns with Partial Automated Systems

Despite the introduction of a higher level of automation, the driver will still have a role in the AHS. Likely mixtures of human input and automation will create a situation known as *supervisory control* in which automated subsystems permit the human to set initial conditions, make adjustments, and receive information from a computer that closes a control loop. The level of interaction that is required from the driver (or level of automation of the vehicle) in order for an AHS to work efficiently will affect safety, usability, and driver acceptance.

Levels of automation can range from manual control, to supervisory control, to fully automatic control.

The AHS can be envisioned as new technologies that will be added to improve the driving task. Although the exact functionality of the end system is still in flux, the most advanced AHS is seen as a "hands-off/feet-off" technology in which the driver is not required to perform tasks once the automobile is engaged in a fully automated mode. However, intermediate stages of deployment may be required to bring the system to this hands-off/feet-off reality.

The concept of the AHS as a series of technology introductions will bring in various human factors issues at each stage of development as the level of supervisory control is increased. These issues will most likely change as the system itself changes and new developments in technology are implemented. The stages of deployment could begin with ACC and a collision avoidance system, then the next stage may include technologies such as a lateral warning system. At this stage of development, there is a relatively low level of automation in the vehicle, and the driver is still required to perform the basic driving task of steering, as well as monitoring the environment. The next stage may be to include vehicle position and speed information from the vehicles, which may come in the form of a lateral guidance system. At this stage of automation, the driver may not need to use the accelerator, brake pedal, or steering wheel. Understanding the driver's monitoring and performance capabilities under a condition like this will be of critical importance to the development of the AHS.

4.5.4.2 General Human Factors Concerns with the AHS Concepts

Many general issues can be determined from the standpoint of the driver as the supervisor. However, other more specific issues cannot be so directly uncovered since the technologies and infrastructure of the AHS are not yet well defined. Several of the general human factors issues are addressed below.

4.5.4.2.1 Issue 1. Understanding the driver's role - performing a task analysis

At the current time, a prominent characteristic of the AHS could be the deployment sequence. Although the long-term goal is a "hands-off/feet-off," dedicated, barriered roadway, industry will bring technologies into the market as they are developed. These

technologies could be integrated into an AHS or the AHS could emerge as the technologies and the infrastructure come together. In this scenario, the driver's role would also change with the deployment of technologies and the development of the AHS infrastructure. Furthermore, the driver's role will change as each new technology changes after its original release. As such, the identification of the driver's roles with each technology and each step in the development of the AHS could be paramount to determining all human factors issues surrounding the AHS.

It is suggested that the greatest human factors issue facing this scenario for the development of the AHS is the fact that all potential driver tasks have not been determined for the possible combinations of technology and infrastructure. Until this task is completed, only general human factors issues can be determined. Thus, it is recommended that, as a first step, appropriate human factors design support analyses (including a function allocation analysis, a task analysis, and a trade study analysis) be conducted to determine the driver roles for the likely scenarios as part of the ongoing AHS design process. Although it is realized that some analyses have been performed, it is recognized that these task analyses are for limited AHS scenarios and do not adequately incorporate the possible range of AHS deployment schemes, or the AHS concept-distinguishing attributes.

4.5.4.2.2   Issue 2: Designing for situation anomalies - performing a failure modes, effects, and criticality analysis

After a task analysis is completed to determine the driver's roles in various driving scenarios, a substantial effort must be expended to address all foreseeable AHS situation anomalies. These anomalous situations will include rare system failures, vehicle failures, driver error, and unusual environmental factors. A "Failure Modes, Effects, and Criticality Analysis" (FMECA) should be conducted for all AHS scenarios that include the driver. Determining the potential failure modes of the AHS as a total system operating with an unpredictable operator in an unpredictable environment will allow for the development of proactive design solutions to address the resulting issues before prototype testing or widespread deployment.

4.5.4.2.3 Issue 3: Vigilance of the driver as monitor

For some levels of automation for specific deployment scenarios, the driver would not be required to use the gas pedal, brake pedal, or steer the vehicle, but would be required to monitor the environment for obstacles, and the interior of the vehicle for warnings. If the driver were to perform such tasks, the issue of driver vigilance while monitoring must be addressed, which raises serious concerns about the viability of this approach.

A driver who is not fully alert when an emergency situation arises may not be able to verify the cause of a warning and react in time to avoid an incident. Although vigilance while driving is a concern with the current highway system, the problem is exacerbated when the driver task requirements are decreased. Furthermore, if the driver is traveling

during times when fatigue may be higher (especially at night during a long trip), the expected level of driver responsibility must be carefully considered.

4.5.4.2.4 Issue 4: Driver intervention capabilities

It would be prudent to determine what tasks the driver could safely perform while the automated system is engaged if the need should arise. Furthermore, the concern applies to the various component stages as well since it is probable that the level of intervention allowed by the system will likely change as the system itself becomes more complex. Intervention capabilities have the potential to change drastically from one stage of the AHS to the next, and should be fully and carefully considered.

4.5.4.2.5 Issue 5: Carry-over effects

The topic of carry-over effects refers to the possibility that driving on the AHS may affect the driver's performance or behavior when transferring to manual driving. The question is how drivers, with little or no driving responsibilities on the AHS, will resume the role of manual driving. More specifically, will the driver suffer any performance degradation following automated driving?

When a driver is traveling on a roadway, he/she will have certain expectations. It is expected that other vehicles will not change speed or direction, that some drivers will exit at an exit ramp, and that events on the roadway will occur at certain instances in time. Based on those expectancies, the driver will perform driving behaviors in a certain manner. For example, the driver will visually search the driving environment at a certain rate, drive at a subjectively safe distance from other vehicles, and maintain a subjectively safe speed.

For a fully automated AHS, the driver will develop expectancies different from those with which he/she is familiar, and those expectancies may be transferred to manual driving.

4.5.4.2.6 Issue 6: Driver population and interface design issues

Driver characteristics vary greatly. For example, drivers vary in terms of vision, hearing ability, language comprehension, reaction times, and risk perception. If the AHS is to be safe, useful, and accepted, it will be necessary to design AHS interfaces such that the drivers will be able to understand the system. Each of these systems will also have to be designed such that information and warnings are easily perceived and understood.

Creating a system that is usable by the general public will require detailed consideration of the user population. Drivers with poor reading skills or poor near-field visual acuity will need to understand instructions or warnings as well as drivers with good reading skills and visual acuity. Drivers who know English as a second language will need to

respond as quickly and efficiently in an emergency situation as a native English speaker. Warnings must be given to allow adequate time for a driver with slower reaction time.

Likewise, care will have to be taken to insure that all interfaces and signals are easily distinguishable from one another for all users of the AHS. Neale, Martin, and Dingus argue that when speed of response is critical, as in warning systems, standardization (e.g., location, coding) will be important not just across technologies but across different manufacturers' implementations of the same technology.

4.5.4.2.7 Issue 7: Driver comfort and acceptance

It is highly likely that the proliferation of AHS technologies will be spurred on by industry as consumers are willing to pay for more items of safety and convenience in their vehicles. This will, of course, require that a significant amount of attention be paid to what the consumers find comfortable and acceptable features of an AHS. Some possible driver concerns include:

Driver privacy – The issue of driver privacy is twofold. First, some drivers may not like the idea of a traffic control center and possibly "traceable" computer records of an individual's location at a given time or on a specific date. Second, drivers may not like the close proximity with enhanced visibility from another vehicle while traveling.

Optimal vehicle separation – Not only is throughput a consideration in this case, but driver comfort level must be incorporated into any system design as well. A problem with close vehicle separation may be that the driver becomes apprehensive about being too close to a leading vehicle.

Merge and exit methods – Drivers become uncomfortable when a vehicle merges in front of them at close range. Drivers who are merging into the AHS are not likely to experience anxiety if there are no vehicles in the area, or none in front of them. However, as the system takes full control of the vehicle and the driver's vehicle begins to close on the main body of traffic, the comfort level of the driver may begin to decrease. Also, since throughput must be considered in the design of the AHS, the possibility of an interaction between driver comfort, transfer of control and throughput should be considered carefully.

4.5.4.3 General Human Factors Concerns Associated with AHS Key Attributes

4.5.4.3.1 Dedicated lanes only or mixed traffic operations

The AHS may begin as a mixed traffic operation as industry releases new technologies for partially automated driving into the market. With this scenario, the existing highway structure would require little or no modification, and drivers with and without AHS technologies would be on the same roadway together. Alternatively, dedicated AHS

lanes and full automation must be considered either initially or for the long-term. Dedicated lane(s) will allow AHS equipped vehicles to travel apart from non-equipped vehicles, and have special features that would not be possible in mixed-traffic lanes (e.g., obstacle exclusion). From a human factors perspective, both the change of the AHS from mixed lanes to dedicated lanes and the transfer of the driver from operating on dedicated AHS lanes to non-AHS or vice-versa, lanes will create unique usability issues. Namely:

- The change of subsystems and the driver's expectation of the operation of those subsystems as this takes place.
- Changes in vigilance required of the driver.
- Driver comfort and acceptance of vehicle spacing in mixed traffic and in dedicated lanes.
- Driver comfort and acceptance of issues specific to dedicated lanes (e.g., privacy).
- Driver behavior when changing from dedicated AHS lanes to mixed, non-AHS lanes.
- Transfer from automated to manual control for dedicated traffic versus mixed traffic.
- Driver intervention capabilities for dedicated traffic versus mixed traffic.
- The interaction between manual drivers and the AHS in mixed traffic.

4.5.4.3.2 Platoons or individual vehicles only

The use of platoons, or strings of vehicles traveling in close coordination, is one of the key design questions for the AHS. The effects on the resulting driver tasks and associated performance and behavior requirements are the primary issues of concern. Driver comfort level and psychological well-being are also considerations for this attribute.

4.5.4.3.3 Obstacle detection or exclusion

Obstacle detection by the driver may be a key component of the AHS during early stages of AHS development. Unless obstacle exclusion is feasible, the driver must remain attentive to all aspects of the driving task until the technology is able to accurately identify all conceivable hazardous obstacles. Also, the current technology is not able to keep the false alarm rate for non-hazards to an acceptable level. The driver may be needed in some fashion to aid with this situation as well.

From a human factors standpoint, requiring the driver to perform these types of monitoring functions while not performing the actual driving task is not a good solution.

4.5.4.3.4 Driver role(s) - override or intervention opportunities

Will the driver be able to intervene at any time during automated driving, or will intervention only be allowed at certain times during operation? A task analysis may determine that intervention is practical unless the vehicle is part of a platoon. Other aspects of driver intervention were discussed in an earlier section.

4.5.4.4 Conclusions and Recommendations

The goal of the research project at Virginia Tech was to identify the most critical human factors issues yet to be addressed in the design of automated highway systems, develop a plan to address these issues, and incorporate this knowledge into AHS design. In the process of developing the report, a major change in the design philosophy was undertaken by the NAHSC. This change involved moving from AHS design "concepts" and carrying forth with a series of potential system "attributes."

An assumption made at the beginning of the project was that sufficient design detail existed to identify the most critical human factors issues. As described above, this was found to be the case at only a general level.

Based on prior experience and review of existing data, there is a substantial knowledge base of human factors principles and guidelines that can be brought to bear on the general human factors issues associated with AHS. This knowledge base can be used to make significant trade-off decisions with respect to broad level attributes, once knowledge is gained from the design process. In large part, this knowledge can be applied via human factors and safety analyses commonly used in large scale system design. Such analyses have historically been accomplished as part of military system applications, such as a major aircraft or missile system. These analyses include function analysis, function allocation, task analysis, failure mode effects and criticality analysis and trade-off study analysis.

The next stage in the process of human factors design support must be the participation by human factors experts experienced in large-scale system design in the AHS design process on a daily basis.

The few AHS human factors experimental research projects that should be undertaken in the near term are those that are necessary for support of the design process. Such projects will generally include those that have the following conditions:

- The human factors or safety issue may be a major "show stopper."
- Sufficient knowledge about the design has been determined to establish appropriate experimental parameters.
- A good answer cannot be arrived at via analytical means.

Despite the fact that the majority of the specific human factors issues will continue to evolve with the AHS design, a number of general, high priority human factors issues have been identified. The most important general issues for further analysis and study are provided below:

Issue 1: Task Analysis

- What are all the possible combinations of technologies and infrastructure deployment that could be included in a task analysis?
- How will the development of individual technologies impact the task analysis?

Issue 2: Situation Anomalies

- What role should the driver have in the event of a malfunction? How will driver alertness impact malfunction management?

Issue 3: Vigilance

- How will a lack of vigilance affect the driver's safety, specifically for critical tasks such as obstacle detection?

Issue 4: Driver Intervention

- Under what circumstances should the driver be able to intervene with the functioning of an AHS subsystem?
- How will the time-staged development of the AHS affect the level of driver intervention?

Issue 5: Carry-Over Effects

- What changes will occur in driver behavior on non-automated roadways as a result of driving on an AHS? Specifically, will changes occur in following distance, speed, or monitoring behavior?

Issue 6: Driver Characteristics

- Who will be the driving public on the AHS? What are their attributes and driving characteristics?

Based on the above discussion, a major question becomes, how will the more specific human factors and driver-related safety issues be determined? These will be determined as the design process proceeds, only if substantial human factors and personnel safety effort is undertaken throughout the prototype design process. In summary, although a precursory step has been made to identify the most critical human factors issues in the design of an automated highway system, the outcome has shortcomings that cannot be rectified until the technologies and infrastructure design of the AHS have been defined and specified in more detail. With the incorporation of a human factors engineering activity into the preliminary design stages, many more specific human factors issues of the AHS will be identified, and plans can be developed to address those issues on an individual basis.

4.5.5 Summary of Planned C3 Work

The Driver Role and Acceptance Critical Issues Team will be initiated at the onset of Task C3 to support the NAHSC development of an AHS architecture by identifying driver role related requirements and design constraints for the AHS functional and physical architecture.

The primary objective of the team is to contribute to AHS decision making by showing that existing knowledge in human factors literature places fundamental constraints on the types of partially or totally automated systems that should be considered. Emphasis will be on the key attributes of the deployment sequence and mixed traffic operations.

The team's approach is primarily integrative. While experimental research tends to generate questions, the situation called for informed judgment to integrate human factors insights with AHS research results to develop broad answers which would place constraints on the ultimate design.

Four examples were proposed of "likely answers", i.e., relatively broad assertions derived from research literature which seem to have direct bearing on critical NAHSC design issues. These likely answers are presented here (in slightly evolved form):

- Driving should not become a vigilance/monitoring task.
    - If the driver is no longer actively involved in moment-to-moment control of the vehicle, then a responsibility such as obstacle detection calls for sustained attention for the occurrence of infrequent, unpredictable events over a long period of time. An extensive literature search suggests that such a responsibility may be untenable because of known human limitations in vigilance/monitoring tasks.

- The driver is inadequate as a fallback option in the case of almost all time constrained, full automation, dedicated lane AHS malfunctions.
    - This conclusion is directly supported by Honeywell PSA research.
    - However, the driver clearly can provide fallback in some full automation conditions, with sufficient notice.
    - The driver will need to be the fallback option with many kinds of partial automation.
    - Voluntary driver override is quite different in critical ways from mandatory driver participation as a fallback option.

- The driver should only need to be aware that a particular configuration's automation (partial or total) is engaged or not engaged, not the states of particular subsystems.
    - This follows directly from a requirement to not increase driver workload or from the need to avoid roles confusion.

- Consideration of driver roles confusion and driver system state awareness places important constraints on acceptable automated vehicle control concepts.
  - If both are available, lateral and longitudinal control should not be operated separately. [4.5-2]
  - Collision avoidance in one dimension, with something less than full collision avoidance in the other, forces the driver to remember to take evasive action in one dimension, but not in the other, although this skill is rarely practiced. [4.5-3; 4.5-4]
  - Don't separate collision warning from collision avoidance. [4.5-5]
  - Fallback schemes where higher level of automation is replaced by lower level (other than manual) may not work. [4.5-6]
  - Multiple collision warning systems may confuse during the critical time when they're supposed to help. [4.5-7]
  - Single collision warning system may distract driver from monitoring road. [4.5-7; 4.5-8; 4.5-9]

This set of likely answers is at the core of the Driver Role Team's work plan for the next three years. The relevance of the assertions will be demonstrated by the contracting of directed literature reviews, by driver role related function definition and task analysis, by experimental driver-in-the-loop simulator or test vehicle research, and by integrative position papers to assure that these human factors results are developed in tandem with analyses and deliberations on technical and institutional aspects of an AHS.

5.   Technology Assessments

5.1   Need For Technology Assessments

The technical feasibility of the concepts developed and evaluated in Task C2 depends on results of the Enabling Technologies assessments being made by the Technology Team in Task B3. It is those assessments that help determine the feasibility of concepts being able to meet reasonable functional and performance requirements. Some of the concepts are technology-dependent; that is, without the development of new technologies, the concept could not become a viable operational concept.

Several B3 technology projects were initiated in parallel with the C2 task. In many cases these projects are in their early stages of investigation. For that reason, there were few results available to the C2 team from these projects other than in the broadest terms. The areas of investigation for the 16 active projects (four being performed by outside contractors) are the following:

- Vehicle-Based Obstacle Detection   6 projects
- Infrastructure-Based Obstacle Detection   -
- Lateral Control   5 projects
- Algorithms   3 projects
- Actuators   -
- Software Safety   1 project
- EMC/EMI   1 project

Even though most of the technology projects could not directly contribute to the C2 work, the Technology Team was able to provide some overall assessments of technical feasibility for some functions. The area of biggest concern was obstacle detection, since it was felt that with known technologies, obstacle detection alone would not be adequate for AHS vehicle operations, and some level of obstacle exclusion would also be necessary. It was also felt that for vehicles operating in mixed traffic, sensing of other vehicles in the lane and distinguishing them from on-coming vehicles, vehicles in another lane, or roadside objects would be very challenging as would predicting movements of the manually driven vehicles.

5.2   Technology Roadmap

The basis for technology assessments in the NAHSC is the Technology Roadmap, which is under development by the Technology Team. The Roadmap represents our best understanding, to date, of the technologies needed by the Program, the criticality of those technologies, and their development status. The Roadmap has 33 technology categories. Each category has the following information maintained by a "custodian" from the Tech. Team:

- **Requirements** – Required capabilities by major milestone
  - The Roadmap provides a long-range view of the capabilities that might be required at three of the major milestones of AHS development and deployment:
  - Prototype Testing (year 2000)
  - Operational Field Test and Evaluation (2005 to 2010)
  - Initial Deployment (2015 to 2020)

- **Technologies** – Technology areas that may meet requirements, their status and their shortfalls

  Types of technologies that might be used to achieve the needed capabilities are identified, and their current development status is defined. Shortfalls are identified by comparing what is achievable today versus what will be needed in the future. This then leads to identification of needed research where major gaps between needs and today's capabilities exist.

- **Need for Research** – Assessment of the relative need for NAHSC research

  The need for research is assessed based on the size of the technology gap, the impact on the program if the needed capabilities were not available when they are believed to be needed, and the amount of on-going research that is being conducted in the area. On-going or proposed research efforts relating to the technology gap are identified, both within the NAHSC and without. The needs are indicated as **HIGH**, **MEDIUM**, and **LOW**.

The intent is that the program's research and development resources should mostly focus on the technology areas where (1) there is a critical program need; (2) there is a large gap between the critical need and the capability that exists (or is foreseen) today; and (3) where little or no research is being conducted. It is these areas where the feasibility of AHS may depend on the success of the research. These areas are described as **HIGH** in the *Need for Research* assessments.

Table 5.1 summarizes the technology categories showing each of the 33 categories and its relative research priority.

The Roadmap is a living document. New categories, changing priorities, and updated requirements and capabilities are being added as the NAHSC gains more information.

Table 5.1. Summary of Technology Roadmap

TECHNOLOGY CATEGORIES (custodian organizations indicated in parentheses)	NAHSC RESEARCH NEED		
	High	Medium	Low
1. On-Vehicle Sensing - Longitudinal Separation Sensing (GM)	X		
2. On-Vehicle Sensing - Obstacle Detection (GM)	X		
3. On-Vehicle Sensing - Lateral Position Sensing and Algorithms (PATH)		X	
4. On-Vehicle Sensing - Vehicle Lateral Position (PATH)	X		
5. On-Vehicle Sensing - Motion Sensing (CMU)		X	
6. On-Vehicle Sensing - Absolute Positioning Systems for AHS (CMU)			X
7. On-Vehicle Sensing - Vehicle Systems Status (including braking capability) (GM)	X		
8. On-Vehicle Sensing - Driver / Surface Conditions (CMU / GM)	X		
9. Roadway and Infrastructure Sensing - Environment (LMC)		X	
10. Roadway and Infrastructure Sensing - Macroscopic Traffic Conditions (Caltrans)			X
11. Roadway and Infrastructure Sensing - Microscopic Traffic Conditions (Caltrans)		?	
12. Roadway and Infrastructure Sensing - AHS Obstacle Detection (CMU)	X		
13. Actuators (Cars, Trucks, Buses) - Steering (GM)		X	
14. Actuators (Cars, Trucks, Buses) - Braking (GM)			X
15. Actuators (Cars, Trucks, Buses) - Throttle (GM)			X
16. Communications - Vehicle-to-Vehicle (Hughes)	X		
17. Communications - Vehicle-to-Roadside (Hughes)		X	
18. Communications - Roadside-to-TMC (Hughes)			X
19. Communications - On-Board Vehicle (PATH)		?	
20. Processing - On-Board (CMU)			X
21. Processing - Infrastructure and TMC (PB)			X
22. Algorithms - Integrated Control (PATH)	X		
23. Algorithms - Check-In and Merging (PATH)	X		
24. Algorithms - Check-Out and De-Merging (CMU)		X	
25. Algorithms - Obstacle Avoidance (CMU)	X		
26. Algorithms - Exit Management (PB)		X	
27. Algorithms - Traffic Flow Management, Including Operating Parameter Determination (PB)		X	
28. Algorithms - Software Safety (PATH)			X
29. Infrastructure and Configuration - Traffic Operations and Maintenance (Caltrans)			X
30. Infrastructure and Configuration - Roadway, Lane and Barrier Designs (Bechtel)		X	
31. Infrastructure and Configuration - AHS-Specific Construction (Bechtel)			X
32. Infrastructure and Configuration - AHS-Specific Maintenance and Rescue Vehicles (Caltrans)			X
33. Infrastructure and Configuration - Obstacle Prevention (PATH)		X	

6. Highway Configuration and Implementation Issues for Dedicated AHS Lane Operation

6.1 Introduction

6.1.1 Purpose

This section outlines configuration options and associated design standard issues related to the introduction of dedicated AHS infrastructure into the existing national freeway network. It also discusses implementation issues in the context of the environment that currently exists for developing major public works projects in the United States (U.S.).

This section is intended to present material for discussion along with issues that will need to be investigated during upcoming phases of AHS development and is not intended to present definitive conclusions regarding configuration and implementation of the program.

6.1.2 Scope

The material in this section provides representative configurations for inserting dedicated AHS infrastructure into hypothetical application scenarios for urban, inter-city, and rural freeway environments and describes some of the main issues related to highway design standards. It also discusses an illustration of what a high-throughput, freeway-to-freeway interchange (combining dedicated AHS and manual lanes) could look like.

6.2 Highway Configuration Alternatives

In most of the current AHS concepts, AHS operation requires the dedication of one or more lanes for the exclusive use of AHS-equipped vehicles. The manner in which new construction of such dedicated lane(s) can be provided can take several alternative forms.

- Shared common right-of-way (ROW) at same level
- Shared common ROW at a different elevation
- Dedicated AHS infrastructure on a separate ROW

A rigorous process to develop acceptable highway configurations and associated geometric design standards for each of these alternatives will have be implemented by the appropriate agencies and organizations at the federal, state, and local levels.

6.2.1 Shared Common ROW at Same Level

This option represents the most likely method of incorporating new dedicated AHS infrastructure into an existing highway infrastructure.

AHS-dedicated lane(s) could share a common ROW with an existing highway facility at the same level in two different configurations. These configurations are differentiated by the use of either shared or dedicated access ramps.

6.2.1.1 Shared Access Ramps

The AHS traffic would share the existing on- and off-ramps with manual vehicles. For example, at entry, the AHS-equipped vehicle would share use of the existing on-ramp with manual vehicles. The AHS vehicle would then cross the manual lanes to a dedicated "transition" lane where check-in activity and transfer of control from manual to automated driving would take place. After transfer of control is complete, the AHS vehicle would enter into the dedicated AHS lane in accordance with a pre-specified protocol. The exit function would be performed in the reverse order of the entry function.

Figure 6-1 shows a plan view and a typical section of this configuration. For each direction of travel, the existing cross-section shows: four 12-foot lanes, a 10-foot outside shoulder, and a Jersey barrier in the middle with no median. The modified cross-section would take away one of the manual lanes (in each direction) and convert it into a dedicated AHS lane, but it would add two Jersey barriers (that separate manual from AHS traffic) and an 8-foot inside shoulder. Such an arrangement would require the addition of 60 feet to the highway ROW for both directions of traffic.

Issues arising from this configuration include:

- Ramp metering
- Queuing time delay
- Throughput and efficiency loss due to constrained access
- Higher weaving volumes that may require longer distances between highway access points

6.2.1.2 Dedicated Access Ramps

In the dedicated ramp option, AHS traffic would enter and exit the highway to the dedicated AHS lane(s) via AHS-dedicated ramps. These ramps could be added to existing interchanges or provided as elements of exclusive AHS interchanges. Figure 6-2 shows the modification an existing highway cross-section to accommodate an AHS dedicated lane fed by a dedicated ramp in an urban environment. This modification is conservative in that it uses today's manual highway dimensions for the AHS lanes.

EXISTING

MODIFIED

DEDICATED LANE WITH TRANSITION LANE
COMMON ENTRY / EXIT RAMPS
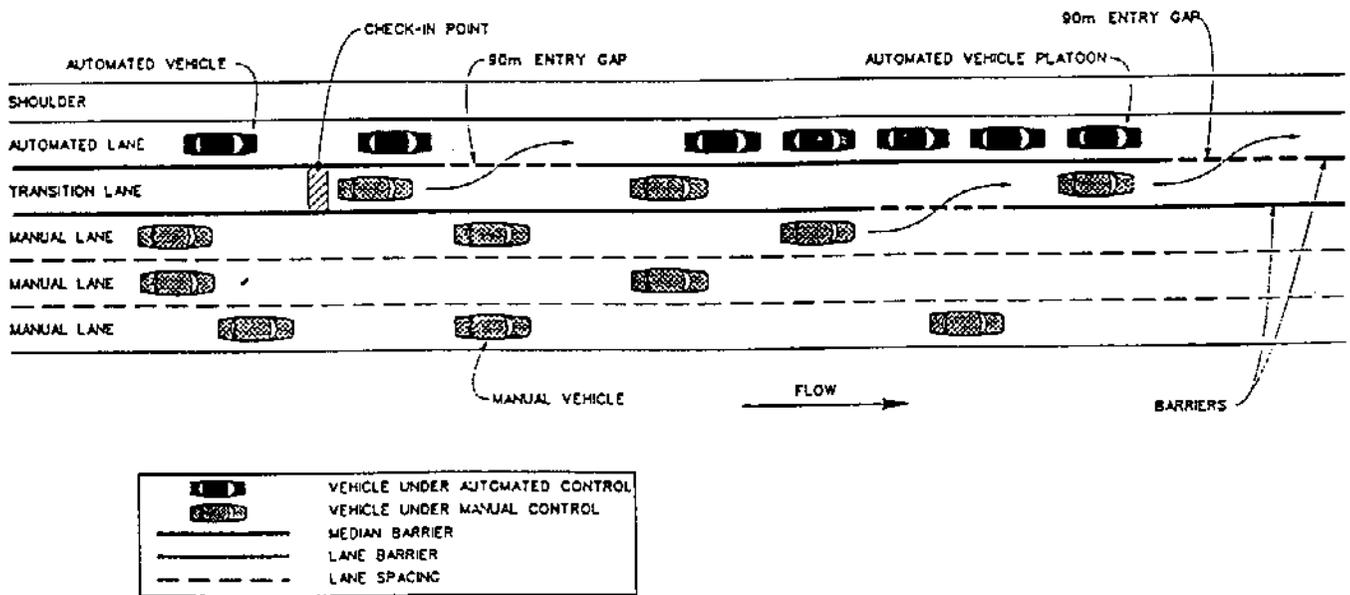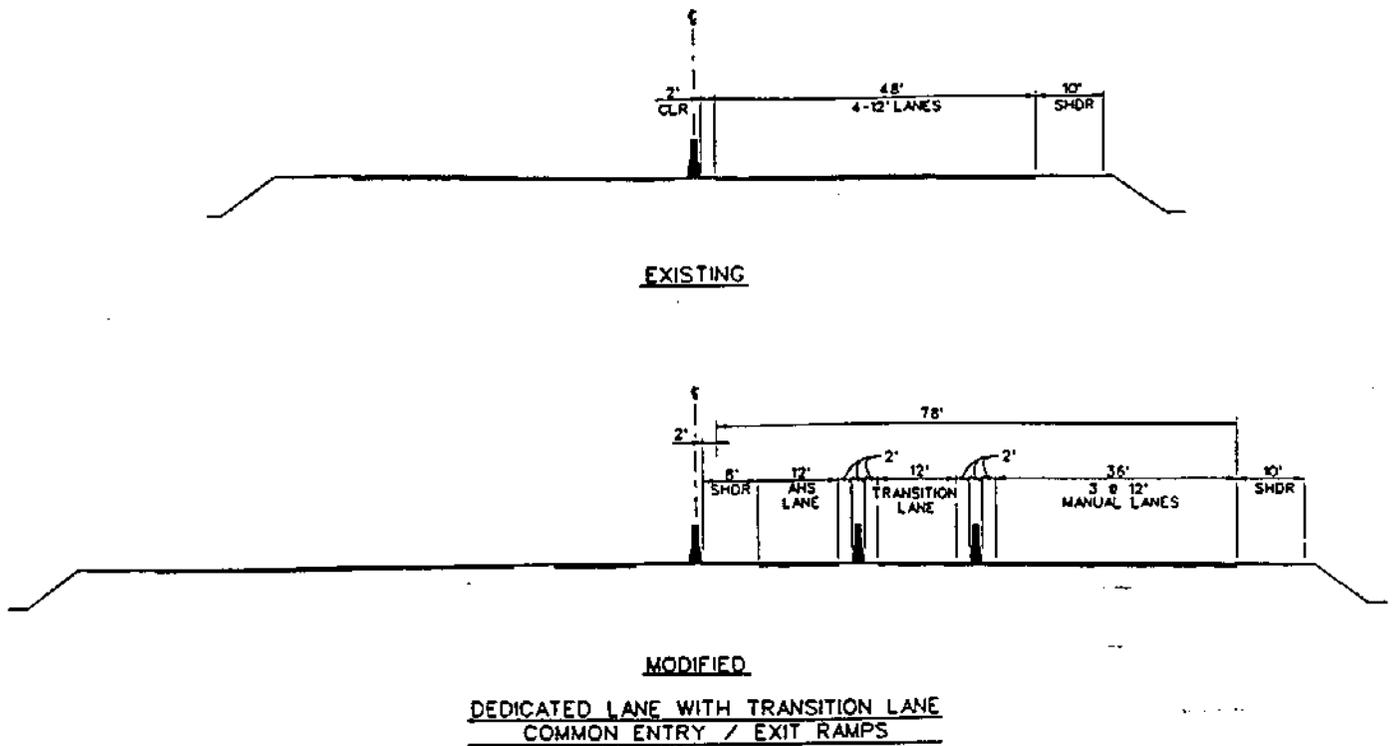
Figure 6-1. AHS Dedicated Lanes - Shared Ramps.

EXISTING

60'

2'

MODIFIED

DEDICATED LANE -
DEDICATED ENTRY / EXIT RAMPS
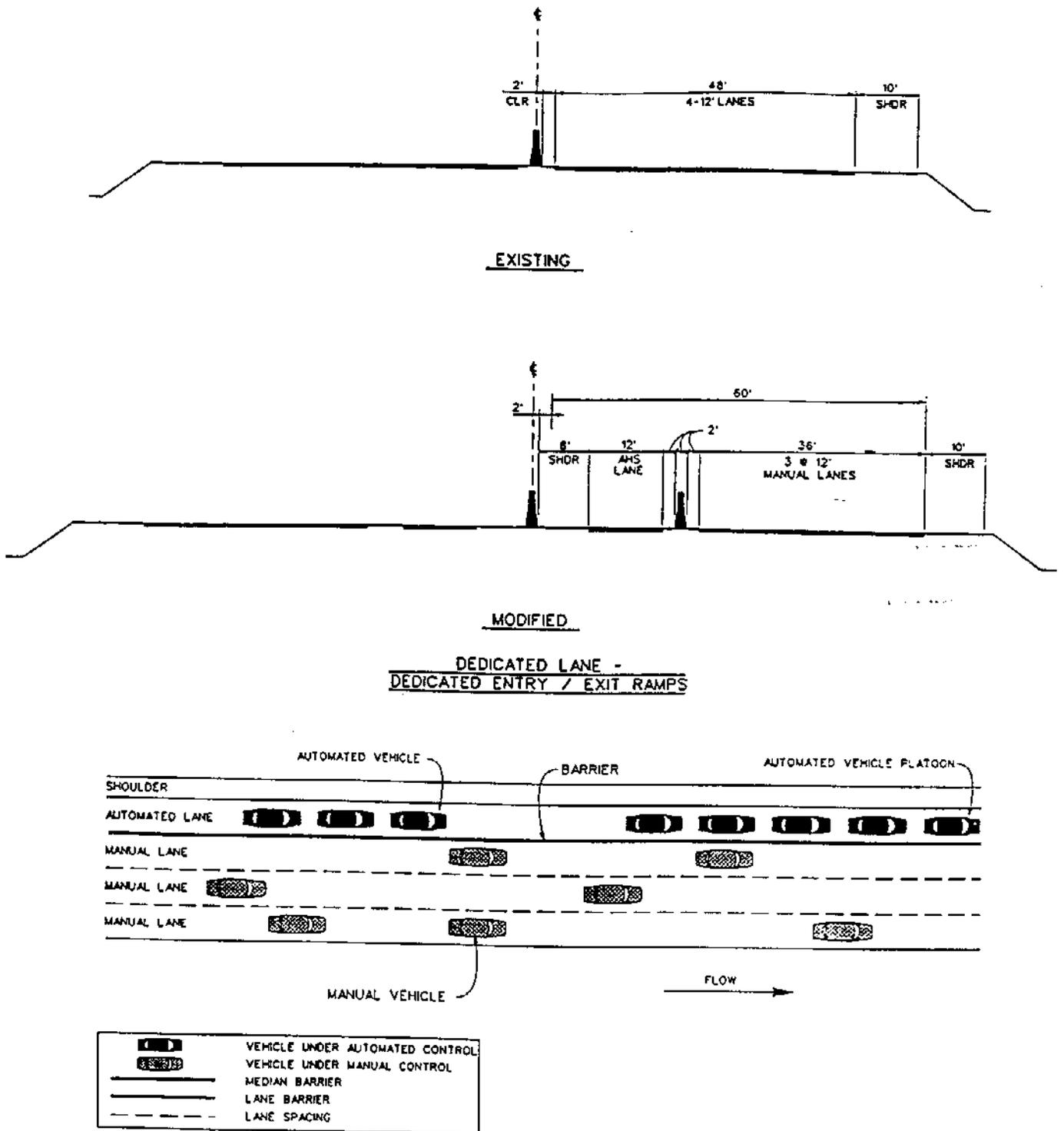
Figure 6-2. AHS-Dedicated Lanes - Dedicated Ramps

To enter the dedicated ramp, the AHS-equipped vehicle would first undergo a check-in function. If the vehicle is accepted, it would then enter the dedicated entry ramp. Figure 6-3 shows a ramp configuration that could accommodate this traffic operation. This particular configuration consists of a dedicated ramp connecting from the center of an overcrossing down to the dedicated lanes located at the inside lanes of the highway. As seen in this configuration, about 1,020 feet is needed to descend from the elevation of the overcrossing down to the elevation of the highway. An additional length is required to accommodate merging with the mainline AHS traffic, followed by a lane drop (taper). The length required to accommodate the merge process is still under study.

A corresponding process is required for the exit function. The combined length for the merge and demerge activities will be a dominant factor in determining the minimum spacing between dedicated interchanges. As a point of reference, existing average spacing between interchanges in urban areas is about 0.7 mile (roughly 1 kilometer), which implies that, in this particular configuration, dedicated AHS ramps would not serve all existing interchanges.

In order to accommodate dedicated entry and exit ramps, and given the requirement to comply with ASHTO on standards for manually driven highways (addressed more fully in section 6.3), additional local widening at each interchange location would be required over and above that shown to accommodate the dedicated AHS lane operation. Figure 6-4 shows a section of how this additional ramp widening could be accommodated. The photograph in Figure 6-5 shows an existing overcrossing constructed in a similar manner – Barranca Parkway Overcrossing on Interstate 5 in Southern California. Although planned for high-occupancy vehicle (HOV) use, this configuration could be adapted for AHS operations. The full ROW shown in Figures 6-4 and 6-5 might not be needed if AHS vehicles have significantly improved performance over conventional vehicles.

6.2.2   Shared Common ROW at a Different Elevation

A dedicated AHS facility could be built on grade separated and segregated structure, sharing the ROW of an existing highway but below or above its grade. Figure 6-6 shows a configuration for an elevated AHS facility, and in assuming compliance to AASHTO design standards. This configuration raises questions such as possible noise mitigation requirements and constraints on future expansion. Soundwalls could possibly be required on the structure; however, for vehicle occupants, this may result in a feeling of being in a trough. The psychological factors would have to be evaluated.

ACCESS / EXIT   **MERGE**

ACCESS / EXIT   **MERGE**   **TAPER**
(D1)   (D1) - ENTER   (D4)
                (D3) - EXIT
                (D2) - D3

PLAN

D1 - 1020'	D2 - ---	D4 - 780'
	D3 - ---	

ELEVATION
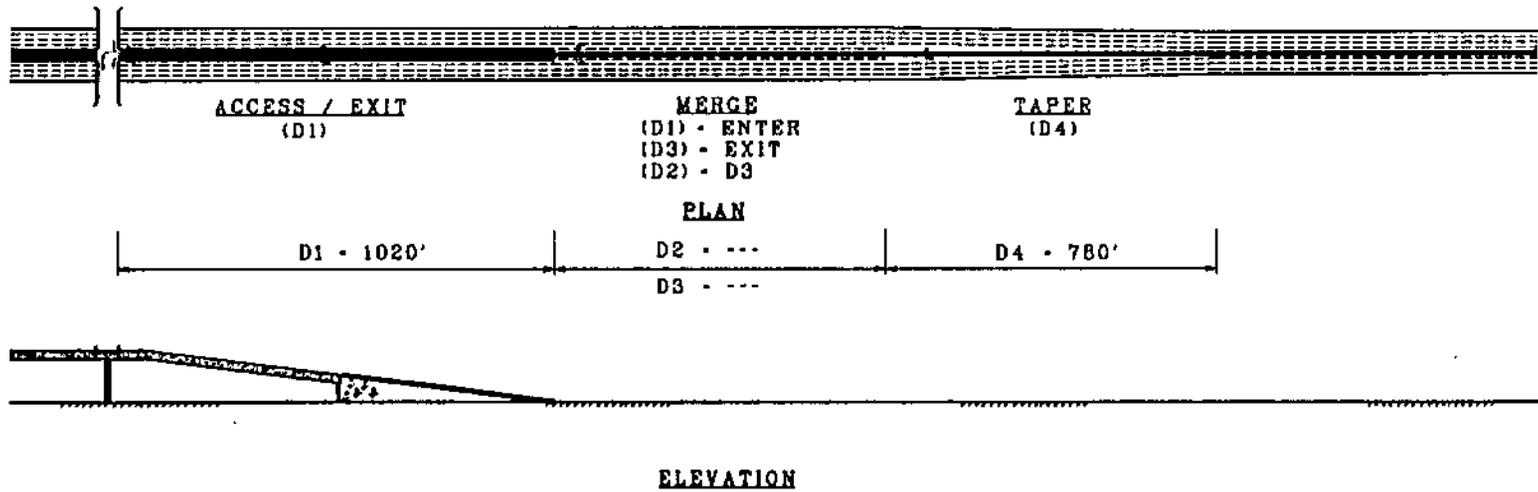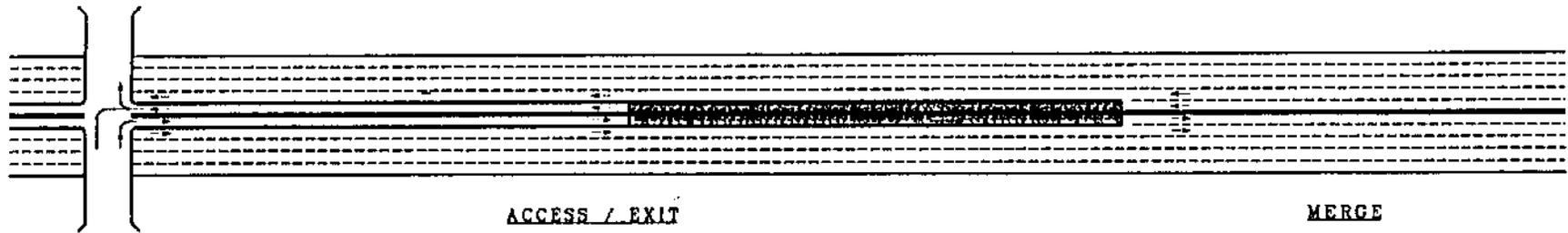
Figure 6-3. Dedicated Entry/Exit Ramp.

C/L SYMMETRICAL

73'

2'

8'	12'		36'	10'
SHDR	AHS LANE		3 @ 12' MANUAL LANES	SHDR

TYPICAL AHS / MANUAL CROSS SECTION

C/L SYMMETRICAL

79'

2' 2'

12'	12'		36'	10'
ACCESS RAMP	AHS LANE		3 @ 12' MANUAL LANES	SHDR
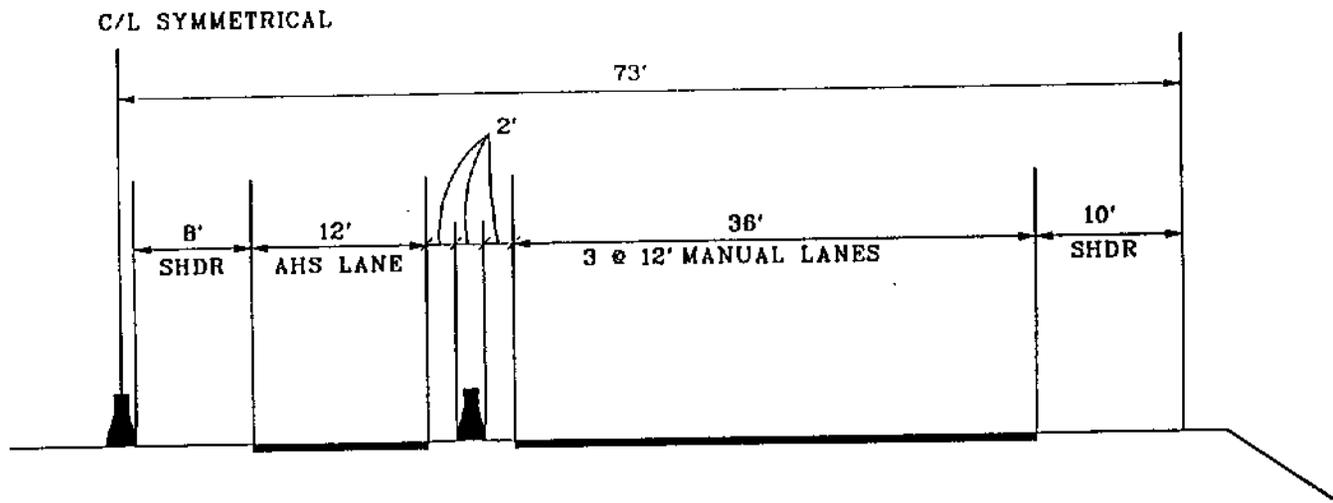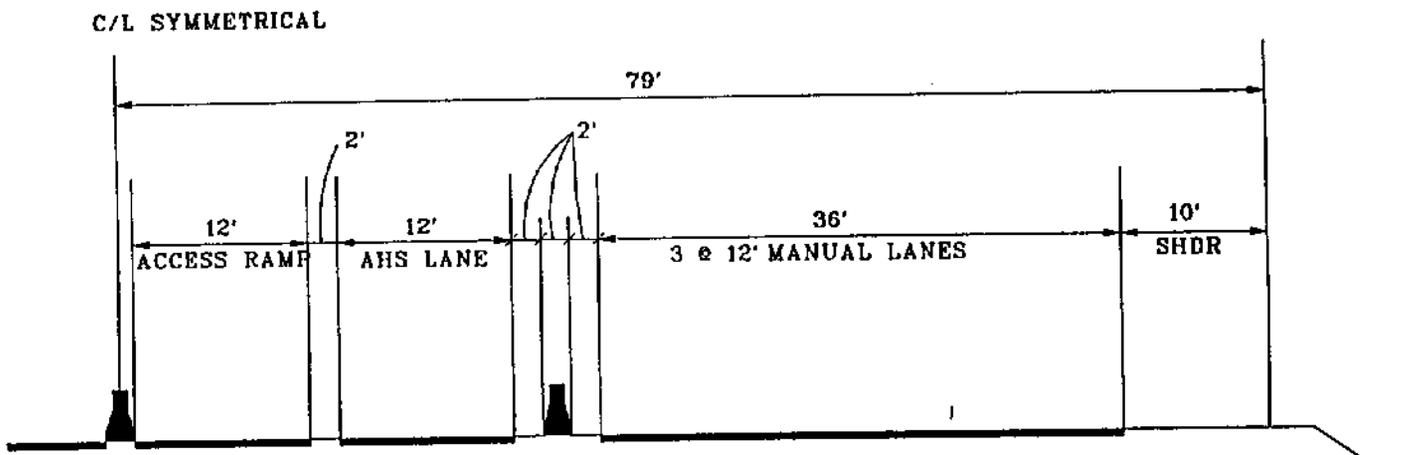
Figure 6-4 Typical AHS Ramp/AHS-Manual Cross-Section.

Note: Photo of median ramp HOV designed by Dokken Engineering.

Figure 6-5. Barranca Parkway Overcrossing on I-5.
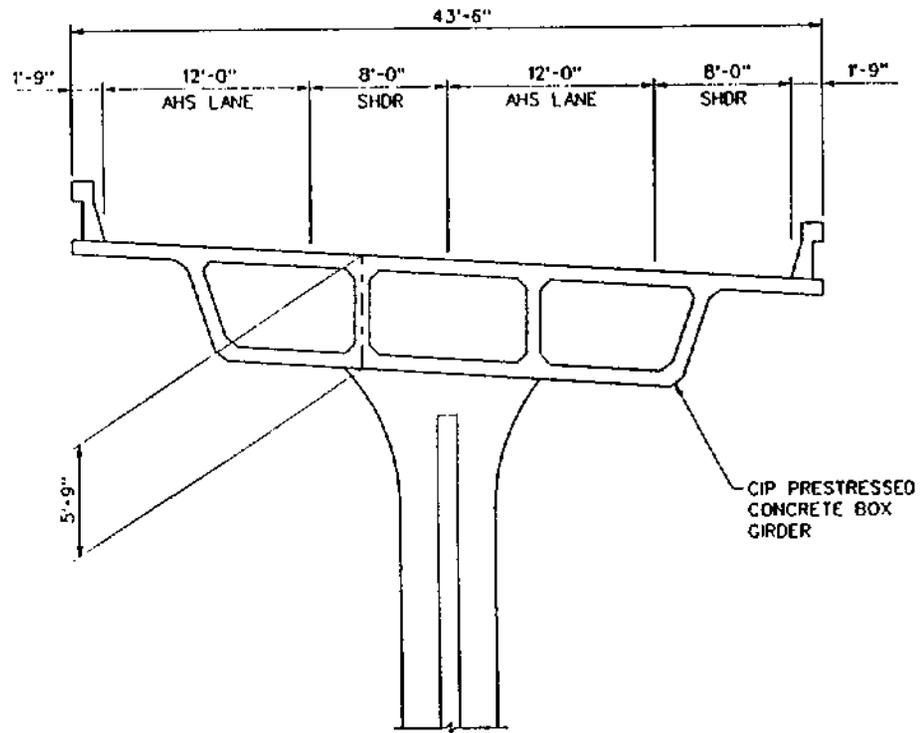
Figure 6-6. Dedicated AHS Structure - Elevated.

6.2.3   A Dedicated AHS Infrastructure on a Separate ROW

A dedicated AHS highway could be built on its own separate and exclusive ROW. Such a configuration could be applicable to urban environments where acquisition of additional ROW along established highway corridors could be expensive. It could also be considered for special long-haul exclusive truck routes along major trade routes. Figure 6-7 shows a "typical" AHS parallel corridor layout of such a facility, assuming today's manual highway lane dimensions for the AHS lanes. This configuration could facilitate early deployment of dedicated lanes and reduce the space requirements for concrete barrier separation from manual lanes, extra shoulder widths, future expansion. It could also be more flexible in construction staging.

6.3   Factors Influencing Design Standards

The selection of any of the configuration alternatives discussed in Section 6.2 above will depend on the AHS application environment and specific local conditions and requirements. Other factors and considerations that will affect selection include: level and maturity of automation technology, extent of driver involvement in AHS operation, throughput requirements, safety levels, liability, and total development cost.

While the discussion of these configuration alternatives assumes the adoption of existing highway design standards, several new factors will arise with the introduction of dedicated AHS operations which could modify or change existing standards. Following is a brief discussion of the more important factors and their possible impacts.

6.3.1   Automated Driving

Current highway design standards are understandably based on the human as the operator of the vehicle. Many geometric design standards are based on the human driver's capabilities and limitations. AHS introduces automated driving with little or no human interference. The degree to which the driver would be involved in operating the vehicle would influence changes in the design standards for AHS infrastructure development. For example, design parameters such as horizontal and vertical curves currently have constraints and are governed by the line of sight of the driver's eye. In the AHS, the new "eye" will likely be a sensing system (e.g., radar, camera, ultrasonic detectors). As the capabilities and constraints of this new technology are better defined and developed, consideration will be given to revisiting existing highway design standards and modifying (or changing) them to suit these new capabilities and constraints. These criteria will likely be a composite of existing and new standards, tempered with the psychological impacts of what will enable passengers to be comfortable.

AHS

MANUAL

AHS INTERCHANGE SPACING
(AS REQUIRED)

AHS I/C
DETAIL 2

LOCAL I/C
DETAIL 1

LOCAL I/C
DETAIL 1

LOCAL I/C
DETAIL 1

AHS I/C
DETAIL 2

LOCAL INTERCHANGE
DETAIL 1

AHS INTERCHANGE
DETAIL 2

AHS INTERCHANGE
OPTION A
(NO STREET CONNECTION)
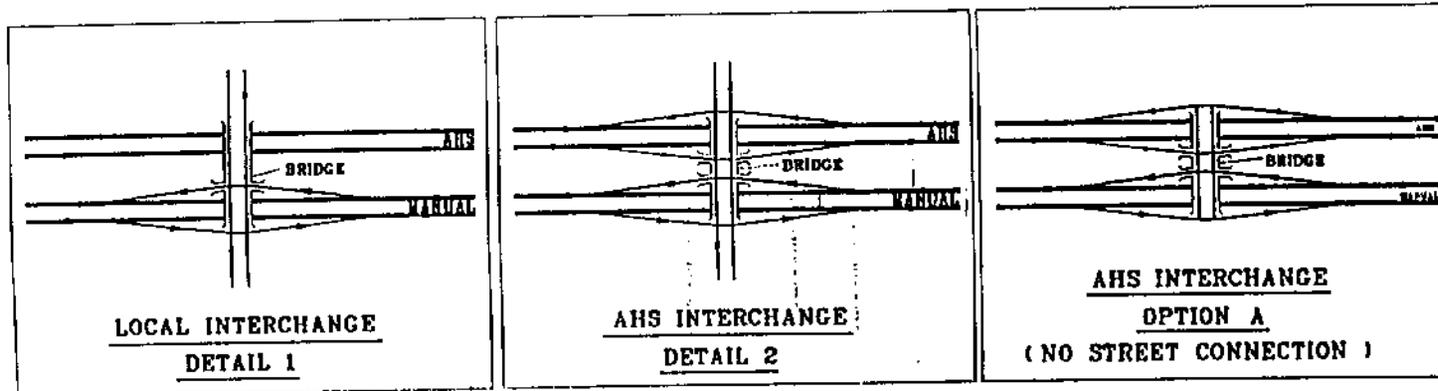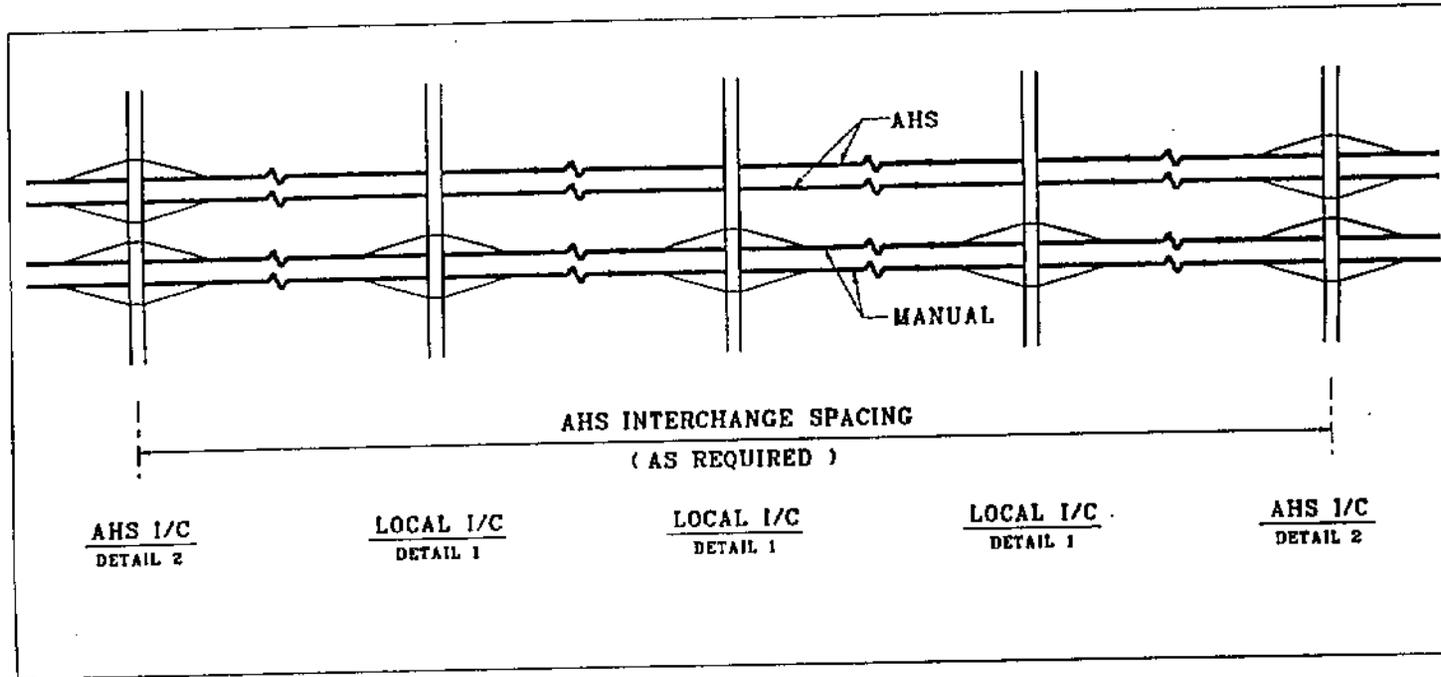
Figure 6-7. AHS Parallel Corridor Inter-Change Layout.

Automation will also influence the width of a traffic-moving lane, whether used as a transition lane or a dedicated lane. Width could also be influenced by the class of vehicles using the lane (e.g., exclusive use by light vehicles, buses, or trucks, or mixed use by all classes).

This is a new area of highway design that will be difficult to research until the capabilities and limitations of the new AHS technology are adequately defined and quantified. Human factors testing will likely be an important part of this research.

6.3.2   Separation Between Automated and Manual Vehicles

In a dedicated AHS operation that would share the same ROW with manual operation, a primary concern will be the safe lateral separation, and corresponding protection, of AHS and manual vehicles. Separation can be accomplished by using:

- **Virtual Barrier** – Essentially a paint stripe between manual and automated lanes, which would offer little or no separation or protection between manual and automated vehicles.
- **Buffer Zone** – A spatial separation between the manual lanes and the AHS lanes which could range from 2 to 14 feet. Again, such a separation offers no positive protection for either manual or automated vehicles in cases of accidents or encroachment of rogue vehicles.
- **Physical Barrier** – A barrier such as a concrete barrier would provide a positive physical separation between the automated and manual lanes. Safety requirements, physical dimension (i.e., shape, width, height, buffer areas), and construction material for physical barriers have not yet been researched and quantified. Many issues would be involved in this research including liability, cost, emergency response, etc.

Figure 6-8 shows configurations for these separation methods.

6.3.3   Provision for Breakdown Areas

In the AHS configurations discussed in this report, we have assumed the provision of a continuous shoulder alongside the automated lane, to be used by disabled vehicles and to provide access to emergency help. Two other configurations were suggested, however, that would save pavement (and ROW) by sharing the breakdown lane between the two opposing AHS directions. The first is shown in Figure 6-9. This configuration would provide one continuous shoulder to be shared by the two opposing directions and that could be used by disabled vehicles in either direction on as available basis. This configuration would prompt serious safety concerns and is unlikely to be adopted as a viable solution. For example, a disabled vehicle with some sort of control problems (e.g., steering, braking, communication, etc.) would represent a clear hazard pulling into a
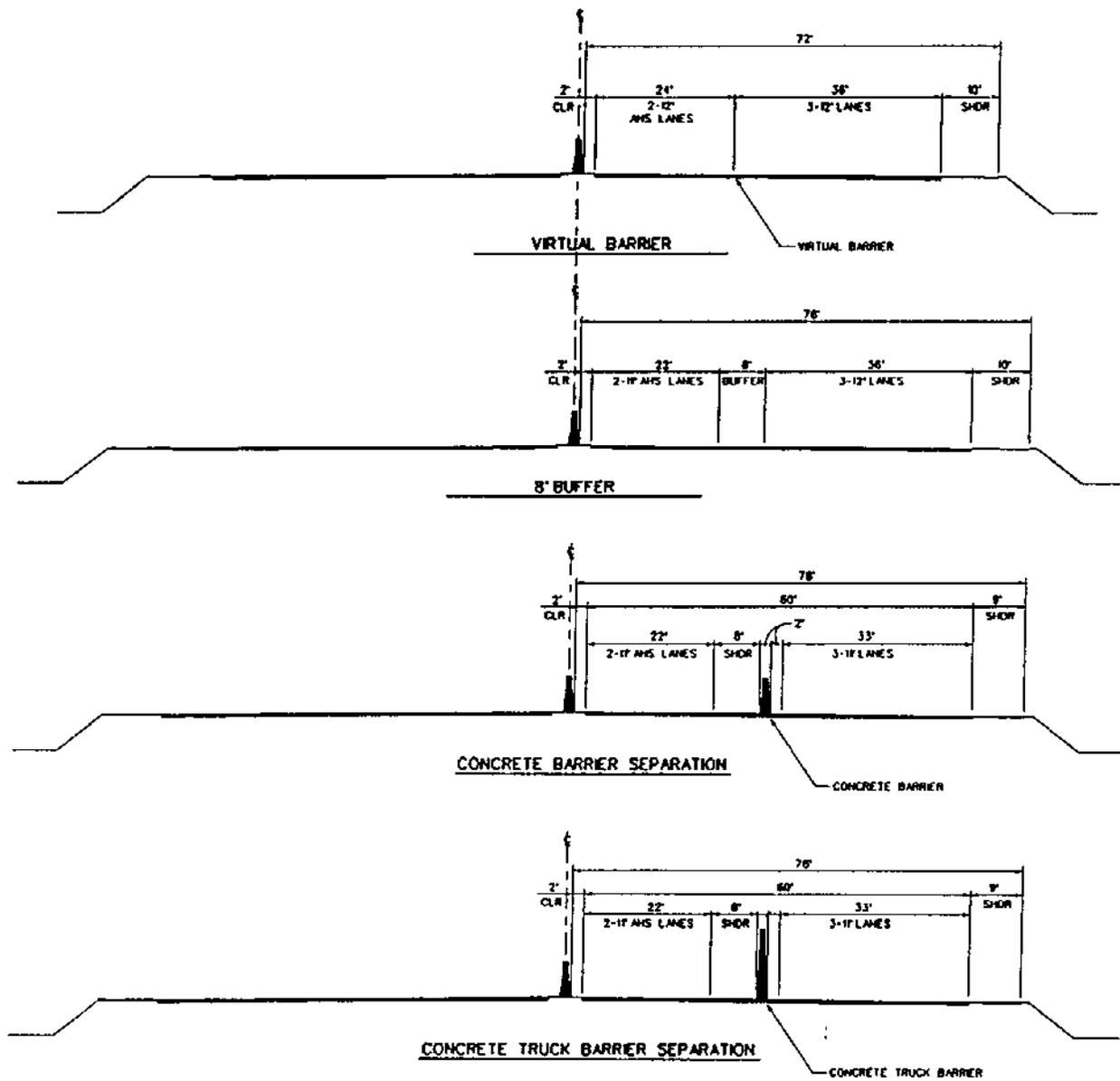
Figure 6-8. Separation Methods
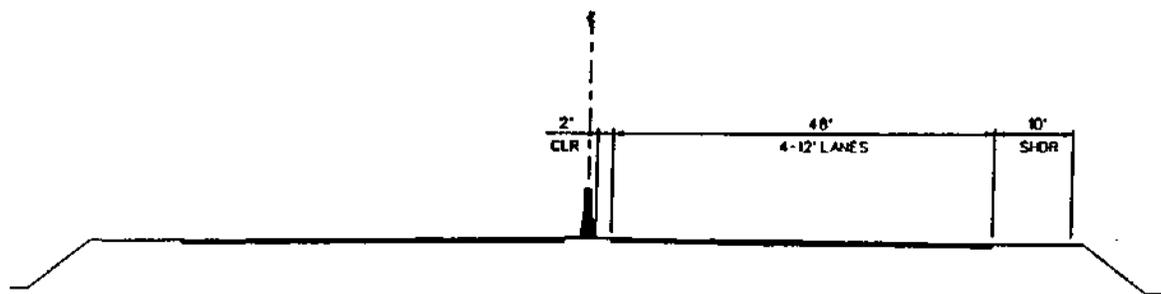
EXISTING
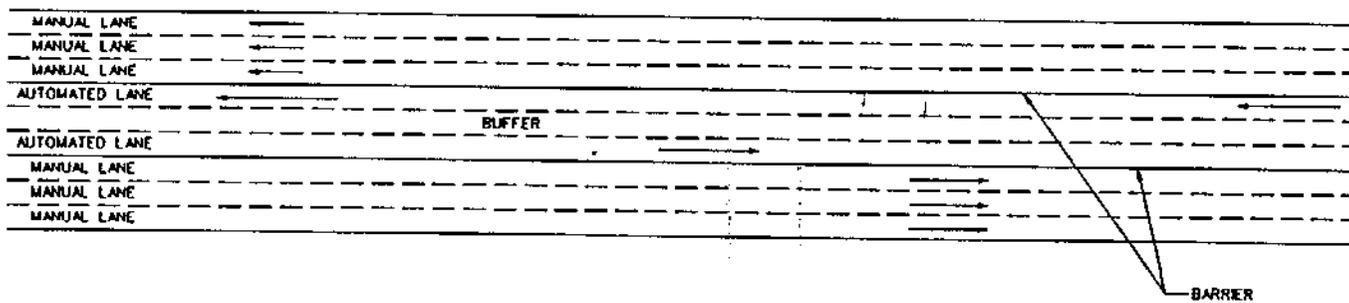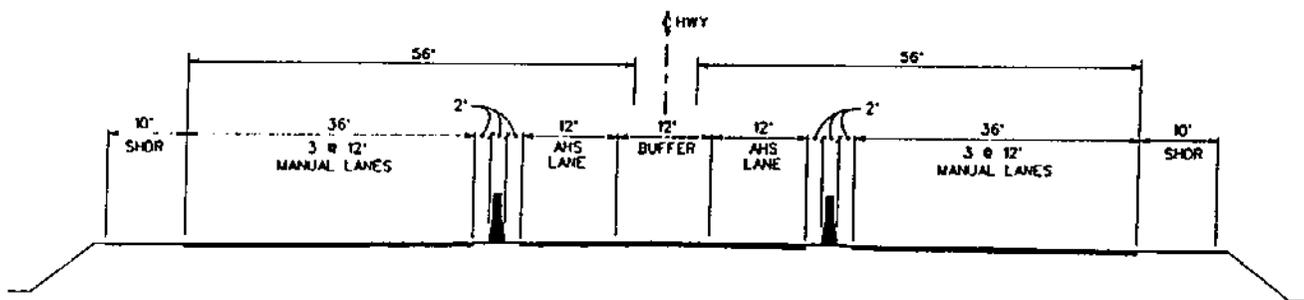
Figure 6-9. Median Separation - Buffer.

breakdown lane (shoulder), adjacent to high speed automated vehicles traveling in the opposite direction. The second configuration, shown in Figure 6-10, would provide one continuous breakdown lane that could be used alternatively by the two opposing directions of traffic, while still maintaining a physical barrier between them. For example, such a breakdown lane could serve one direction for about 1,000 to 2,000 feet, then would transition and serve the other direction for the next 1,000 or 2,000 feet.

6.3.4   Throughput

A goal of the AHS system is to increase highway system throughput. Throughput can be influenced or constrained by different design parameters and the physical geometrics of the system. Interchange spacing and ramp configuration are the primary design parameters that affect geometrics. For example, on- and off-ramps shared by AHS and manual vehicles, where AHS-equipped vehicles must weave through manual lanes to get to dedicated AHS lane(s), will require sufficient distance to accomplish the weaving maneuver without degrading the throughput of the manual traffic operation. In urban applications, where both AHS and manual traffic volumes are high, and where highway on-ramp spacing is frequent, this can be expected to have a significant negative impact on traffic flow and throughput. In the design process, this can be mitigated by using dedicated on- and off-ramps and thus eliminating the necessity for any weaving maneuvers. However, dedicated on- and off-ramps require additional infrastructure, with a corresponding increase in construction cost.

Throughput will also be influenced by the capability of the system end points to safely and adequately absorb the high volumes of AHS traffic. If sufficient capacity is not provided at these end points, the resulting overflow would backup on the highway proper and degrade the throughput of the system. In Workshop #3, a suggestion was made that AHS traffic monitoring and control operation may need to extend beyond the domain of the highway to include and integrate traffic monitoring and control with the adjacent local arterial and city street network. This combined monitoring and control activity could be accommodated at a regional Traffic Management Center (TMC).

Throughput will also be impacted by the entry/exit protocols that will be set up to allow AHS-equipped vehicles to merge into/or exit from AHS-dedicated lanes. Such protocols will depend on the AHS technology finally selected.

EXISTING

LOCATION OF
BARRIER VARIES

L - TO BE DETERMINED

MANUAL LANE
MANUAL LANE
MANUAL LANE
AUTOMATED LANE
AUTOMATED LANE
MANUAL LANE
MANUAL LANE
MANUAL LANE

BREAKDOWN AREA
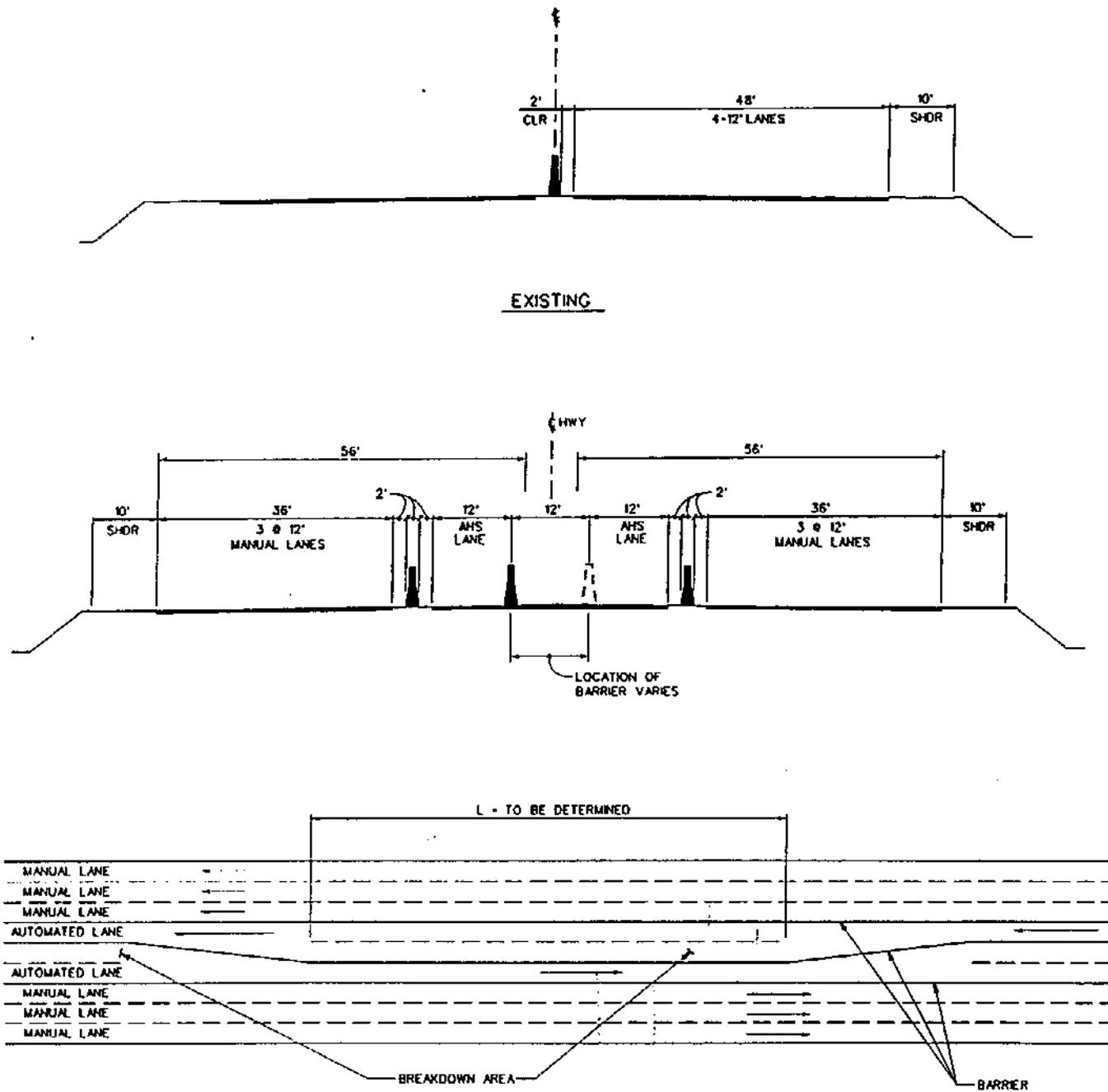
BARRIER

Figure 6-10. Median Separation - Variable Barrier.

6.3.5 Highway-to-Highway Interchanges

Interchange capacity is typically a constraining factor in system throughput, particularly interchanges connecting two intersecting controlled-access highways. There are several alternative general configurations for highway-to-highway interchanges. The first configuration can be used with low traffic volumes on both highways, such as in rural applications. AHS vehicles would exit the dedicated lane through a transition lane, revert to manual control, weave their way through manual traffic, and use existing interchange ramps to make the desired turn. Once on the desired highway route, AHS vehicles would again weave through manual traffic and rejoin the dedicated AHS lane(s) by going through another set of transition lanes.

The second configuration would also use manual connecting ramps at regional interchanges, but would eliminate the weaving maneuvers. This is achieved by using a flyover from the AHS lane(s), going to the right side of the manual lanes, reverting to manual control, and then merging with the manual turning traffic and using the common connecting ramps of the regional interchange to reach the desired direction on the crossing highway. Once on the crossing highway, a reverse maneuver would position AHS vehicles to return to automated control and then join the AHS dedicated lane(s). A schematic of this configuration is shown in Figure 6-11.

The third configuration would be to construct a new set of ramps for the exclusive use of AHS traffic, which would directly connect the two crossing highways. This would provide the highest level of service but at the expense of higher construction and ROW acquisition cost. Specific decisions on what type of configurations to be used at intersecting highways will likely be made at the state or local level, in much the same manner as dedicated HOV interchange lanes.

To help visualize this third configuration, a typical existing highway-to-highway interchange is shown in Figure 6-12. Another set of ramps would be added to this interchange to accommodate the AHS movements required to connect two crossing highways. The result is a six-level regional interchange as shown in Figure 6-13. A possible alternative configuration to reduce this height is the four-level interchange shown in Figure 6-14. The reduction in the height of the interchange is compensated for by a significant increase in additional ROW acquisition.

Figure 6-15 shows a fourth configuration that avoids the conflict of manual ramps and AHS-dedicated ramps at the same interchange. This could be accomplished by using one interchange for the manual ramp connections and a new separate interchange to accommodate the AHS-dedicated ramp connections. This would require a new interchange and new ROW and ramp connections between the new interchange and the existing cross highway.

AHS
AHS
MANUAL
MANUAL
MANUAL

AHS

AHS

MANUAL

AHS
AHS
MANUAL
MANUAL
MANUAL

AHS

MAIN LANE

TURNING RAMP

MIXED TRAFFIC
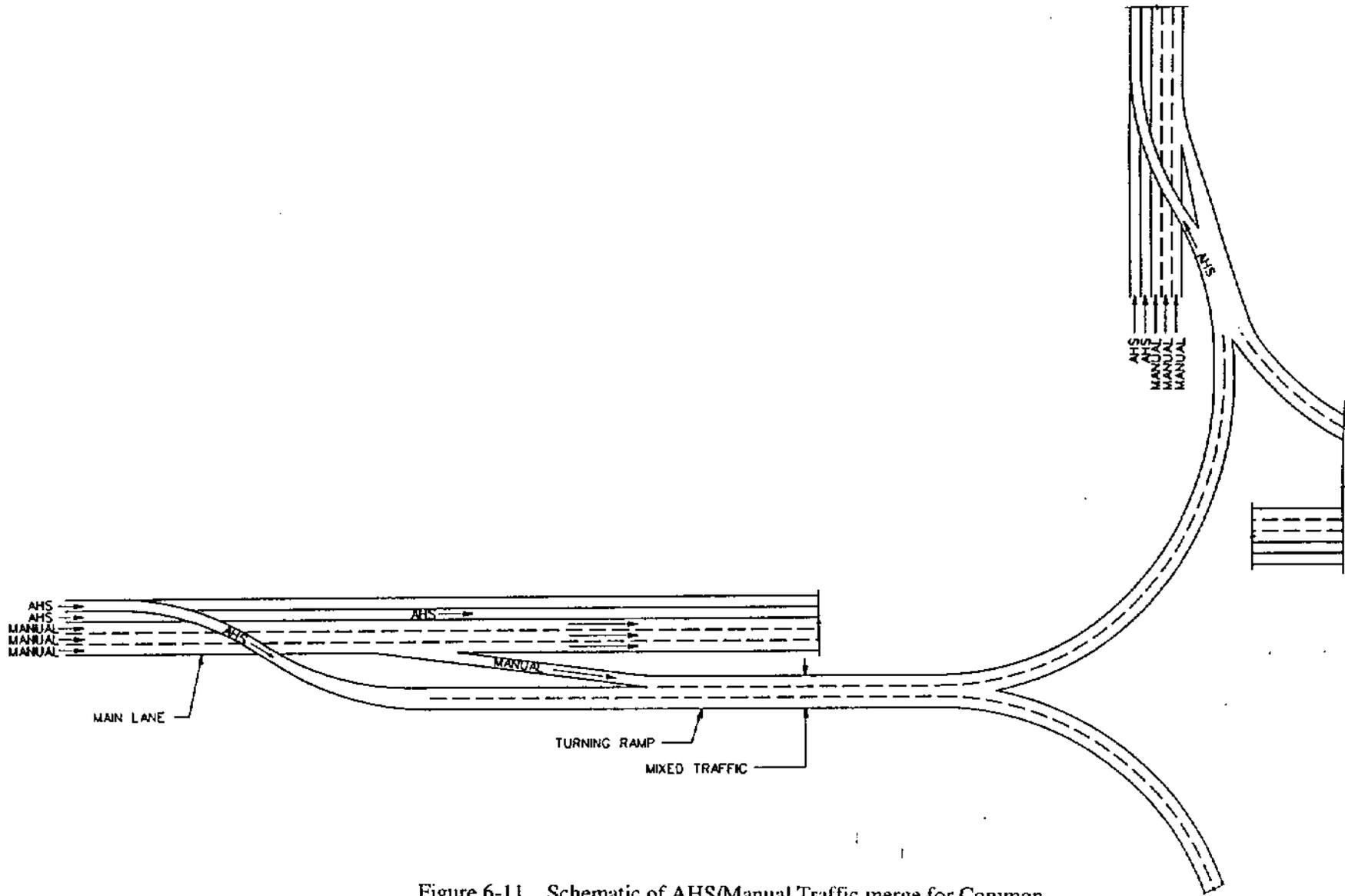
Figure 6-11. Schematic of AHS/Manual Traffic merge for Common
Ramp Connections at Regional Interchange.
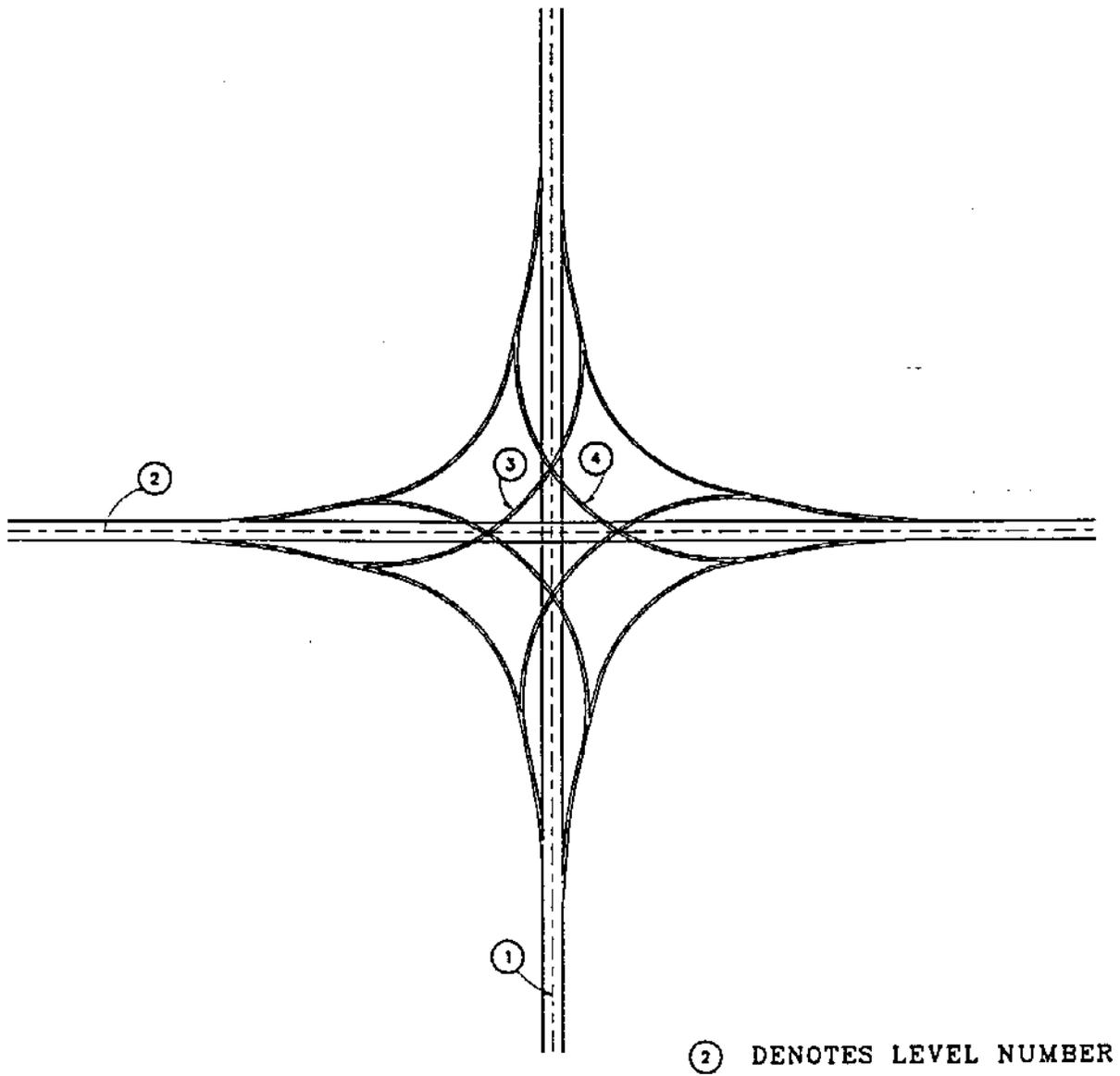
Figure 6-12. Typical Direct Connection Interchange.
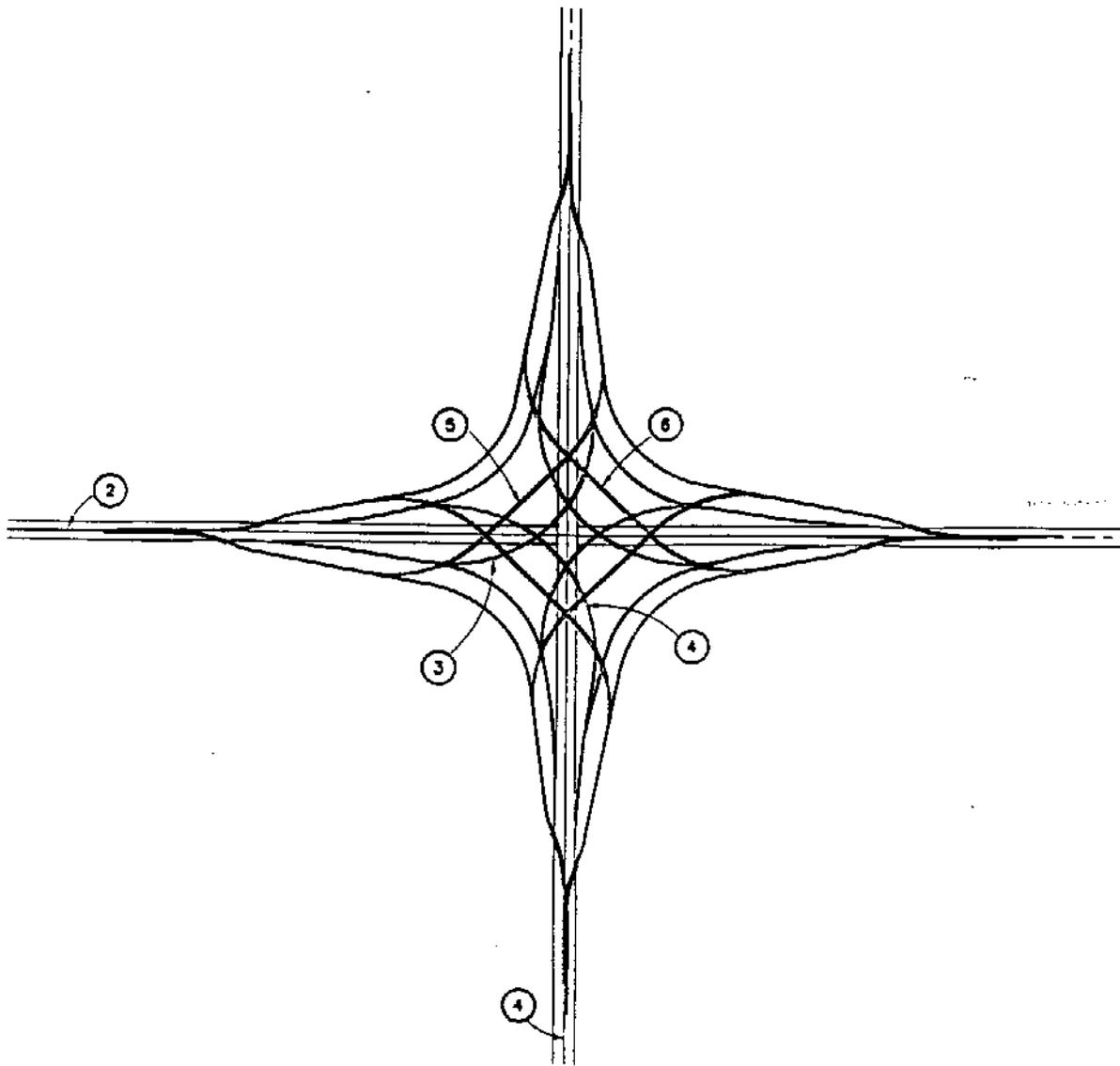
Figure 6-13. Six-Level Regional Interchange.
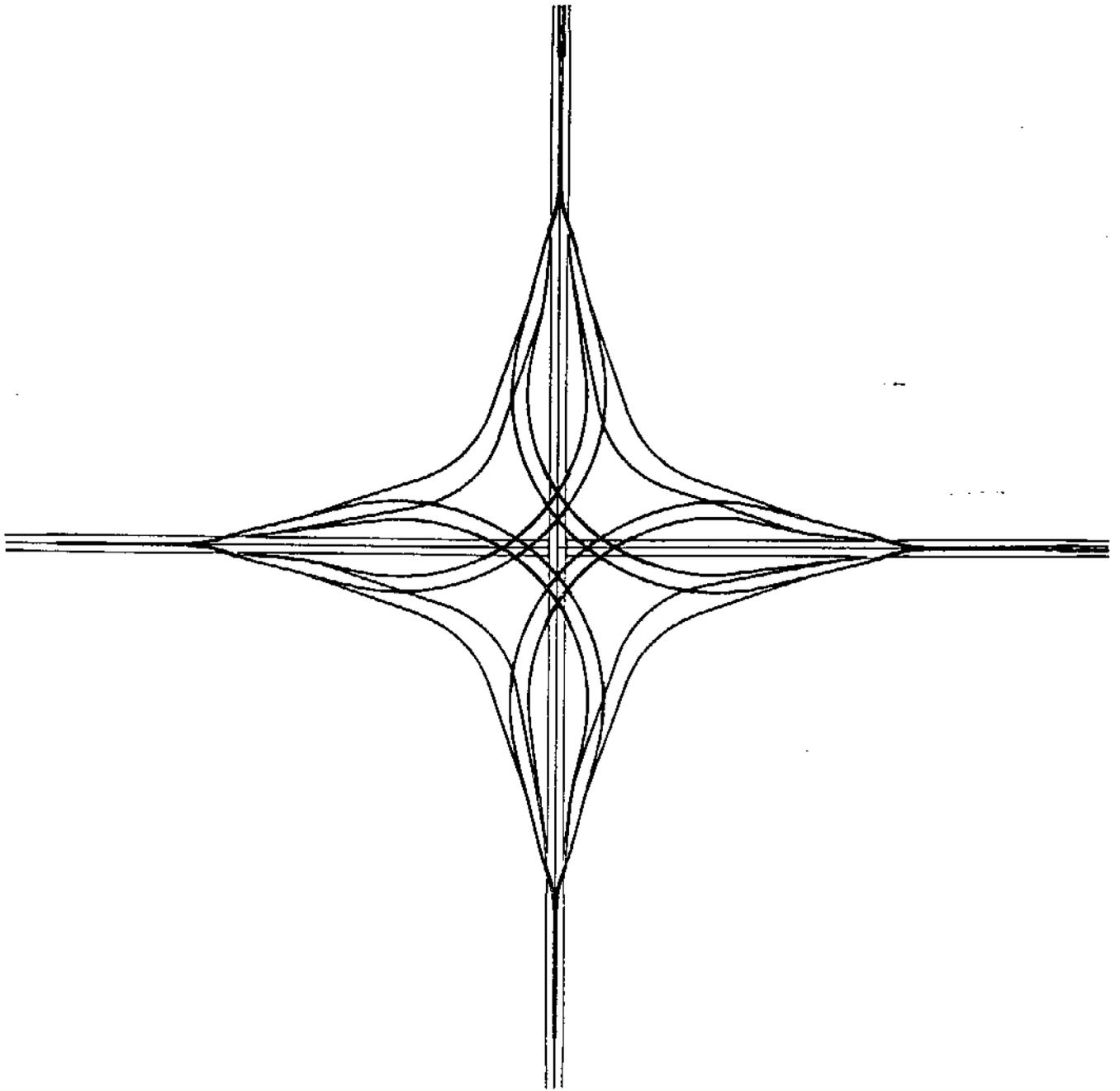
Figure 6-14. Four-Level AHS/Manual Regional Interchange.

AHS EXCLUSIVE INTERCHANGE
(AHS RAMP CONNECTIONS ONLY)

AHS EXCLUSIVE
RAMP CONNECTIONS

MANUAL LANES

MANUAL LANES

REGIONAL INTERCHANGE
(MANUAL RAMP CONNECTIONS ONLY)
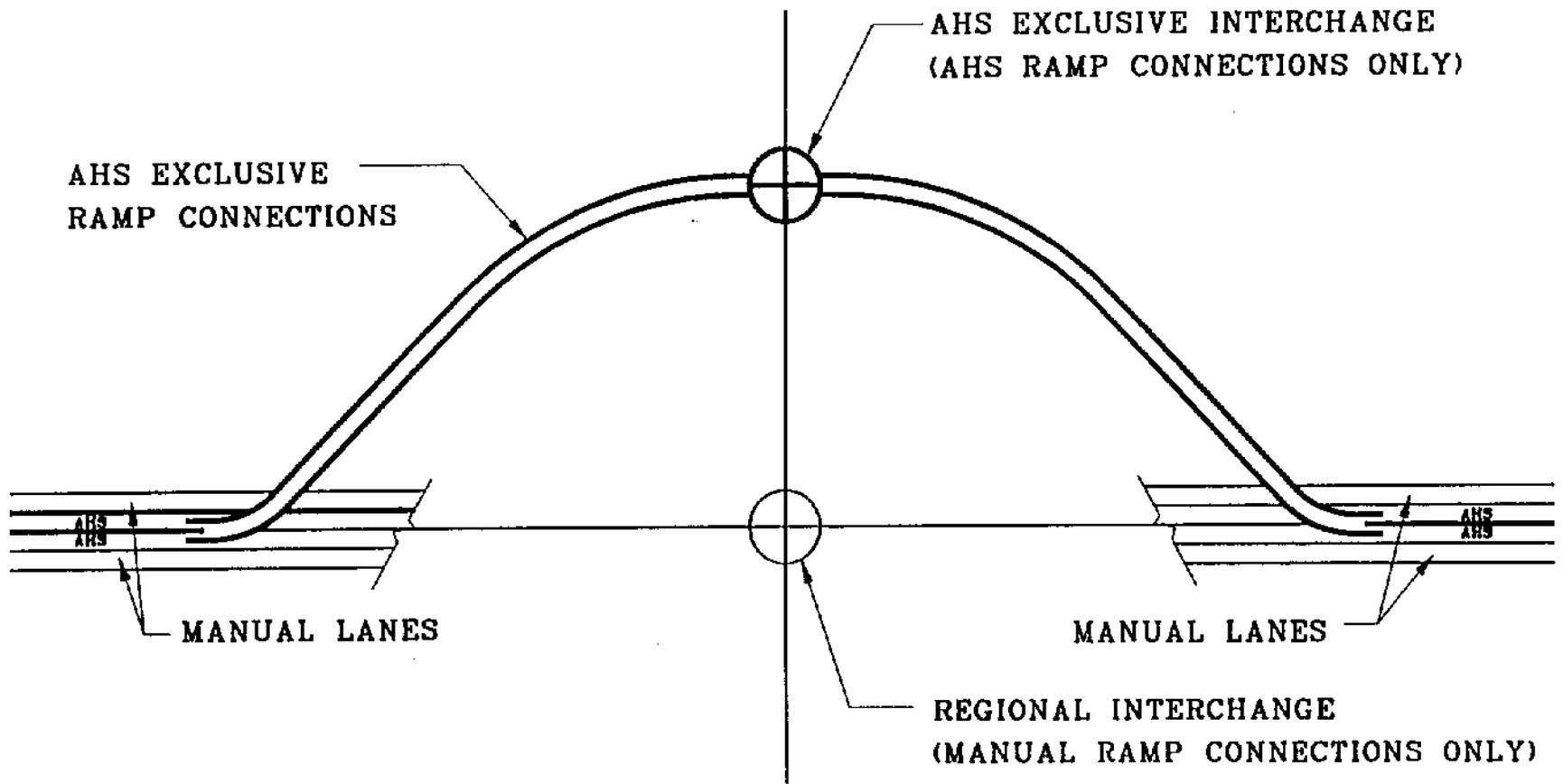
Figure 6-15. AHS Exclusive Regional Interchange.

6.3.6 Other Design Issues

Other issues affecting design include the areas needed to accommodate check-in and check-out procedures as well as storage areas for AHS vehicles that failed such procedures. Depending on the viability of on-the-fly check-in and check-out, there may be a need for a sheltered ramp queuing area. This could require space in addition to that discussed in the above configuration. This issue will require further research and investigation.

6.4   Application Environment

One of the mandates of the AHS is its nationwide application. Highways to which dedicated AHS infrastructure would be added are located in different environments around the country – mainly urban, inter-city, and rural. Each one of these environments would pose a number of challenges that need to be identified and resolved. Although most of these challenges are site-specific and have to be dealt with at the local or the project level, there are a number of common issues, as discussed below.

6.4.1   Urban Applications

Adding dedicated AHS lane(s) to existing urban highways could be a challenging undertaking due to the necessity of interfering with the high levels of "manual" traffic using these highways and the limited availability of ROW that would be needed to accommodate AHS operation. In such a setting, it is natural to try to maximize the use of existing infrastructure as much as possible.

One of the critical issues in the urban application is the way AHS vehicles access dedicated AHS lane(s). One of the configurations discussed in Section 6.2 entails the use of common on- and off-ramps to feed the dedicated AHS lane through a dedicated transition lane. Upon entering the highway, AHS traffic would weave its way through manual lanes to reach the transition lane. A research report by the University of Wisconsin [6-1] indicates that such a configuration would introduce significant disturbances to manual traffic operation and would result in significant deterioration in the level of service and safety of the manual lanes. Related PSA studies also bring up safety questions. Although the viability of such a configuration is questionable in a dense urban environment, it may have limited application in suburban environments. To maintain efficient traffic flow in manual lanes on a densely traveled urban highway, it would be necessary to feed AHS-dedicated lanes through dedicated on- and off-ramps.

An important and still unresolved issue with a dedicated on-ramp configuration is the length of merging lane required to allow AHS vehicles to enter the dedicated AHS lane and join the mainstream of automated AHS operation. The length will be dependent on the technology to be adopted for the AHS system, the manner in which vehicles will operate (i.e., singly or in platoons), classes of vehicles to be permitted to operate on the

dedicated AHS lane, distribution of intelligence between vehicles and roadside, and the protocol that will be used to control vehicles merging into the dedicated AHS lane. All of these parameters are currently undergoing research.

Similar issues will affect the length of exit ramps from the dedicated AHS lane(s). The combined length of merging and demerging lanes will obviously influence the spacing between interchanges serving dedicated AHS operations.

Adequate queuing space at both dedicated on- and off-ramps must also be considered to:

- In the case of on ramps, avoid blocking the arterial network surrounding the AHS highway
- In the case of off-ramps, avoid traffic back-up on the main AHS lane

For a discussion of typical sections in an urban environment see Section 6.2 above.

6.4.2   Inter-City Applications

In applying dedicated AHS operation in an inter-city environment, consideration was given to adding a dedicated AHS lane(s) to existing highway configurations, using existing ramps in common between AHS and manual traffic. It was also postulated that a continuous dedicated transition lane may not be necessary due to the relatively long distance that separates interchanges. A transition lane could occupy a segment of a manual lane at locations where AHS-equipped vehicles shift control to automated operation and are ready to join the dedicated AHS lane. The same configuration could also be adopted for exiting AHS traffic. The typical section, assuming compliance to AASHTO highway design standards, is shown in Figure 6-16. Other alternative configurations will be investigated further as part of future research and development work.

6.4.3   Rural Applications

A similar arrangement to that shown for inter-city application is presented for rural application. The typical section is shown in Figure 6-17. Although this is being used as the typical configuration, alternative configurations are being considered and researched. These include AHS operation in a mixed-traffic mode, with AHS vehicles using basic driver assist functions (i.e., collision avoidance, and "run off the road" warning systems) rather than dedicated lanes.

C/L

73'

| 6' | 12' | | 36' | 10' |
| SHDR | AHS LANE | 2' | 3 @ 12' MANUAL LANES | SHDR |

EXISTING

C/L

79'

| 12' | | 12' | 2' | 36' | 10' |
| ACCESS RAMP | 2' | AHS LANE | | 3 @ 12' MANUAL LANES | SHDR |

**MODIFIED
ADD / AHS LANE
WITH BARRIER**
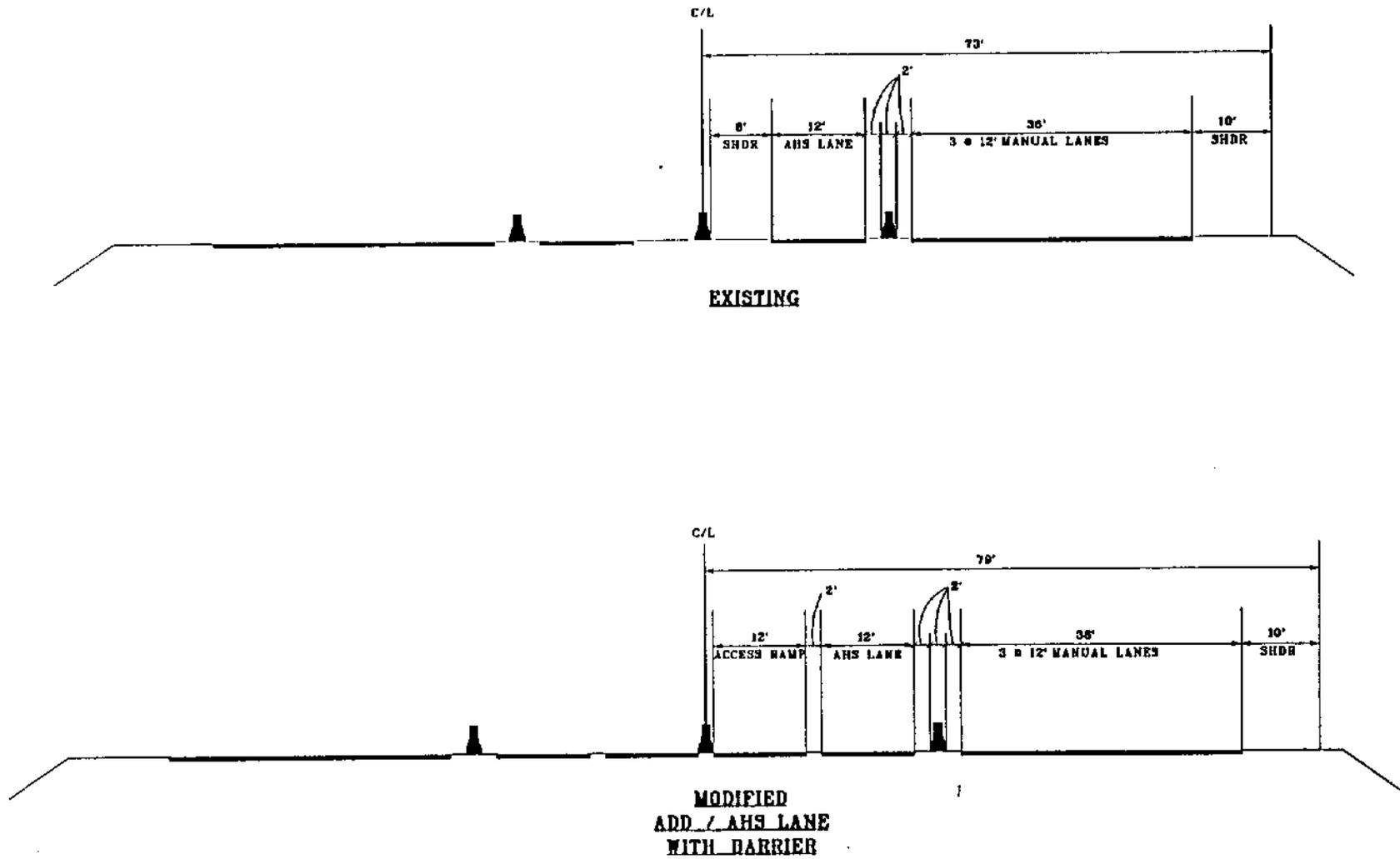
Figure 6-16. Inter-City Application Typical Section.

EXISTING

8'
SHDR

24'
2-12' LANES

8'
SHDR

NO RIGHT OF
WAY REQUIRED

8'
SHDR

12'
AHS LANE

4'

24'
2-12' LANES

10'
SHDR

ASSUME MEDIAN IS WIDE
ENOUGH THAT NO MEDIAN
BARRIER IS REQUIRED
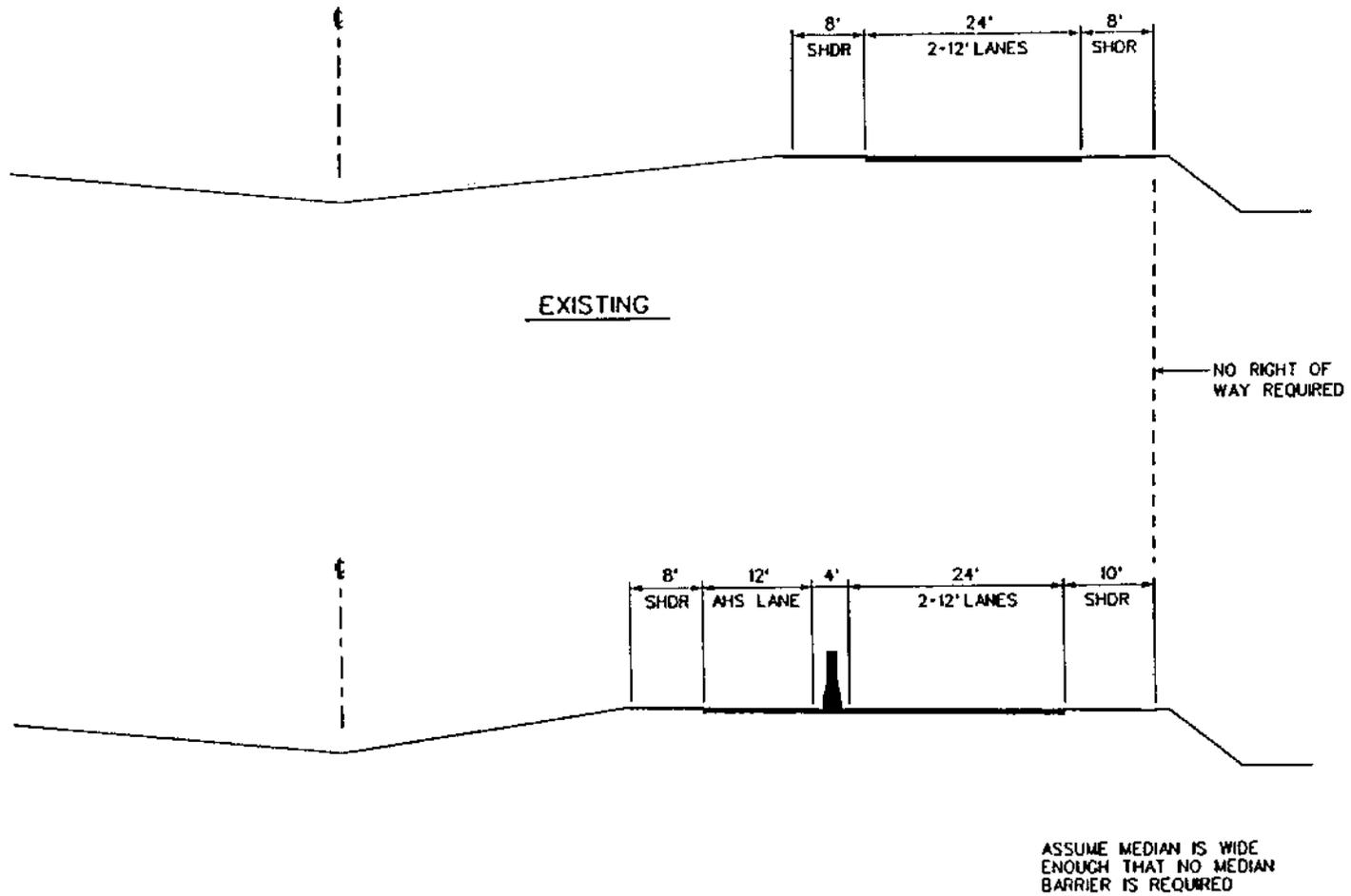
Figure 6-17. Rural Application Typical Section.

6.5   Planning, Deployment, and Financing Issues

In general, it is anticipated that the development cycle for AHS implementation will be similar to that for major public works projects. However, due to the advanced technological content of AHS and its interaction with an existing and mature highway systems, several new issues arise.

One of the issues discussed at Workshop #3 was whether there could be an "acceptable" construction cost of AHS infrastructure per vehicle of throughput. At the Workshop, several people pointed out that there are certain areas where implementation may be necessary regardless of the cost per mile, such as the Boston Central Artery and the Long Island Expressway.

Additional issues for further research and consideration include:

- Existing and predicted future highway demand/supply imbalances
- "Add-a-lane" vs "take-away-a-lane"
- Addition of dedicated AHS lane(s) in the future to accommodate increases in market penetration and demand
- Selective application of exclusive AHS facilities in severely congested urban areas, for transitways, for truckways, etc.
- Negotiating long tunnels, bridges, and viaducts
- Time needed to develop approved AHS standards for infrastructure
- Time needed to plan, approve, design, and build AHS facilities for the various configurations discussed above
- Public/private partnerships for financing and development of AHS projects
- "Acceptable" construction cost of AHS infrastructure considering throughput, safety, and other benefits

These and other issues will be the subject of research and investigation over the next 3 years during work on the next phase of Concept Evaluation (Task C3).

6.6   Conclusions

- Selection of a specific highway configuration for AHS-dedicated operation will have to be decided at the local level, considering a myriad of site-specific issues.

- Existing highway design standards will be modified by experts at the local, state, and federal levels to accommodate the specific characteristics and limitations of the new AHS technology.

- Extensive research and development efforts will be required to study the implications of changes in existing design standards on such areas as cost, safety, throughput, liability, human factors, and constructibility.

- Many of the configuration and design standard issues are dependent on the specific technical characteristics of the selected AHS concept. Such characteristics are still under development.

- Although there are common planning/environmental/implementation issues pertaining to AHS application, many of these issues will have to be resolved at the local level.

- Case studies were suggested as a desirable medium to resolving many of the issues discussed in this section.

7. Mixed-with-Manual-Traffic Operations and Technology Issues

7.1 Introduction

Probably the biggest issue in the definition and deployment of a national AHS is whether the automated vehicles will share the road with manually driven vehicles. If they can, it will avoid common concerns about dedicating lanes or roads exclusively to AHS. One of the reported findings of "Operation Community" in Boston, May 30 through June 6, was, "There will be very few locations where dedicated lane(s) will be available, given the problems of cost, limited rights of way, community impacts, etc."

If feasible, mixing with manual traffic would certainly allow a smooth transition from AVCSS technologies, such as adaptive cruise control, currently being developed for use on ordinary roads. Basically, the argument for mixing automated traffic with manual is that the political, social and implementation issues are critical and can prevent the success of a dedicated system. The argument for dedicated lanes is that the technical issues related to safe operation among unpredictable manual vehicles are not solvable within the foreseeable future.

There are some basic assumptions within which the decision is to be made.

(1)   Fully automated operation will occur only on limited access highways. (While far future systems may support automated operation on surface streets, that is not within the scope of the AHS.)

(2)   Every automated vehicle must be manually operable on non-AHS roads. Automated vehicles must be able to take you door-to-door, and so must be able to operate in a manual mode when appropriate (e.g., on residential streets). In the manual mode, the vehicle should be functionally indistinguishable from vehicles that are always driven manually.

(3)   Full capacity and safety benefits are achieved only when in full automation, with precise coordination and fast reaction. Thus the AHS, when fully developed, does not allow driver control except for navigation and rare failure situations. In particular, even though there are many promising semi-automated vehicle systems that facilitate the path to full automation, they are not AHS.

(4)   The AHS must support at least an option for dedicated lanes. Clearly, dedicated roadways or lanes allow the most control and the most efficiency, and are going to be needed for AHS deployments where congestion relief is a major concern. Thus any solution must be able to evolve to and to support dedicated lanes and highways.

The question is whether there should also be an option for roadways that allow manual and automated vehicles simultaneously, for example, when there is not sufficient market

penetration of automated vehicles to justify a dedicated lane, or where it is not cost-effective to build or convert lanes.

It is the deployment sequencing issue that has generated the most interest in mixed traffic operations. This was especially evident in seven concepts developed under contract by the NAHSC during Task C1. The wish is to facilitate the transition from driver aids such as adaptive cruise control to full automation. Another way to look at the issue is the "chicken and egg" problem of whether the roads will be built first, motivating people to equip their vehicles, or whether the vehicles will be equipped first, motivating communities to instrument roadways to support them. The latter approach will require mixing with manual traffic at least in the early stages.

The other reason for considering mixed traffic operations is that some roadways may never support dedicated automated operation since the traffic volumes do not justify the costs. A truly national system should support these roadways as well.

The following table summarizes the differences between these two approaches to AHS. The conclusion has important implications for many aspects of the AHS.

Table 7-1. Comparison of Mixing With Manual and Dedicated Lanes

	Mixed with manual	Dedicated lanes
Key rationale for the approach	Building dedicated lanes is not acceptable	Safe operation in manual traffic is not technically feasible
What starts deployment	Individual vehicle	Dedicated lane
Throughput benefits	Small throughput increases on all highways	Greatly improved throughput on selected highways
Major challenge	Detection, recognition and avoidance of all hazards	Cost and institutional constraints on lane construction or conversion
How early systems maintain safety	Driver is kept engaged	Tight control of dedicated lanes
Time frame for fully automated operation	Very long term	Long term

It is important to point out that there are two different aspects of mixed operation. The first is as an intermediate stage. This mixed operation is the next deployment step beyond driver aids. It gets the process started when there are few equipped vehicles and roads. This interim solution may be rudimentary, lacking the precision of later systems. It may require the driver to stay alert and respond to emergencies, and thus is not a true AHS. This is often referred to as "pre-AHS" or "partial automation."

The other aspect is the ultimate AHS, or target system. The question here is whether the fully deployed AHS will support both dedicated and mixed traffic lanes. If feasible, supporting both has advantages, because it has low infrastructure cost where a high capacity AHS is not needed, and hence has national applicability. The following focuses on this question, and the mixed traffic system as an intermediate step figures heavily in the driver role and AHS deployment.

7.2   The Role of the Driver

The reason mixed traffic is difficult is that automated and manually driven vehicles have different driving characteristics. Automated vehicles are good at precise control, fast response and consistency. An automated vehicle can follow an appropriately marked lane with much more precision and accuracy than can a human driver, and maintains more accurate and complete knowledge about the surrounding vehicles and possibly the entire highway system. Compared to human reaction times, it responds almost instantly according to plan. Barring failure, these responses are consistent for each occurrence and from vehicle to vehicle. This makes it possible for automated vehicles to anticipate other automated vehicles' actions. Manual drivers, on the other hand, are good at complex tasks such as image interpretation and situation assessment and prediction. A good driver uses subtle clues to decide whether there is an incident ahead, whether another driver may be impaired, whether an animal is about to enter the roadway, whether an obstacle in the roadway is a threat, or whether he or she should merge in front of or behind an adjacent vehicle. While an automated vehicle can respond more precisely to situations that it has been programmed or trained for, the manual driver is better in new situations.

Figure 7-1 below shows a possible growth path for automated vehicle control technology over time. Note that the earliest products are those that provide precise control, while the later ones rely on higher levels of intelligence. Note that there may also be various related warning systems that are not shown here.

The fact that drivers and automated systems excel at different facets of vehicle operation suggests that the best solution may be a combination of driver and computer, with the computer doing the precise and repetitive, and the driver watching for and reacting to the unusual. In fact, as the automated systems improve over the years, they could take over more and more of the driving tasks, making a smooth transition from current AVCSS technologies to fully automated, even driverless, systems, as illustrated in Figure 7-2.

Natural technology development over time

| Speed keeping | Vehicle following | Lane change | General collision avoidance | |
| Lane keeping | Forward collision avoidance | Situation awareness | | General hazard response |

Routine, precise
Easy to automate
Tedious for human

Uncommon, complex
Hard to automate
Easier for human
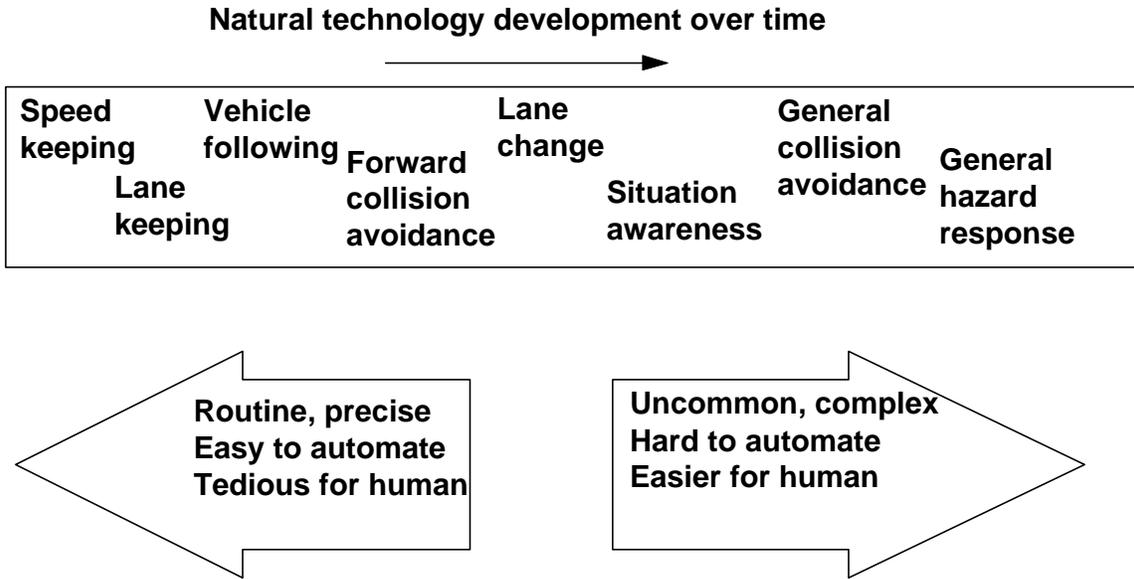
Figure 7-1. Vehicle Control Functions.

Automation

Driver

Manual   Driving aids   Partial automation   Fully automated

time
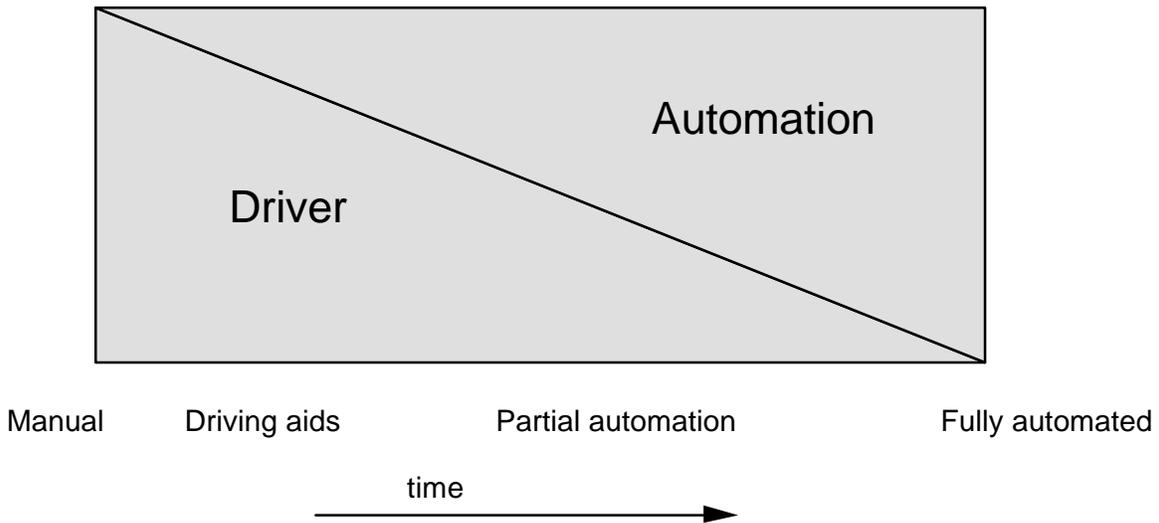
Figure 7-2. The Ideal Evolution from Fully Manual to Fully Automated.

This path, if feasible, would make a gradual transition into the automated highway.
Driving aids, such as lane departure warning or collision warning devices, are currently
being developed. As the technology advances, these could be extended to maintain the
lane and safe spacing automatically. As obstacle detection and avoidance mature,
automation could take over those tasks, until finally a fully automated vehicle would
emerge, driving, as it has been all along, mixed with manual vehicles. As the number of
such vehicles increases, dedicated lanes could be implemented for their use. This path is
attractive, starting with automation doing what it does best, and gradually, as technology

matures, taking over more of the tasks that the human does. There has been considerable interest among stakeholders in this path.

The potential problem with this approach is the underlying assumption that the driver will maintain at least the same level of involvement in the tasks he continues to perform. In fact, it may seem intuitive that the driver may concentrate on these tasks even more, since he has been freed of others. However, the tasks that the driver is called on to do are, by their very nature, rare occurrences. This may mean that his/her attentiveness diminishes. He may even fall asleep if he does not need to be actively involved. Even today, drivers are sometimes seen looking at maps, shaving or putting on makeup. One can only surmise what drivers will be doing once automation lets them drive hands off and feet off. There may be a point at which automation has taken over so much of the driving chores that the driver is no longer involved. If that happens before full automation is achieved—including obstacle detection and avoidance—the above chart may actually look like the one below.
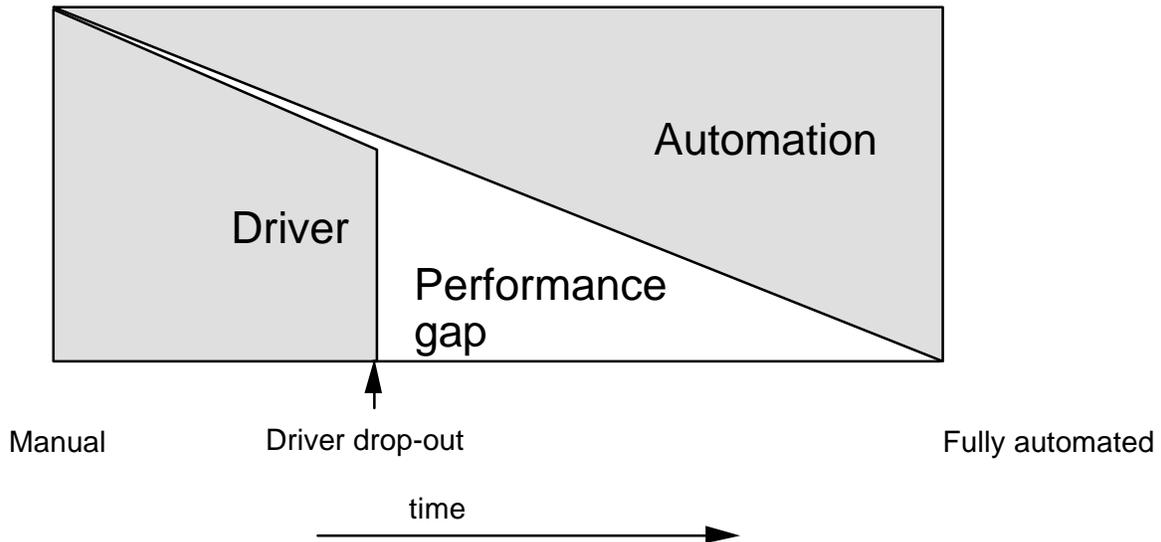
Figure 7-3. The Performance Gap Resulting When Technology Does Not Provide Full Automation, Yet the Driver is Not Kept Involved.

As the vehicle becomes increasingly automated, the driver's attention becomes less focused, possibly even giving less total capability than a manual driver. Worse yet, there may be a point at which the driver "drops out," no longer seeing himself as a part of the driving process, and is essentially unavailable to respond to emergencies or unusual situations. It may be that this occurs once the vehicle takes over second-by-second control of steering, brakes and throttle. Drivers normally do a continual situation assessment of the vehicle, the roadway and the surrounding vehicles. This important function, which is very difficult to automate, will not get done.

Thomas Plocher of Honeywell cites analogous studies in which tasks were automated, leading to low vigilance by the operators. He concluded, "In general, such automated

environments appear to create conditions of boredom and monotony. Such conditions facilitate habituation to stimuli in the environment, decrease arousal, and degrade performance." [7-2]

Whether or not this driver drop-out occurs, and at what point of automation, is an important issue for both mixed and dedicated approaches. It means that rather than a smooth transition, there is a point at which the very nature of the system changes abruptly. The drop-out point will likely vary from driver to driver, but the system changes at the point of automation at which it can no longer rely on the driver in general, and must provide protection for any contingency.

The consensus among NAHSC members at this time is that driver drop-out will occur when brake, accelerator and steering are automated (and possibly even before). In other words, hands-off, feet-off implies brain-off. This hypothesis is based in part on limited simulator studies, in which driving was automated for a time, and then drivers saw a warning sign and had to merge manually. Even though they had been told to watch for such situations, some of the drivers dozed off. One performed a panic maneuver in the merge that would have been dangerous in a real car. Despite issues of the validity of simulator studies in safety situations and the small sample size, it does indicate that the human driver is not to be relied upon for reaction to unusual situations, if the basic driving tasks are taken from him. Human factors research confirms this (see Section 4.5.5). This also makes sense intuitively, since it is harder to stay alert on a straight, flat country road in which little driving activity is needed. The implication is that it is not safe to provide the public with fully automated lane and distance keeping without also providing some provision for responding to anomalies, such as obstacles and merges. While these constitute a very small percentage of driving activities, they contribute to the vast majority of safety risks. So while in one sense we are "almost there" with lane and headway keeping, in another sense we are far from there. The further implication is that rather than a smooth shift of duties from the driver to the automated system, there are two very distinct systems -- one in which the driver will and must remain alert ("pre-AHS"), and the other in which it is safe for the driver to disengage himself (full AHS).

The closing of the gap comes from two directions. The first is to keep the driver involved. One way is to operate using trained and alerted drivers in all vehicles until full automation of all functions is possible. This is what is being done now in automated vehicle research. The driver keeps his hands inches from the wheel, ready to take over at a moment's notice. This is not a viable long-term option for widespread use. The driver may also be kept involved by the sharing of control with him. Research needs to be done on how this might be performed and whether it is more or less stressful than conventional driving. One promising possibility is to add resistance to driver actions that are inappropriate, while allowing the driver to override this if necessary. Similarly, the driver may be given some of the routine tasks to perform, while others are automated. For example, pre-AHS systems would include adaptive cruise control but only lane departure warning, so that the driver would need to steer.

The other means of closing the gap is to expedite research in the automation of these non-routine functions. The first step is the cataloging of anomalous driving behavior. There is little data or research in this area, especially in potentially hazardous actions that other drivers react to naturally and safely. Thus at this point it is not possible to say whether the automation of these tasks is easy or infeasible. Task C3 will explore this further.

An alternative solution is to control the environment to minimize the gap between manual and automated, for example by preventing obstacles and precluding manually driven vehicles. This requires a dedicated lane. There are feasibility issues to this solution, as well, as discussed above.

7.3   Mixing Options

Mixed traffic is not an all-or-nothing choice. Following are some of the options. The last two are dedicated lane options and are included to complete the continuum.

7.3.1   Automated Vehicles Mix with Manual on Any Major Roadway

In this case, automated vehicles are designed to operate on any well-maintained limited-access highway along with ordinary traffic. There are no requirements for road maintenance above and beyond those for ordinary traffic, nor does the road need any additional equipment. Some technology exists to support such vehicles. For example, sensors exist to follow roadway striping. The automated vehicles may have additional capabilities to sense the actions of manual vehicles, say, through detecting brake lights.

7.3.2   Automated Vehicles Mix with Manual on Some Roadways

The operation of the automated vehicles may be enhanced by minor improvements to the infrastructure, such as special lane markings or digital broadcasts. Such changes to the roadway will be transparent to the motoring public, who will continue to use these roads. In this situation, the automated vehicles will operate only on the improved roads along with manual traffic.

7.3.3   Automated Vehicles Mix with Manual Only When Following a Lead Vehicle with an Engaged Driver

A promising option for starting AHS deployment is to equip commercial and transit vehicles first, since their heavy use makes even early, expensive systems cost-effective. A by-product of this approach is the opportunity to form convoys of vehicles belonging to the same fleet. For example, a trucking company may send out its trucks in groups that form into platoons. The lead driver stays alert while the others rest, and they trade off at intervals. This may be an intermediate stage before fully disengaged driving is safe.

7.3.4   Automated Vehicles Mix with Manually Driven Vehicles That Have Been Suitably Equipped

There may be simple modifications to manual vehicles that make them easier to deal with automatically, such as an electronic tag, or electronic signals linked to brake and signal lights. Some roads will be designated as automated highways, and will be restricted to the use of automated vehicles and suitably equipped manual vehicles. All other roads will be available only to manual vehicles. For example, enhanced toll tag transponders could send such information as position, velocity, acceleration and desired exit to the automated vehicles. Even passive electronic markers on vehicles could facilitate detection.

7.3.5 Automated Vehicles Operate Only on Designated Lanes, and Mix with Manual Only During Failures

This is the least strict of the dedicated lane cases. The vehicles are designed for fully automated operation only on dedicated lanes; they optimize their performance by coordination with other automated vehicles in the vicinity. If, however, a manual vehicle inadvertently ends up on the dedicated lane, for example as a rogue vehicle, a failed automated vehicle, or a spill-over from an incident on an adjacent manual lane, the automated vehicles are equipped to recognize it as a problem and to deal with it safely (though possibly with degraded highway performance).

7.3.6 Automated Vehicles Operate Only on Lanes That Are Strictly Controlled to Exclude Manual Vehicles

The automated vehicles are again designed to operate only on dedicated lanes. The automated highway ensures that no manual vehicles may enter, through strict controls such as check-in and barriers. Physical features may also be in place to exclude obstacles. This is a strict dedicated lane.

7.4 Progressive Deployment

One major impetus for considering mixed with manual is its heavy use in the seven concepts that were developed under contract to the NAHSC. Each of these concepts put great emphasis on progressive deployment, more than the NAHSC had been considering previously. In many of these, the deployment path includes a phase in which automated vehicles are traveling mixed with manual traffic. Since then, the stakeholders have repeatedly urged the NAHSC to consider mixed lanes as an intermediate step.

The premise driving a deployment via mixed traffic is that the institutional issues are hard: technology needs to make AHS generally applicable. The sequence is to build vehicles first based on AVCSS, automate when feasible, and dedicate lanes when there is enough demand and this represents a cost-effective solution to local transportation problems. This allows all roads to be used by automated vehicles, but probably not as early as a dedicated lane deployment.

The premise behind a dedicated lane deployment is that the technical issues are hard: institutions need to help simplify the problem. The sequence is to build the lanes first, next equip high-payoff and trial vehicles, and then assume growth through driver demand. This provides earlier full automation, but on only a few roads.

7.4.1   Progressive Deployment for Mixed with Manual

By deploying vehicles that can operate mixed with manual traffic, the AHS would evolve gradually as the number of automated vehicles increases. This would not initially require any changes to infrastructure. As the market penetration increases, automated vehicles would be prevalent enough to dedicate lanes to them, giving efficient operation where needed. On the other hand, the automated vehicles could use any limited-access highway.

This would be a market-driven deployment. Consumer demand for the automated vehicles that can be driven anywhere would spur the vehicle manufacturers to produce them and after-market companies to provide add-on systems, assuming that the additional benefits would be sufficient to justify the higher costs. The last step would be the dedication of lanes to take advantage of the existing vehicles.

The process would start with pre-AHS driver aids such as adaptive cruise control, lane departure warning and collision warning. The motivation would be individual safety (sensing and warning systems) and convenience (ACC). While the driver would remain engaged, these systems would help him to get comfortable with and trust automated control. When obstacle detection and avoidance is mature enough that the driver can disengage, fully automated vehicles would be produced, built on these precursors.

7.4.2   Progressive Deployment for Dedicated Lanes

The dedicated-lane AHS deployment would be moved along by the building or conversion of roadways, with vehicles being equipped in order to use these roads. While the mixed deployment is market-driven, this is infrastructure-driven. The initial lanes would of necessity be sparse, only the vehicle owners that use the equipped corridors would be motivated to equip their vehicles. Hence, initial vehicle deployments may need to be subsidized.

7.4.3   Progressive Deployment from Dedicated Lanes to Mixed

A hybrid solution is based on the reasonable assumption that designing a vehicle to operate in mixed traffic is technically more difficult than designing one for dedicated lanes. Yet there are benefits from the ability to mix with manual traffic, especially in rural areas that may never get dedicated lanes. This approach would start with dedicated lanes, initially highly controlled commensurate with the early level of technology and limiting the situations that it does not handle well. As the vehicle increases its repertoire in response to situations, the controls would be eased. Each stage would serve as a

testbed for the next, until a fully automated vehicle would be able to operate intermixed with manual vehicles.

7.5   Safety

7.5.1   Background

A fully automated vehicle in mixed traffic must react, without driver assistance, to any emergency. Debris will fall off other vehicles and other drivers will drive erratically. The system cannot control the actions of these other drivers, and in fact such actions are difficult to predict. One reason is that there is a wide range of driver conditions, skill, and style. There are elderly, inexperienced, drunk or aggressive drivers, among many other characteristics. Normal driver response patterns are difficult to emulate, and in some cases, such as reaction time, should not be emulated. What makes it difficult is that automation development tends to focus on correcting what drivers do wrong, but there is much that they do right, especially in unusual situations. To be credible the automated system must do at least as well.

The real issue is what the system must handle. There are certainly highway situations from which no safe response is possible by man or machine. There are other situations that are so rare that it is not reasonable to address them.

One question is whether the AHS can or must do everything better than the human driver. There are undoubtedly unusual situations in which the human could respond better than the automated system. Some "obvious" hazards are hard to recognize automatically, for example, a deer standing by the road, possibly ready to dart into traffic. Some "obvious" non-hazards may cause a hazard response, for example, a mylar balloon may look large and solid to a radar. This may cause a hazard response which is annoying at best and dangerous at worst. If the system does not respond properly to something that "any driver could handle" there is a loss of credibility and possible legal liability.

This indicates that there may need to be higher requirements for response to situations that are easy for a human driver. Some of the stakeholders in Workshop #3, however, agreed that if overall statistical safety was better for the automated system than for the purely manual one, that would be sufficient. Automation promises to reduce or eliminate the 60 to 90% of all crashes caused by human error, so that says that overall safety improvement is potentially achievable without improvement under every possible condition.

The safety question centers on a model of both normal and anomalous driving behavior. Driving behavior is not well understood, other than as averages such as spacing and speed, and as inferred from accident statistics. The major task of the NAHSC's Mixed With Manual team in Task C3 will be research into the various potentially hazardous driver actions, and automated responses to them.

In particular, a feasible response to each hazardous situation will need to be developed. This response may not emulate the response of the human driver, who relies heavily on higher intelligence. The automated vehicle may have a strong sensing capability but weak interpretive capability, and so the response will need to take full advantage of sensors that never blink, fast communications and fast response. Task C3 will determine whether these capabilities will be sufficient to respond safely to each individual safety threat, without benefit of higher level intelligence.

7.5.2 System Malfunction

A dedicated lane has the potential to build in redundancy between the vehicles and the infrastructure to keep the system safe during a malfunction. A system that allows fully automated operation in mixed traffic could rely on the infrastructure but this would require an investment by the infrastructure operating agencies. A more sophisticated vehicle-based system would not necessarily rely on the infrastructure. Such a system could revert to manual control (individual vehicles or all vehicles), in response to malfunctions under certain conditions that would not jeopardize safety.

7.5.3 External Hazards

The safety task is greatly simplified in dedicated lanes. This is because many potential obstacles can be excluded, including external hazards introduced by the presence of manual vehicles, including those vehicles themselves.

The challenge is to maintain safe spacing relative to the surrounding vehicles, which requires knowledge of those vehicles and what they might or might not do. In the dedicated lane there is a limited and well-understood set of maneuvers. Barring failure, there is predictability about the actions that the other vehicles will take. It is easier to coordinate maneuvers, since the response characteristics of the vehicles are homogeneous.

Introducing manual vehicles means that there are two categories of vehicles with essentially different characteristics. The manual vehicles have slow responses, do not operate consistently and do not follow protocol or system commands. The automated vehicles may also pose problems for the human drivers, who base their driving on their own predictions of the actions of other humans. In particular, they do not have the reaction time to cope with following an automated vehicle that is braking hard and fast. They are also used to sending subtle signals to other drivers that the automated vehicles may not pick up, and so may make dangerous maneuvers after "requesting" a lane change.

Since the human driver is unpredictable, we must assume with a human in the loop that anything the vehicle is physically capable of doing will occur, and so responses need to be included. On the other hand, an automated vehicle can fail, so we need to make the same assumption about the automated vehicle on a dedicated lane for potential failures. The

difference is one of degree; some hazards of concern in a mixed traffic situation may be rare enough to be ignored on a dedicated lane.

Humans will take many inappropriate actions. These are common enough that the system needs to be designed to respond safely. For example, they may change lanes into a blind spot, not react quickly enough, block view of an obstacle by delaying a lane change, stop suddenly or cut off traffic to make an exit, or suddenly abort a maneuver. Unfortunately, this is all based on anecdotal information; there is little or no statistical data on erratic driving behavior. The vehicles themselves are also unpredictable, since they have not undergone check-in and so may fail, lose components, or drop parts or loads.

Humans are also very adaptable. They may try to "game" the system if they see an advantage to manipulating the programmed responses. Or they may become complacent, overly relying on the surrounding vehicles. They may copy the tight spacing that they see, even though they cannot react as quickly. In any case, driving behavior is expected to change as a result of driving for repeated periods among large numbers of automated vehicles. This will certainly have an impact on safety, but currently the effects cannot be predicted.

7.5.3.1 General Safety Concerns

Any automated highway must respond to roadway hazards. Obstacles cannot be entirely eliminated, although dedicated lanes may included provisions to make them less likely. While many of these hazards will show up on any AHS, using a dedicated lane can mitigate much of this. Hazard response may require coordination with other vehicles. The obstacle avoidance analysis discussed in 4.2 showed that there is a benefit in being able to coordinate a lane change to avoid a road hazard. Dedicated lanes could ensure that all vehicles in the area are similarly automated.

Rogue vehicles are unauthorized manual vehicles on the automated lane. This may occur from a driver sneaking onto the automated lane, an incursion from an adjacent manual lane or an automated vehicle that fails on the highway. In any case, they cannot be completely prevented. Unless they are driving erratically, they are not a problem for a mixed traffic system, since such a system would be designed to operate with manual traffic. In a dedicated-lane system, this would require the system to increase vehicle spacings around the rogue, reducing throughput to levels comparable to the mixed traffic system.

7.5.4 National Safety

Mixing with manual leverages the safety benefits of the Automated Highway, since all limited-access roads can presumably be used by automated vehicles. Of particular

importance are rural roads, because of their disproportionate share of traffic fatalities. So even though automated vehicles will have higher safety levels on dedicated lanes, the safety of those vehicles can also be improved during their use in mixed traffic on non-dedicated lanes. At least in the early stages, dedicated roadways would constitute only a small part of all roadways.

7.6   Roadway Capacity

7.6.1   Capacity Implications of Mixing with Manual

In general, manual drivers maintain only 60% of the safe following distance. This suggests that the following distance of an automated vehicle behind a manual one may be larger than that between two manual vehicles, although the difference may be negated by the automated vehicle's superior response times. This is an issue for AHS because if the spacing does increase, the overall roadway capacity will actually decrease with low market penetrations of automated vehicles. This issue deserves careful analysis since some of the roadways that are promising for AHS are exactly those that are already over capacity. An additional issue is the effect of the presence of automated vehicles on the driving behavior of people sharing the lanes. This may cause changes in separation between manual vehicles as well.

Figure 7-4 is based on a simple capacity analysis from some preliminary assumptions; very little is known at this time about following behavior in mixed traffic. While the actual numbers will change as more is known, some conclusions can be drawn based on the shape of the curve. The assumptions were that the manual vehicles would maintain spacing to average 1600 vehicles per lane per hour, based on UMTRI data. [7-1] Presumably, they cannot tell an automated vehicle from a manual one, and so will maintain this same spacing with any vehicle. The automated vehicles are assumed to be able to communicate extensively with each other so that they can synchronize braking, and will maintain the minimum safe spacing based on their respective braking capabilities. It is also assumed that the average spacing will be 25% more to account for entries, exits and lane changes. The automated vehicles will not platoon. Since the automated vehicles communicate with each other, they will know when they are behind or in front of a manual vehicle. It is assumed that an automated vehicle will leave an additional half second of spacing when following a manual vehicle to allow time to track it and predict its movement.

The chart below shows the results for a 67 mph case on a five lane road. It shows the effect on capacity as the proportion of vehicles on the road that are automated increases. This static model does not account for turbulence associated with merging and weaving maneuvers. Future work will study the effect of turbulence, and whether inserting automated vehicles into manual traffic helps to damp out fluctuations, or whether mixing two very different kinds of vehicles increases traffic instability.

Based on these assumptions, there is no drop in throughput as automated vehicles are introduced. This is because the average spacing does not increase. However, a more complete analysis would consider the turbulence effects due to the fact that traffic is neither steady nor uniform. Also, a similar analysis reported in Section 4.1 showed an initial drop in capacity if the automated vehicles could not communicate with each other.
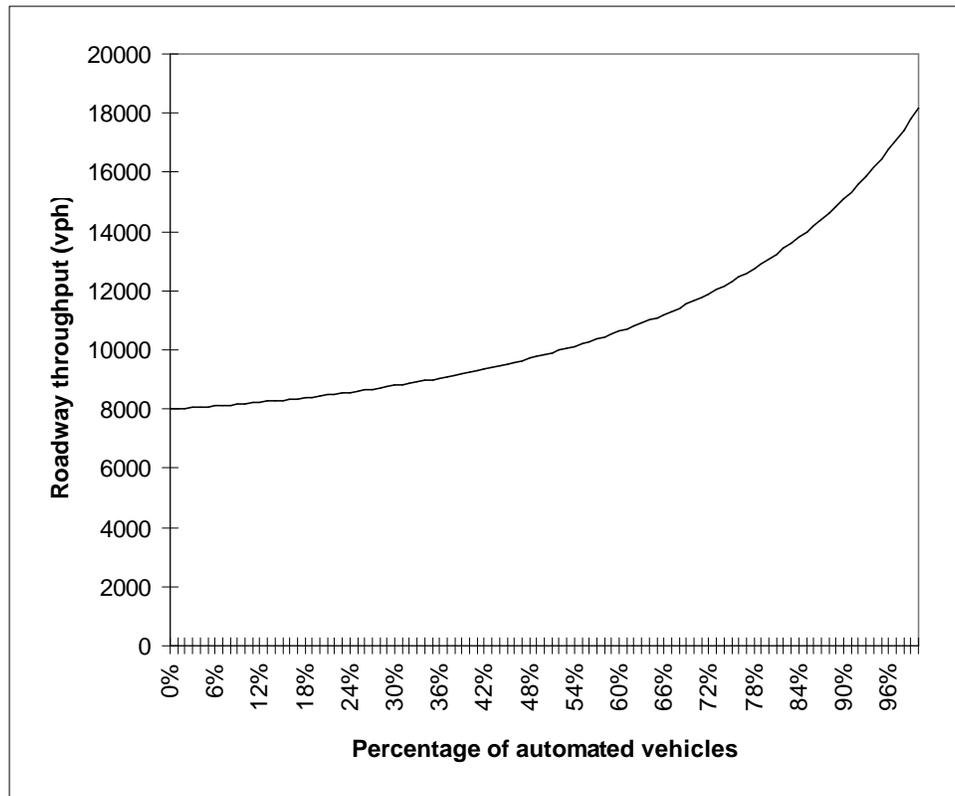
Figure 7-4. Five-Lane Mixed-Traffic Roadway Capacity as a Function of
Market Penetration of Automated Vehicles.

In any case, the increase in throughput starts out slowly. Even with 50% local market penetration there is little improvement in capacity. This says that throughput requirements on mixed systems must be conservative. On the other hand, small improvements in throughput may be sufficient to ease congestion in some locations and may be sufficient motivator for communities to support automated vehicles. The exact magnitudes of these improvements are preliminary pending more definitive data.

7.6.2 System Throughput

Throughput needs to be looked at in a broad context, rather than focusing on a single lane, as in analysis of an initial dedicated lane. Once the automated vehicles are sophisticated and prevalent enough to improve throughput, there is a difference in the mixed and dedicated cases as to how the improvement is distributed. The dedicated lanes concentrate the throughput improvement in those lanes. The expected dramatic improvements in throughput will attract traffic and strain the roads that interface with the lanes. The mixed case distributes more modest throughput improvements over the area, possibly enough to relieve congestion.

The other consideration is throughput per highway width. Because the limiting factor in many congested urban areas is available right-of-way, the object is not to increase throughput per lane, but overall throughput. For example, the "independent" plot in Figure 7-5 shows the throughput achievable on a roadway in which there may be dedicated, but no mixed lanes and in which the vehicles operate as in the previous section. Specifically, it is assumed that automated vehicles may travel on the manual lanes in manual mode, but manual vehicles may not travel on the automated lanes, and in fact the automated vehicles will choose a manual lane if the automated lanes are operating at full capacity. It is also assumed in this example that this is a five lane roadway as above, but that if there are both manual and automated lanes, one of the lanes will be taken up by a barrier and an additional break-down or access area. This assumption is based on Figure 6-2, in which 12 feet of shoulder and barrier are added for the AHS lane.

Given these conservative assumptions, it does not make sense in terms of capacity to convert to an automated lane until 40% of the vehicles traveling on this highway are automated. If more than 66% are automated, two automated and two manual lanes give best throughput, and more than 89% is best handled with three automated and one manual lane. If all vehicles are automated, all five lanes may be used for maximum throughput. The jumps in the graph are from lane conversions. The plateaus occur when the automated lanes have reached full capacity, but there are not yet enough automated vehicles to convert another lane. Note the sharp increase when 100% of vehicles are automated and all five lanes can be used once again, now all automated. If there were an additional parallel highway or arterials in the corridor with comparable capacity, the conversions to AHS lanes could be made at half the levels of market penetration assumed here.

It should be noted that this analysis is dependent on the assumptions about physical infrastructure requirements. In particular, the high lane-keeping accuracy of an automated vehicle potentially allows narrower lanes, which would greatly increase the throughput when there is high penetration of automated vehicles. Furthermore, strictly controlled dedicated lanes allow tight platooning and other strategies that may also enhance throughput. A similar plot for dedicated lanes that allow platooning is shown in the figure for comparison.
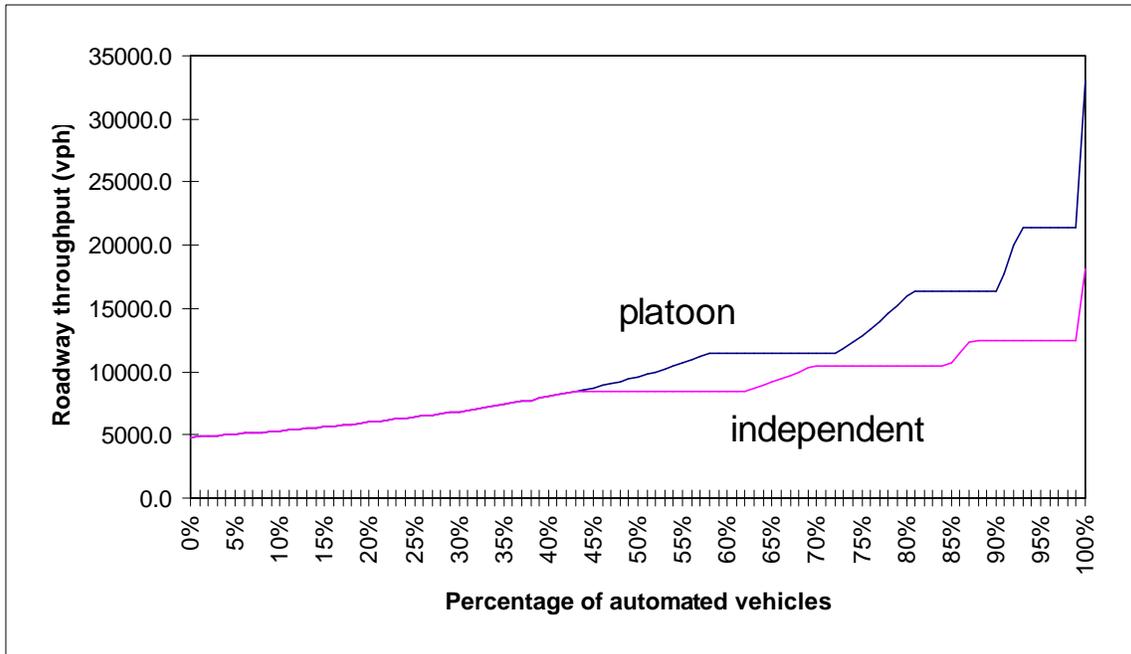
Figure 7-5. Five-Lane Roadway Capacity with Both Dedicated and Manual Lanes, as a Function of Automated Vehicle Market Penetration.

When looked at as overall roadway throughput, throughput growth, with increases in local market penetration is slow as it was in the manual case. On the other hand, market penetration may occur much faster if there are dedicated lanes.

7.7 Conclusions

7.7.1 Throughput

High throughput requires a large percentage of automated vehicles, which means designated or dedicated lanes should be implemented as soon as market penetration (considering all parallel lanes in the corridor) is sufficient. This is true even of mixed traffic roadways that can designate lanes for automated use without giving up roadway to barriers.

The first automated vehicles have little impact on throughput. This is true whether they are designed for mixed traffic or dedicated lanes. Of course, if an existing manual lane is converted to a dedicated AHS lane before there are sufficiently many equipped vehicles there would be a decrease in throughput. Under the assumptions of the analysis, there is no decrease in throughput in introducing automated vehicles into manual traffic, assuming that they communicate heavily with each other.

7.7.2 Safety

A major challenge is responding to all safety threats. These threats are not well understood, especially those caused by other drivers. A major activity in the next phase is an evaluation of these threats.

Driver involvement is critical to a safe deployment path. The driver will need to have some level of moment-by-moment control until the technology is ready to react to all threats. Dedicated lanes can limit the hazardous situations, and hence have a technically simpler problem to solve. Hence, it is expected that dedicated lanes will have safe, fully automated operation earlier.

7.7.3   General

• Mixing with manual traffic supports a wide range of applications in all regions of the country, is highly supported by the stakeholders, and so should at least be a very long-term goal.

• Early mixed traffic "pre-AHS" systems have significant safety benefits, such as preventing run-off-road accidents in rural areas. But the driver will need to be kept involved until full emergency reaction is perfected.

• Research into driver action is necessary to assess when and whether full automation is possible in manual traffic.

• Early fully automated systems, such as the prototype and early operational tests, will require controlled, dedicated lanes to constrain the problem to a manageable complexity.

7.7.4   Next Steps

Task C3 will continue to evaluate mixed traffic relative to dedicated lanes. The major issue is one of technical feasibility – whether an AHS system can be developed that can operate safely in mixed traffic, and if so, how soon and at what cost. Initial explorations of this issue indicate that it can under normal circumstances. In fact, a Delco/CMU vehicle was driven across the country "hands off" with driver intervention needed only under poor or anomalous environmental conditions for detecting the lane markings; however, the driver was responsible for obstacle detection and dealing with the surrounding manual drivers. Those are the most difficult problems for mixed with manual operation. Hence the Mixed with Manual task of Task C3 will first catalog the safety threats and their frequencies and then determine the current and future state of the art of automated response to them.

8.   Deployment Time-Staging Approaches

The definition of achievable time-staged deployment sequences for AHS has been recognized as one of the salient challenges facing the NAHSC. An achievable sequence needs to be credible in terms of:

*   technical feasibility
*   social, institutional, and political feasibility
*   economic desirability for key decision makers at each stage

At this early stage in the definition of AHS, there are large uncertainties about the evaluation in each of these categories for any proposed deployment sequence. This means that it is too early to converge on a single preferred sequence, and indeed for reasons to be explained later in this chapter there may never be a unique sequence that applies for all AHS deployments.

8.1 Deployment Importance, Concerns, and Impediments

The deployment sequencing issue is vitally important to the success of AHS for a variety of reasons. It must be addressed at this early stage of AHS definition because it imposes significant constraints on the feasibility of AHS concepts. It is not sufficient to define a mature AHS concept if there is no achievable sequence of deployment steps that can be followed to get there. Definition of the deployment sequence is also important to gain credibility in the stakeholder community, because there is skepticism at this time about whether feasible deployment sequences have been found for some of the AHS concepts. This skepticism must be addressed with further progress on the deployment issue.

AHS deployment is challenging because of the three-way credibility tests that any deployment sequence must pass. Each of these tests can be viewed as a constraint on the feasibility of deployment. If these tests are in conflict, finding the feasible solution becomes more difficult.

The largest technical constraints revolve around the difficulty of developing an automated system that can operate mixed with manual traffic. The largest institutional/political constraints revolve around the difficulty of developing dedicated-lane infrastructure, and achieving the close public/private coordination and cooperation needed to integrate the development of AHS vehicles and infrastructure. The benefit/cost constraints are affected by both the vehicle and infrastructure development costs, with the cost challenges being most acute for the fully automated systems and the benefit challenges most acute for the earlier partially automated systems. Any deployment sequence can be vulnerable to the "weakest link" along the way, because each stage of deployment must have a good enough benefit/cost relationship or reason to motivate the key decision makers to move forward. Those benefits and costs need to be construed in very broad societal terms for the public sector decision makers.

Some believe that the individual deployment steps or increments should be as small as possible in order to make them easy to achieve. However, there are large disagreements about the "size" of many of the hypothesized deployment steps, which makes it difficult to gain agreement on the relative merits of competing sequences. These disagreements are essentially unavoidable at this stage of the AHS program because of the large uncertainties surrounding many of the key issues that determine the difficulty of taking each step:

- How much will people be willing to pay for driver warning and control assistance systems of varying levels of capability? What mixtures of manual and automated control will be feasible based on human factors considerations? What will it cost to provide each level of AVCSS and AHS user service? To what extent do they provide stepping stones toward AHS?

- How difficult will it be to gain public approval for construction of a dedicated-lane AHS facility, particularly at an early stage when very few vehicles are AHS-capable? What will such a facility cost? How can the infrastructure and vehicle developments be coordinated so that the facility construction and vehicle market penetration are synchronized?

- How difficult will it be to develop a fully automated vehicle to operate mixed with manual traffic? What kinds of hardware and software technologies will be needed, how long will it take to develop, and what will they cost? Can such a system be protected adequately from the unpredictable behaviors of manual drivers and unpredictable environmental disturbances?

Obviously, these are extremely difficult questions to answer. Just as obviously, it will be hard to choose the "preferred" deployment sequence(s) until we have some reasonably good answers to many of these questions.

8.2 Alternative Approaches to Deployment

Recognizing the difficulty of answering the key questions that affect the feasibility of different deployment sequences, we still need to be able to move forward. Therefore, we hypothesized three distinctly different sequences to provide a starting point for consideration of the deployment questions and to focus the discussions about deployment. Each sequence is based on different premises about which problems will be the hardest to solve and which deployment increments will be the easiest to achieve.

All of the sequences are based on the same foundation set of assumed steps, which begin with today's vehicles and then proceed to adaptive cruise control (ACC) systems. The ACC is assumed to be available on 10% of the new vehicles sold in the United States by 2004 based entirely on existing market developments, entirely unaffected by the AHS program. Other Advanced Vehicle Control and Safety Systems (AVCSS) that could contribute to progress on all of the deployment sequences are lane-departure warning

systems and cooperative control assistance and warning systems (providing vehicles with position and speed information about other vehicles by means of communication from the other vehicles or the infrastructure). These latter systems might be available on 10% of the new vehicles sold by 2015. They could be helpful to AHS development, but may not be essential early steps in that direction.

8.2.1 Policy-Driven Sequence

The first sequence, which is illustrated by the steps shown in Figure 8-1, is called policy-driven or alternatively public-interest-driven.
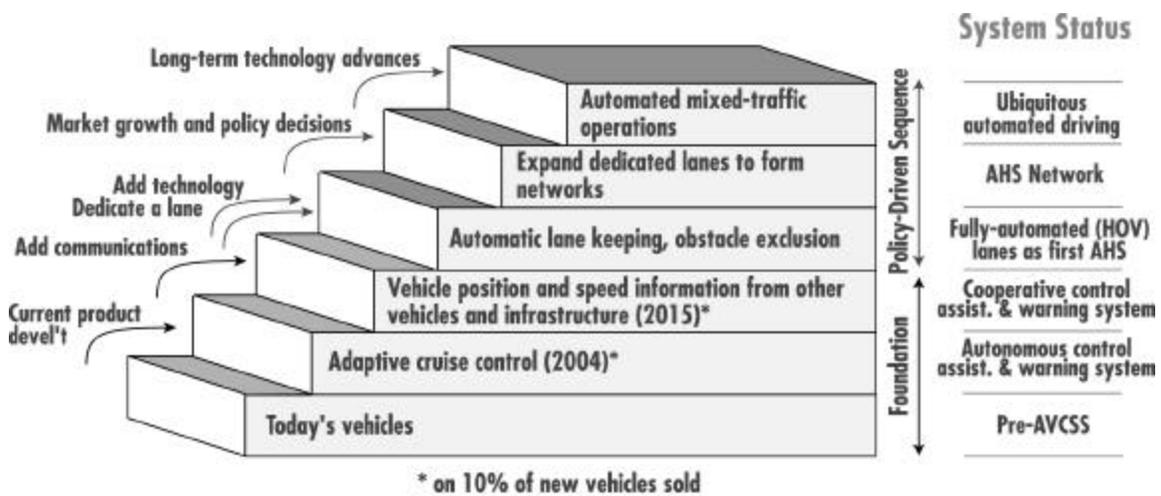
Figure 8-1. Policy-Driven Sequence

In this sequence, the next step after the foundation systems are in place is a public policy decision to dedicate a limited-scale facility for use by a special fleet of fully automated vehicles. These could be transit buses, trucks or HOVs traveling in a specific corridor. Subsequent steps would involve extending the scale of the dedicated lane facilities, connecting them to form an AHS network, while the increased attractiveness of traveling on these facilities would encourage more people to acquire AHS-capable vehicles. In the more distant future, automated operations mixed with manual traffic might be supported if this proved to be technically feasible.

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.

The primary advantages of the policy-driven sequence are:

- it simplifies the technical problems that need to be solved in the early stages of AHS development;
- it offers maximum safety and throughput gains to the system users and operators as quickly as possible.

The primary disadvantages of this sequence are:

- it requires infrastructure investments to be made early in the sequence, which may be vulnerable to institutional and political impediments, the probable need for public/private cooperation and the lengthy environmental review process;

- the market penetration for vehicles with capabilities close to AHS (AVCSS user services) will need to develop quickly enough to provide a base for AHS to build upon;

- the initial AHS deployments will be limited in scale, which means that the initial benefits will be local or regional only, and the vehicle market may be too small to attract the interest of the vehicle industry without incentives;

- it could be difficult to obtain a broad base of public support for proceeding with it.

8.2.2 Market-Driven Sequence

This sequence, which is illustrated in Figure 8-2, is called market-driven, and is based on a set of premises opposite to those behind the policy-driven sequence.

Following the foundation steps, the next steps in this sequence are a series of enhancements to driver warning and assistance systems that would be used for partially automated driving in mixed traffic. The first of these would be limited automatic forward obstacle detection and avoidance (by braking only), which is hypothesized to be available in 10% of the new vehicles sold in the United States by 2010 to 2015. After that would come automatic lane-keeping, then automatic lane-changing, and comprehensive obstacle detection and avoidance, leading gradually to the stage of permitting fully automated driving in normal highway lanes, mixed with manual traffic. Once the number of vehicles equipped for automated operations is large enough to justify a dedicated lane, then lanes would be dedicated for use by these automated vehicles to achieve higher throughput and increased safety.

In contrast to the first 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.
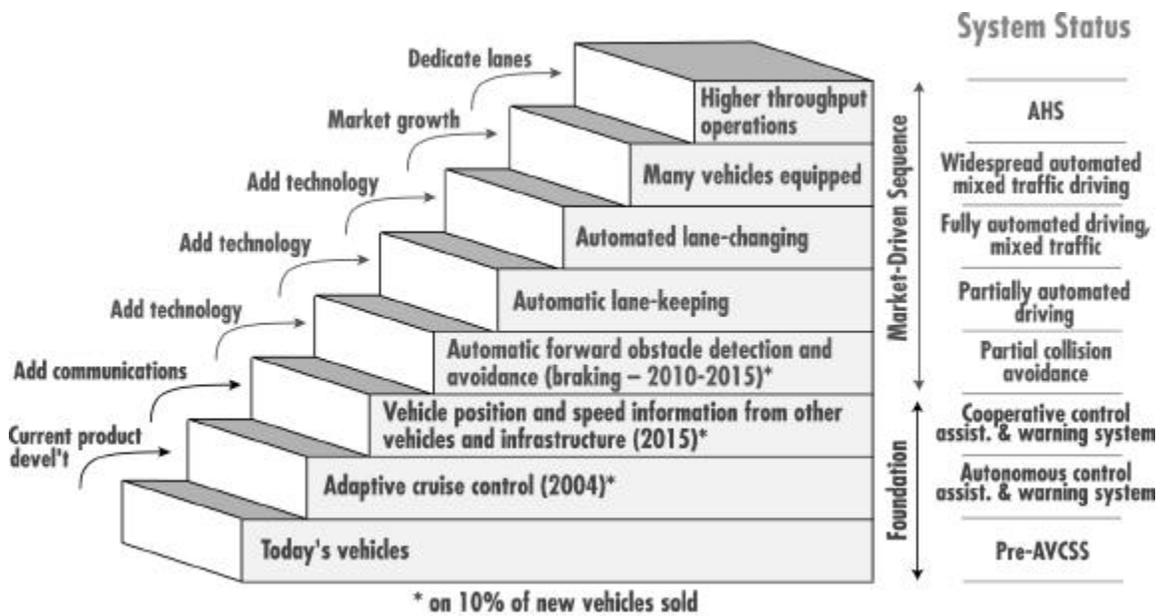
Figure 8-2. Market-Driven Sequence

The primary advantages of the market-driven sequence are:

•   it avoids the need for infrastructure until very late in the process, minimizing the more near-term need for public investments and the associated planning process delays;

•   by the time the infrastructure is needed, there is sufficient market penetration of AHS-capable vehicles that political support for the infrastructure development should be easy to obtain.

The primary disadvantages of the market-driven sequence are:

•   it requires solving significantly more difficult technical problems (especially comprehensive obstacle detection and avoidance) earlier in the sequence;

•   it is likely to require higher vehicle costs because of the increased complexity of the vehicle functions;

•   its safety is uncertain because of the unpredictability of the behavior of the manual drivers with whom it must interact;

- it offers minimal congestion relief until vehicle market penetration is so high that dedicated lanes can be easily justified, politically, which is late in the sequence;

- standardization among vehicles will be hard to achieve because each vehicle manufacturer will pursue its own marketing and technology strategies; therefore, achieving higher safety and throughput through vehicle cooperation may be very difficult to achieve;

- it is vulnerable to human factors problems associated with partially automated driving at the intermediate stages of development;

- its timing is highly uncertain because of both technical and market issues, but expected to be longer than the policy-driven approach;

- its success is dependent on the market for AVCSS developing in a direction that leads to AHS.

8.2.3 Bootstrapping Approach

This sequence, which is illustrated in Figure 8-3, is called bootstrapping, and is intended as a hybrid of features from the previous two sequences. It seeks to use both market forces and policy initiatives to "bootstrap" each other in leading toward full AHS capability.
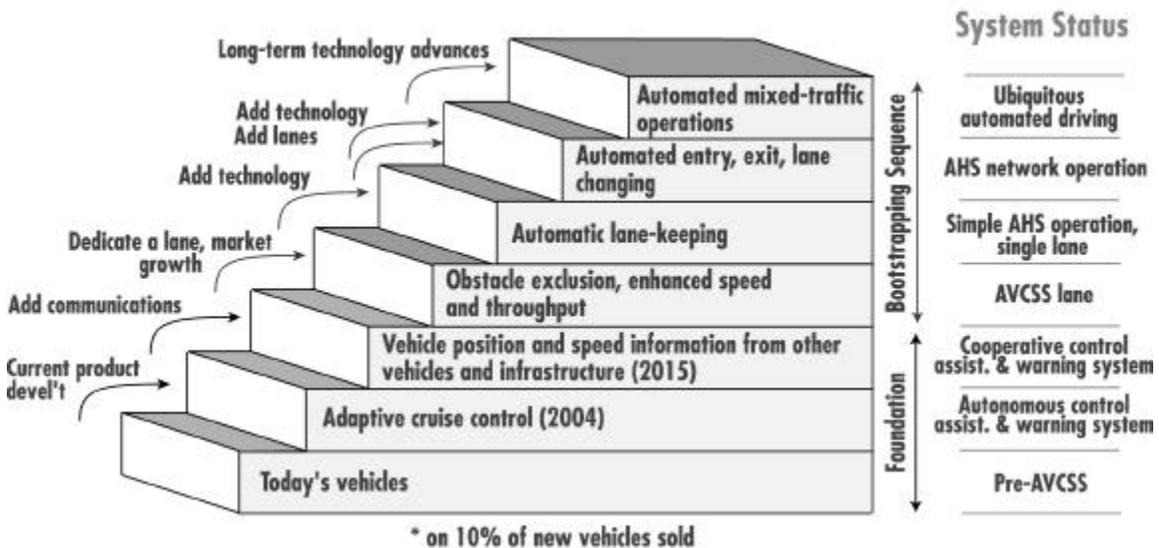
Figure 8-3. Bootstrapping Sequence

Following the foundation steps, the next step in this sequence is dedicating a lane for exclusive use of vehicles equipped with some AVCSS capabilities (but not full automation). This provides travel time and safety advantages to the drivers of those vehicles, who should be numerous enough even at the early stage to provide political support for creation of the dedicated lane. Once the dedicated, protected lane is available, the vehicle capabilities can be expanded to include automatic lane keeping for a very basic level of AHS service. As the AHS-capable vehicle market grows, the dedicated lanes are extended in scope, so that by the time they are ready to be connected to form a network the vehicle capabilities will also include automated lane changing, entering and exiting. In the more distant future, automated operations mixed with manual traffic might be supported if this proved to be technically feasible.

The primary advantage of this approach is the synergy that it seeks between the market- and policy-driven approaches.

- it provides a strategy for addressing the "chicken-and-egg" problem of AHS implementation;

- it provides earlier throughput and safety benefits compared to the market-driven approach;

- it lessens the resistance to first dedicated lanes;

- it provides a logical platform for safely advancing to lateral control and full AHS.

The primary disadvantages of this approach are in many regards the same as the disadvantages of the policy-driven approach, but with some differences:

- it requires infrastructure investments to be made very early in the sequence, which are vulnerable to institutional and political impediments, the probable need for public/private cooperation and the lengthy environmental review process;

- the initial deployments are limited in scale, which means that the large system-scale benefits are deferred until later;

- its progress is dependent on the development of the private market for AVCSS vehicles;

- it requires favorable decisions by multiple constituencies, any one of which could delay or halt its progress; and

- it could be difficult to obtain a broad base of public support for proceeding with it, particularly because of its vulnerability to accusations of elitism ("Lexus Lanes").

8.2.4 Special Deployment Cases for Fleet Vehicles

The foregoing deployment sequences were primarily oriented around private personal passenger vehicles. However, there are some special cases that do not fit that mold, involving special-purpose fleet vehicles. These offer the possibility of overcoming some of the difficulties with the prior sequences, perhaps enabling some earlier progress toward AHS capabilities.

There are several advantages to starting with automation of special purpose fleet vehicles:

(a)   their ownership, maintenance and operation can be consolidated within a professional organization, where they can be handled much more consistently than with private individuals;

(b)   the fleet owner/operator (e.g., transit agency) could also develop, own and operate the infrastructure, helping to overcome some of the institutional impediments;

(c)   the productivity increases of automation will show up directly in bottom-line benefits, which can help to justify the higher initial cost of the automation technology;

(d)   the vehicles are more likely to have consistent origin/destination travel patterns, which means that they can benefit significantly from even a limited-scale infrastructure deployment;

(e)   in some scenarios specially-trained drivers could provide the obstacle detection and avoidance function in the lead vehicle of a convoy or platoon, with the following vehicles being fully automated and perhaps even driverless. This helps to overcome the most severe technical impediment to automated operations mixed with manual traffic. Special-purpose deployment sequences for fleet vehicles, with a human driver for the lead vehicle, have been proposed for a variety of applications:
    • for intercity heavy trucks, specifically the "electronic towbar" in the "Chauffeur" project in Europe;
    • for transit buses on busways or HOV facilities;
    • for deadheading of station cars in the "Praxitele" project in France.

8.3 Scheduling Constraints on Deployment Timing

There are significant timing uncertainties associated with the steps in each of the deployment sequences. Some of these are based on technical factors, some economic and some political and institutional. Sometimes the uncertain time intervals run in parallel with each other and sometimes they are in series or combinations of both series and parallel. It is important to understand these timing dependencies before deployment time lines can be developed.

8.4 Stakeholder Concerns and Interest in Deployment

The stakeholder community has expressed strong interest in and concern about the deployment sequencing issue. They are concerned that each incremental step that must be taken be of a manageable size so that progress is not stalled by a particularly difficult step. At Workshop #3 they reviewed the three example sequences described in Section 8.2 and discussed them in depth.

There were diverse reactions to the three example deployment sequences. Some of the workshop breakout groups voted on the three sequences and came up with different relative preferences, while some of them determined that none of the sequences would represent THE answer. This is probably the most important outcome of the stakeholder consideration of the deployment issue. The potential applications of AHS are sufficiently diverse that it appears that no single deployment sequence will be appropriate for all of them. There was strong interest in having each potential AHS deployer go through its own decision tree process to determine what sequence is best suited to its needs. The NAHSC was advised to develop a portfolio of deployment sequences, which could be adapted to serve individual local needs. This approach of a RAMP (Reactive Adaptive Management Portfolio) was preferred to the steps that were described previously.

Other specific recommendations about AHS deployment that came out of the Workshop #3 breakout discussions included:

(a)   Start seeking deployment champions early (DOTs, transit and commercial vehicle operators), and look for special deployment opportunities (CVO or HOV corridors);

(b)   Expect very diverse attitudes and approaches to deployment of new systems such as AHS because of the diversity of the potential deployers;

(c)   Consider AHS implications for separating light and heavy vehicle traffic (propounded by advocates of both truck-only and auto-only AHS);

(d)   Provide "building block" options for deployment of AHS to meet the expected diversity of preferences;

(e)   Emphasize market forces leading toward AHS deployment, until these cease to produce progress, and then identify policy initiatives that should be taken;

(f)   Apply a "decision tree" model for local consideration of deployment options and timing;

(g)   Consideration of human factors issues must be coupled very closely to deployment sequencing decisions;

(h)   Emphasize standards needed for vehicle/vehicle and vehicle/roadside interoperability, consistent human/machine interfaces, and safety-critical systems;

(i)   Choose the timing of standardization very carefully, because it is important that it not be done too early or too late in order to be successful;

(j)   Consider completely separate rights-of-way for AHS (apart from existing highway rights of way) only in non-urban environments.

8.5 Designing AHS for Diversity of Deployment Sequences

The diversity of AHS deployment sequences adds a dimension to the challenge of designing an AHS concept and system. If there were a single deployment sequence the design problem would be simpler because the capabilities needed at each stage would be clearly defined. With the multiple deployment sequences, there is considerably more uncertainty about what capabilities are needed at what time, and indeed it may be impossible to anticipate those needs. The system developers and deployers are likely to need to negotiate with each other for the capabilities to be included with each implementation. The task of the NAHSC is then to define the portfolio of capabilities from among which the choices can be made.

9. Summary of Knowledge Gained in AHS Concept Definition Effort

The quantity and level of detail of the results that have been developed may make it difficult to focus on the key knowledge that has been gained as well as on the key remaining unknowns. This chapter seeks to bring these together in one place as a summary of the knowledge gained in the Task C2 concept definition effort.

9.1 Knowledge Gained on AHS Throughput

9.1.1 Throughput-Sensitive Factors

The vehicle automation technology of AHS can increase the throughput of a roadway compared to manual driving. However, the extent of the increase is heavily dependent on a number of issues:

Communication among vehicles:

If vehicles can communicate to other adjacent vehicles, then throughput is significantly increased, as is safety. A vehicle can electronically convey its operating parameters (speed, acceleration, braking capability, etc.) to the following vehicle, allowing it to operate more closely.

Knowledge and consistency of braking performance:

If vehicles can measure their own braking performance accurately, and if they can communicate their braking capabilities to other vehicles behind them, then the following vehicle's spacing from the lead vehicle can be tailored to those braking capabilities rather than being based on worst-case assumptions. The more consistent the braking performance among the vehicles, the more closely they will be able to follow each other without risking collisions in the event of hard braking-on failures.

Percentage of heavy vehicles in traffic:

Even a relatively small percentage of heavy vehicles can significantly reduce throughput compared to operations with light-duty vehicles only. This is because the braking response times and maximum braking rates for the heavy vehicles are typically much poorer than for the light vehicles, requiring that they leave large spacings ahead of them to ensure that they will not collide with a light vehicle that suffers a hard braking-on failure.

Conservatism of safety policies:

The spacings that are maintained between vehicles are typically determined based on safety policies. If there were no safety considerations to address, those spacings could be arbitrarily small and the throughput would be correspondingly large. However, one must typically make some assumptions about failure occurrences and ability to respond to those failures in order to specify "safe" spacings between vehicles. If these assumptions are optimistic (i.e., not considering worst case conditions), some collisions may occur under malfunction conditions – fewer than on manual lanes – but throughput will be higher. In contrast, if the safety assumptions are more conservative (considering more adverse conditions), fewer collisions will occur in response to malfunctions, but the throughput will be reduced. There is no single "right" answer to be had, but this is a fundamental trade-off in system design that must be decided by those who decide to deploy AHS, based on their needs and the transportation problems they are trying to solve.

Merging protocols:

The principal limitation to throughput occurs at the merge points where entering traffic joins the through traffic. This limitation can be minimized with close coordination of the maneuvering of the entering vehicles with the maneuvering of the vehicles already traveling on the mainline lane. This coordination typically requires considerable communication among the vehicles or between the vehicles and the roadside. The protocols that govern the merging must be based on the information available to all the vehicles, which can vary widely depending on the communication, sensing and logic that are assumed to be implemented.

Whether or not platoons are supported:

The clustering of vehicles in platoons permits significantly higher throughput than operations of individual vehicles only, when all else is held equal, but at the cost of high-cooperative communication requirements, some additional actuator performance and the increased risk of intra-platoon collisions when a failure occurs. The relative advantages and disadvantages of platoon operations need to be considered together when deciding if platooning is appropriate for a particular AHS application.

9.1.2 Throughput for Automated Vehicles Mixed with Manual Traffic

Automated vehicles operating mixed with manual traffic are significantly constrained by the behavior of the drivers of the manual vehicles. The unpredictability of the behavior of those drivers will probably require the automated vehicles to keep substantial spacings from the manually driven vehicles. This limits the potential of the automated vehicles to increase throughput until the market penetration of automated vehicles becomes substantial; then the automated vehicles have more opportunities to cluster together and operate closer to each other. If the market penetration were that substantial (of the order

of 50% or greater), it would appear to be relatively easy to gain political support for dedicating a lane of roadway to automated vehicle operations. In that case, the throughput in that lane could then be increased substantially more.

9.1.3 Throughput-Insensitive Factors

For a believable range of parameter values, throughput does not appear to be very sensitive to the following technology-specific characteristics:

*   communication time lag
*   sensing time lag
*   data processing time lags.

If the values for these parameters become extremely long (hundreds of milliseconds), they do have a deleterious effect on throughput, however such large values are not likely to be required in most cases.

9.2 Knowledge Gained on AHS Safety

The analyses have yielded quantitative results for a wide variety of conditions, making it possible to compare the safety of different methods of implementing AHS. However, in the absence of evaluatory designs of AHS systems it is not possible to predict failure rates for the different modes of AHS failures, which means that absolute levels of AHS safety cannot yet be predicted for comparison with the safety of today's manual driving. The conclusions that can be drawn at this point about the relative safety of different AHS implementations are:

(a)   Maneuver coordination between vehicles improves both safety and throughput. When a vehicle experiences a problem, the probability and severity of a crash can be reduced if that vehicle can tell other vehicles about its problem directly, rather than waiting for them to sense abnormalities in its behavior.

(b)   Increasing speed reduces both safety and throughput. The higher speeds require longer sensor ranges and faster signal processing in order to identify obstacles in time to permit avoidance maneuvers. They also increase the consequences (crash severity) of failures.

(c)   Alternate separation policies produce trade-offs between the probability and severity of crashes when failures occur. The individual vehicle separation policy should have crashes very rarely, but some fraction of those crashes could occur with high speed differentials, which could cause serious injuries and perhaps even fatalities, as well as property damage. The platoon policy is likely to have somewhat more frequent crashes within platoons (although these would still be rare), but these crashes would all be at low speed differentials, which would only produce property damage but not injuries or fatalities.

9.3 Knowledge Gained on AHS Infrastructure Development Issues

Many of the issues associated with AHS dedicated lane infrastructure are specific to the individual deployment locations, however there are some more general infrastructure issues that have been resolved.

(a)   There is a trade-off between the level of intelligence used to coordinate merging of traffic into an AHS lane and the length of merge ramps that must be provided. If there is no coordination between the mainline AHS traffic and entering traffic, the entering vehicles must seek gaps in the mainline traffic while they are on the entry ramp or lane, and must then accelerate or decelerate to align themselves with the gaps. This can require substantial distances if the traffic is heavy. On the other hand, if the locations of the gaps are communicated to the entering vehicles and the entering vehicles can request that those gaps remain available, the entry maneuvers can be timed precisely and the ramp length can be limited to the distance needed to accelerate the vehicles to the mainline speed. There are obviously other intermediate assumptions about level of intelligence and ramp length that could be applied as well, but the trade-off relationship remains the same.

(b)   In congested locations separate AHS entry and exit ramps are greatly preferred. It is well known that weaving maneuvers can be very disruptive to traffic flow, even if the volume of weaving traffic is relatively small. If vehicles entering or exiting an AHS lane must weave across other lanes of manual traffic, they could adversely impact the rest of the traffic, as well as suffering significant delays themselves. This tends to rule against use of transition lanes for AHS entry and exit in congested locations. Particularly considering that one of the primary purposes of the AHS lane is accommodating large traffic volumes, one should expect to encounter substantial volumes of weaving maneuvers for the entering and exiting vehicles.

(c)   The costs of building new infrastructure for AHS will vary widely, based on specific local conditions of available right of way, local construction costs, need to avoid interference with existing traffic operations, etc. In some cases, where the right of way is already available or where the AHS construction can be treated as an increment on top of another construction project, the costs may be very small. In other cases, they can be substantial. Based on some hypothetical examples representing typical environments, and with relatively conservative assumptions about designs, costs and contingencies, it appears that the AHS civil infrastructure construction costs in 1996 dollars per two-way lane mile could range up to:
        $3.3 million in rural areas
        $6.6 million in intercity corridors
        $50 million in high-density urban areas.

Costs were not estimated for very extreme conditions such as the Boston Central Artery project. The estimated costs are consistent with costs of current highway

development projects in the major California urban areas and with HOV lane costs from around the country. The electronic systems infrastructure costs have not been estimated because these will be strongly dependent on the distribution of intelligence that is assumed. They could range from zero for systems that include no roadside intelligence to upper values that are still likely to be relatively small fractions of the civil infrastructure costs.

9.4 Knowledge Gained on AHS Deployment Issues

Most issues associated with deployment time-staging of AHS remain controversial and unresolved, however there are a few general issues that appear to be settled:

(a) The AHS infrastructure development process can be managed in the same ways as conventional infrastructure development projects. Public decisions about deployment will be based on the same kinds of trade-offs between public costs and liabilities on the one hand and public benefits on the other hand. The AHS decisions will be subjected to benefit/cost evaluations against other alternatives, including the do-nothing alternative, within the existing Major Investment Study (MIS) process. The infrastructure costs should be expected to vary widely from one location to another, depending on the specific local conditions.

(b) There is a large step from partial automation to full automation because of the fundamental change in the role of the driver. This is the primary challenge in defining deployment sequences, because that change in driver role has important implications for technology, liability and public acceptance:

Technology – The fully automated system cannot depend on the driver as a back-up sensor or decision maker, so it must have significantly higher capabilities and robustness than the partially automated systems;

Liability – With partially automated systems, the primary responsibility remains with the drivers, as it is today, however with fully automated systems that responsibility shifts to the developers and operators of the systems;

Public acceptance – Full automation is a significant change in the driving experience, which is likely to require some adjustment by drivers. The public may demand higher standards in performance and safety because the driver is not in control.

(c) The step from partial to full automation must be taken before the level of automation is sufficient to detract from driver attentiveness. This means that it is probably not possible to develop a continuum of gradually increasing levels of automation leading all the way to full automation. As automation takes over more of the driving functions, the driver will pay less attention to the driving task and will be less likely to detect problems (which the automated system may not be designed

to address). The key threshold in this appears to be associated with the steering function. Once the steering is automated, in addition to the throttle and brakes, the system needs to be able to assume complete driving responsibilities because of the driver's expected loss of effectiveness.

(d)   The two primary technological impediments to full automation of driving in mixed traffic appears to be: (1) the lack of a comprehensive obstacle/hazard detection and avoidance capability; and (2) the ability to detect and respond to the extreme actions of adjacent manual drivers. The complexities of providing these capabilities involve problems of sensing, target identification and tracking, threat assessment, estimation of intentions of other drivers, and determination of principles for weighing the consequences of different crash avoidance tactics (i.e., minimizing danger to my vehicle only or seeking a societal optimum).

(e)   It is not expected that AHS deployment will follow a single uniform sequence in all places. Rather, the deployment sequences are likely to differ in different locations and for different categories of AHS users. Each potential AHS deployer is likely to need to apply its own decision tree to its deployment decisions, adapted to its own needs, which will lead to diverse outcomes. The diversity of these outcomes must be bounded by the need to ensure national interoperability.

9.5 Knowledge Gained on Stakeholder Perspectives on AHS

There has been considerable stakeholder involvement in the concept definition work of Task C2, through the large public meetings such as the Stakeholder Forum and Workshop #3, as well as through the smaller stakeholder focus groups. These revealed diverse stakeholder points of view on many issues, in large part reflecting the diversity of opinions expressed within the internal NAHSC discussions on the same issues.

In some broader dimensions, there were also differences between the perspectives of the stakeholders outside the NAHSC Core and those within the Core. The primary areas in which these differences appeared were:

(a)   The outside stakeholders appeared more interested in the partial automation services of driver warning and assistance systems than in the fully-automated AHS. The NAHSC work has not yet progressed to the stage that the benefits of full automation were explained convincingly enough to satisfy the stakeholders that it is worth doing.

(b)   The outside stakeholders were more interested in understanding the differences between AHS and more conventional transportation alternatives, while the Core Participants were focused on comparisons among different AHS alternatives. This contrast is not that surprising, but reflects the very early stage in the development of AHS. The Core Participants have been most interested in narrowing down the range of alternative AHS implementations in order to find the "best", which can

then be compared with non-AHS alternatives. The outside stakeholders do not need to care much about these internal issues, but rather need to know how AHS compares to its competitors so that they can decide how suitable AHS would be for their use. Considerably more analysis, design and evaluation work will be needed before their questions can be answered satisfactorily.

(c)   The outside stakeholders were most interested in the non-technical characteristics of the different AHS alternatives, while the NAHSC analyses have concentrated on the technical characteristics. This reflects a difference of priorities at this early stage in the AHS program. The NAHSC work plan has been aimed at first selecting the most appropriate technical characteristics of the AHS, and then addressing the issues involved in implementing any AHS (regardless of its design characteristics) in various locations. The stakeholders are not much interested in the design issues, but are concerned about how to address the policy issues that affect implementation. They would like to have a catalog of solutions to the non-technical issues even more than they would like to have the catalog of AHS technical capabilities.

The stakeholder focus group developed a listing of eight priority issues that they would like to see the NAHSC address:

1.   AHS options should be developed in a needs-driven, market-driven process. That could involve such measures as:
       –   continuing to convene focus groups or other stakeholder representative groups to elicit their preferences;
       –   other efforts in market research;
       –   continuing to have stakeholder representatives continue to sit on Consortium planning groups.

2.   For the reasons discussed in the focus group report (Ref. 3-1) – including marketing, acceptance, risk management, flexibility, timing, and coordination of all parties concerned – emphasize incremental deployment of AHS scenarios, being mindful of the negative aspects.

3.   Institutional and legal aspects should be included as AHS concept attributes. That could involve:
       –   having stakeholders and other people with specific expertise in those aspects involved in the development of AHS options;
       –   specifying options for the "Five Who's" (who pays, who owns, who operates, who maintains, who regulates);
       –   defining institutional innovations, such as public-private partnerships, or private entities to set up and manage AHS options.

4.   AHS options should be evaluated in terms of real-site case studies, including interfaces into the existing transportation grid/system. Those case studies should include not only urban, but also inter-urban and rural scenarios.

5. The Consortium should consider a broader range of primary benefits, to include safety, productivity, capacity, and broader economic, socioeconomic, and environmental benefits.

6. AHS options should be developed to compete with other transportation options just as they will in actual implementation: versus traditional options, in mainstream transportation planning, within budgetary constraints. That should include supporting the option comparisons conducted by implementing government agencies by presenting estimates of AHS performance on the dimensions those agencies use in those comparisons.

7. Liability and risk management are key concerns, and should be addressed in AHS option development. That could involve:
   – including people with specific expertise in liability and risk management in the development of AHS options;
   – including the setting up of a legal framework covering liability as a role of the Consortium.

8. The Consortium should become a central, proactive agency in standard setting, specifying how and when standards are to be established and implemented. It should make AHS standards a timely deliverable. It should establish an AHS presence on all relevant standard-setting committees.

9.6 Unresolved Concept Issues

Numerous important issues cannot be resolved at this early stage in the AHS program because of lack of data, theory or designs. The fact that they remain open does not imply any reduced importance; indeed, they are among the most important issues that must be addressed before an AHS concept can be selected. Rather, this reflects the difficulty of resolving them.

(a) Absolute safety levels needed and achievable

The AHS concepts and designs will be heavily influenced by the target safety levels, including a variety of measures of safety (reflecting both frequency and severity of crashes that would occur). Higher fidelity stakeholder inputs are needed to establish just how much safer than today's freeway driving the AHS should be (is 10% better good enough, or should it be 100 times better, and using which measure?). The probability of achieving any target safety level will depend on basic concept attributes as well as on the costs that the market will bear for both vehicle and roadway elements.

(b) Maturity and costs of enabling technologies (especially for obstacle detection and avoidance)

There are large differences of opinion regarding the technical difficulty of solving a variety of AHS-related problems, especially for automated operations mixed with manual traffic. The planning horizons are sufficiently long that it is very difficult to make technology predictions with any significant level of confidence. Simple extrapolations about growth in computing power (such as Moore's Law) are not relevant to issues as complicated as those confronted here, particularly considering the possibility that some fundamental limits will be encountered along the way. The first step should be to seek agreement on what performance requirements must be met.

(c) Throughput levels achievable and compatible with the rest of the transportation network

The simple throughput analyses are not subject to uncertainties as large as those for some of the other analyses (such as safety), but they do depend on a variety of assumptions. Throughput studies closer to real-world conditions are needed, in the context of site-specific case studies, to develop an understanding of how the traffic entering and exiting the AHS will interact with the rest of the transportation network. The results are bound to be site-specific, which means that the studies will need to be done in a variety of representative application scenarios so that the results can be interpolated to other sites. This is particularly important in the context of determining what improvements may be needed to the streets and traffic signals located right at the AHS access and egress points.

(d) Relationship between public benefit of increased throughput and individual benefits of reduced travel times

The public benefit of increased throughput can be quantified more easily for AHS than the private benefits of reduced travel times for individual travelers. The linkage between these public and private measures is very application specific, depending as it does on the amount of travel the traveler needs to take on the non-AHS part of the road system and on the degree of congestion encountered both with and without the AHS. This also needs to be studied in site-specific case studies, in order to determine how the private benefits to the travelers can exceed their costs so as to motivate the decision to purchase an AHS-capable vehicle.

(e) Complete definition of driver capabilities and roles in normal and abnormal conditions

There is a wide range of opinions about what drivers will want to do and what they will be capable of doing safely and effectively in AHS vehicles. It is important that these opinions be superseded by more solidly-based research results before decisions are made about driver roles in both normal and abnormal operating conditions. The possibilities range all the way from permitting the driver to intervene in automated operations

whenever he wants to never permitting the driver to intervene (with the possible exception of a "panic button" to stop his vehicle in an extreme emergency). The intermediate cases, with some mixture of driver and AHS system responsibility, are the most complicated and difficult to address.

(f)   Deployment sequencing of infrastructure and vehicle capabilities to avoid chicken-and-egg problems

There is a wide range of opinions about the most suitable AHS deployment sequence to follow, but there is at least some motion toward agreement that there will not be a single uniform and universal solution. Everyone would like to make the deployment sequence as easy as possible by proceeding in manageable-size steps (or increments). There remain significant disagreements about the size (difficulty) of some specific steps in each of the proposed deployment sequences. Therefore, attention needs to be focused on determining the relative feasibility of the most controversial of these individual steps.

(g)   Trade-offs between vehicle-vehicle and vehicle-roadside coordination of maneuvering and traffic flow

This is a more detailed technical issue that significantly affects the distribution of intelligence that should be chosen for the AHS. The key questions revolve around the degree of simplification in the communication protocols and technologies that would be accomplished by permitting some roadside involvement in the coordination function.

(h)   Stakeholder decision priorities and willingness to pay for various AHS and pre-AHS services

Considerably more detailed interaction with stakeholder representatives is needed before we will have a clear picture of their priorities and willingness to pay.   It is particularly challenging to obtain an accurate representation of an entire stakeholder category based on a very limited number of participants in workshops and focus groups. The idea of AHS is sufficiently new and different that it is hard to ensure that the stakeholders fully understand what it is and how they could use it. Furthermore, there are notorious biases associated with stated-preference studies as compared to revealed preferences, but given the unavailability of AHS for some years to come there are no alternatives to stated preference.

The willingness to pay issues must consider both the public and private sector participants in AHS deployment, involved in all stages from planning to product or system development to end users. All user categories (including special fleet users such as trucks and buses) need to be considered. Finally, the willingness to pay information is every bit as important for the intermediate pre-AHS (driver warning and control assistance) user services as it is for the fully-capable AHS. If the benefits do not exceed the costs for each intermediate-stage service for all of the key decision makers, the deployment sequence is not likely to be workable. Developing the knowledge about

willingness to pay will require some well-conceived marketing studies, which will need to be based on thoroughly described and realistically portrayed descriptions of each AVCSS and AHS user service.

9.7 Design Details That Can Be Deferred for Later Resolution

Some aspects of AHS design do not need to be decided at this early stage in the program. Although they might appear to be very dramatic and visible features that distinguish one AHS from another, their effects on the system users are not so fundamental that they need to be determined right away. Examples of these design details are:

- selection of lane sensing technology;
- selection of ranging sensor technology;
- selection of technologies for vehicle/vehicle and vehicle/roadside communication;
- definition of in-vehicle user interfaces;
- definition of roadway geometric characteristics.

9.8 Issues to be Resolved as Local Deployment Choices

Many aspects of AHS will be determined based on specific local circumstances, and probably do not need to be determined uniformly for the entire country. This does not mean that they are not important, but only that one single size will not fit all applications around the country because of the diversity of needs that must be met. The NAHSC will not define a single solution or answer for each of these, but will identify a range of tailoring options from among which potential AHS deployers can select:

(a)   Who owns/operates/maintains/regulates/pays/benefits/loses ?

The so-called "five who's" raised at the Boston Stakeholder Forum were subsequently expanded to seven. In each case, there are many possible answers. These will depend on pre-existing local institutional structures and relationships, the financial and technical wherewithal of the organizations involved, the political and legal environment, the public attitudes towards transportation investments, and the presence of AHS "champions" in specific organizations.

(b)   Roadway alignments

AHS lanes could be developed at grade or elevated, in the median or periphery of an existing highway right of way, or even in a new right of way, depending on local conditions. The selection of roadway alignment for any particular AHS implementation will need to be based on consideration of costs and benefits of different choices, including careful consideration of local politics. There is no single right or wrong answer.

(c) Access and egress ramp configurations and locations

As with conventional highways, the access and egress ramp decisions must be tailored to local needs and constraints. They must be based on the travel demands, the operations of the rest of the transportation network, the cost and ease of modifying existing infrastructure, right of way availability and local politics. Once again, there is no single universally applicable configuration for such ramps.

(d) Policies for mixing heavy and light-duty vehicles

Local needs may lead toward preferences for AHS use only by heavy vehicles or only by light-duty vehicles, or even toward different preferences at different times of day. All of these possibilities have been proposed by various stakeholder representatives, and all should be considered in local deployment decisions. There have also been suggestions that the access and egress ramps might be separated for the different vehicle classes. This should be explored seriously because the performance limitations of the heavier vehicles will require significantly longer ramps for acceleration and deceleration. It is possible that economic evaluations will show the desirability of building only a limited number of the ramps to accommodate the full range of vehicle classes.

(e) Interactions with local streets and highways

The AHS is intended to relieve congestion problems, and in order to do that effectively it must be connected well with the local street and manual highway network. The connection points need to have sufficient capacity to avoid becoming congestion bottlenecks themselves and the number and location of these points must be chosen in order to avoid overburdening the manual network with the traffic entering or leaving the AHS. There are no universal solutions to these issues because of the diversity of traffic patterns and existing roadway infrastructure. Rather, each AHS deployment needs to be studied carefully to determine the appropriate way of interfacing the AHS roadway with the rest of the transportation system.

10. Description of the Catalog of AHS Concept Attributes to Bring Forward into Task C3

Based on the analysis results and the inputs of the stakeholders in Workshop #3 and the stakeholder focus groups, it appears to be important to retain diversity in the definition of AHS. The potential applications of AHS are very diverse and the uncertainties about technical, economic, institutional and societal issues are sufficiently large that it appears prudent to keep the definition of AHS broad at this stage. Rather than a single narrowly defined AHS concept, the emphasis is more on definition of a "catalog" of attributes from which a potential deployer could choose. Subsequent research will need to determine the feasibility of retaining this much breadth and flexibility.

10.1 Complete Automation Only in Dedicated Lanes or Mixed with Manual Traffic

The dichotomy between these two attributes is the most fundamental one in AHS, and seems to be difficult to "straddle" with an intermediate or combined approach. The challenges faced by these systems and the advantages they offer are nearly mirror images of each other. The dedicated lane AHS provides the simplest technical solution but involves the most challenging public sector responsibilities, while the mixed traffic AHS provides the minimum public sector responsibility but involves the most challenging technical problems. In the new phase of concept definition work, there are studies focusing on the problem areas associated with each attribute in order to determine the severity of these problems. These should lead to reduction of some of the remaining uncertainties so that subsequent work can be focused most productively.

Attention is being devoted to identification of possible intermediate AHS options, in which automated and manually driven vehicles might be able to coexist under some limited conditions, such as:
* designated AHS lanes that have been approved for use by both automated and manual vehicles, and are appropriately maintained for this use;
* lanes specially equipped to support automated vehicles, for example with magnetic markers and infrastructure-vehicle communications, while allowing manual vehicles to operate on them as well;
* lanes restricted to the use of automated vehicles and suitably equipped manual vehicles; for example, the manual vehicles may be required to be at least partially automated or to have specified vehicle-vehicle communications;
* mixing of manual with partially automated (rather than fully automated) vehicles in earlier deployment stages;
* mixing of automated vehicles with manual and/or partially automated vehicles only in carefully controlled environments, such as existing HOV facilities or dedicated, protected lanes.

The full range of such possibilities is being explored in order to determine which might be most achievable.

10.2 Driver Roles

The current state of knowledge about driver capabilities does not permit definitive resolution of the question of what the driver's role should be in AHS. The diversity of possible AHS applications is such that it appears that there will be a range of driver roles, depending on the degree of automation and the density of traffic.

There appears to be agreement that it does not make sense to require the driver to perform a monitoring or obstacle detection function if the vehicle is otherwise being driven automatically (hands-off and feet-off). The monitoring function would at most be optional under those conditions. However, with lesser degrees of automation it could be possible to give the driver more monitoring responsibility and authority.

In high density or high speed AHS traffic, where the throughput and/or speed are higher than on manual lanes, the operating conditions will exceed the capabilities of normal drivers. This will limit the roles that the driver can be given, including under emergency conditions. In lower density AHS traffic, on the other hand, it might be possible to give the driver more responsibility and authority, especially in emergencies. The boundaries that define how driver roles should vary with AHS operating conditions are not yet specified, but will depend on human factors research that has not yet been performed.

The net result is that the driver roles could still range anywhere from complete authority to intervene in vehicle operation to no authority except to request a vehicle stop by activating a "panic button". The final AHS specification could provide for some or all of this breadth to be retained, based on the diversity of possible operating conditions.

10.3 Distributions of Intelligence and Separation Policy

These attributes have significant effects on AHS safety, throughput and costs and involve complicated interactions. It appears that a wide range of options could be retained here, depending on the needs of specific AHS applications. The final AHS specifications could be defined to be adaptable to local needs, although not necessarily in exactly the way described by the "Maximally Adaptable" concept family.

The distribution of intelligence could vary from location to location, depending on the investment that local deployers choose to make in infrastructure intelligence. With higher infrastructure intelligence, system performance could be extended beyond that available with lower infrastructure intelligence. Likewise, vehicle purchasers might be able to purchase vehicles having varying levels of capability. The primary challenge here is in ensuring vehicle interoperability so that vehicles are able to operate in as many AHS locations as possible and manufacturers are not pushed to develop different vehicles to match different local infrastructures. It is not yet clear how far the flexibility in distribution of intelligence can be extended without jeopardizing vehicle interoperability, but this will be an important issue for further study.

The separation policy could also vary from location to location, with platoon operations supported in some locations but not in others. In locations where platoons are supported, it would not be essential for all vehicles to be capable of operating in platoons. Some vehicles could still operate individually, although they would impose a throughput penalty on the system as a whole and might therefore need to pay a higher facility use charge. Similarly, vehicles that are capable of operating in platoons would be able to operate individually in locations that do not support platooned operations.

10.4 Obstacle Management

The basic alternatives for obstacle management range from providing each AHS vehicle with complete obstacle detection and avoidance capability on one hand to providing complete infrastructure-based obstacle exclusion on the opposite hand. There are obvious trade-offs in vehicle and infrastructure costs associated with these choices, and there is some coupling with the mixed traffic vs. dedicated lane attribute because obstacle exclusion is only possible with dedicated lanes.

A variety of intermediate solutions are also possible for obstacle management. For example, there could be infrastructure-based obstacle detection, which would provide the basis for communicating warnings of the presence of obstacles to approaching vehicles. The first vehicle to detect an obstacle could also communicate that information to other vehicles and the infrastructure. There may also be a mixture of obstacle detection and exclusion functions, limiting the capabilities that would need to be incorporated into both vehicles and infrastructure. The challenge here is that the most difficult obstacles to exclude may also be the most difficult to detect (deer and other animals, low-profile debris on the road surface), so these approaches do not really complement each other very effectively.

Both obstacle detection/avoidance and exclusion options are being considered in the next stage of concept definition work. It will be necessary to develop a clearer definition of the obstacles that must be managed and the challenges of managing each of them before the options can be narrowed significantly in this attribute.

10.5 Deployment Sequence

The theme of diversity is most prominent in discussions of deployment sequencing, as already explained in Chapter 9. Given the present-day uncertainties about all of the challenges to AHS deployment, it is impossible to settle on a single preferred deployment sequence. The participants in Workshop #3 had diverse responses to the three example deployment sequences that were presented, ranging from split votes among the three, to rejection of all three, to a preference for leaving each deployer to make its own decision, adapted to its specific needs and capabilities.

Given the diversity of the potential AHS applications, it seems unlikely that a single sequence will suit all of them. However, the range of possibilities needs to be narrowed

considerably from what it is today in order to provide a basis for making decisions about technology developments, transportation system improvements and product introductions. Once the issues involving automation in dedicated lanes and mixed traffic, especially the question of when each becomes feasible, are clarified, the deployment sequencing issue should become considerably clearer than it is today.

11.   Lessons Learned About the Concept Definition Process

We have learned much about the concept definition process, as well as about the AHS concepts and attributes themselves. The process is difficult because of the uncertainties surrounding many of the key issues and it is complicated by the NAHSC governance, which requires the development of consensus on virtually all issues (and especially all important issues).

The lessons learned during this stage of concept development can be applied in the subsequent stages, continuing throughout the duration of the AHS program:

Lessons for the analysis process

(1)   The major issues that distinguish AHS concepts cannot generally be settled easily or quickly, because a high level of technical "proof" is generally needed before consensus can be reached.

(2)   Focused, in-depth analyses help focus concept debates on specific and resolvable technical issues, rather than unresolvable differences of opinion. It is important to concentrate more effort on such analyses in order to avoid the perils of "conversational engineering".

(3)   Most AHS concept issues continue to be surrounded by sufficient uncertainty that it remains important to conduct sensitivity studies, varying important assumptions. These parametric variations are important to have so that people who disagree about the appropriateness of different input assumptions can find value in the study results and can mutually understand the dependency of the results on the assumptions.

(4)   It is important to use site-specific application examples to address many of the AHS concept comparison issues in a credible way. This credibility applies to both the analysts and the more general stakeholder community.

(5)   Consistency of assumptions across the different studies of AHS needs to be fostered so that the results of the studies can be compared meaningfully.

Lessons for stakeholder interactions

(6)   AHS is very difficult to explain in ways that are both accurate and readily understandable. The level of understanding of AHS in the stakeholder community, even among those that have been involved in the AHS program, remains low. Careful attention needs to be given to finding effective ways of communicating substantial information about AHS issues (not just the "sales pitches") to the audience outside of the NAHSC Core.

(7)   It is important to find effective ways of obtaining good **two-way** communications between the technical people working on concept development within the NAHSC and the stakeholders. It is very important that the communication channels be open in both directions so that the concept developers can learn to understand the perspectives and concerns of the stakeholders and can at the same time educate them about AHS. This is a slow process of mutual understanding, with multiple iterations, that appears to work more effectively in small focus group dialogues than in larger workshops.

(8)   The diversity of potential AHS applications and of the interests that must be satisfied both within the NAHSC and within the broader stakeholder community are such that:

- a deployable AHS approach will need to have the flexibility to be adapted to serve diverse needs;

- no single deployment sequence is likely to satisfy all needs, but different deployment sequences may be applied in different places; and

- the institutional frameworks for AHS deployment are likely to differ widely from place to place around the country.

(9)   Everybody wants to be able to advance toward AHS in manageable-size steps (or increments), but there remain large differences in the estimates of the difficulty of taking each step. This makes it hard to reach agreement about the relative suitability of different deployment sequences until the difficulty of each step can be established with higher certainty.

(10) It is essential to cultivate the trend-setters and visionaries in the various stakeholder communities, to get them involved in the AHS program so that they can become advocates and champions. AHS is sufficiently new and different from "business as usual" in the transportation field that it is not likely to have a broad-based appeal for some time yet. This means that the stakeholders who are on the leading edge will need to be the ones to take the first steps toward deployment. Their initial successes and their advocacy will need to become the means of convincing the rest of their communities to follow suit.

12. Next Steps – Develop an AHS Architecture

12.1 Purpose

The Task C3 activity will develop and document an AHS architecture. The architecture will support partially and fully automated driving, near term and long-term deployment considerations, and embrace stakeholder needs with tailorable application configurations. The architecture will support a technically, socially, and economically feasible AHS implementation. The architecture will facilitate specification of the prototype AHS to be developed during the E-leg tasks of the NAHSC program. Figure 12-1 illustrates WBS C3 in context with the AHS program plan.
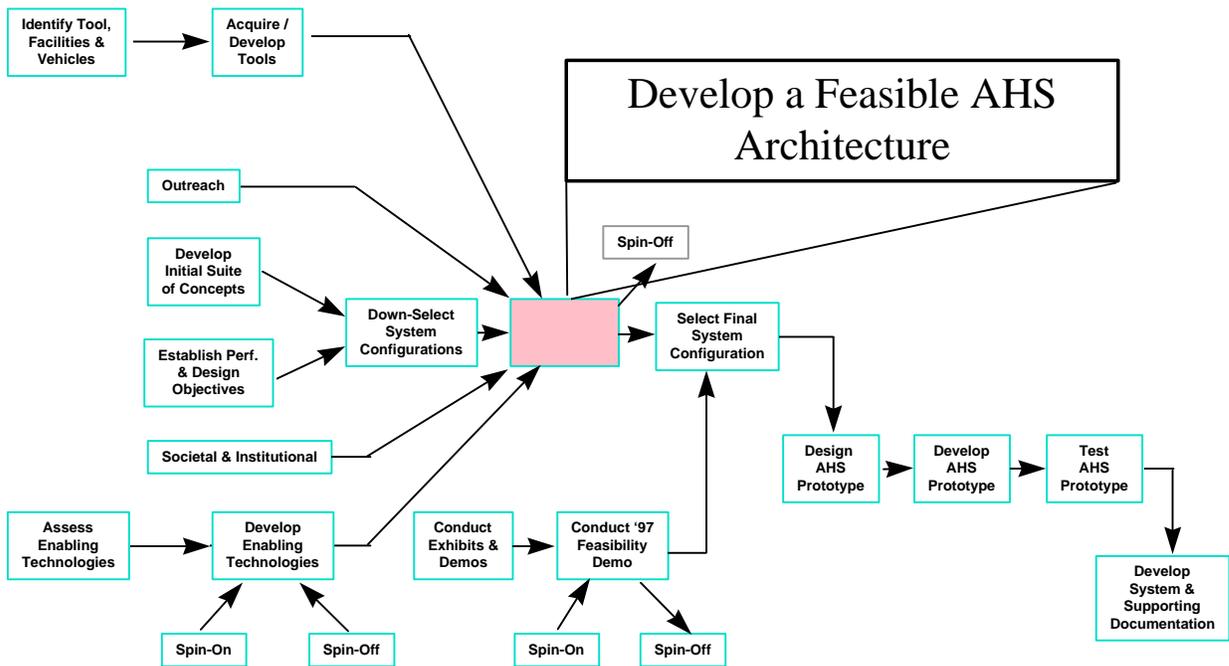
Figure 12-1. C3 Program Context.

12.2 Objectives

- Specify a single AHS architecture to: represent a fully featured AHS; embrace stakeholder needs in consideration of societal and institutional deployment issues; and facilitate specification of a sufficiently demonstrable prototype AHS in task E3
- Define a multiple-stage AHS deployment strategy that considers current and near term technology developments, regional differences with respect to potential application, existing and planned infrastructure enhancements, and institutional procedures for project commitment.
- Prove feasibility of systems and subsystems comprising AHS to ensure technical viability, cost effectiveness, and social acceptability.

- Identify spin-off opportunities that may facilitate near-term benefits of applied automated technology and hasten practicality of AHS.
- Differentiate AHS from traditional highway systems with respect to costs and benefits to stakeholders
- Achieve national consensus of stakeholders on the AHS architecture to ensure a meaningful prototype development and demonstration.

12.3   Activity Plan

The Task C3 activity plan spans 3 years, commencing October 1, 1996, and is divided into 3 Phases as shown in Figure 12-2. Each Phase corresponds to a fiscal year; i.e. FY97 is Phase I, FY98 is Phase II and FY99 is Phase III.

Each phase is divided into three primary tasks: AHS Architecture Definition (C3A), Critical Issues Resolution (C3B), and Architecture Evaluation (C3C). In addition to the NAHSC evaluations performed in C3C, Task C4C is performed, in parallel with the C3 work, using independent subcontractors to evaluate the C3 products and working papers. This independent review further ensures the feasibility of the AHS architecture and facilitates achieving national consensus. Phase III culminates with Task C3D producing the final documentation to achieve Milestone 4: the selected AHS concept. The three primary tasks are further divided into subtasks described in the Phase I subtask below.

The first phase results in a baseline AHS Architecture and complementary Specification, as well as tentative allocation of AHS functions to subsystems (e.g., Vehicle, Infrastructure, and Roadway). This allocation derives from appropriate analysis, simulation, and case studies to answer key questions and validate the initial architecture assertions.

Phase II work refines the AHS and Subsystem Specifications and updates the AHS architecture accordingly. The third phase focuses on: validation and refinement of these products; and prototype planning and strategy development for the prototype development work of the E-leg tasks. Elemental prototyping is expected, along with continuation of analysis, simulation, and case studies, in Phases II and III.

The three phases implement three cycles of the spiral process. Within each phase, the Task C3 activity will: create a baseline architecture; assess and align issues; develop and execute a strategy for issues mitigation or resolution; and revise the baseline before beginning the next phase. The architecture task (C3A) integrates the results of the other tasks to minimize risk and optimize system design. Cross-cutting analysis tasks (C3B and C3C) provide assessment and mitigation of issues (e.g., system performance, safety, human factors, cost/benefit, etc.). Design tasks (e.g., vehicle, transportation management system, and roadway) will be created during Phases II and III as warranted by the increasing detail needed as the spiral process proceeds.

Each phase ends with a workshop and appropriate reports. In Phase I, the workshop coincides with the NAHSC Technical Feasibility Demonstration '97 (Milestone 3). Phases II and III end with Workshops 4 and 5, respectively. In addition, springtime stakeholder forums, quarterly technical interchange meetings, and additional stakeholder participation/meetings/focus groups are planned for each phase. Stakeholder participation is fundamental to the C3 task plan, and C3 presentations, publications, mini-demonstrations, and exhibits are planned for stakeholder meetings and focus groups. Stakeholder meetings include those sponsored by national associations, such as ITS America, IEEE, ITE, SAE, and others. In this way, the C3 activity plan identifies intermediate products and assigns venues that facilitate stakeholder inputs and help ensure national consensus is achieved.
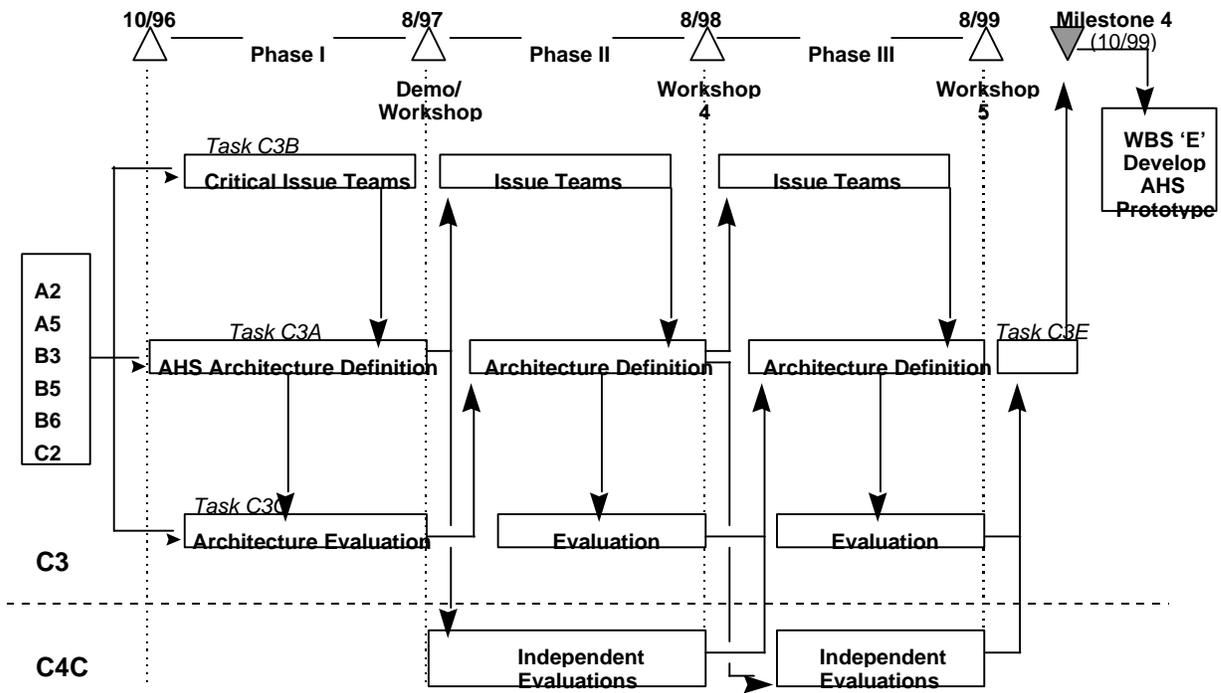
Figure 12-2. C3 Work Process.

The Task C3 activity is interdependent with other consortium work tasks, as indicated in Figure 12-3. Each subtask is responsible provide domain expertise for specific requirements in the AHS Specification (Task A2). Task A5 supports the C3 activity in liaison efforts with stakeholders and facilitating the spring forum and other meetings. The Task C3 activity identifies potential applications for which technology may provide solutions, and Task B3 provides evaluation of current and future technologies that may be applied. Task B5 provides analytical and simulation tools to support C3 analysis requirements provided to B5. Interactions with B6 are anticipated to better understand societal and institutional ramifications in addressing key questions during the C3 activity.

	A2	A5	B3	B5	B6
C3A Architecture					
User Needs	✓	✓		✓	✓
Architecture	✓	✓	✓	✓	✓
Deployment	✓		✓		✓
C3B Critical Issues				✓	
Driver Role	✓		✓	✓	✓
Dedicated lanes	✓		✓	✓	✓
Mixed traffic	✓		✓	✓	✓
Obstacle management	✓		✓	✓	✓
Vehicle separation	✓		✓		✓
C3C Arch. Evaluation				✓	
Case studies	✓	✓		✓	✓
Cost	✓			✓	✓
System performance	✓			✓	
Risk	✓		✓	✓	✓
Safety	✓				
Stakeholder consensus	✓	✓			✓

Figure 12-3. Key Interfaces.

The process outlined above is consistent with the spiral product development process described in the NAHSC Systems Engineering Plan. The approach envisioned for the cumulative architecture development activity is an iterative cycle of optimizing the operations concept, functional and physical architecture. This entails defining relevant issues, determination of what, when and how work will be accomplished to solve the issues, and then performance of that planned work. Based on optimizing the overall system architecture, the preferred or optional solution are then incorporated into the system documents causing an update from the previous baseline.

12.4   Task Description Summaries – Phase I

Summary level subtask descriptions are provided in the following paragraphs.

12.4.1 C3A AHS Architecture Definition

Assess and apply available information to develop/integrate draft baseline architecture documents. Perform analyses and evaluations to optimize system architecture design. Assist in the prioritization of cross-cutting studies and technology development. Coordinate incorporation of requirements: stakeholders and internally derived. Define and develop application scenarios.

Continue the definition started in Tasks C1 and C2 to establish what is an AHS, how it operates, and how could it be deployed. Incorporate the results of this task in the AHS System Specification, AHS Operations Concept, AHS Functional Architecture, AHS

Physical Architecture, updated AHS System Objectives and Characteristics, and AHS Deployment Strategy. This activity has been divided into subtasks to focus on the analytical work required to develop and refine the architecture.

12.4.1.1 C3A.1 User Needs Assessment

Working with the Consortium's Outreach Team (A5), Societal and Institutional Team (B6), and associate participant stakeholder involvement, update the user needs, application scenarios, and the System Objectives and Characteristics Document.

12.4.1.2 C3A.2 Develop AHS Architecture

Develop materials to update, refine and verify the AHS requirements in the System Specification including the AHS operations concept, functional architecture and physical architecture. Facilitate system specification and requirements development. Integrate the results of the issue teams and architecture evaluation analyses to produce the AHS architecture. Identify and prioritize issues to be further addressed for architecture development.

Perform the overall system integration of developing the AHS architecture. Phase I - Develop draft 'baseline' architecture. Incorporate decisions and trade-off analyses from issue teams. Phase II - Update/refine architecture based on initial evaluations and issue resolutions. Phase III - Continue to update based on more rigorous evaluations of architecture requirements and performance.

12.4.1.3 C3A.3 Deployment Plan

Develop the evolutionary deployment strategy for the architecture. Create deployment options based on the different application scenarios. Identify high leverage "spin-off" opportunities. Help the NAHSC align "spin-on" opportunities, ongoing ITS operational tests, IDEAS, etc. activities.

12.4.2 C3B AHS Concept Critical Issues

Perform specific analyses, evaluations, and trade-studies needed to resolve key issues for the architecture definition to move forward. This activity will be divided into focused teams to address the issues and provide specific results. Based on the Task C2 work, the issue teams for Phase I of Task C3 are as follows.

12.4.2.1 C3B.1 Driver Role and Acceptance

Make specific recommendations as to the degree of driver involvement and acceptance for the AHS architecture definition and deployment tasks. Develop human interface requirements.

12.4.2.2 C3B.2 Assessment of Dedicated Lanes

Evaluate the dedicated lanes option including rejection at entry, effects on arterials, societal and institutional impediments. Provide recommendations to resolve architecture issues for the dedicated lane traffic environment.

12.4.2.3 C3B.3 Mixed Traffic Performance

Perform feasibility evaluation of a mixed automated, non-automated traffic environment. Provide recommendations to resolve architecture issues for the mixed traffic environment.

12.4.2.4 C3B.4 Obstacle Management

Perform analyses of the feasibility of various obstacle management policies. Provide obstacle detection, avoidance and exclusion requirements for the architecture. Include obstacle characterization and technology being studied by B3.

12.4.2.5 C3B.5 Vehicle Separation Policy

Perform evaluation of various separation policies with respect to safety, merging, and throughput. Provide validated separation policy requirements to support the architecture development and evaluation.

12.4.3 C3C Architecture Evaluation

As the architecture is developed, evaluation teams will perform assessments of the architecture with respect to the System Specification, AHS Objectives and Characteristics, MOEs and design criteria. The evaluation teams will utilize the tools from B5 and inputs from B3 and B6, along with the appropriate level of C3 analysis, simulation, case studies and tests to provide feedback to the architecture definition team. The evaluation teams for Phase I are as follows. Teams for Phase II and III will be defined based on the results from Phase I. The actual evaluation work will begin after the architecture teams and issue teams make progress in developing the architecture. The case study work will proceed as soon as possible to establish the evaluation framework.

12.4.3.1 C3C.1 Case Studies

Identify and facilitate case study development. Work with other C3 teams to develop the integrated requirements for, execute and obtain the results needed to resolve issues, evaluate architecture attributes, validate system requirements, and provide baseline data for architecture evaluations and analysis. Ensure that the case study results provide the needed data to validate the identified application scenarios.

12.4.3.2 C3C.2 Cost Evaluation

Develop cost/benefit projections of the architecture to support trade-off studies and design decisions.

12.4.3.3 C3C.3 System Performance

Perform analyses and simulations to support architecture trade-off studies and requirements development. Using the Case Studies, evaluate the AHS architecture to assess ability to provide the desired benefits: throughput, mobility, reduced trip time, etc., and satisfy the system MOEs.

12.4.3.4 C3C.4 Risk Analysis / Feasibility

Perform risk analyses of the evolving architecture to identify risks and plan risk mitigation strategies. Work with B3 and B6 to ensure that the AHS architecture is feasible with regards to societal/institutional barriers and technology.

12.4.3.5 C3C.5 Safety

Derive the AHS Safety requirements. Perform system safety analyses to ensure that the evolving architecture meets the safety requirements. Provide assessments to identify safety hazard issues and plan mitigation strategies.

12.4.3.6 C3C.6 Stakeholder Consensus

Working with the Outreach Team, ensure the proper flow of C3 information to stakeholders, development of specific C3 related surveys, and conduct focus meetings to provide periodic evaluation of stakeholder consensus with the developing architecture.

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AUTOMATED HIGHWAY SYSTEM (AHS)

MILESTONE 2 REPORT

APPENDICES

TASK C2: DOWNSELECT SYSTEM CONFIGURATIONS AND WORKSHOP #3

JUNE 1997

NAHSC

APPENDICES

MILESTONE 2 REPORT

TASK C2: DOWNSELECT SYSTEM CONFIGURATIONS AND WORKSHOP #3

Appendix A. An AHS Concept Based on an Autonomous Vehicle Architecture

Appendix B. Cooperative Vehicle Concept Description

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Appendix A.   An AHS Concept Based on an Autonomous Vehicle Architecture

A.1 Abstract

This paper presents a system architecture for autonomous driving based on individual, intelligent vehicles operating on a freeway system very much like today's. The development of this architecture is in response to the expanding national surface transportation requirements, which can no longer be met with the brute-force method of building new and expanding existing freeways. The cost and environmental impact of such expansions significantly limit the usefulness of this solution. In response to the paradox of needing expanded transportation capability while minimizing requirements for new infrastructure, the Automated Highway System (AHS) project has been initiated and funded through the Intermodal Surface Transportation Efficiency Act, or ISTEA.

The AHS is dedicated to introducing new and existing technologies into the existing freeway system in order to reduce congestion, improve safety, and enhance the economic vitality of the nation through enhanced transportation capabilities. The use of much of the existing infrastructure is critical to nation-wide deployment, and as such, the success of such a project.

Under Task C2, the National Automated Highway System Consortium (NAHSC) considered five AHS concepts. The concept presented here is based on autonomous vehicles that operate within, and evolve from the existing manual system. This concept, called *The Independent Vehicle Concept*, is premised upon market penetration and deployment options which make autonomous driving not only technically possible, but economically deployable. It assumes that technology can be developed and integrated such that autonomous vehicles can safely operate in the same traffic flow as manually driven vehicles, and that the overall throughput and safety of the freeway system will be enhanced by the quick responses of sensor-based driving.

The Independent Vehicle Concept is formulated by assessing, in addition to the technology issues, the social, political, and market-based restrictions that inhibit such a system from becoming deployed nationwide. These restrictions are considered at least as important as the technology development and integration issues surrounding autonomous vehicle development. By considering the acceptability surrounding the deployment of an AHS, this concept has departed from previous conceptions that require new and dedicated lanes for operations. The Independent Vehicle Concept embraces incremental, market-based deployment without requirements for new or modified infrastructure. It strives for applicability to both rural and urban applications by the use of existing infrastructure. This approach is intended to satisfy the trucking, transit, and passenger-vehicle communities through global applicability, and to environmentalists and transportation planners by providing meaningful alternatives to building new lanes.

A.2 Introduction

The AHS program is a collaborative effort between government, industry, and academia to introduce automation technologies into the vehicle-highway system. The partial and/or full automation of vehicles will provide enhanced safety, mobility, and quality of highway travel; it will help conserve energy resources, and is intended to support community-based economic development, land use, and air quality goals.

The AHS is designed with several constraints taken into account. First, the improvements to the transportation system will be made using existing highway infrastructure wherever possible. The system must provide an affordable and implementable alternative to local transportation planners for the alleviation of congestion. It must be safe, and it must provide benefits to important industries such as to trucking and to services such as transit. It must also provide environmental benefits in relation to land use, air quality, and economic development. [1]

The NAHSC has considered five different AHS concepts that must satisfy these goals. Each of these concepts varies in important ways by employing different deployment strategies, by varying the distribution of on-vehicle and infrastructure-based intelligence, and by requiring different amounts of infrastructure modification.

The Independent Vehicle Concept presented here shares many of the same characteristics of other concepts by employing on-vehicle equipment for lane-keeping, velocity and acceleration control, and obstacle avoidance. Where it differs is in the amount of off-vehicle intelligence; there is no infrastructure involvement in route determination, nor infrastructure control of vehicle trajectories. More significantly, this concept promotes a deployment strategy that incrementally introduces automation technology into the existing manual system, rather than requiring dedicated lanes on which automated vehicles operate. The assumption that the market will be able to provide partially, and over time fully autonomous vehicles that are capable of operating in the manual traffic stream eliminates the requirement that automated vehicles must only operate on segregated, dedicated lanes. This, in turn, allows AHS to be deployed both in urban and rural locations

These fully autonomous vehicles are capable of driving in and around manually driven vehicles on all freeways, and provide limited capabilities such as obstacle and lane departure warning for use on arterials and local streets. Existing infrastructure is used to the greatest extent possible without the addition of sensors, infrastructure-based communications systems, or additional highway lanes. The vision of an incrementally deployable system is motivated by social, economic, political, and market-penetration issues that could each significantly limit the desirability and applicability of an AHS.

The infrastructure operator has no access to vehicle-specific origin/destination information and no knowledge of who is driving on the roadway. This concept does not currently provide for vehicle-to-vehicle nor vehicle-to-infrastructure communication;

however, it does support incoming roadway and congestion information based on Intelligent Transportation Systems (ITS) services.

This appendix first presents the technologies being considered to accomplish the autonomous driving task. Three deployment stages are then presented. Lastly, the benefits and issues associated with the deployment of this autonomous vehicle architecture are addressed.

A.3 Potential Technologies

Many different existing and developing technologies have been explored for use in an AHS. The following is a list of potential candidate vehicle-based technologies that show great promise in enabling fully autonomous driving.

- vision systems for lane keeping, tactical reasoning, lane transition [2]

- vision systems for obstacle avoidance

- radar sensors and signal processors for obstacle detection and avoidance [3]

- ladar sensors and signal processors for obstacle detection and avoidance

- infrared sensors and signal processors for obstacle detection and avoidance

- ultrasonic sensors for close-proximity vehicle detection

- magnetic nails for lane keeping, as proposed by the University of California PATH program

- Differential Global Positioning System (DGPS) and a map-based system for location determination and route planning

Combining the functionality of the different sensors and processors into a working, coordinated whole continues to be an area of concentrated study. Researchers are developing tactical-level reasoning and sensor integration models that enable information sharing between sensors and create a voting arbitration scheme that determines appropriate and safe vehicle maneuvers.[4] Ongoing simulation-based analyses, as well as real-world systems testing, are providing encouraging results that autonomous driving within the manual traffic flow is realizable in addition to being desirable.

A.4 Incremental Deployment

The Independent Vehicle Concept is designed to be deployed incrementally and to be globally applicable. Each of three steps in the deployment process is presented below.

A.4.1 Pre-AHS

In the *Pre-AHS* phase, vehicle capabilities are used for obstacle warning, adaptive cruise control, and lane departure warning. These technologies are not yet integrated into a fully automated system, and the driver is ultimately responsible for the control of the vehicle. These technologies are applicable on all roadways, including arterials and side-streets,

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and many of these technologies are currently under development for other purposes besides the AHS.

A.4.2 Early AHS

In the **Early AHS** phase, lateral control, longitudinal control, obstacle avoidance, and lane-keeping are integrated to create fully autonomous vehicles that can operate within existing manual traffic. The driver is fully disengaged from this stage forward.

Where ITS services such as Advanced Traveler Information Services (ATIS) and route guidance are available, the vehicle will make use of that information for route planning. Vehicles are able to maintain absolute privacy about vehicle identity and destination. Privacy is maintained through all stages of deployment and use of the Independent Vehicle Concept.

The Early AHS can be broken into two distinct parts: the **Urban AHS** and the **Rural AHS**. This distinction is based on the existing roadway configurations, as the implementation will be different depending on the number of lanes available. On urban freeways where three or more lanes in each direction are available, it will be possible to convert the left-most lane to a "dedicated AHS lane" when market penetration warrants and only if there will be a positive or neutral impact to flow on all of the lanes. The remaining lanes will continue to operate with a mix of both automated and manual traffic.

Many rural freeways have only two lanes in each direction, distinguishing them from multi-lane urban freeways. Because manual vehicles will need to retain the ability to pass using the left-most lane, it is impossible to dedicate that lane for automated use only. The rural AHS, therefore, will continue to have a mix of manual and automated vehicles on all lanes.

A permutation of automated driving may be desirable for users not interested in having the driving task fully automated, wishing instead to have the automation technologies supplement their own capabilities. For example, a driver can have an "emergency braking" function enabled, whereby sensors on the vehicle will monitor the environment for the existence of obstacles. If a driver does not respond quickly enough in an emergency situation, the vehicle may initiate emergency braking to supplement the delayed manual response of the driver. The autonomous vehicle can simply monitor the driver responses, and intervene when the driver is unaware or unable to respond appropriately and safely. Because all privacy is maintained, the competency of the driver is not made known to authorities or to the public.

A.4.3 End State AHS

As more manual vehicles are retired from service, an increase in automation will be seen throughout the nation's freeways. Eventually, this will lead to a mostly-automated system which can continue to handle manually driven vehicles and vehicles using older or partially automated capabilities. This last phase is known as the **End State AHS**. Automation capabilities will continue to evolve and expand to the side-streets and

arterials as the technologies and on-board algorithms progress to handle these types of traffic situations.

A.5 Benefits and Limitations

This concept is devised to be incrementally deployable and marketable by mixing within the manual traffic flow. There are benefits to this strategy, as well as limitations. Deployability and marketability are intricately tied to issues of social and political acceptance. These benefits will be addressed in this section, followed by a discussion of the limitations.

A.5.1 The Mixed Traffic Solution

A catch-22 exists in deploying an AHS. If a system requires dedicated lanes, the public will likely not purchase equipped vehicles prior to the lanes being built. If new lanes are built and little market penetration has been achieved, the public may clamor for those lanes to be used for all vehicles, especially if they are empty while the manual system is at a crawl. The second option, taking an existing lane and using it exclusively for AHS traffic, may be even less appealing in the early deployment stages, given inadequate early local demand. During the period of low market penetration, the manual lanes will experience serious congestion due to the loss of a lane, and the public is likely to not view such a system positively.

The market penetration issue is further complicated for systems requiring dedicated lanes. AHS dedicated lanes will be limited to locations with appropriate rights-of-way and to locations that can afford building new lanes; the vehicle market would likewise be limited to commuters using the dedicated lane route, and to truck and transit organizations which also use those particular routes.

The Independent Vehicle concept resolves the market penetration by incrementally introducing automated vehicle technology into the existing system. New lanes need not be built, nor are existing lanes necessarily converted to automated lanes until the market is adequately penetrated and until there is a positive or neutral effect in doing so. Local and state highway operators have the flexibility to decide when and if to convert lanes based on local needs, impacts, costs, and benefits.

This gradual introduction of automation through early, incremental deployment not only provides early user benefits, but also fosters perception changes that alleviate user fear and leads to wider market acceptance. Even more importantly, older technology never becomes obsolete. There is no need for global infrastructure-based software nor in-vehicle software upgrades and the ensuing complexity of verifying that old and new versions work together properly. By making all vehicles function much like manually driven vehicles but with faster responses, smoother accelerations, and more controlled maneuvers, compatibility issues are practically eliminated.

Other beneficiaries of the Independent Vehicle Concept include the trucking, transit, and passenger vehicles which heavily utilize the *rural* interstate system. These users will not be limited in their access to the AHS system by the requirement of a dedicated lane. Although rural areas often have the rights-of-way to build new lanes, the expense of doing so for such great lengths may be prohibitive. By making the Independent Vehicle Concept deployable, regardless of geographical location, all users may benefit from automation technologies.

The use of existing infrastructure mandates that the vehicle perform self-system checks rather than enter a dedicated system through physical "check-in" and exit through "check-out" stations. This mandate simplifies the infrastructure requirements, spreads implementation and maintenance costs of elaborate evaluation stations, and potentially makes the system more user-friendly for the driver.

The performance improvement of a system in which automated and manual vehicles cooperate is of course difficult to quantify. Although simulations are currently under development, no conclusive results are yet available. The authors believe, however, that there will be noticeable improvements in safety and throughput even with small market penetrations. Safety will go up with the continuous 360 degree vision and rapid reactions of computer-controlled cars. Throughput will increase because of more consistent and, on the average, closer spacing, as well as less bunching and filling, in computer driven cars. Even when mixed with manual traffic, the consistent headways of the automated cars will allow each automated car to take much less space than a typical manually driven car. For instance, the usual throughput number of 2000 manually driven vehicles per lane per hour (vplph) equates to a 45 meter headway. Automated vehicles will likely be capable of operating with 15 meter headways, enabling each automated vehicle to occupy a third the lane space of a conventional car. When merging is taken into account, it is anticipated that 4000 vplph is easily achievable for automated lanes, and significant improvements over the 2000 vplph benchmark are achievable in mixed traffic. (See sections 4.1 and 4.2.) Tighter spacings, as proposed in the AHS Precursor Studies, would provide even greater throughput gains. [5]

Environmental benefits include emissions and energy savings which begin early in the deployment process due to more uniform driving cycles. There may also be fewer issues associated with land use and environmental impact of building new roads and additional entrances and exits in this concept.

The emphasis on the maintenance of individual privacy will be appealing to many users and advocacy groups. For example, privacy issues surrounding psychological awareness tests being broadcast across a network will not be an issue.

Liability is another concern which is simplified in this concept. No additional liability is incurred by state and local governments for vehicle maneuvers and safety. Liability remains similar to today, with the vehicle industry responsible for the product, and users responsible for using the product in the appropriate manner.

Lastly, financing may be less of an issue for the Independent Vehicle concept. Issues of "who owns" and "who pays for" and "who maintains" the AHS are greatly simplified: the user owns and maintains the vehicle. Civil infrastructure development and maintenance costs are considerably reduced over alternate AHS concepts, as are additional potential costs associated with dedicated lanes.

A.5.2 Limitations and Constraints

The Independent Vehicle concept faces many of the same technical challenges as the other concepts: the integration of lateral guidance, longitudinal control, and obstacle detection. The unique technical challenge is sensing and reacting to the motions of manually-driven vehicles. Sensing other vehicles does not appear to be a major problem. Any sensor suite adequate to detect non-metallic roadway obstacles (e.g. deer, pallets) should be able to detect other vehicles. Several sensors, such as stereo video or ladar, have more than enough acuity to localize vehicles to a few centimeters, even at ranges of 100 meters. The more difficult problem is probably encoding the rules of defensive driving. The automated vehicles will have several advantages over human drivers: continuous 360 degree sensor coverage, rapid reactions, and full attention on the driving task. Simulated autonomous vehicles already interact with human drivers in situations such as the Iowa Driving Simulator, and appear to drive realistically and safely. Several researchers are currently pursuing approaches to automated driving in mixed traffic, both inside the NAHSC and elsewhere. [4] We continue to follow those results at the same time that we further develop the concept definition.

In a mixed traffic situation the threat analysis task to be performed by the automated vehicles is a challenging task and could make the whole concept unsafe for implementation. For example, how would an automated vehicle distinguish between a manual vehicle that is approaching it at a high relative speed at an angle from the neighboring lane during a lane changing maneuver and a manual vehicle that is moving the same way during a malfunction or accident, or because of the fault of the driver, etc.?

Another issue is how drivers will be affected when surrounded by vehicles without human drivers. How will they interact with such vehicles?

Other challenges to the development of this concept concern issues of inspection and proper operation. Automated vehicles will likely require more thorough inspections than is currently standard. This may be an issue in states with no existing or not very thorough inspection programs, and may cause less acceptance of the system. In relation to proper system operation, technology developers must ensure that the automated vehicle owners will not enable full automation on unsuitable roadways. This issue is likely to be addressed through a DGPS and map-based system which will identify all applicable, limited access roadways.

A.6 Conclusions

The Independent Vehicle Concept is one of five candidate concepts being considered by the NAHSC for a national AHS architecture. This concept is designed for incremental and global deployment based on on-vehicle technologies; the market-based deployment scheme allows for automated vehicles to operate within existing manual traffic flows on all freeways. Numerous advantages are noted for this concept, including system simplicity, rapid deployability based on available technologies and market-forces, and no explicit requirement for new or upgraded infrastructure. By introducing automated vehicles into the manual environment, system throughput and safety will be increased; these improvements will become more noticeable as higher percentages of automated vehicles begin driving on the freeways. Lastly, the technologies developed will also provide significant safety enhancements for other driving environments.

This concept is dependent on proving that it is not only feasible, but safe, to operate degrees of automation within manual traffic. The NAHSC will be addressing this issue over the coming years of study.

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Appendix B.   Cooperative Vehicle Concept Description

Vision of the Cooperative Concept

In the Cooperative Concept, vehicles use on-board sensors and computers to drive, and share information among other AHS-equipped vehicles so they can coordinate their motion for safety and high throughput.
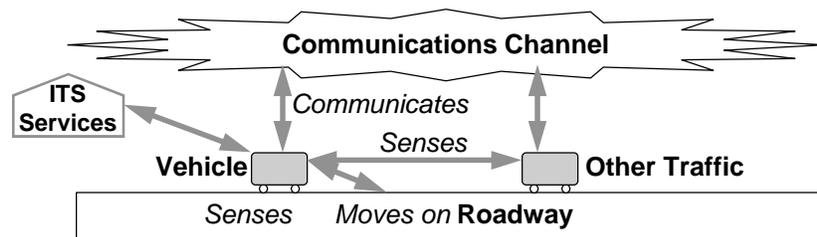
Figure B-1.. The Cooperative Concept uses a Vehicle Centered Physical Architecture, with
the Functional Architecture Organized around the Shared Communications Channel.

The first premise of the Cooperative Concept is that all viable concepts will require AHS vehicles with sufficient sensors, computers and communications to drive with close headways, to coordinate immediate responses to contingencies even when they unfold in high throughput traffic, and to detect and avoid obstacles. With these capabilities, it will be a minor extension for the vehicles to do all the necessary decision-making for AHS, thus removing any requirement for roadside infrastructure intelligence. Deployment will unfold much faster since the rate will depend on individual purchase decisions, not infrastructure investment decisions. The Cooperative design does not prohibit infrastructure intelligence as a local option, but does not rely on that option for required functionality.

The second premise of the Cooperative Concept is that falling costs, especially for computers, will make the necessary sensing, computation and communications affordable.

The concept expects the final AHS Standards will not dictate what vehicles look like inside, but will define how vehicles act towards each other. Those actions are primarily defined in the communications protocol. To define how vehicles talk and listen, and what messages are passed, which is the focus of the Cooperative Concept, thus appears to largely to define any AHS concept.
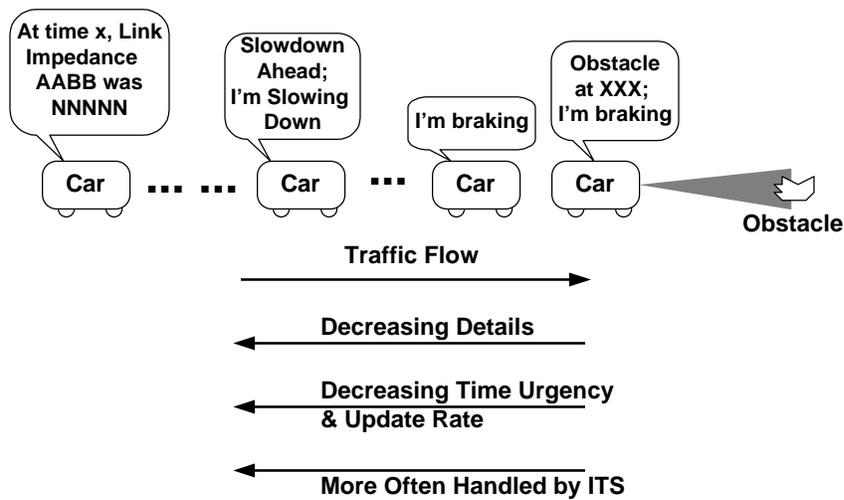
Figure B-2. Specific information flows through message passing. As information flows outward, it can be repeatedly digested into less precise, more aggregate information, with less frequent updates.

The technical vision of the communications protocol revolves around the recognition that only information about close traffic need be detailed and accurate to the split second, and that information about further points can be less precise and updated less often.
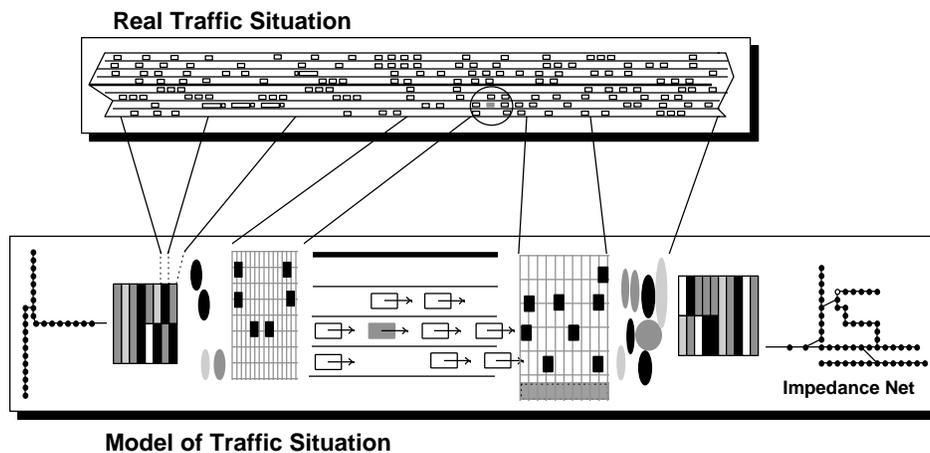
Figure B-3. Each vehicle models it's own view of the world, with detailed and rapidly updated models of the vehicles around them, and less accuracy further away.

Features and Attributes of the Cooperative Concept

The following are key features and attributes of the Cooperative Concept:

- A Design-To-Cost goal of under $1000 for AHS as a new vehicle option after 2010. The target is to use the most cost-effective computer chips in 2010, and upgrade to more advanced computers as they become available.
- Vehicles will have several on-board sensors (e.g., radar and vision sensors) to "see" the road and what is going on around them.
- Vehicles can use ITS services where available, for example, to obtain real time traffic information about the roadway ahead.
- Vehicles continuously communicate with each other about what they are doing and what is going on around them.
  Vehicles pass information up and down traffic lanes, summarizing as it moves along.
  Vehicles do not repeat information which has already been passed on.
- Each vehicle keeps track of what is going on around it, with lots of detail about the immediate area, and decreasing detail further away.
- The National AHS standard specifies how vehicles behave, while leaving internal designs to be decided and improved in the market.
- Operating rules are established to ensure vehicles are coordinated smoothly. For example, if a vehicle asks for a lane change, the rules tell vehicles in the adjacent lane to yield as appropriate.
- The concept facilitates adherence to operating rules, since many vehicles can see what an individual vehicle is doing.
  For example, if a vehicle is supposed to yield and does not, nearby vehicles will notice that the vehicle is not following the rules, and is possibly malfunctioning. This will identify the vehicle so they can stay clear. That identification will also allow traffic enforcement to pull the vehicle over and give it a "fix it" ticket.
- Operating rules describe how vehicles rapidly agree on a joint response to problems, such as failed vehicles or obstacles on the roadway.
- Automated vehicles can drive on regular lanes safely with regular traffic when technology has advanced enough to do this, possibly after 2010. Obstacle detection looks like the critical technology.
- On special AHS-only lanes, cooperative vehicles can drive closely with little wasted space, thereby increasing throughput and decreasing congestion on lanes.
- The use of platooning is an option for the Cooperative Concept, contingent on further investigation showing that platooning is necessary for maximum throughput and is safe.

Contingency Plan Approach for Immediate Response to Unfolding Incidents

One of the most challenging tasks for any AHS is to properly respond to an unfolding incident in the midst of high-throughput traffic over the initial few seconds. Cooperative has developed the outlines of one approach to this problem, in order to estimate the

requirements for things like reaction time, processing load and communications load that this problem may put on a Cooperative system. The remainder of this section is a digression explaining and illustrating the contingency plan approach for the record.

The essence of the Contingency Plan approach is that vehicles in a local area maintain a set of commonly defined contingency plans. This will include a primitive set which will be incorporated into the Cooperative protocol. A contingency plan is a compatible description of what every vehicle in the immediate area would do if that contingency plan were invoked. One of its major purposes is to allow vehicles to propose and ratify responses to incidents at the moment they occur, without having to fully describe those responses in the communications during that frantic moment when the vehicles try to sort out their response. A primitive contingency plan would be "all vehicles behind point X brake hard to a stop while remaining in their lane. Pass along the information that we are doing this." A locally defined contingency plan would be very specific to the exact conditions, including the state of the road and the relative positions of vehicles.

A vignette is shown in the figures below, illustrating this contingency plan approach in the context of Cooperative vehicles. (Note: the intervehicle spacing suggested by these illustrations would only be feasible between vehicles which have significantly more similar performance than the full spectrum on the road today. This short spacing stresses the Contingency plan protocol, however, and is thus used in the example.)
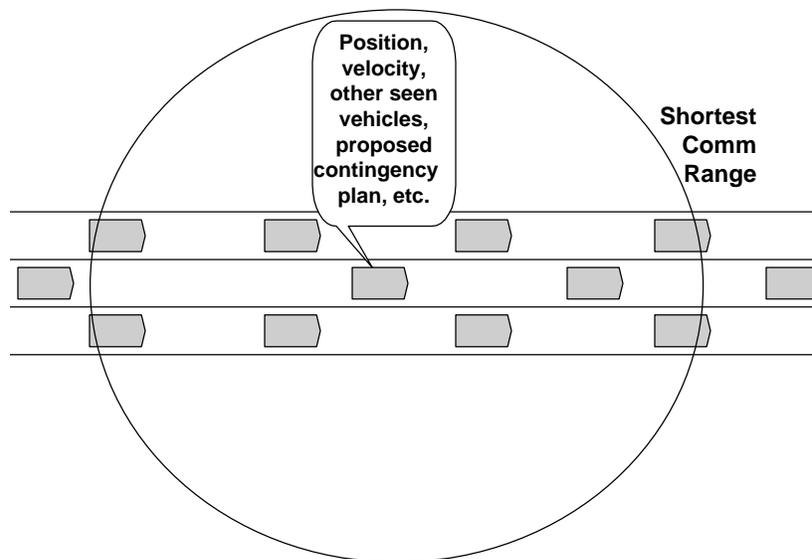
Figure B-4. Initial operations are safe, but include continuous broadcast by vehicles describing their characteristics and intentions.

Initially, the vehicles are traveling along the roadway to the right. They are broadcasting continuous updates, which all vehicles in a short range hear directly. Free-agent spacing might entail an update rate of 10 Hz. By rebroadcasting summary information, vehicles know in some detail the positions and actions of vehicles just beyond their listening range.
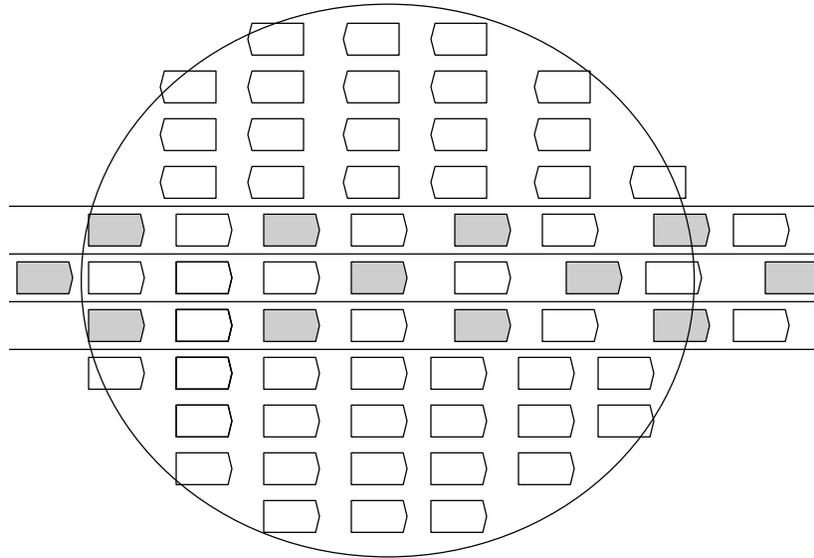
Figure B-5. Communications Channel Must be Sized for Ultimate Growth. When not needed, this communications capacity is used to send lower priority information.

The protocol used must be able to accommodate the densest packing of vehicles that might occur in the far future. The Cooperative protocol, however, is designed to effectively use this surplus bandwidth by dynamically loading the airspace with information sorted by priority.

Coordinated Braking in Lanes At Maximum Local Capability

Left Lane Swerve to Middle, Half Middle Swerve Right, All Coordinate Brake at 0.15 gs
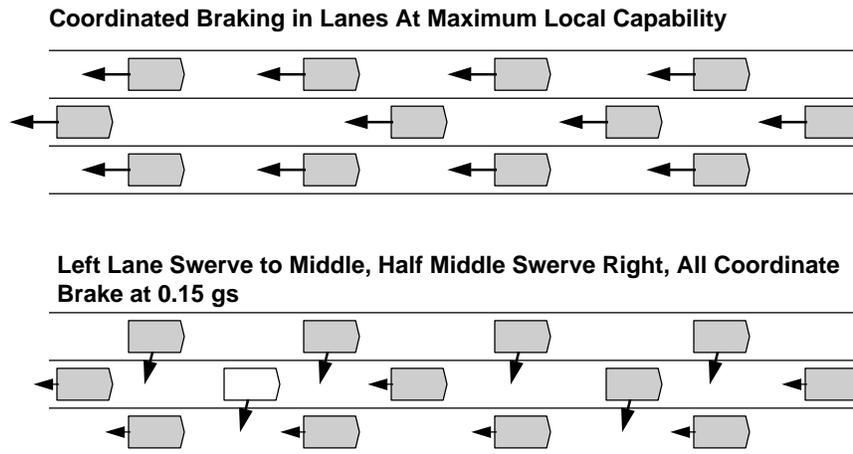
Figure B-6. Standard contingency plans are defined in the protocol, and need not be specified on the fly. Two examples are shown.

The purpose of the contingency plan approach is to have such a wide and varied set of contingency plans that given an incident, an appropriate plan can be quickly selected from the set. A single contingency plan unambiguously tells every vehicle in the immediate vicinity what it should do. A number of simple contingency plans are easily defined and broadly applicable, and those should be standards which remain predefined on the list of contingency plans that vehicles could select from. Note, the arrows are acceleration vectors. The velocity vectors are all initially to the right.
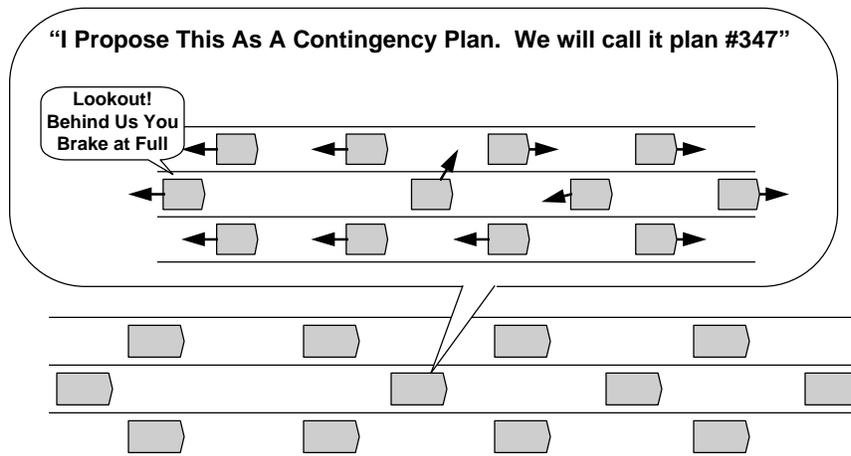
Figure B-7. Each vehicle regularly proposes well defined contingency plans. This illustrates one possible contingency plan that could be established.

A proposed local contingency plan should be free of any conflict should it be implemented. It also should be significantly different from any other contingency plan current on the local "list." The local contingency plans might be updated on the order of 100 plans/second. Virtually every contingency plan proposed would be kept as an option for a short while, and then replaced with another contingency plan, without ever being invoked.
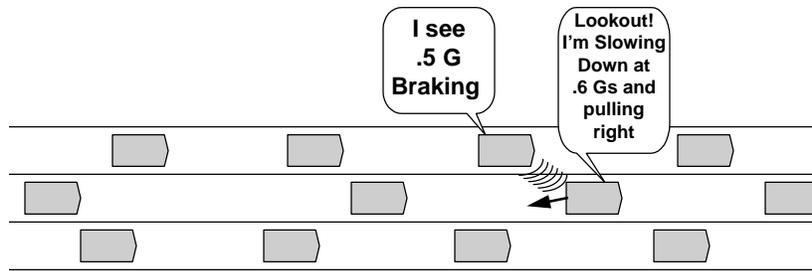
Figure B-8. A half-second later—trouble! Every once in a while something will go wrong somewhere.

Assume for purposes of this vignette that the vehicle shown experiences unexpected accelerations. The vehicle should immediately broadcast when it detects that something is wrong, and other vehicles should broadcast if they see another vehicle misbehaving.
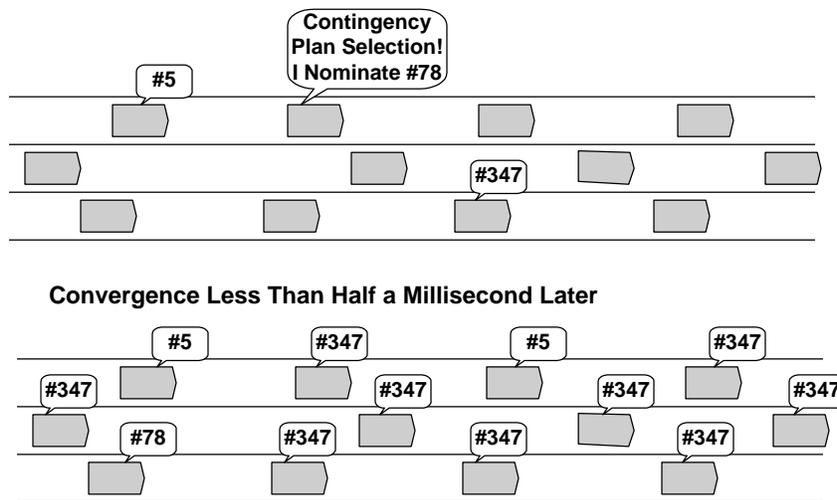
Figure B-9. Vehicles go through a rapid process to select from their available list of contingency plans.

When something is going wrong, a vehicle can initiate the contingency plan selection process. This must be a well-defined process that is guaranteed to rapidly converge and that should robustly converge on a reasonably good contingency plan. The process need not be optimal. An example of such a protocol might be two rounds of each vehicle naming (by number) its preferred contingency plan to invoke, 1 round of voting, and a final round in which all vehicles acknowledge (broadcast) back the selected plan. A variant of this approach would be to allow vehicles to veto a contingency plan, in lieu of proposing, in either of the first two rounds. Other variants, and many other approaches, could be defined. For the moment we need just assume that a particular protocol is defined and followed.

Note that in this example, the vehicles converged on the contingency plan proposed earlier. There is nothing magic about this. The vehicles had to converge on something, and this vignette just made a point of illustrating earlier the contingency plan that was selected. Also note that in contingency plan #347, the second vehicle in the middle was supposed to make a maneuver very similar to the actual maneuver it is making due to its loss of control. That similarity is a major reason this particular contingency plan was selected in this example.

The plan is implemented...

...and as the plan unfolds, ordinary operations continue*

* Possibly under special operation rules designated by the particular plan selected
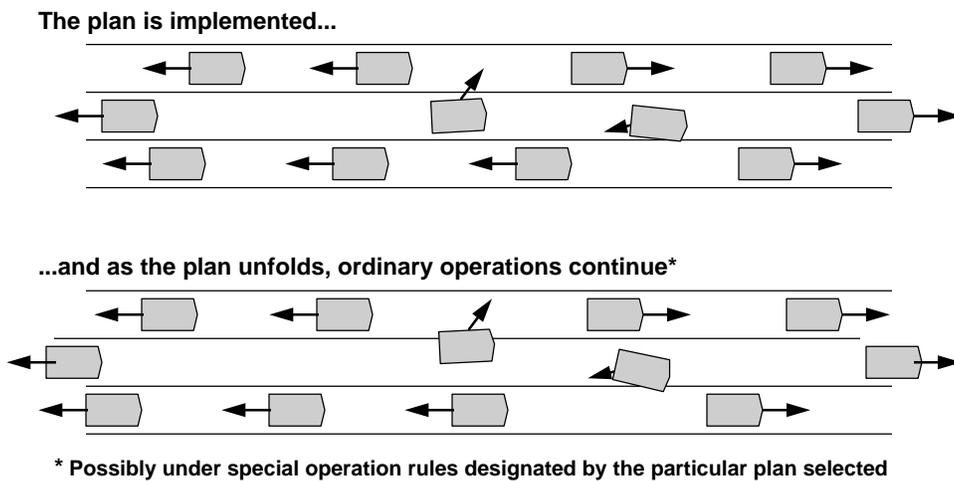
Figure B-10. Once a contingency plan is selected, that coordinates the immediate actions and planned evasive response of the vehicles.

The selection of a contingency plan is followed by its implementation. The plan defines what all the vehicles need to do, creating a coherent strategy for dealing with the critical seconds between the start of the incident, and when everything is safe, and possibly stopped.

Ordinarily, that would be how an invoked contingency plan plays out. But what happens if half-way though a contingency response, something else goes wrong?
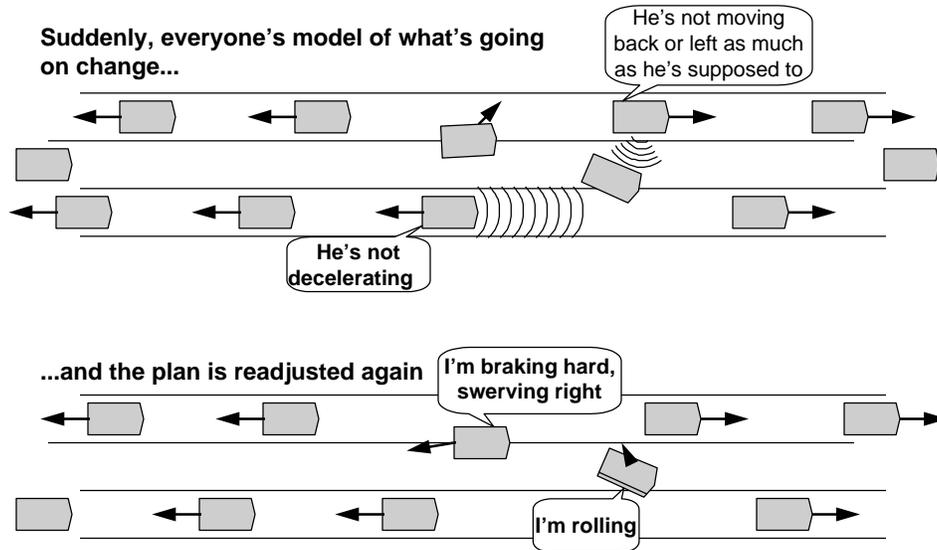
Figure B-11. As circumstances change, the vehicles can respond.

In this vignette, the one vehicle turns over too hard, first moving to the right, then slipping into a roll. (This is an induced failure to stress the incident handling capabilities of the contingency plan approach.) That roll makes the initial plan of the vehicle following to accelerate and pass on the left a bad idea. That vehicle, however, is pulling away from every other vehicle, and can change tack to brake while swerving right without threatening any other vehicle. Also, contingency plan selection could be re-invoked. There would automatically be "continue with the current plan" as one option to choose from (although it would be a bad choice in this case).

A good rule of thumb for contingency plans is to open up the space. Have vehicles in front on the incident continue, maybe even accelerate slightly. Have vehicles behind the incident brake fairly hard, and spread out the vehicles immediately following the incident. This provides more room to maneuver and makes it easier for the vehicles in the midst of the action to safely respond to the unfolding incident.

The new plan plays out...

...as safely as possible
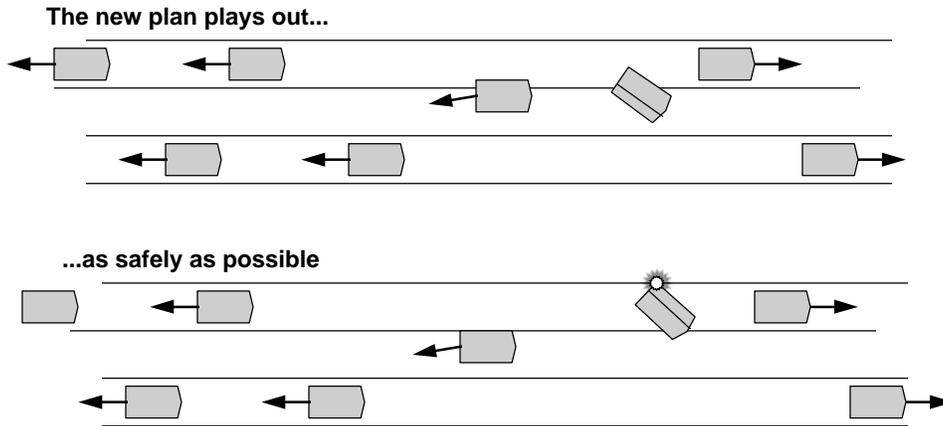
Figure B-12. Revised contingency plans continue to play out.

Note that contingency operations are invoked when a deviation from proper operations ooccurs. For example, a trailer separates, the engine falls out of a car, a boulder falls on the roadway, or a plane takes out a bridge. In such situations, the sheer physics of the situation may guarantee that some accident will occur. The contingency plan protocol will not be able to guarantee that all external events can be totally mitigated, only that the vehicles will deal with immediate incidents as well as reasonably possible.
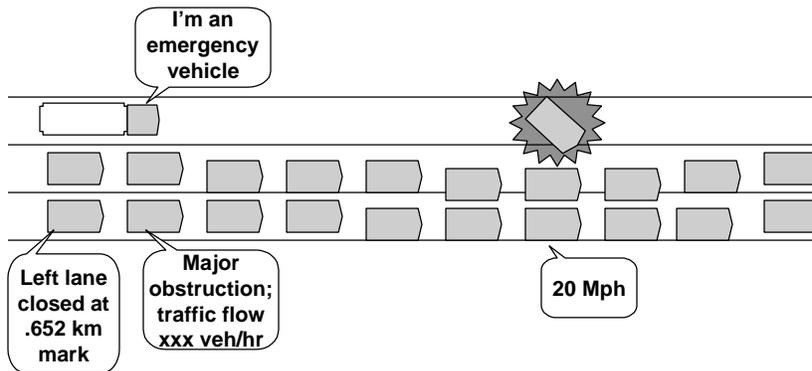
Figure B-13. Ultimately, steady state traffic flow is established around the incident.

The AHS protocol continues operating, even after the incident has taken out a lane or caused some other moderate problem. It would be reasonable for vehicles to carry with them "black boxes," recording their own behavior and what they see, allowing incidents to be reconstructed.

Contingency plans are not necessarily the approach that would be specified in the final protocol, but they, or something like them, would have to be defined and managed for any AHS to be able to deal flexibly with incidents.

In-Vehicle Processing and Communications Requirements

The most challenging technical requirements for this concept are for processing and communications. If they can be affordably met in the time frame of interest, then the concept becomes extremely attractive.

The computing needs are difficult to estimate, depending a great deal on the computational requirements for obstacle detection. One approach to examine computing needs (McKendree, unpublished) has been to make multiple different estimates, and examine the range. This approach suggests that per vehicle processing requirements should be somewhere between 300 MIPS and 9000 MIPS, with over 1000 MIPS expected. It is expected that this level of computation will be affordable in vehicles by 2010. Higher initial costs are acceptable which limit deployment to high-end systems in 2010, if processing costs continue to fall after 2010, widening affordability.

For the communications protocol, the architecture implies a peer-to-peer system. Non-line of sight communications is very desirable, so that when automated vehicles are mixed in manual traffic they can still talk to each other. Latency needs are uncertain, depending primarily on whether or not platooning is ultimately supported. This could require a 20 msec guaranteed latency, but for Cooperative vehicles which did not support platooning, a 100 ms average access time might be acceptable. The requirement for the undetected forward error rate need not be challenging, since post-processing will be required in any case to fuse data, and such preprocessing already must be able to operate with inconsistencies in data. A 10^{-6} undetected forward error rate should be attainable and adequate. There is a possibility however of certain rare emergency messages that might need a much better rate, such as
10^{-12} undetected forward errors.

The challenging part of the protocol is that all vehicles should be able to receive all the messages in their immediate area (something between 35 m and 100m). It would also be convenient if the range for the immediate area were adjustable. Since information is passed in message hopping, and in light traffic large gaps might arise, a medium range (200 m to 800 m) side channel with a low throughput (5 kbps - 50 kbps) would be very useful to maintain longer-range channel continuity. In traffic too light to avoid even those gaps, there would be no need for longer-range information which ITS could not provide.

The communications protocol must encompass an emergency communications protocol. Those emergency communications may include quick alerts, which the channel must accommodate.

It is desirable that the channel throughput reach up to 1 Mbps. The overhead for maneuvering could consume from less than 1/10 to 1/4 of a Mbps. Ongoing communications to be prepared for emergencies (essentially the continuous broadcast of situation-specific contingency plans) could use 1/4 of a Mbps. The ITS-like functions, which include detailed situational awareness about vehicles in the graceful stopping zone which cannot be directly sensed, could consume from less than 1/10 to 1/2 of a Mbps. The desired Side Channel will consume from 1/200 to 1/20 of a Mbps (plus the fact that it's longer range will reduce the ability for frequency reuse). Finally, some margin would likely be very useful over the life of the AHS.

None of these communications requirements are infeasible, but the combination is somewhat unusual, and requires more than just standard approaches.

Communications Messages

An initial review of the communications flow suggests supporting the following messages in the protocol.

Timeliness	Regular Messages	Exception Messages
Time Urgent		"Lookout!" (The initial quick alert that a incident has started to unfold) Sudden Obstacle Detection Ongoing Vehicular Mishap
Fraction of a Second	Changes to baseline vector Intended major changes to baseline vector Next contingency plan proposed Generalized plans (first order estimate: 1 plan = 1 byte for each of up to 50 vehicles = up to ~400+ bits/plan) Immediate response to "Lookout!" (can have very low return rate)	"Lookout!" ahead Observed, unreported changes in other vehicle's vector Vector on moving obstacles Proposal or ratification for Contingency plan (e.g., 2 rounds proposal, 1 round vote, 1 round awk back) Emergency command of other vehicles [when commandership is prenegotiated]
Couple or Few Seconds	Vehicle baseline vector [and orientation difference] Propose Ordinary Gross Maneuver (e.g., Lane Change) Ordinary Gross Maneuver Ok Acknowledge Confirmation on known, fixed obstacles Detailed upcoming roadway geometry Summary Vehicle Characteristics (fully looped by each vehicle)	Possibly suspicious vehicle "I am an Emergency Vehicle!" Pull Over Hazard Warning to Proposed Ordinary Gross Maneuver

Timeliness	Regular Messages	Exception Messages
Many Seconds to a Minute	Traffic Status next few exits Preset Merge protocol for upcoming merge point Parameter values for upcoming merge (e.g., traffic in other lane and req'd spacing density in this lane (implicit)) Upcoming gross (e.g., logical) roadway geometry (including:) Logical starting and ending of lanes Block upgrade level of a stretch of roadway Other gross roadway geometry information Vehicle Characteristics	
A Minute to Many Minutes	Additional Vehicle Characteristics (broadcast at a very low rate; when vehicles quickly pass each other, they may not receive all vehicle characteristics) Top-level description of extant platoons (size, location, speed, makeup) Preplan contingency plans (set fully looped)	
Very Rarely	Clock synchronization Long range map database changes Sensor Cross Calibration (but high instantaneous data rates)	

Deployment Stages and Time Frame

The Cooperative Concept envisions four major time frames, with two parallel tracks running through them. The two tracks are Dedicated Lanes and Mixed with Manual Traffic.

	Prototype & Early Automation	Operational Test & Enhanced Automation	Full AHS	Follow-on AHS
Dedicated Lanes	Prototype testing, Development for Operational Tests	Operational Test of AHS in dedicated lanes	Relieve congestion on very high traffic corridors where appropriate	Option for subsequent development; details TBD until after National Rollout
Mixed with Manual Traffic	Commercially available pre-AHS vehicles and systems	Commercial systems; Possible Operational Test; Full brain-off driving if privately offered	National AHS on remaining highways; smaller local deployment step	Option for subsequent development; details TBD until after National Rollout

△
National AHS
Rollout

Figure B-4. The Cooperative Deployment Stages balance controlled activities and dedicated lane deployments with market activities and general access lane deployments.

First Phase

The prototype AHS is evaluated, the draft National standard for AHS is refined, and Operational Tests are defined and built. Meanwhile, precursor automation products such as adaptive cruise control and obstacle warning systems are sold in the commercial market.

Second Phase

Operational Tests are conducted, and the results used to finalize the National AHS Standard in support of a national AHS rollout. Meanwhile, the commercial automated precursors will become increasingly sophisticated and robust. A car company might surprise the market by successfully offering an option for full brain-off driving on ordinary highways. The earlier release of a draft National AHS standard will help make vehicle automation upwardly compatible with AHS.

Third Phase

This stage is the full AHS envisioned in the Cooperative Concept, with operation on dedicated lanes where necessary, and operation nationally on ordinary highways once technically feasible.

The Cooperative Concept recognizes that follow-on evolution is desirable, and explicitly makes provisions to support subsequent phases to be designed and developed after full AHS deployment.

Benefits and Limitations

All the concepts share the generic benefits of being Automated Highway Systems. Benefits of the Cooperative Concept also include:

- Allows AHS operations without the cost, delay and difficulty of legally and physically dedicating a separate AHS-only lane
  Drivers can use Cooperative vehicles for automated driving on any highway
- Supports the local option of dense traffic on dedicated lanes for very high throughput
- Provides extreme flexibility in local deployment options, without the confusion or difficulty of multiple communications systems
  Some options, such as having roadside computers that tell every vehicle what to do at a merge, could be offered, but are not now included because they appear unnecessary
- Vehicles talk to each other, giving them a very good idea of the nearby traffic they cannot directly see
  Allows detailed maneuver coordination
  Helps when driving in manual traffic when another Cooperative vehicle is nearby

Potentially unique disadvantages of Cooperative are:

- May impose some higher standard (e.g., striping with radar reflective tape) on all highways, not just dedicated AHS only lanes
- May require that vehicles guarantee smaller uncertainty in their braking capabilities
- Requires high bandwidth for robust communication network, with associated RF spectrum.

Conclusion

One promising concept for AHS examined by NAHSC during its Select System Configuration (C2) phase is highly Cooperative. This concept involves all the automated vehicles communicating with those in their immediate neighborhood, creating a distributed network to coordinate and manage traffic. Indications are that such a concept could provide all of the technical capabilities of a more centrally managed concept, but requires continued growth in computer cost effectiveness before it could be affordable.

Appendix C.   Infrastructure Supported Concept

C.1   Introduction

This document describes one of five Automated Highway System (AHS) concepts, namely *Infrastructure Supported AHS,* to be examined in NAHSC Task C2. In its final deployment, the Infrastructure Supported AHS concept (hereafter concept), is designed to support *fully automated vehicles on dedicated lanes.* The concept description describes several states. These states correspond to different deployment stages in time and tailored options for different localities e.g., urban, rural, inter-urban etc. The aims of the concept design are to

- achieve higher throughput by using platooning when necessary (free agent operation otherwise)
- achieve higher safety by guaranteeing cooperative vehicle behavior
- achieve greater reliability by including infrastructural facilities for system-wide flow control
- achieve reduced emissions by using system flow control and automated vehicle control systems for smoother acceleration and deceleration patterns
- achieve better inter-modal and inter-jurisdictional coordination by system-wide flow control
- achieve better local control of system demand and congestion patterns by system-wide flow control.

The concept design in this document is based on conservative technological assumptions with respect to vehicle sensing and actuation capabilities. Vehicle and infrastructure communications are used to simplify sensor requirements. It is also assumed that AHS safety levels higher than present day levels can only be attained by guaranteeing cooperative vehicle behavior. This requires standardized inter-vehicle coordination protocols, that eliminate aggressive or drunk driving and reduce chance phenomenon such as pinch maneuvers in lane changing. It also requires that the automated vehicles be isolated from vehicles that may not behave in a cooperative manner, i.e., placing the automated vehicles in dedicated lanes. Safety may be further enhanced by using physical barriers to separate the dedicated lanes, thereby limiting the number of obstacles encountered by the automated vehicles.

This concept supports a variety of options representing different distributions of intelligence between vehicle and infrastructure. The appropriate option can be selected based on local factors, vehicle and infrastructure cost trade-offs or infrastructure cost and social benefit trade-offs. The local tailorability section describes both local factors and local options in greater detail. In all options, the infrastructural intelligence wherever present is not safety critical. If the infrastructure fails the concept is designed to either operate safely with reduced service or have the system shut down safely. In other words the system will degrade safely and gracefully. The degraded mode section describes this in detail.

The concept is designed to have several incremental deployment paths that are feasible in societal and institutional terms and in terms of technological maturity. The deployment paths envisage incremental growth in vehicle and infrastructure intelligence, and incremental conversion of existing manual highway facilities to automated highway facilities, in tandem with increasing market penetration. The deployment section describes one such deployment path.

The following are some salient features and requirements of the concept.

- *Standardized inter-vehicle coordination protocols to guarantee cooperative vehicle behavior.*
- *Separation of automated vehicles into dedicated lanes for fully automated operation.*

This ensures that the presence of non-cooperative vehicles, and the associated hazards are rare events. Physical barriers and well designed check-in procedures can further reduce the probability of such events.

- *Short range, high data rate inter-vehicle communications for platooned operation.*
- *Medium-range low data rate communications required for coordinated maneuvers such as lane changes in multi-lane operation and emergency responses.*
- *Infrastructure to vehicle broadcast communications in entry and exit zones with long entry and exit lanes.*
- *Global infrastructure to vehicle broadcast communications for system-wide flow control or static signage for speed limits, separation policy etc.*

Such communications may also be required to assist vehicle routing. These requirements may be partially met by ITS services such as in-vehicle signage or ATIS.

- *Global infrastructure surveillance system to do data collection for system-wide flow control.*

Again, some of these requirements may be offset by ITS services such as probe vehicles, roadside data collection beacons, surveillance systems.

- *Vehicle to infrastructure communications for emergency notification, incident reporting and emergency advice.*

These requirements may be supported by ITS services on non-AHS specific communication media such as CDPD.

This concept differs from the other four concepts in the following principal technical respects. The infrastructure assisted concept assumes two way vehicle to infrastructure communications in specific zones. This concept assumes that no such communication exists anywhere. The independent vehicle concept assumes there are no AHS specific

inter-vehicle or infrastructure to vehicle communication requirements. The cooperative concept assumes that there are no AHS specific infrastructure to vehicle communications. This concept assumes that vehicle sensing must be supplemented by both inter-vehicle and infrastructure to vehicle communications.

The concept description is organized as a reference state and several other states. For descriptive convenience the reference state describes fully automated vehicles on dedicated lanes in an urban, high traffic volume environment, with benign weather and equipment conditions. This is expected to represent the most sophisticated state of the concept. We describe both normal and degraded mode operation. Other concept states are described by their differences from the reference state. Section C.2 describes the reference state, Section C.3, deployment states, Section C.4 describes states for local tailorability, Section C.5 the degraded mode operation of the reference state, and Section C.6 discusses specific societal and institutional issues associated with this concept. Section C.7 is a concluding comment.

C.2   Concept Reference State Description

Each state specifies the driving environment, operational functionality and responsibility/liability. Driving environment includes the ambient environment surrounding AHS, the physical structure of infrastructure, the traffic on AHS, and the set of all events that can occur on an AHS. Note that such events include not only normal events but also failure and emergency events. They also include those events resulting from responses by AHS to failures and emergencies. If the driver of an AHS vehicle plays a role during AHS driving, however minor it may be, these events also include those that result from human actions or intervention. This concept is intended to require minimum driver role, if any at all. This is achieved by physically segregating the automated lanes from the manual lanes.

It is well known that the difficulty of obstacle detection could create technology and cost issues, so such physical segregation could also help reduce the types of possible obstacles on AHS and the frequencies of their presence. It has been decided that the responsibility/liability issues should be investigated in the future.

The rest of this document, therefore, concentrates on the operational functionality. AHS functionality for normal operations can be put in four major categories: recognition, movement/maneuver decision, movement/maneuver planning and coordination, and movement/maneuver control.

- Recognition functions include roadway geometry recognition, roadway and other conditions recognition (including obstacles), ambient environment recognition, traffic regulation recognition, and traffic condition recognition.
- Movement/maneuver decision includes those regarding speed, spacing, lane change timing and location.
- Movement/maneuver planning/coordination is needed for merging, lane-changing, entry, exit, platoon formation and dissipation.

- Movement/maneuver control implements the decisions.

In addition to normal operational events, vehicles must be alerted to nearby abnormal events, e.g., failures or collisions, either
1. through detection by on-board sensors or
2. through notification by the failed or collided vehicles directly or indirectly by the infrastructure.

The vehicle system must be able to respond to such events safely.

This section focuses on normal operations; failure events & degraded modes will be the focus of Section C.5.

Vehicle Classes: All

Assumptions: Fully automated vehicles on dedicated lanes, benign weather and equipment conditions.

Figure C-1 represents a physical architecture diagram showing components of the automated vehicle and infrastructure control system. An automated vehicle consists of sensors, actuators, communication devices and controllers. Self state sensors sense the state of the vehicle such as velocity, acceleration, yaw rate, etc. Neighborhood sensors obtain information about roadway geometry and the state of the surrounding vehicles and obstacles. This information is used by the feedback control laws for different maneuvers. For operation in a platoon, the following vehicles require the acceleration information about the preceding and the lead vehicle which can not be sensed. This information is provided by the intra-platoon communication system. Without this communication, the vehicles can still operate as free agents. The planning and coordination system on the vehicle is responsible for taking strategic decisions such as lane change decision, speed & inter-vehicle separation decision, platoon join-split decision. In making these decisions, the planning and coordination system uses the suggested routing, incident, emergency and weather information broadcast by the infrastructure control system. The join, split, lane change maneuvers are coordinated with neighboring vehicles by exchanging a structured set of messages (protocol) using inter-vehicle communication systems. The structured maneuver execution results in increased throughput and safety. The entry, exit and merge maneuvers are performed as regular lane change maneuvers, on an extended entry, exit and merge area, using on-board sensing and inter-vehicle communication.

The infrastructure control system is divided into sectional controllers and one central network controller called Automated Highway Management Center (AHMC). The adjacent sectional controllers are connected by a wireline network with each other and with AHMC. The sectional controllers themselves contain stretch,[1] entry, exit and merge controllers as subsystems. The stretch control system broadcasts suggested speed,

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[1] A *stretch* control system operates on a highway *link* without any decision nodes such as entry, exit, merge points.

separation and routing as well as incident, obstacle, emergency and weather information to the automated vehicles in its range. It uses roadside flow sensors to obtain local flow information and the wireline communication network to obtain flow information of adjacent sections and highways. The infrastructure based sensors are also used for obstacle detection. The entry, exit and merge controllers, in addition, broadcast suggested speed and separation so as to facilitate entry, exit and merging. They also provide entry metering functionality. The AHMC controller calculates global routing parameters such as estimated delays based on traffic information obtained from individual sectional controllers.

The hierarchical decomposition of the control system allows safe and efficient operation with lower sensing and control complexity and robust fault tolerant operation.

The remaining section describes the concept reference state in terms of the physical architecture table and description of operational functions. The physical architecture table contains a list of systems and brief description of their functionality. Each function description section contains an information flow table showing the interconnections between different systems. Some of the detailed information flow requirements that are necessary for executing almost all vehicle control laws are not mentioned separately in each function description. For example, most of the control laws need to know vehicle parameters such as mass, rolling resistance, cornering stiffness of the tires, etc. to calculate the feedback control. These quantities are either sensed by sensors or are adaptively identified using available sensor readings.

Figure C-1: Automated Highway System Architecture
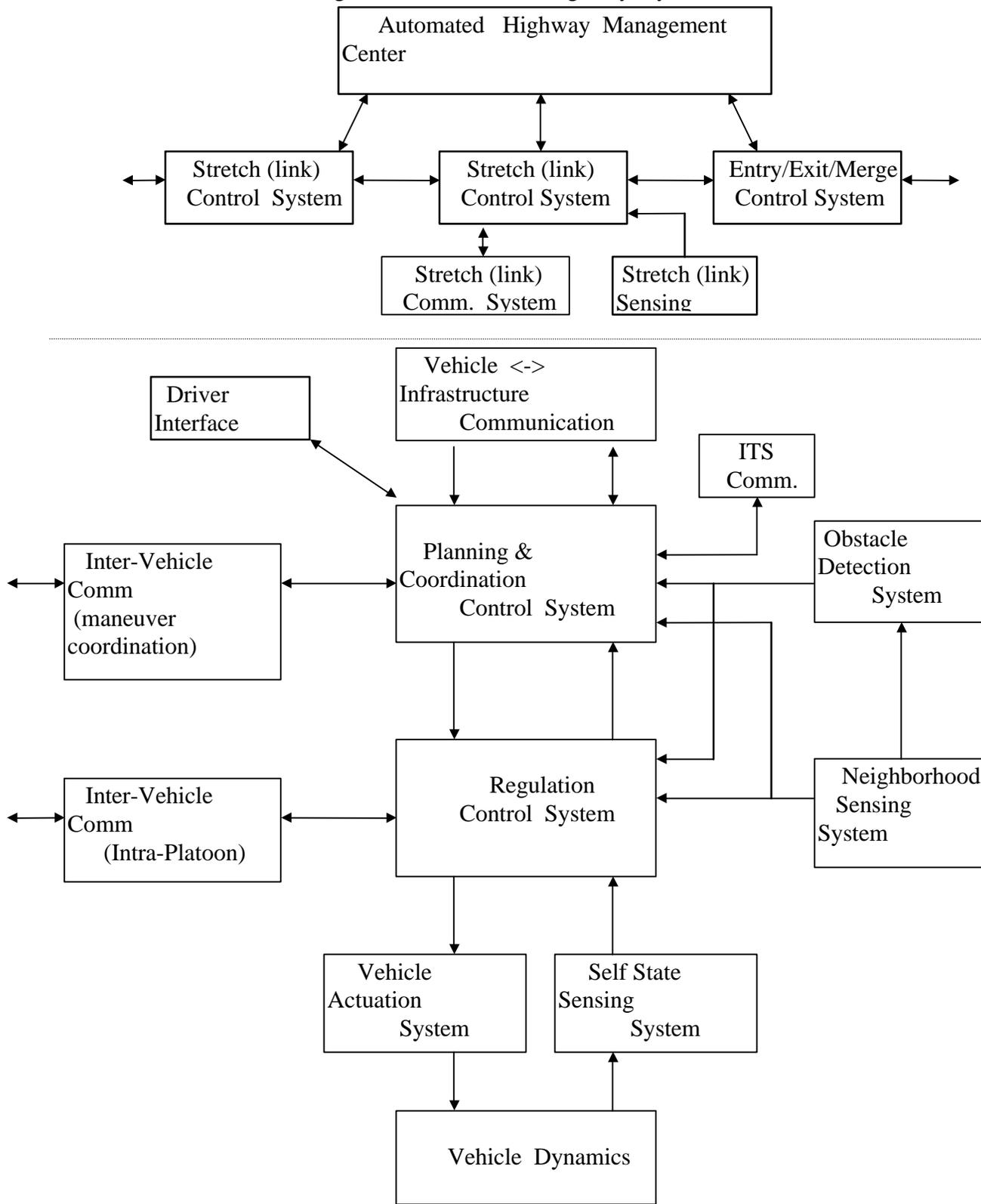
Table C-1. Physical Architecture Table

Location	System Type	System Description	
Vehicle	Control System	Name	**Planning and Coordination System**
		Function	Execution of all Strategic Driving Functions
		Subsystems	Planning System, Coordination System
		Name	**Planning System**
			Speed decision, Entry decision, Exit decision, Inter-vehicle separation decision, Join decision, Split decision, Merge planning, Obstacle avoidance planning, Emergency Response Planning
		Name	**Coordination System**
		Function	Gap negotiation, Join negotiation, Split negotiation, Stop coordination , Entry coordination, Exit coordination, Merge coordination
		Name Function	**Regulation Control System** Speed control, Longitudinal separation control, Intra-platoon separation control, Inter-platoon separation control, Join control, Split control, Lane keeping, Gap alignment, Move-over Note: Lane changing performed by gap alignment and move-over.
	Sensors	Name	**Vehicle Neighborhood Sensing System (VNSS)**
		Function	To sense all roadways, vehicles and obstacles in the lane of the vehicle and in adjacent lanes (including entry and exit ramps if required by design). Thus the system does Obstacle detection, Lateral position sensing, longitudinal separation, and speed of neighboring vehicles sensing.
		Technology	Most probably a fused sensing system, including either radar or vision as the primary technology. Can include lidar or some other proximal sensing technology such as sonar or capacitance detectors.
		Name	**Vehicle Self-State Sensing System**
		Function	Sense speed, lateral accl., longitudinal accl. and other parameters of associated vehicle.
		Technology	Tachometer, Magnetic encoders, Accelerometer
	Communication Systems	Name	**Intra-platoon Communication System**
		Function	Communicate acceleration and speed of platoon lead vehicle, acceleration of vehicle in front.
		Technology	Military protocol packet radio Spread spectrum systems operating in unlicensed bands Radar/communications hybrid devices Infrared

Location	System Type	System Description	
Vehicle		Name	**Inter-vehicle Communication System**
		Function	Communication for Gap negotiation, Join negotiation, Split negotiation, Stop coordination, Obstacle detection
		Technology	Analog and digital cellular Cellular digital packet data (CDPD) Military protocol packet radio Spread spectrum systems operating in unlicensed bands Radar/communications hybrid devices Infrared
	Communication Systems	Name	**Vehicle to Roadside Communication System**
		Function	Communication for Speed decision, Lane change decision, Entry/Exit metering, Maximum platoon size, Obstacle detection, Hand-off for Entry, Hand-off for Exit .
		Technology	Analog and digital cellular Cellular digital packet data (CDPD) Military protocol packet radio Spread spectrum systems operating in unlicensed bands Radar/communications hybrid devices Infrared Include: tag (on vehicle) and beacon (@ roadside)
		Name	**ITS Communication System**
		Function	Communication for Routing, Emergency response, Emergency detection and other ITS services.
		Technology	Analog and digital cellular Cellular digital packet data (CDPD) Military protocol packet radio Spread spectrum systems operating in unlicensed bands Radar/communications hybrid devices Infrared FM subsidiary communications authorization (SCA) FM radio broadcast data system (RBDS) TV secondary audio programming (SAP) Highway advisory radio (HAR) Global positioning satellite (GPS) For infrastructure-to-infrastructure: Spread spectrum systems operating in unlicensed bands Microwave radio Twisted pair fiber optic cable

Location	System Type	System Description	
Vehicle	Actuators	Name	**Throttle Actuator System**
		Function	Throttle control
		Name	**Brake Actuator System**
		Function	Braking control
		Name	**Steering Actuator System**
		Function	Steering control
	Other Systems	Name	**Driver Interface**
		Function	Communication with driver for Emergency monitoring and response, Obstacle detection, recognition and avoidance, Exit decision, Entry decision, Routing, Hand-off, Hand-on.
		Technology	Motion sensing Absolute position systems Vehicle system
		Name	**Driver Monitoring System**
		Function	Monitor the alertness of the driver for Hand-on.
		Name	**Obstacle Recognition System.**
		Function	Data fusion for obstacle recognition
		Name	**Emergency Detection System**
		Function	Data fusion for emergency detection
	Driver	Function	Obstacle recognition, Emergency detection and response, Exit decision, Entry Decision, Hand-off, Hand-on
Roadside	Control System	Name	**Section Control System**
		Function	Speed Decision, Inter-Vehicle Separation Decision, Lane Change Decision, AHS Flow Control, AHS Admission Control, Emergency Detection & Monitoring, Emergency Response & Incident Clearing
		Subsystems	Stretch Control System, Entry Control System, Exit Control System, Merge Control System
		Name	**Stretch Control System**
		Function	Speed Decision, Inter-Vehicle Separation Decision, Lane Change Decision, AHS Flow Control, AHS Admission Control, Emergency Detection & Monitoring, Emergency Response & Incident Clearing
		Subsystems	Stretch Sensing System, Stretch Communication System

Location	System Type	System Description	
Roadside	Sensors	Name	**Stretch Sensing System**
		Function	Sensing of average speed, flow, road image for obstacle recognition and emergency detection.
	Communication Systems	Name	**Stretch Communication System**
		Function	Broadcasting from roadside to vehicle, two-way emergency communication from roadside to specific vehicle.
	Control Systems	Name	**Entry Control System**
		Function	Entry metering, check-in, hand-off
		Subsystems	Entry Rate Controller, Entry Sensing System, Entry Communication System, Entry Check-in Controller
		Name	**Entry Rate Controller**
		Function	AHS admission control (entry rate metering)
	Sensors	Name	**Entry Sensing System**
		Function	Sense entry queue length, average speed and density in entry zone of automated highway, road image for obstacle recognition and emergency detection.
	Communication Systems	Name	**Entry Communication System**
		Function	Broadcast communications to all vehicles in the entry zone of the highway. Broadcast of suggested speed and separation.
	Control Systems	Name	**Entry Check-in Controller**
		Function	Vehicle and driver status monitoring, hand-off

Location	System Type	System Description	
Roadside		Name	**Exit Control System**
		Function	Exit Rate metering, check-out, hand-on
		Subsystems	Exit Sensing System, Exit Communication System, Check-out Controller, Exit Rate Controller
	Sensors	Name	**Exit Sensing System**
		Function	Sense exit queue length, average speed and density of exiting traffic, road image for obstacle recognition and emergency detection.
	Communication Systems	Name	**Exit Communication System**
		Function	Broadcast communications to vehicles in the exit zone of the highway.
	Control Systems	Name	**Check-out Controller**
		Function	Vehicle check-out, driver status checking, hand-off
		Name	**Exit Rate Controller**
		Function	Exit queue control, To control rate of vehicles entering local traffic.
		Name	**Merge Control System**
		Function	Highway to highway merging, speed decision, separation decision in merge zone
		Subsystems	Merge Sensing System, Merge Communication System
	Sensors	Name	**Merge Sensing System**
		Function	Sense speed, distance of vehicles in the merge zone, road image for obstacle recognition and emergency detection
	Communication Systems	Name	**Merge Communication System**
		Function	Broadcast communications (traffic flow information in merging lanes) to all vehicles in the merge zone of the highway.

Location	System Type	System Description	
AHMC	Control System	Name	**Network Control System**
		Function	AHS Routing, AHS Flow Control, AHS Admission Control, Obstacle Recognition, Emergency & Incident Detection, Emergency Response & Incident Clearing
		Subsystems	Network Routing Controller, Emergency Detection & Monitoring System, Obstacle Recognition System, Roadside Communication System.
		Name	**Network Routing Controller**
		Function	Highway to highway routing, Dynamic O-D demand estimation, Desired entry rate computation, current and predicted link travel time estimation
	Communication Systems	Name	**Roadside Communication System**
		Function	Two way communication between roadside control systems and AHMC and roadside control systems.
		Technology	Wireline Network
	Other Systems	Name	**Emergency Detection & Monitoring System**
		Function	Process road images to detect and recognize emergencies, process messages from section control systems to detect and recognize emergencies
		Name	**Obstacle Recognition System**
		Function	Process road images to recognize obstacles and process messages from vehicles, section control systems and other external agencies for the same.

C.2.1 AHS Function Descriptions

C.2.1.1 Speed Tracking

General Description: This function is provided by the *regulation control system* in conjunction with the inter-vehicle separation tracking function. For this purpose, the *regulation control system* receives desired reference speed and desired inter-vehicle separation from the *planning system*. Based on the actual and reference speed, an actuator command (throttle or brake) is calculated. The reference speed is tracked only if the vehicle in front is farther than the desired inter-vehicle separation and moving at least as fast. The speed tracking controller maintains passenger comfort standards for acceleration and jerk. The *regulation control system* needs information about vehicle speed and acceleration from the *self state sensing system* as well as front vehicle distance and relative velocity from the *neighborhood sensing system*.

Information Flow

Description	From System	To System
Desired reference speed	Planning system	Regulation control system
Desired inter-vehicle separation	Planning system	Regulation control system
Vehicle speed	Self state sensing system	Regulation control system
Vehicle acceleration	Self state sensing system	Regulation control system
Front vehicle distance	Neighborhood sensing system	Regulation control system
Front vehicle speed (relative)	Neighborhood sensing system	Regulation control system
Throttle command	Regulation control system	Throttle actuator system
Brake Command	Regulation control system	Brake actuator system

Highway Geometry Modification: None

C.2.1.2 Inter-vehicle Separation Tracking

General Description: This function is provided by the *regulation control system* in conjunction with the speed tracking function. For this purpose, the *regulation control system* receives desired inter-vehicle separation (either as distance or time headway) and desired reference speed from the *planning system*. Based on the actual and desired separation, an actuator command (throttle or brake) is calculated.
- In case of the platoon leader and free agent, the inter-vehicle gap is given by a constant-time or a constant safety factor separation. If the vehicle in front is farther than the desired inter-vehicle separation and moving at the same speed or faster, the

desired speed is tracked instead of the desired separation. Actual vehicle speed never exceeds reference speed during separation tracking.

- The followers of the platoon typically maintain a constant intra-platoon distance from the preceding vehicle. To avoid slinky (accordion type) effect, the controller needs values of acceleration of the preceding vehicle as well as velocity and acceleration of the lead vehicle of the platoon. This information is provided by short-range high data rate vehicle-vehicle communication.

The separation tracking controller also requires acceleration and jerk measurements to maintain passenger comfort.

Information Flow

Description	From System	To System
Desired inter-vehicle separation	Planning system	Regulation control system
Desired reference speed	Planning system	Regulation control system
Vehicle speed	Self state sensing system	Regulation control system
Vehicle acceleration	Self state sensing system	Regulation control system
Front vehicle distance	Neighborhood sensing system	Regulation control system
Front vehicle speed (relative)	Neighborhood sensing system	Regulation control system
Front vehicle acceleration, lead vehicle velocity/acceleration	Inter-vehicle communication (platoon follower operation)	Regulation control system
Throttle command	Regulation control system	Throttle actuator system
Brake Command	Regulation control system	Brake actuator system

Highway Geometry Modification: None

C.2.1.3 Lane Keeping

General Description: This function is performed by *regulation control system*. The objective is to maintain the vehicle in the center of the highway lane. The controller receives sensor readings from the *neighborhood sensing system* that describes the deviation of the vehicle from the center of the lane[2] and the lane geometry preview. The lane keeping controller sends a steering command to the *steering actuator system*. The

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[2] In case of magnetic marker/magnetometer system, the sensors directly provide deviation from the center of the lane. In case of cameras, the deviation must be calculated using the information about the lane markers in the image.

calculation of steering command requires the knowledge of the state variables of the lateral dynamical system such as lateral velocity, lateral acceleration and yaw rate.

Information Flow

Description	From System	To System
Deviation from the lane center	Neighborhood sensing system	Regulation control system
Road geometry preview	Neighborhood sensing system	Regulation control system
Lateral velocity	Self state sensing system	Regulation control system
Lateral acceleration	Self state sensing system	Regulation control system
Yaw rate	Self state sensing system	Regulation control system
Longitudinal velocity	Self state sensing system	Regulation control system
Steering command	Regulation control system	Steering actuation system

Highway Geometry Modification: Depending on the neighborhood sensing system, the highway should be modified so that the deviation from the lane center as well as lane preview can be easily obtained. Thus, for a magnetic marker/magnetometer system, magnetic markers/tape should be installed in the center of each automated lane. For vision system, lane markers should be appropriately marked/painted.

C.2.1.4 Lane Changing

General Description: This function is performed by *regulation control system*. The decision to change lane (either to the left or right) is taken by the *coordination system*. The function is split into two elemental functions, namely, gap alignment and move over.

Once the lane change decision is taken, the coordination system checks (using the *Neighborhood sensing system)* for the appropriate gap in the target lane. If the gap exists, the coordination system commands the regulation system to move over. If the gap does not exist, the coordination system uses the communication capabilities to coordinate with the neighboring vehicles so as to create the appropriate gap. The coordination protocol is described in Section C.2.1.11. If the coordination is successful, the coordination system commands the regulation system to execute gap alignment. Gap alignment involves acceleration/deceleration so as to align with a gap in the target lane. The gap alignment can take place due to joint movement of vehicles in both lanes.

The move over function involves planning a path for lateral movement to the target lane and commanding the steering actuator system to execute the path. Thus the complete lane change function involves both longitudinal and lateral movements.

Information Flow

Description	From System	To System
Lane change commands	Planning system	Regulation control system
Desired gap (in adjacent lane)	Planning system	Regulation control system
Vehicle speed	Self state sensing system	Regulation control system
Vehicle acceleration	Self state sensing system	Regulation control system
Lateral velocity	Self state sensing system	Regulation control system
Lateral acceleration	Self state sensing system	Regulation control system
Yaw rate	Self state sensing system	Regulation control system
Road geometry preview	Neighborhood sensing system	Regulation control system
Front vehicle distance & velocity	Neighborhood sensing system	Regulation control system
Relative distance & velocity of vehicles in target lane on either side of the gap	Neighborhood sensing system	Regulation control system
Steering command	Regulation control system	Steering actuator system
Acceleration command	Regulation control system	Acceleration actuator system
Braking command	Regulation control system	Brake actuator system

Highway Geometry Modification: Necessary modification depending on lateral sensing technology.

C.2.1.5 Road Geometry Recognition

General Description: The neighborhood sensing system on each vehicle is responsible for road geometry recognition. This information is mainly used by the regulation layer controller for maintaining lateral position along the center of the lane, lane changing and tracking of speed and inter-vehicle separation. A certain amount of road geometry preview is also needed for lateral control. The information can either be obtained by using *vision sensors* (cameras) mounted on vehicles that detect the *lane markers* on the road or by installing *magnetic markers/ magnetic tape* in the center of the lane and using *magnetometers* on the vehicle to sense the lane center. The *preview* information can either be encoded in the *magnets*, broadcast by *roadside beacons* or displayed on roadside *message signs* that can be sensed by the vehicle sensors.

C.2.1.6 Obstacle Recognition

General Description: Several systems perform the function of obstacle detection. In the reference state, the driver is not required to participate in obstacle detection. This concept

requires minimal obstacle detection as the infrastructure physical restrictions exclude many obstacles. The *vehicle neighborhood sensing system* and the *roadside sensing systems* (which consists of *stretch sensing system, entry sensing system, exit sensing system,* and, *merge sensing system*) both have (multiple) sensors for obstacle detection. Obstacle detection includes detection moving and fixed obstacles (including vehicles). If the roadside sensing system detects an obstacle (other than a normal moving vehicle), it sends communication messages (broadcast) to all vehicles in the appropriate geographical location. The information from multiple on-board sensors and roadside communications is fused in the vehicle obstacle recognition system in order to perform the obstacle recognition function. The obstacle recognition information is communicated back to the roadside.

Information Flow

Description	From System	To System
Obstacle detection information	Neighborhood sensing system	Obstacle recognition system
Obstacle detection information	Roadside sensing system	Obstacle recognition system of all vehicles in range (broadcast communication)
Obstacle detection information	Roadside sensing system	(other) Roadside control systems (wireline communication)
Obstacle recognition information	(vehicle) Obstacle recognition system	Roadside control systems

Highway Geometry Modification: Necessary changes to aid obstacle detection sensors on vehicles and roadside.

C.2.1.7 Obstacle Avoidance

General Description: Obstacle avoidance is performed by the vehicle on-board controllers. Driver assistance is not required in the reference state implementation. The *vehicle planning and coordination system* contains special obstacle avoidance maneuvers, such as following the moving obstacle at a safe distance, stopping behind a stationary obstacle or changing lanes to avoid an obstacle. It also contains the logic to select the appropriate maneuver. The *coordination control system* has the responsibility to coordinate the obstacle avoidance maneuver with the neighbors, communicating the maneuver decision to neighboring vehicles and roadside, as well as, asking the *regulation control system* to execute the obstacle avoidance maneuver.

Information Flow

All the information flow represented by the tables in Sections C.2.1.1, C.2.1.2, C.2.1.4, C.2.1.8, C.2.1.9, C.2.1.10, and C.2.1.11 is essential. Additional information flow is given by the following table.

Description	From System	To System
Obstacle recognition information	Obstacle recognition system	Planning & coordination system

Highway Geometry Modification: None

C.2.1.8 Speed Decision

General Description: The *planning system* on the vehicle receives reference speed command from the appropriate *roadside control system*. This message transfer can be achieved either by broadcast communication, roadside beacon, or by variable message signs that are read by the vehicle sensors.

The planning system uses this as an <u>advisory</u> information to calculate the desired reference speed for the *regulation control system* to track. Depending on the local conditions (road surface condition or environmental disturbances to sensing and communications) and the vehicle state, the planning system may ask the regulation controller to track a <u>lower speed </u>than the reference speed command it received from the roadside. This speed reflects the local safety requirements.

The roadside control system calculates the reference speed for the entire section taking into account safety and flow optimization. Refer to Section C.2.1.20 for AHS flow control description and the corresponding information flow table. We now present the additional information flow table.

Information Flow

Description	From System	To System
Reference speed command	Roadside control system	Vehicle planning system
Vehicle self state information (e.g., Brake pressure, Cornering stiffness)	Self state sensing system	Vehicle planning system
Environmental disturbance info	Neighborhood sensing system	Vehicle planning system
Desired reference speed	Vehicle planning system	Regulation control system

Highway Geometry Modification: None

C.2.1.9 Inter-Vehicle Separation Decision

General Description: Similar to the speed decision, the *planning system* on the vehicle receives reference inter-vehicle separation command (for both leader and follower operation) from the appropriate *roadside control system*. The separation policy is provided for all vehicle classes and it can be either fixed distance or time headway command. This message transfer can be achieved either by broadcast communication, roadside beacon, or by variable message signs that are read by the vehicle sensors. In the merge and entry sections, the suggested inter-vehicle separation may be higher so as to allow merging and entering vehicles to change lane.

Based on this information, the planning system calculates the desired reference inter-vehicle separation for the *regulation control system* to track depending on the local safety requirements.

The roadside control system calculates the reference inter-vehicle separation (for all vehicle classes) for the entire section taking into account safety and flow optimization. Refer to Section C.2.1.20 for AHS flow control description and the corresponding information flow table. We now present the additional information flow table.

Information Flow

Description	From System	To System
Reference separation command	Roadside control system	Vehicle planning system
Vehicle self state information (e.g., Brake pressure, Cornering stiffness)	Self state sensing system	Vehicle planning system
Environmental disturbance info	Neighborhood sensing system	Vehicle planning system
Desired reference separation	Vehicle planning system	Regulation control system

Highway Geometry Modification: None

C.2.1.10 Lane Change Decision

General Description: Vehicle *planning system* decides when to change lane. There are two main reasons to change lane in normal operations; to equalize the flow across AHS lanes, and to be able to exit. The *roadside control system* calculates the lateral flow requirements between lanes so as to balance the flow. It broadcasts this information along with the exit information to the vehicles in range. This functionality of the roadway control system proves to be very important in order to dissipate the resulting congestion after an incident. The vehicle planning system interprets this information to decide whether to change lane. Of course, close to the intended exit and during emergencies (e.g., obstacle avoidance), the vehicle planning system decides to change lane on its own. The change lane decision is passed to the vehicle *coordination control system*.

Information Flow

Description	From System	To System
Lane change proportions	Roadside control system	Planning system
Exit Information (distance to exit)	Roadside control system	Planning system
Obstacle information	Obstacle recognition system	Planning system
Lane change command	Planning system	Coordination system

Highway Geometry Modification: None

C.2.1.11 Lane Change Coordination

General Description: Once the lane change decision is taken by the *planning system*, the *coordination system* coordinates the lane change maneuver with the neighbors. The coordination involves finding appropriate gap in the target lane. If the gap exists, the vehicles next to adjacent lane are notified of the lane change intent (so as to avoid two vehicles changing lane into the same gap, i.e., the pinch maneuver). If the gap does not exist, communication is established with the neighboring vehicles in the adjacent lane in order to create a gap. The gap negotiations are successful if the other vehicle/platoon is not engaged in another maneuver. During the gap creation process, one or both vehicles decelerate/accelerate to align the gap with the vehicle that wants to change lane. After the gap alignment, the *regulation control system* is asked to execute the lateral move-over maneuver. If any time during the gap creation or alignment maneuver, safety of the vehicles in either lane is threatened, the maneuver is aborted.

Information Flow

Description	From System	To System
Lane change decision	Planning system	Coordination system
Relative positions and velocities of vehicles in two adjacent lanes (target & adjacent to target lanes)	Neighborhood sensing system	Coordination system
Relative position and velocity of vehicle in front	Neighborhood sensing system	Coordination system
Gap creation negotiation	Coordination system	Coordination system of neighboring vehicle in target lane
Lane change negotiation	Coordination system	Coordination system of neighboring vehicle in target lane
Lane change negotiation	Coordination system	Neighboring vehicle in next to target lane
Move-over command	Coordination system	Regulation control system
Gap alignment command	Coordination system	Regulation control system

Highway Geometry Modification: None

C.2.1.12 Platoon Formation and Dissipation

General Description: This function is only applicable to platooning. The above function can be decomposed further into elemental functions such as planning, coordination and execution of platoon formation and dissipation.

Planning: Depending on the traffic flow, the roadside control system decides a maximum platoon size that is communicated to the *planning system*. As platooning helps increase capacity, the planning system attempts to join with the platoon ahead whenever the *neighborhood sensing system* senses a vehicle in front as long as the combined platoon size does not exceed the maximum size. Platoons are separated so as to facilitate vehicles within the platoon change lanes and exit. Platoon splits may also occur due to reduction of maximum platoon size by the roadside control system. Depending on the lane change technology, a platoon may be split into up to three platoons with safe inter-platoon gap between them, or a small break-up allowing a vehicle to change lane/exit and then rejoin. The request for change lane from the planning system of one of the vehicles in a platoon initiates platoon separation.

Information Flow

Description	From System	To System
Maximum platoon size	Roadside control system	Planning system
Front vehicle distance	Neighborhood sensing system	Planning system
Platoon join or split command	Planning system	Coordination system

Coordination: Platoon leaders engage in structured exchange of messages to coordinate joining of two platoons or splitting of a platoon into two. The platoons check that their combined size will not be above the maximum platoon size and that they are not involved in any other maneuver at that time. Once the coordination is complete, the coordination system of the appropriate vehicle asks its *regulation control system* to execute the maneuver.

Information Flow

Description	From System	To System
Platoon join/split command	Planning system	Coordination system
Join/split negotiations	Coordination system	Coordination system of the vehicle in front/behind
Platoon join/split execution command	Coordination system	Regulation control system

Execution: The *regulation control system* executes the platoon join/split command. In the join maneuver, the platoon behind accelerates to catch up with the platoon in front. During the platoon split maneuver, the platoon splits at the designated location and the rear part of the platoon (which is now a separate platoon) decelerates to safe inter-platoon separation. Both maneuvers are executed as feedback control laws based on sensor readings of relative velocity and position of the vehicle in front. The maneuver may involve planning reference trajectory and then tracking it using feedback.

Information Flow

Description	From System	To System
Platoon join/split execution command	Coordination system	Regulation control system
Front vehicle relative velocity and position	Neighborhood sensing system	Regulation control system
Vehicle velocity and acceleration	Self state sensing system	Regulation control system
Throttle command	Regulation control system	Throttle actuation system
Brake command	Regulation control system	Brake actuation system

Highway Geometry Modification: None

C.2.1.13 Vehicle Operation Status Monitoring

General Description: This function is performed by the *vehicle self state sensing system*. The purpose is to monitor all subsystems of the sensing, communication, actuation and control system to determine if they are functioning at their full capability. If a loss of capability is detected, the *vehicle planning system* is notified. The planning system switches to a degraded mode of operation so as to ensure safety. The self state sensing system contains *fault detection and diagnosis subsystem* for performing sensor data

fusion. The *emergency detection system* works in a similar fashion except it is also responsible for emergency situations developing in the surroundings.

During entry, the vehicle operation status monitoring system is used to determine the capabilities of the vehicle to operate on the AHS. Vehicles that do not have the required capability are denied access to the AHS.

Information Flow

Description	From System	To System
Self state sensory data	Vehicle self state sensor system	fault detection/diagnosis system
Self state sensory data	Vehicle self state sensor system	Emergency detection system
Vehicle operation status info	fault detection/diagnosis system	Entry control system
Vehicle operation status info	fault detection/diagnosis system	Vehicle planning system
Emergency detection information	Emergency detection system	Vehicle planning system

Highway geometry Modification: None

C.2.1.14 Driver Status Monitoring

General Description: As the reference state does not require driver involvement for driving on the AHS, the driver status monitoring is used before hand-on to the driver takes place during exit. The objective of this function is to determine that the driver is alert (physically and mentally awake) and is ready to take over control. The vehicle has sensors to monitor the physical state of the driver and the mental awareness and readiness is signaled by the driver by taking partial control of the steering wheel. The sensors are also used to check if the driver is having physical problems (e.g., heart attack) during AHS operation. If any problem is detected, the vehicle planning system is notified which then takes vehicle out of the highway at the nearest exit. The overall task of driver status monitoring is performed by the *driver monitoring system*.

Information Flow

Description	From System	To System
Sensor readings about driver alertness	Driver sensing system	Driver monitoring system
Driver readiness to take over	Driver sensing system	Driver monitoring system
Driver alertness information	Driver monitoring system	Hand off control system
Driver physical alertness info.	Driver monitoring system	Vehicle planning system

Highway Geometry Modification: None

C.2.1.15 Vehicle Entry

General Description: This function is the entry of the vehicle into AHS from the non-AHS environment. Both the transition lane and dedicated entry/exit facilities are supported in this concept. The entry functionality is similar for both options. The differences are mainly in terms of the effects on safety, throughput and cost. The transition lane entry/exit affects the throughput of both the AHS and non-AHS highway lanes as both the traffic flows affect each other. The transition lane also requires gaps in the barriers that may enable a non-AHS vehicle to enter the AHS.

The entry function can be broadly categorized into <u>check-in</u> , <u>hand-off,</u> and <u>vehicle entry.</u>

<u>Check-in</u>: The driver drives the vehicle to the check-in station (which is at the beginning of the dedicated entry ramp or the transition lane). The vehicle status monitoring system (or the operator at check-in) certifies that the vehicle is capable of AHS operations. The check-in control system on the roadside check-in station allows the vehicle to proceed. Vehicles that fail check-in are routed back to the manual highway. The check in can be performed by many ways, such as on-the-fly, or while stopped at the check-in station, etc.

<u>Hand-off</u>: After check-in, the driver initiates the hand-off to the automatic control system on the vehicle (e.g., by pushing a button). After the hand-off, the vehicle is controlled by the vehicle control system.

<u>Vehicle-entry</u>: The infrastructure based *entry control system* determines the speed and density of traffic upstream of the entry point on the automated lane using its *entry sensing system*. If the entering traffic flow can not be accommodated, it creates the space by broadcasting lower speed or increased spacing decisions to the vehicles on the automated lane. The entry control system also calculates entry flow that can be sustained and uses that to set the metering rate. The entering vehicle accelerates such that by the time it reaches the entry point, its speed is same as the average speed of the traffic in the automated lane which is broadcast by the entry control system. Once on the AHS, the vehicle can use its sensors and inter-vehicle communication to coordinate a lane change maneuver to get onto the continuing automated lane. The gap negotiation is carried out by the *coordination system* and the gap alignment and move over executed by the *regulation control system*. Execution of entry as a lane change maneuver requires extended entry zone where the continuing lane and the entering lane are adjacent to each other so that the vehicles in both lanes can sense and communicate using on-board devices. Extending the entry zone may need additional infrastructure construction cost.

Information Flow

Description	From System	To System
Vehicle operation status info	Vehicle self state sensing system	Check-in control system
Vehicle check-in / reject	Check-in control system	Vehicle planning system
Hand-off control	Driver	Vehicle control system
Entry request	Vehicle planning system	Entry control system
Traffic flow information (AHS and non-AHS)	Roadside control systems, Entry sensing system, AHMC and ITS service providers	Entry control system
Suggested speed, separation on AHS	Entry control system (Broadcast)	Vehicle planning systems of vehicles on the automated lane
Entry metering	Entry control system	Entering vehicle planning system
Average speed on the AHS	Entry control system (Broadcast)	Entering vehicle control system
Relative positions and velocities of vehicles in two adjacent lanes (target & adjacent to target lanes)	Neighborhood sensing system	Coordination system
Relative position and velocity of vehicle in front	Neighborhood sensing system	Coordination system
Gap creation negotiation	Coordination system	Coordination system of neighboring vehicle in AHS lane
Lane change negotiation	Coordination system	Coordination system of neighboring vehicle in AHS lane
Move over command	Coordination system	Regulation control system
Gap alignment command	Coordination system	Regulation control system

Highway Geometry Modifications: Necessary modifications depending on the technology used for lateral movement and sensing of vehicles by entry sensing system.

C.2.1.16 Vehicle Exit

General Description: This function is the exit of the vehicle from AHS to non-AHS environment. Again, there are two configurations that are supported, dedicated exit and transition lane exit. Both of them are very similar in functionality. The exit consists of three functions, vehicle exit, hand-off and check-out.

Vehicle-exit: This function involves taking the vehicle from the automated lane to the exit ramp/transition lane. It is executed either as a regular lane change or as a highway split. The *vehicle planning system* gets the information about traffic flow on the transition lane/exit ramp from the *exit control system* on the road. The exit control system adjusts

the flow on the transition lane by issuing appropriate speed and separation commands. If the exit is congested, the exit control system may suggest rerouting the vehicle to the next exit. If the driver does not like the suggestion, the vehicle joins the queue on the ramp/transition lane which might ultimately slow down the traffic on the automated lanes.

Check-out: The vehicle passes the check-out station where the driver status monitoring system checks that the driver is ready to take over control. If the driver is not ready an attempt is made to alert him/her, otherwise the vehicle is automatically parked at the parking lot where assistance is provided. The check-out can be done either on-the fly or while the vehicle is stopped. Many other functions such as toll collection can be performed at the check-out.

Hand-off: If the driver is alert, the vehicle control is turned over to the driver. The driver has to follow a certain procedure to take over control. If he/she fails to do so, the control is returned to the automated system and the vehicle is taken to the parking lot. After taking over control, the driver drives onto the non-AHS street/highway. An exit-metering light is provided for flow control onto manual highway.

Information Flow

As in the case of entry, the vehicle coordination and regulation control system needs all information necessary to execute speed tracking, inter-vehicle separation tracking and lane change maneuvers. The following table shows additional information flow requirements.

Description	From System	To System
Information about traffic flow on the exit ramp/transition lane	Exit control system	Exiting vehicle planning system
Traffic flow information (AHS & non-AHS)	Roadside controllers, AHMC and ITS providers	Exit control system
Exit traffic flow/queuing information	Exit sensing system	Exit control system
Suggested speed and separation	Exit control system	Coordination system of vehicles on exit ramp/transition lane
Driver alertness report	Driver status monitoring system	Check-out control system
Wake up call	Driver status monitoring system	Driver
Hand-off control signal	Driver	Vehicle control system
Exit metering signal	Exit control system	Driver

Highway Geometry Modifications: Necessary modifications depending on the technology used for lateral movement and sensing of vehicles by exit sensing system.

C.2.1.17 Automated Highway Merging

General Description: This function is the movement of automated vehicles from one automated highway to another. As the neighborhood sensing system of the vehicles may not be able to detect gaps in the merging traffic because of difference in curvature, banking, elevation of the merging highway lanes, the two merging lanes need to be adjacent to one another for extended distance so that the merging vehicles can execute a regular lane change maneuver. The *merge control system* on the roadside uses *merge sensing system* to sense the traffic flow on merging lanes before and after merge-point and broadcasts suggested speed and separation to the vehicles on both highways in an attempt to create sufficient gaps in traffic for the lane changes at the merge-point. The system supports merging two streams of platoons. If the appropriate traffic density does not exist, the merge control systems can slow down the vehicles, increase inter-platoon separation or change the maximum platoon size. The merge control system also receives upstream flow information on merging highways from the AHMC and adjacent stretch control systems.

Information Flow

The vehicle coordination and regulation control system needs all information necessary to execute speed tracking, inter-vehicle separation tracking and lane change maneuvers. The following table shows additional information flow requirements.

Description	From System	To System
Traffic flow on the merging highways	Roadside control systems and AHMC	Merge control system
Traffic flow on merging lanes	Merge sensing system	Merge control system
Suggested speed, separation, platoon size on merging lanes	Merge control system	Vehicle planning system
Traffic speed and density on merging lanes	Merge control system	Vehicle planning system

Highway Geometry Modifications: Necessary modifications to help vehicle detection by merge sensing system and lane change/merging lateral control system on the vehicles.

C.2.1.18 Lane to Lane Routing

General Description: No explicit lane to lane route is computed in this concept during regular operation. Explicit lane to lane routes may be supplied to emergency vehicles in order to help them reach a particular site quickly. Refer to Section C.2.1.23 for the description.

C.2.1.19 Highway to Highway Routing

General Description: The network routing controller combines average entry and exit rates from the entry and exit controllers with historical data to generate dynamic O-D trip demand estimates.

Information Flow

Description	From System	To System
incident report, emergency report	Incident & Emergency Detection System	Network Routing Controller
average section speed, average section flow	Section Control System	Network Routing Controller
average entry rate	Entry Control System	Network Routing Controller
average exit rate	Exit Control System	Network Routing Controller
dynamic O-D trip demand estimates	ITS Information Service Providers	Network Routing Controller
current and predicted AHS link travel time estimates	Network Routing Controller	ITS Information Service Providers
current and predicted AHS link travel time estimates, recommended routes	Network Routing Controller	Vehicle Planning & Coordination System

C.2.1.20 AHS Flow Control

General Description: AHS flow control is achieved by controlling lane change rates for lane flow balancing, entry metering, speed regulation and inter and intra platoon separation regulation. Lane changes are regulated by broadcasting a lane and destination specific lane change fraction e.g., 60% of the vehicles traveling to exit d and in lane l should move to the right lane.

Information Flow

Description	From System	To System
desired speed, desired inter-platoon separation, desired intra-platoon separation, maximum platoon size	Stretch Control System	Vehicle Planning and Coordination System
desired entry rate	Section Control System	Entry Controller
lane and destination specific lane change fraction	Stretch Control System	Vehicle Planning and Coordination System

C.2.1.21 AHS Admission Control

General Description: This function consists of the regulation of entry rates. The network routing controller computes desired entry rates over a certain time period and communicates this to the section control system, which then modifies this based on section conditions and communicates a desired entry rate to each entry control system.

Information Flow

Description	From System	To System
recommended entry rate	Network Routing Controller	Section Control System
desired entry rate	Section Control System	Entry Control System
vehicle present or not present	Entry Sensing System	Entry Rate Controller
entry metering command	Entry Rate Controller	Vehicle Planning and Coordination System

C.2.1.22 Emergency Detection/Monitoring

General Description: Multiple information sources i.e., roadside sensing system, messages from the automated vehicles, and messages from other external agencies can be used for this function. It is assumed that the road image from the roadside sensing systems is transmitted to the AHMC where it can be processed for obstacle and incident detection or viewed by human operators.

Information Flow

Description	From System	To System
flow, speed, road image	Roadside sensing system	Incident & Emergency Detection System
road image	Roadside sensing system	Operator
obstacle information, emergency messages	Vehicle Planning and Coordination System	Neighboring Vehicle Coordination System
obstacle information, emergency messages	Vehicle Planning and Coordination System	Roadside Control System
obstacle information, emergency messages	Vehicle Planning and Coordination System	Incident & Emergency Detection System
emergency information	Law Enforcement Agencies	Incident & Emergency Detection System
emergency, incident information	ITS Information Service Providers	Incident & Emergency Detection System

C.2.1.23 Emergency Response and Incident Clearing

General Description: It is expected that for this function Emergency Service Providers will recommend emergency action plans and dispatch emergency vehicles as necessary for emergency medical services or for incident clearing. The section controller will adjust its flow control function by formulating lane change and speed policies to clear a path for emergency vehicles. It may communicate a lane to lane route to the emergency vehicle which is compatible with its flow control actions. The emergency vehicle will be able to communicate with the vehicles on AHS to obtain maneuver coordination. Emergency vehicle maneuvers will be assigned higher priority than the normal mode maneuvers.

Information Flow

Description	From System	To System
emergency report, incident report	Incident & Emergency Detection System	Network Control System
emergency report, incident report	Incident & Emergency Detection System	Emergency Service Providers
Description	**From System**	**To System**
emergency action plan, emergency vehicle dispatch	Emergency Service Providers	Network Control System
emergency response recommendation	Network Control System	Section Control System
position, destination, assistance request	Emergency Vehicle	Section Control System
recommended lane to lane route	Section Control System	Emergency Vehicle

C.2.1.24 Driver Interrupt Handling

General Description: Driver interventions are permitted for vehicle routing, exiting, obstacle recognition, emergency detection and incident detection. In all cases the driver requests are complied with only in a safe manner. If the safety of the driver or other vehicles will be compromised by compliance then the vehicle control systems will override the request.

Information Flow

Description	From System	To System
take next exit, take particular exit, take exit for a particular highway, follow particular route, stop request, obstacle of particular type and shape in particular location, emergency of particular type in particular location, ready to hand-off	Driver	Vehicle Planning and Coordination System
will exit shortly message, take control of vehicle request, emergency alert message, downstream congestion info, suggested rerouting	Vehicle Planning and Coordination System	Driver

C.3 Deployment Stage Variations

There exist a number of different possible deployment scenarios. This section summarizes two of them in Subsections C.3.1 and C.3.2.

C.3.1 A Market Driven Scenario

This scenario consists of six main stages. See Figure C-2 for chronological order. The structure of this scenario is identical to its Infrastructure-Assisted counterpart. However, the contents are actually quite different.
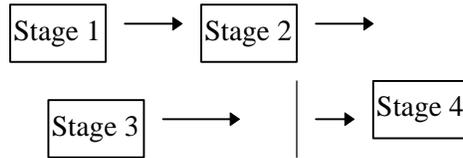
Figure C-2. A Market-Driven AHS Deployment Scenario

This scenario can be partitioned into three major different components of stages. Stages 1 and 2 are pre-AHS stages, which are designed to build up public demand for automation technology. Stage 3 constitutes an AHS but is designed to serve as a technological testbed for a fully automated AHS and to showcase user and societal benefits. In other words, it builds up the supply. Note that Stages 1 and 2 can be deployed in parallel with Stage 3. After the deployment of Stages 1, 2 and 3, Stages 4, 5 and 6 can then be deployed. Stages 4, 5 and 6 all constitute an AHS, but with different operational functionality. Stages 5 and 6 can be combined to provide congestion relief faster, if the technological difference between them turns out to be insignificant and the public is eager to adopt Stage 6.

The first two stages are identical to their counterparts of the market-driven deployment scenario for the Infrastructure-Assisted concept. However, the rest of this scenario is actually quite different from its Infrastructure-Assisted counterpart. The major differences stem from the lower functionality of this concept. Lack of active infrastructure assistance at merge points through infrastructure-to-vehicles-broadcast communication necessitates performing traffic merging through regular lane changes at the extended merge area. While it is likely that ITS services will induce vehicle owners to purchase communication features enabling communication between the infrastructure and the vehicle, it is not clear what might induce the vehicle owners to purchase the feature of vehicle-to-vehicle communication for purposes other than AHS and prior to deployment of AHS. We therefore do not assume that sufficient vehicles would be equipped with vehicle-to-vehicle communication capability when there is sufficient vehicle population adequately equipped for automated driving on one dedicated lane. As a result, during the first generally deployed AHS stage (Stage 4), lane-changing by free-agents (no platoons yet) for merging purposes at merge points like on-ramps is performed without vehicle-to-vehicle communication and coordination but with the information transmitted by the infrastructure. However, platoon lane-changing (to be supported in Stage 6) will likely require vehicle-to-vehicle communication and will be so supported in Stage 6.

In the absence of infrastructure assistance, identifying the communication parties and establishing (assigning) dedicated channels for the identified parties could be a technological challenge. Such assistance and assistance in facilitating safe and efficient

merging of two streams of traffic into one or lane-changing may be particularly valuable for platooning, due to the longer length of a platoon when compared to that of a free-agent. This further sets apart this deployment scenario from its Infrastructure-Assisted counterpart.

At this concept development stage, we propose to use regular lane-changing to achieve traffic merging at merge points (with an extended merge area). How infrastructure-to-vehicles-broadcast communication can safely and efficiently support true merging should be further investigated. Since such investigation requires much technological expertise, involvement of the Tech Team of the Consortium is recommended.

C.3.1.1 Stage 1: Delegation of Driving Chores

This stage has the following features:

- vision-based lane-line tracking for lane-keeping
- radar-based adaptive cruise control
- full driver supervision while delegating driving chores
- driver alertness and attentiveness monitoring
- usefulness on all roadways, including freeways and city-streets
- no infrastructure modification needed
- applicability to all vehicle classes
- trucking industry as a potential first customer

Geographical Scope: all roadways with lane lines
- rural highways
- city streets
- freeways

Vehicle Classes Supported: all vehicle classes, including trucks
Vehicle Type: partial automation
Absent AHS Functions: (See Functional Descriptions below.)
Identical AHS Functions: (See Functional Descriptions below.)

C.3.1.1.1 Functional Descriptions

Functions with a "+" indicate those being added at this stage. Those without that mark are to be provided at later stages.

+ 2.1.1 Speed tracking
+ 2.1.2 Inter-vehicle separation tracking
+ 2.1.3 Lane keeping
   2.1.4 Lane changing
+ 2.1.5 Road geometry recognition: only lines for current lane
   2.1.6 Obstacle recognition
   2.1.7 Obstacle avoidance

2.1.8 Speed decision
2.1.9 Inter-vehicle separation decision
2.1.10 Lane change decision
2.1.11 Lane change coordination
2.1.12 Platoon formation and dissipation
2.1.13 Vehicle operational status monitoring
+   2.1.14 Driver status monitoring
2.1.15 Vehicle entry
2.1.16 Vehicle exit
2.1.17 Automated highway merging
2.1.18 Lane to lane routing within a single highway
2.1.19 Highway to highway routing
2.1.20 AHS flow control
2.1.21 AHS admission control
2.1.22 Emergency detection/monitoring
2.1.23 Emergency Response and Incident clearing
2.1.24 Driver Interrupt Handling

C.3.1.1.2 Stakeholders' Participation

Stakeholder	Role	Benefits
Vehicle Industry	manufacturing, servicing	potentially large market
Vehicle Electronics	manufacturing, servicing	potentially large market
Highway Design & Construction	none	none
Trucking	use	comfort, safety & productivity
Transit	use	comfort, safety & productivity
Environmental Interests	neutral (AHS automating driving)	none
Transportation Users	use	comfort, safety & productivity
Government Agencies	none	none
Insurance	underwriting and collecting data	potentially large market

C.3.1.2 Stage 2: Delegation to More Automation, Under More Conditions

This stage features the following:

–   Stage 1 + more automation capabilities
     => higher degree of automation
     => useful under more driving conditions
–   still full driver supervision while delegating more driving chores
–   driver alertness and attentiveness monitoring continued
–   useful on all roadways
–   infrastructure modification begins

– lane markers
– infrastructure-to-vehicles-broadcast communication

Geographical Scope: all roadways
Vehicle Classes Supported: all classes
Vehicle Type: partial automation
Absent AHS Functions: (See Functional Descriptions below.)
Identical AHS Functions: (See Functional Descriptions below.)

C.3.1.2.1 Functional Descriptions

Functions with a "+" indicate those being added at this stage. Those with a "v" mark have been implemented in the previous stage(s). Those without that mark are to be provided at later stages.

v 2.1.1 Speed tracking
v 2.1.2 Inter-vehicle separation tracking
v 2.1.3 Lane keeping
+ 2.1.4 Lane changing: (turn-signaling included)
v 2.1.5 Road geometry recognition: neighboring lanes
+ 2.1.6 Obstacle recognition: limited, supervised by driver
+ 2.1.7 Obstacle avoidance: limited, supervised by driver
+ 2.1.8 Speed decision
+ 2.1.9 Inter-vehicle separation decision
+ 2.1.10 Lane change decision: limited, subject to driver supervision
     2.1.11 Lane change coordination
     2.1.12 Platoon formation and dissipation
+ 2.1.13 Vehicle operational status monitoring
v 2.1.14 Driver status monitoring
     2.1.15 Vehicle entry
     2.1.16 Vehicle exit
     2.1.17 Automated highway merging
     2.1.18 Lane to lane routing within a single highway
     2.1.19 Highway to highway routing
     2.1.20 AHS flow control
     2.1.21 AHS admission control
     2.1.22 Emergency detection/monitoring
     2.1.23 Emergency Response and Incident clearing
     2.1.24 Driver Interrupt Handling

C.3.1.2.2 Stakeholders' Participation

Stakeholder	Role	Benefits
Vehicle Industry	adding features	potentially large market
Vehicle Electronics	adding features	potentially large market
Highway Design & Construction	adding markers & comm	profit
Trucking	use	more comfort, safety & productivity
Transit	use	more comfort, safety & productivity
Environmental Interests	neutral	none
Transportation Users	use	more comfort
Government Agencies	infra. investment	safety and traffic control
Insurance	insuring and collecting data	potentially large market

C.3.1.3 Stage 3: Testbed and Showcase of Full Automation

The features of this stage are:

- – full bus automation: hands-off and feet-off on dedicated lane(s)
- – closed system
- – physically segregated bus and HOV lane
- – vehicles centrally maintained and inspected
- – supervised by professional drivers
- – technology testbed
- – with infrastructure-to-vehicles-broadcast communication
- – with vehicle-to-vehicle communication
- – system benefits showcase

Note that, in this concept, merging of two streams of traffic into one is performed through vehicle/platoon lane-changes.

Geographical Scope: closed systems, e.g., Lincoln Tunnel, etc.
Vehicle Classes Supported: bus
Vehicle Type: full automation
Absent AHS Functions: (See Functional Descriptions below.)
Identical AHS Functions: (See Functional Descriptions below.)

C.3.1.3.1 AHS Function Descriptions

+ 2.1.1 Speed tracking
+ 2.1.2 Inter-vehicle separation tracking
+ 2.1.3 Lane keeping
+ 2.1.4 Lane changing

+ 2.1.5 Road geometry recognition
+ 2.1.6 Obstacle recognition
+ 2.1.7 Obstacle avoidance
+ 2.1.8 Speed decision
+ 2.1.9 Inter-vehicle separation decision
+ 2.1.10 Lane change decision
+ 2.1.11 Lane change coordination
+ 2.1.12 Platoon formation and dissipation
+ 2.1.13 Vehicle operational status monitoring
+ 2.1.14 Driver status monitoring
+ 2.1.15 Vehicle entry: check-in can be done at garages
+ 2.1.16 Vehicle exit
   2.1.17 Automated highway merging
+ 2.1.18 Lane to lane routing within a single highway
+ 2.1.19 Highway to highway routing
+ 2.1.20 AHS flow control
+ 2.1.21 AHS admission control
+ 2.1.22 Emergency detection/monitoring
+ 2.1.23 Emergency Response and Incident clearing
+ 2.1.24 Driver Interrupt Handling

Note that Function 2.1.17 (Automated Highway Merging) is not explicitly supported.

C.3.1.3.2 Stakeholders' Participation

Stakeholder	Role	Benefits
Vehicle Industry	technology testbed	technology verification
Vehicle Electronics	technology testbed	technology verification
Highway Design & Construction	infrastructure mod.	little but high potential
Trucking	none	none
Transit	use	comfort, safety & productivity
Environmental Interests	support	people throughput
Transportation Users	transit users use	trip time reduction, comfort, safety
Government Agencies	investment	people throughput, cong. red.
Insurance	collecting data	potential large market

C.3.1.4 Stage 4: Segregated and Infrastructure-Supported "Free-Agents" with Infra-V. comm but without V-V Comm.

This stage features:

- full automation on a single dedicated lane (no mixing with manual v.); since merging, e.g., at on-ramps, is performed through vehicle lane-changing from the merge ramp to the single mainline lane, lane-changing is required
- infrastructure -> v. comm. required
- free-agent (no platoons yet) lane-changing for merging of two streams of traffic into one is performed on the extended merge area, without vehicle-to-vehicle communication, but with the information provided by the infrastructure
- lane-changing at merge area facilitated by infrastructure's broadcasting of non-vehicle-specific information about (i) vehicle position tracking on the mainline and the merge area and (ii) speed and spacing regulation on the mainline and the merge area
- "pricing out" vehicles with lower automation capabilities, e.g. those with no V<->V and infra.<->V comm.

Geographical Scope: adding or converting a dedicated lane
Vehicle Classes Supported: all + electrical and other 0-emission classes
Vehicle Type: mixing vehicles with different auto. capability
Absent AHS Functions: (See Functional Descriptions below.)
Identical AHS Functions: (See Functional Descriptions below.)

C.3.1.4.1 AHS Functional Descriptions

v 2.1.1 Speed tracking
v 2.1.2 Inter-vehicle separation tracking
v 2.1.3 Lane keeping
v 2.1.4 Lane changing
v 2.1.5 Road geometry recognition
v 2.1.6 Obstacle recognition
v 2.1.7 Obstacle avoidance
v 2.1.8 Speed decision
v 2.1.9 Inter-vehicle separation decision
   2.1.10 Lane change decision
   2.1.11 Lane change coordination
   2.1.12 Platoon formation and dissipation
v 2.1.13 Vehicle operational status monitoring
v 2.1.14 Driver status monitoring
+ 2.1.15 Vehicle entry
+ 2.1.16 Vehicle exit
   2.1.17 Automated highway merging
   2.1.18 Lane to lane routing within a single highway
+ 2.1.19 Highway to highway routing
+ 2.1.20 AHS flow control
+ 2.1.21 AHS admission control
+ 2.1.22 Emergency detection/monitoring

+ 2.1.23 Emergency Response and Incident clearing
+ 2.1.24 Driver Interrupt Handling

C.3.1.4.2 Stakeholders' Participation

Stakeholder	Role	Benefits
Vehicle Industry	manufacturing and servicing	potential large market
Vehicle Electronics	manufacturing and servicing	potential large market
Highway Design & Construction	infra. intel. & construction	potential large market
Trucking	use	prod., comfort & safety
Transit	use	safety, comfort & prod.
Environmental Interests	neutral (0-emission vehicles)	none
Transportation Users	use	trip time reduction
Government Agencies	funding	system throughput and safety
Insurance	underwriting & coll. data	potential large market

C.3.1.5 Stage 5: Segregated and Infrastructure-Supported "Free-Agents" with Infra-V. and V-V Comm.

The main features of this stage are

- full automation on multiple dedicated lanes
- v-v and infrastructure <-> v. comm. required
- merging through lane-changing at the extended merge areas performed more efficiently through v-v maneuver coordination enabled by the required v-v communication capability
- regular lane-changing also coordinated through v-v comm.
- spontaneous platooning
- "pricing out" vehicles with lower automation capabilities, e.g. those that cannot platoon

Geographical Scope: more dedicated AHS lanes
Vehicle Classes Supported: all, including 0-emission ones
Vehicle Type: mixing of vehicles with different auto. capabilities,
Absent AHS Functions: (See Functional Descriptions below.)
Identical AHS Functions: (See Functional Descriptions below.)

C.3.1.5.1 AHS Functional Descriptions

v 2.1.1 Speed tracking
v 2.1.2 Inter-vehicle separation tracking
v 2.1.3 Lane keeping
v 2.1.4 Lane changing

v 2.1.5 Road geometry recognition
v 2.1.6 Obstacle recognition
v 2.1.7 Obstacle avoidance
v 2.1.8 Speed decision
v 2.1.9 Inter-vehicle separation decision
+ 2.1.10 Lane change decision
+ 2.1.11 Lane change coordination
+ 2.1.12 Platoon formation and dissipation
v 2.1.13 Vehicle operational status monitoring
v 2.1.14 Driver status monitoring
v 2.1.15 Vehicle entry
v 2.1.16 Vehicle exit
  2.1.17 Automated highway merging (performed through lane-changing)
+ 2.1.18 Lane to lane routing within a single highway
v 2.1.19 Highway to highway routing
v 2.1.20 AHS flow control
v 2.1.21 AHS admission control
v 2.1.22 Emergency detection/monitoring
v 2.1.23 Emergency Response and Incident clearing
v 2.1.24 Driver Interrupt Handling

C.3.1.5.2 Stakeholders' Participation

Stakeholder	Role	Benefits
Vehicle Industry	manufacturing and servicing	potential large market
Vehicle Electronics	manufacturing and servicing	potential large market
Highway Design & Construction	intel. enhancement	potential large market
Trucking	use	prod., comfort & safety
Transit	use	safety, comfort & prod.
Environmental Interests	neutral (0-emission included)	none
Transportation Users	use	more comfort (flow stability), more trip time reduction, more safety
Government Agencies	funding	more throughput, safety
Insurance	underwriting & coll. data	potential large market

C.3.1.6 Stage 6: Segregated and Infrastructure-Assisted Platooning with Infra-V. and V-V Comm.

The main additional features of this stage include:

– platooning, during peak hours and perhaps on designated lanes only
– vehicles without v-v and infra-v comm. disallowed

Note: Stages 5 and 6 can be combined to provide large capacity gain faster.

Geographical Scope: designating platooning lanes
Vehicle Classes Supported: all vehicle classes
Vehicle Type: mixing vehicles with different capabilities, e.g. "free-agent" vs.
"platooning"
Absent AHS Functions: (See Functional Descriptions below.)
Identical AHS Functions: (See Functional Descriptions below.)

C.3.1.6.1 AHS Function Descriptions: ALL will be available for platoon maneuvers. Traffic merging will not be explicitly supported.

C.3.1.6.2 Stakeholders' Participation

Stakeholder	Role	Benefits
Vehicle Industry	manufacturing & servicing	potential large market
Vehicle Electronics	manufacturing & servicing	potential large market
Highway Design & Construction	intel. enhancements	potential large market
Trucking	use	prod., comfort & safety
Transit	use	more trip time reduction
Environmental Interests	neutral	none
Transportation Users	use	more trip time reduction
Government Agencies	funding	more throughput
Insurance	underwriting	potential large market

C.3.2 A High-Level Market-Policy Driven AHS Deployment Scenario

This subsection describes at a high level a market and policy driven AHS deployment scenario.

This scenario has four major stages, which are accompanied by deployment of automotive enabling technologies in parallel. The following three major automotive technologies serve as a backdrop for the deployment of AHS:

a. Electronic throttle control
b. Electronic power steering
c. Electronic brake control

The four stages are

Stage 1: Adaptive Cruise Control (ACC)
Stage 2: ACC plus lane departure warning
Stage 3: Automated lane built on special-purpose facility

The special-purpose facilities include:

- urban commuter tollway
- urban HOV/transitway
- urban truck lane

The incremental user services include:

- fully automated driving (hands-off and feet-off) on a dedicated lane: no mixing of automated vehicles with manually driven vehicles in the same lane
- end-to-end service (no merging or lane changing), free agents
- add more entry/exit points, extend length
- add mixed vehicle classes
- add platoons as traffic level increases

Stage 4: Automated lanes expanded to network

- extend from individual link(s) to network
- connect multiple roadways
- extend from single to multiple lanes as traffic levels increase

C.4   Local Tailorability

The Infrastructure supported concept offers the following architectural options in its final deployment. A valid combination is one choice from each of the five pairs. There are 16 local options. All are expected to be compatible with the concept. It is assumed that all automated traffic is on dedicated lanes.

1. platooning or free agent
2. single or multiple lanes
3. dedicated or transition lane entry and exit.
4. global infrastructure supported flow control or static sign flow control

All 16 combinations are expected to be equally safe. In general, the different combinations will differ in the maximum throughput levels they can support and the sophistication of flow control they offer. Enhanced flow control capability can be used to facilitate inter-jurisdictional cooperation, corridor control, inter-modal interaction and flexible pricing. It can also be used to improve service reliability. Just as the different combinations differ in the benefits they offer, they will also differ in their investment requirements. Thus local communities may construct architectures by choosing options

based on their needs. Possible dimensions defining need may be
- average area travel demand
- time of day travel demand
- travel demand by vehicle automation level
- manual vehicle travel demand
- highway real estate availability and cost
- desired benefit levels
- public investment priorities

We highlight salient features of the architectural options by discussing two examples.

Example 1: A typical rural area, after analyzing some of the given dimensions, may choose to support free agent operation, single dedicated lane, transition lane entry and exit, and static signage flow control. This combination is expected to have the lowest control and communication infrastructure cost. It also supports the largest class of automated vehicles since it has the minimal set of vehicle system requirements, i.e., systems for long vehicle following, lane keeping, gap alignment, lane-shift and obtain information via static road signs. More sophisticated vehicles remain compatible.

Example 2: An urban area with high volume traffic may choose to support platooned operation, multiple lanes, dedicated entry and exit, and global infrastructure supported flow control. This combination is expected to have the highest control and communication infrastructure costs. It also has the maximal set of vehicle system requirements, though it is expected to deliver the highest level of benefit. The global infrastructure supported flow control can be used for fast and reliable incident identification and clearing, thus reducing trip time variance. It can be used for vehicle lane assignment to achieve transit priority, people priority (HOV), commercial vehicle lanes. The twin benefits of trip time reliability and priority lane assignment can support flexible pricing schemes to manage congestion and yield higher returns on investment. The tighter flow control capabilities can be used for the dynamic re-allocation of freeway capacity to balance congestion in different freeway/arterial corridors. This allows inter-jurisdictional coordination in the form of coordinated control of multiple transportation networks. Increased freeway trip time reliability and priority lane assignment to transit or other commercial traffic facilitates inter-modal planning and interfacing. The global dynamic flow control capability can be used to support time of day variations such as platooning during peak period congestion and free agent operation during lean congestion periods. It can be used to broadcast vehicle class specific separation policies for, e.g., special isolation of HAZMAT vehicles.

C.5   Degraded Modes of Operation

Distributed intelligence allows robust fault tolerant operation and graceful degradation of

performance in case of failures or adverse environmental disturbances. A closer examination of the functionality of each system reveals the following information.

- The infrastructure control system is not safety critical for the operation of automated vehicles on the AHS. Therefore a loss of functionality by the infrastructure (either due to infrastructure system failure or infrastructure to vehicle communication failure) does not result in reduced safety for vehicles. The throughput can no longer be optimized globally. The failure of the overall infrastructure controller will be a very rare occurrence because of the distributed design of the infrastructure controller itself. Each link of the roadway is divided into several stretch control systems which are independent but communicate with each other and with the AHMC over wireline network (high reliability). Therefore the probability of all the stretch control systems failing simultaneously is very slim. A single stretch control system failure affects the throughput locally. Similarly a failure in the wireline network may result in some of the stretch control systems not receiving network wide global traffic information which might result in slight loss of throughput.

- The physical infrastructure at the entry/exit/merge locations is designed such that the maneuvers can be executed as a regular lane change with suggested speed and separation information from the infrastructure based entry/exit/merge controllers. Again, because of the distributed design, the probability that all the entry or exit or merge control system will fail simultaneously is very low. If one of these controllers fails, the maneuvers can still be carried out at a lower efficiency at a reduced speed and (probably) by reverting to free agent mode of operation.

- The automated vehicle with its sensors, actuators, communication devices and controllers can operate safely by itself without infrastructure assistance. There are three modes of operation for any vehicle; as a platoon leader, platoon follower or free agent. There may be different sensors and communication devices for short range and long range operation. The functionalities of these different sets of sensors and communication devices can be used to supplement the reduction in capability due to failure.

- The inter-vehicle communication capability allows notification of failures to neighboring vehicles and can be used to execute emergency maneuvers so that the faulty vehicle can safely exit, or stop on the shoulder/lane. Thus, the communication (vehicle-vehicle, vehicle-infrastructure) can be effectively used to localize the extent of a fault so that the performance within a small neighborhood of the faulty vehicle is temporarily affected and the rest of the highway operation continues undisturbed.

- In case of an on-board vehicle failure, the infrastructure control system can inform the neighboring vehicles and secure their assistance in taking the faulty vehicle to the shoulder or exit.

- Special maneuver protocols and control laws are designed for emergencies and degraded modes of operation so as to ensure the safety of the faulty vehicle. These maneuvers are assigned higher priority than the normal mode maneuvers (join, split, lane change, entry, exit), thereby ensuring that the neighboring vehicles will immediately assist the faulty vehicle to execute the emergency maneuver. The faults can be classified according to their effect on the capability of the automated vehicle, and then degraded mode strategies can be designed for faulty vehicles. The purpose of

the emergency maneuvers is to localize the fault and assist the faulty vehicle to stop (in the lane or on the shoulder) or take the next exit.

- In case of an incident (such as a collision, stopped vehicle, etc.), the infrastructure control system can actively participate in dissipating the congestion and providing access to emergency vehicles.

In summary, the distribution of intelligence allows fault localization and rapid response to clear an incidence or help the faulty vehicle to safely continue travel, take the next exit or stop. The platooning organization implies multiple modes of operation thereby allowing the failed vehicle to be assisted in several efficient ways. Even vehicles with brake failures can be stopped safely with assisted braking from the preceding vehicle in the platoon. In terms of layered functionality, if the roadside control system fails or loses contact with the vehicles, the vehicles can operate in cooperative mode. If the vehicle can not communicate with other vehicles, it can still function as a free agent autonomous vehicle with highly reduced functionality until it reaches the nearest exit. If the AHMC or the communication between AHMC & sectional controller fails, the sectional controllers can still operate using local information. Thus, the concept allows a gradual degradation of performance in case of failures of increasing severity while maintaining safety.

We look at specific failures of some of the systems and the corresponding degraded modes of operation:

1. Stretch Control System: The stretch control system supplies the information to improve throughput, such as desired speeds, lane change proportions, averages delays downstream, etc. Even if this information is unavailable to the vehicle (because of the infrastructure controller being down), the vehicles can still operate as cooperative vehicles and follow the posted speed limits. There won't be dynamic updates about downstream traffic conditions and incidents which can reduce throughput. If the infrastructure capability of detecting obstacles and relaying this information is also lost, then the vehicles have to rely solely on the on board obstacle detection system. At this point, they might reduce the speed and increase the spacing so as to increase safety. Overall, this is not a safety critical system.

2. Entry, Exit, Merge Controller: The infrastructure based entry, exit and merge control systems communicate traffic flow information to traffic in both lanes and broadcast suggested speed and separation so that lane changes at the entry, exit and merge locations can be efficiently executed. If a particular entry (exit) control system develops a failure, as the entry (exit) lanes are long enough, the automated entry/exit can still be carried at a reduced speed or reduced entry rate and possibly using free agent mode of operation. This requires a backup beacon/message sign system that informs the vehicles in the automated lane to slow down and not to engage in any maneuver. In this mode, the entrance ramp also invokes a backup entry metering system that allows entry at a slow rate. In case of merge controller failure, the platooning mode is turned off and desired speed reduced near affected area to allow sufficient time for vehicles to complete their lane change maneuvers in the space provided. Again, the performance of the system may reduce, such as missed exits, slow entry rate, etc. but the safety of the vehicles is not affected.

3. <u>Inter-Vehicle Communication (Regulation):</u> If vehicle-vehicle communication used for intra-platoon information exchange does not work for a vehicle, then the faulty vehicle can not be part of a platoon, but it can still function as a free agent. This affects the capacity of the local neighborhood but otherwise has no effect on safety or global throughput.
4. <u>Neighborhood Sensing System:</u> If any of the sensors in the neighborhood sensing system fail, then the redundant sensors (or sensor readings from other sensors with data processing, e.g., acceleration information can be extracted by differentiating the speedometer output) are used. The vehicle immediately breaks up from its platoon and operates as a free agent. It should take the immediate exit using degraded mode maneuvers and get the problem repaired at a service station.
5. If the ability to be a free agent or a leader goes down, (e.g., multiple sensor failure, inter-vehicle communication failure, etc.) then the vehicle can stop, either in the middle of the lane or on the shoulder if the adjacent lanes are lightly loaded and the capability to change lane using sensors still exists. On the other hand, the vehicle may still be able to function as a follower in a platoon. In this case, it can be electronically towed out (to the shoulder or the exit) by another normal operating vehicle, acting as a lead vehicle, using degraded mode maneuvers.
6. <u>Inter-Vehicle Communication (Maneuver Coordination):</u> If the inter-vehicle communication fails, the faulty vehicle can still operate as a free agent, but all the maneuver executions must be entirely sensor based. Thus in a dense traffic scenario, the vehicle will not be able to change lanes. If its infrastructure communication system is working, the vehicle can notify the infrastructure which in turn may increase the inter-platoon spacing so that the faulty vehicle can change lane and exit the highway.
7. <u>Actuation System:</u> If the throttle or the steering actuators fail, the vehicles applies emergency braking to come to a halt. If the brake actuator goes down & if the vehicle is operating as a follower, the vehicle ahead can help this faulty vehicle to come to a halt. The faulty vehicle can be allowed to collide with preceding vehicle at a very low velocity without affecting the safety of vehicles or the passengers. The assisting vehicle can then bring both the vehicles to a stop.
8. Robust controllers are designed for some of the critical failures such as tire burst, range, range rate sensor failures, accelerometer failures, and actuator failures so that the vehicle can still function at a reduced speed and functionality.
9. The normal mode and degraded mode control laws are designed such that in inclement weather condition, the parameters of the controller (such as required gap for lane change, speed, inter-vehicle separation, etc.) can be tuned so as to maintain safety. The performance (throughput) of the system will be reduced due to inclement weather conditions. The information about the environmental disturbances is obtained via multiple sources, including broadcast from infrastructure, on-board sensors and estimation algorithms in the regulation layer controllers that identify vehicle parameters such as tire cornering stiffness, rolling resistance, road surface condition, etc.

The highly distributed and layered configuration of the system implies that only

extremely rare combinations of multiple simultaneous system failures could produce catastrophic conditions.

Degraded AHS Function Description Table

Degraded AHS Function	Cause of Degradation	Degraded Mode of Operation
Throughput Optimization	Stretch control system failure	Vehicles perform their own routing based on static info.
Efficient entry/exit/merging	Entry/Exit/Merging system failure	Low speed free agent operation entry/exit/merging
Throughput	Environmental disturbances (inclement weather)	(Depending on the disturbance) Increase spacing, Decrease speed, Update maneuver control law parameters, etc.
A vehicle can not operate in a platoon	Inter-vehicle communication fail (necessary for follower operation) or short range sensing failure	Vehicle operates as a free agent
Vehicle actuation & steering	Throttle, steering failure	Vehicle stops on the highway
Vehicle braking	Brake failure	1. Front vehicle in the platoon can assist to stop 2. Vehicle slowly stops by itself
Maneuver coordination	Inter-vehicle comm. Failure	Vehicle stops either on the road or on shoulder
Any	Multiple on-board systems failure	Vehicle stops
Sensing of surrounding vehicles or self state	Self state or neighborhood sensor failure	Vehicle uses info obtained from other sensors and communication to safely change lanes and exit or stop on shoulder.

C.6   Societal and Institutional Factors

What we are looking for are societal and institutional factors, both potential advantages and disadvantages, relative to this concept that may be used as a concept discriminator to assist in the concept evaluation process. Societal and institutional factors are discussed and are felt to be concept discriminators, however, the discrimination between the two infrastructure-based concepts, supported and assisted, has thus far not been made.

- Being part of the MPO/State DOT planning and decision-making process

The deployment of automated highway systems (AHS) will require flexibility so that it can be shaped to fit the planning and decision-making processes at the MPO and State DOT levels. The AHS alternative will have to compete with other transportation options to address problems such as congestion and air quality. Infrastructure plays a substantial role in this concept via providing dynamic signage information to vehicles. The question to ask in order to discriminate among the five concept families is the following: With what degree of ease or difficulty does this concept fit into the planning and decision-making processes at the regional and state levels? The AHS having both vehicle and infrastructure components could make satisfying this factor more complex than for other concepts.

- Public and private roles in AHS construction, operation, and maintenance

The construction, operation, and maintenance of an AHS, in particular, the funding of each of these factors, the extent of institutional involvement, and institutional inter-relationships are important factors to consider as concept discriminators. The AHS having both vehicle and infrastructure components could make this factor more complex than for other concepts.

- Liability implications and other legal issues

    The identification of such legal issues is significant and will serve as concept discriminators. Such issues were explored during the PSA studies and it was concluded there that most of these are not unique to AHS and/or that they are being addressed through earlier ITS technology deployments, e.g. privacy. These issues must be monitored throughout the NAHSC process for their implications on design and deployment. The one issue that is believed to have implications unique to AHS is liability. Examples of potentially relevant legal requirements and principles include those pertaining to:

        liability for traffic accidents resulting from the transfer of control from the driver to   the vehicle and/or the roadway including allocation of responsibility among the driver, vehicle manufacturer, vendors of other components, and the AHS highway authority.

- liability for accidents from catastrophic system failure

Examples of issues that could arise from application of such principles to AHS include:

- whether highway authorities or vehicle manufacturers will be subject to unacceptable liability risk for accidents caused by an AHS malfunction
- whether vehicle manufacturers will demand a high degree of standardization in AHS approaches to reduce liability risk
- whether drivers' privacy rights or the public's right to information could subject highway authorities to unacceptable liability risks

The AHS having both vehicle and infrastructure components with an option of driving in platoons could make this factor more complex than for other concepts.

- Human in the system issues

Ensuring a very high degree of safety and driver confidence will be critical for AHS to be successful. Such assurance is complex to achieve in aviation, where operators, i.e. pilots, must have hours of training and pass certification and licensing tests. It will be more difficult in a highway environment, as vehicle operators, i.e. drivers, are likely to include anyone with a valid driver's license. Human-in-the-system factors that arise and that will differ across the concepts include the following:

- psychology of human responses to automation (willingness and comfort level associated with giving up control of driving)
- driver performance under circumstances of automated control
- acceptability of hands off vehicle movement at high speed
- ease with which driver resumes control upon transfer from automated to manual operation
- driving under conditions of lane width reduction or close proximity to physical barriers
- adaptability to driving in a platoon formation

- Integrating AHS with transit operations from an S&I perspective

Transit has the potential to have significant benefits in such roadway transportation problem areas as congestion, safety, air quality, and fuel consumption, and in addressing social equity, land use, and other environmental issues of AHS. Transit provides the opportunity for AHS to serve the needs of people and markets other than automobile owners and drivers. Transit applications, particularly in early deployments, also offer the opportunity to demonstrate AHS technologies with a group of trained drivers and vehicle maintainers. In addition to the technical issues associated with fully integrating transit vehicles into an AHS concept, there are numerous non-technical issues as well that should be considered upon examination of the five concepts. The transit industry is an

important stakeholder and it could have concerns about the extent of the technological changes associated with a particular AHS concept and the degree they may be accepted within the industry. Other concerns include the potential changing role of the driver with the potential for changes in driver training, salaries, work rules, insurance, liability, and management/labor relationships.

- Social equity considerations for AHS

An often heard concern from some AHS critics that needs investigation is their perception that AHS will not be accessible to all people and it has a responsibility to develop a system that is maximally accessible as possible at least partly since the NAHSC is a publicly funded program. AHS is viewed by some critics as "another toy for the rich". This issue of accessibility is related to cost, ability and willingness to pay, and breadth of vehicle types that are amenable to automation. For example, the successful integration of AHS with transit operations that ultimately improves transit safety, level of service, and even potentially, increases ridership could go a substantial way toward moderating the criticism of AHS as elitist. At least qualitatively, this factor is a concept discriminator.

- Transportation/land use interactions and linkages with emissions and fuel consumption

There are travel-related factors stemming from concerns over the consequences of AHS implementation and operation on how much more travel is made, by what means and its impacts on vehicle emissions and fuel usage.

The current transportation paradigm or model of "how things are done" or "the way the urban transportation system works" may be described succinctly as people driving alone in their cars on vast networks of urban freeways that over time has led to urban sprawl. The issue is that AHS, as currently envisioned by some critics, would only encourage the continuation of this same type of "business as usual" behavior, i.e. more driving, more single-occupancy-vehicle (SOV) driving, and more urban sprawl. AHS would emphasize the further development of highways and make only SOV driving more attractive by increasing its convenience and comfort at the expense of other modes of travel, such as public transit and high-occupancy-vehicle (HOV) driving.

The encouragement of more SOV driving could then mean an increase in trips, trip length, and volume of drivers, even above what such increases might be over time without automated highway systems. These effects could be the result unless there were in place strong measures to counteract them, such as (1) transportation demand management, (2) congestion pricing, (3) parking pricing, and (4) land use planning and management. The AHS program has not been viewed as having mitigating measures such as these or others at a central and important place in its research and development effort.

The concern that automated highway systems would encourage and eventually lead to an increase in driving is also referred to as the induced or latent demand effect. Recall that induced demand may be moderated by the advent of the measures such as transportation demand management or land use planning and management. Associated with induced demand is a concern for the potential increase in vehicle emissions. Several variables, however, play a role in the determination of the actual net impact on emissions.

Emissions may be affected through changes in the (1) operation of the vehicle, (2) number of drivers, (3) volume of trips, and (4) trip length. The most prevalent environmental concerns expressed about automated highway systems concerned the potential for leading to increases in volume of drivers, trips, and trip length, which on an aggregate basis in terms of total emissions' tonnage, would mean an emissions' increase. Moreover, certain pollutants, such as, oxides of nitrogen, tend to increase with increases in speed. Thus, with more freely flowing traffic and greater speeds associated with AHS, amounts of such pollutants could increase. Also, if vehicles accessing or egressing the AHS develop into lengthy queues, additional emissions' build-ups could result at the on- and off-ramps.

AHS research and development, however, will proceed along with other technological advances in areas such as emission control technologies, clean fuels, electric vehicles and other areas that could have the effect of reducing emissions on a per mile basis. Moreover, AHS associated with these two infrastructure concepts could smooth out the flow of traffic, remove or at least reduce stop-and-go, idling, and sharp acceleration and deceleration driving modes which contribute to vehicle emissions. Moreover, in the context of automated vehicles traveling with much smaller headways than presently possible, i.e., in platoons, preliminary research has indicated there are emission reductions for all vehicles, including the lead vehicle.

Also associated with induced demand is a concern for the potential increase in vehicle fuel usage. As in the case for vehicle emissions, several variables play a role in the determination of the actual net impact on fuel usage. AHS may have the impact of leading to an increase in driving, which on an aggregate basis of total fuel consumed would mean a fuel usage increase. Moreover, fuel economy is a function of speed, and increases in speed associated with AHS could lead to increases in fuel consumption. Also, if vehicles accessing or egressing the AHS develop into lengthy queues, vehicle fuel consumption would be affected.

Again, AHS R&D will proceed along with other technological advances in areas such as vehicle fuel economy in addition to possible increases in the national corporate average fuel economy (CAFE) standards that would have the effect of reducing fuel consumption on a per mile basis. In addition, AHS associated with these two infrastructure-related concepts could smooth out the flow of traffic as previously described which could reduce vehicle fuel usage. As in the case for vehicle emissions, in the context of automated vehicles traveling with much smaller headways than presently possible early research has indicated there are fuel efficiency increases for all vehicles.

The infrastructure assisted concept differs from the concept of infrastructure supported AHS in that the latter functions without any infrastructure-to-individual-vehicle communication. Infrastructure supported AHS does include infrastructure-to-vehicles-broadcast communication over some given area. Overall, the two infrastructure-related concepts will likely cost more in control and communications but have the potential to provide a substantially greater degree of benefits. A cost-benefit tradeoff is necessary to help understand the differences among the concepts.

C.7   Other Issues

Section C.6 addresses societal and institutional issues. In this section, we address technological and other issues. We first discuss some important technological requirements for implementing this concept. We then discuss, in the context of this particular concept, the possible requirement differences between supporting platooning and supporting the free-agent vehicle following rule.

Vehicle-to-vehicle communication needs the communicating vehicles to be identified and dedicated channels be set up. Such communication is needed for maneuver coordination. (Due to the short distance between two adjacent intra-platoon vehicles and the companion line-of-sight, it is assumed that communication between these vehicles is easy. Same can be assumed if the safety distance between two free-agents is sufficiently short.)

Many possibilities of performing traffic merging without infrastructure assistance have been contemplated. Since none of them seems sufficiently promising, the current concept calls for
(i) extended merge lane at merge points and
(ii) using lane changes on the extended lane to emulate the merging process.
Further development of this concept and design can benefit from the expertise of the Consortium's Technology Team.

This concept calls for vehicle-to-vehicle and infrastructure-to-vehicles-broadcast communication capabilities for safety and throughput reasons. A vehicle, in performing maneuvers, can fuse the information obtained from several different sources, namely on-board sensors, on-board maps, information communicated from the infrastructure and information communicated from the neighboring vehicles. This fusion task may be complicated. Fusing microscopic information about the roadway geometry and traffic condition from the on-board sensors and from the infrastructure requires merging of relative-distance-based description of the moving vehicle's surroundings with the absolute-position-based description (actually relative to the location of the infrastructure sensors). This will in turn require an accurate vehicle positioning system, perhaps to the accuracy of several meters. Whether such fusion will be required for lateral positioning remains to be seen. If it is indeed required, then the accuracy requirement is likely to be much higher. These may pose some technological challenges.

Some people have observed that much of the design task for a complex system with high safety requirements is devoted to detailed failure event analysis and to achieving fail-safety or fail-softness after failures. Such detailed analysis work is yet to be performed for this concept and may eventually result in significant changes to the concept described in this document.

In the rest of this section, we point out the major differences between supporting platooning and supporting the free-agent vehicle following rule in this concept.

We first address normal operations. The high throughput potential of platooning may require higher degree of technological sophistication. The large majority of the hardware and software needed to make platooned AHS work are also needed for fully automated but non-platoon AHS. The features that would be peculiar to a platoon AHS are:

– vehicle-to-vehicle communication system capable of transferring reasonably high bandwidth control information (in the range of kilobytes per second) over short intra-platoon distance;

– ranging sensors with accuracy of several centimeters within the range of a few meters;

– software logic for joining and splitting platoons.

Platooned operations may also impose more stringent performance requirements than the free-agent separation policy in the following areas.

– safety-verified cooperative maneuvering protocol;

– very fast and precise throttle and brake control actuators.

Merging two streams of platoons into one may require longer merge ramps because of the longer length of the platoons than the individual vehicles.

Appendix D.   Infrastructure Assisted Concept

D.1 Introduction

This document describes one of five Automated Highway System (AHS) concepts, namely *Infrastructure Assisted AHS,* developed for NAHSC Task C2. In its final deployment, the Infrastructure Assisted AHS concept (hereafter concept), supports *fully automated vehicles on dedicated lanes.*

This concept is very similar to the Infrastructure Supported concept described in Appendix C. In terms of its physical capabilities it differs only in the extent of support available during entry, exit and highway to highway merging. This adds additional options to the local tailorability. This appendix only discusses aspects of this concept that are different from the Infrastructure Supported concept.

The following summarizes the salient features and requirements of the concept. All items other than number 6 are identical to the Infrastructure Supported concept.

1. *Standardized inter-vehicle coordination protocols to guarantee cooperative vehicle behavior.*
2. *Separation of automated vehicles into dedicated lanes for fully automated operation.*
3. *Short range, high data rate inter-vehicle communications for platooned operation.*
4. *Medium-range low data rate communications required for coordinated lane change in multi-lane operation.*
5. *Infrastructure to vehicle broadcast communications in entry and exit zones with regular entry and exit lanes.*
6. *Infrastructure to vehicle two-way channel communications in entry and exit zones with short lanes and highway to highway merge zones.*
7. *Global infrastructure to vehicle broadcast communications for system-wide routing and flow control or static signage for speed limits, separation policy etc.*

These requirements may be partially met by ITS services such as in-vehicle signage or ATIS.

8. *Global infrastructure surveillance system to do data collection for system-wide flow control.*

Again, some of these requirements may be offset by ITS facilities such as probe vehicles, roadside data collection beacons, surveillance systems.

9. *Vehicle to infrastructure communications for emergency notification, incident reporting and emergency advice.*

These requirements may be supported by ITS services on non-AHS specific

communication media such as CDPD.

This concept differs from the other four concepts in the following principal technical respects. The infrastructure supported concept assumes no two-way vehicle-to-infrastructure communications anywhere. This concept assumes that such communication exists in entry, exit and merge zones. The independent vehicle concept assumes there are no AHS specific inter-vehicle or infrastructure-to-vehicle communication requirements. The cooperative concept assumes that there are no AHS specific infrastructure-to-vehicle communications. This concept assumes that vehicle sensing must be supplemented by both inter-vehicle and infrastructure-to vehicle-communications.

The next section describes the physical and functional architectures required to support entry, exit and merging in the concept reference state. The section after the next one describes the differences in local tailorability.

D.2 Concept Reference State Description

The following table describes the physical architecture of the roadside control systems for entry, exit and highway to highway merging.

Location	System Type	System Description	
Roadside		Name	**Exit Control System**
		Function	Exit Rate metering, check-out, hand-off
		Subsystems	Exit Sensing System, Exit Coordination Controller, Exit Communication System, Check-out Controller, Exit Rate Controller
	Sensors	Name	**Exit Sensing System**
		Function	Sense exit queue length, exiting vehicle location, speed and communication-id on off-ramp, road image for obstacle recognition and emergency detection.
	Control Systems	Name	**Exit Coordination Controller**
		Function	Speed of exiting vehicle. Speed, separation decision and lane change decision for vehicles in exit-zone of highway.
	Communication Systems	Name	**Exit Communication System**
		Function	Two way communication with vehicles on the off-ramp and the exit zone of the automated highway. Broadcast communications to vehicles in the exit zone of the highway.
	Control Systems	Name	**Check-out Controller**
		Function	Vehicle check-out, driver status checking, hand-off
		Name	**Exit Rate Controller**
		Function	Exit queue control, To control rate of vehicles entering the local traffic
		Name	**Merge Control System**
		Function	Highway to highway merging, gap creation, gap negotiation, gap alignment, speed decision, separation decision and lane change decision in merge zone
		Subsystems	Merge Sensing System, Merge Communication System
	Sensors	Name	**Merge Sensing System**
		Function	Sense speed, distance of vehicles in the merge zone, road image for obstacle recognition and emergency detection
	Communication Systems	Name	**Merge Communication System**
		Function	Two way message based communication with vehicles in the merge zone of the automated highway. Broadcast communications to all vehicles in the merge zone of the highway.

D.2.1 AHS Function Descriptions

This subsection describes the execution of the entry, exit and merging functions. These are functions 15, 16 and 17. All other functions are executed exactly as described for the Infrastructure Supported concept.

Vehicle Entry

General Description: This function is the entry of the vehicle into AHS from the non-AHS environment. Both the transition lane and dedicated entry/exit facilities are supported in this concept. The entry functionality is similar for both options. The differences are mainly in terms of the effects on safety, throughput and cost. The transition lane entry/exit affects the throughput of both the AHS and non-AHS highway lanes as both the traffic flows affect each other. The transition lane also requires gaps in the barriers that may enable a non-AHS vehicle to enter the AHS.

The entry function can be broadly categorized into check-in , hand-off, and vehicle entry. Check-in: The driver drives the vehicle to the check-in station (which is at the beginning of the dedicated entry ramp or the transition lane). The vehicle status monitoring system (or the operator at check-in) certifies that the vehicle is capable of AHS operations. The check-in control system on the roadside check-in station allows the vehicle to proceed. Vehicles that fail check-in are routed back to the manual highway. The check in can be performed by many ways, such as on-the-fly, or while stopped at the check-in station, etc.

Hand-off: After check-in, the driver initiates the hand-off to the automatic control system on the vehicle (e.g., by pushing a button). After the hand-off, the vehicle is controlled by the vehicle control system.

Vehicle-entry: The automated vehicle is assisted by the roadside control system. The *entry control system* determines the available space upstream of the entry point on the automated lane using its *entry sensing system*. If the space does not exist, it creates the space by communicating with the vehicles on the automated lane. The entry control system then informs the entering vehicle of the gap and assists in establishing communication between the entering vehicle and the vehicles on either side of the gap on the automated lane. The entering vehicle then accelerates and aligns itself with the gap on the automated lane and changes lane (or merges) with the AHS traffic. The gap negotiation is carried out by the *coordination system* and the gap alignment and move over executed by the *regulation control system*. The gap has its own dynamics depending on the downstream flow on the AHS. Therefore, the vehicles on either side of the gap communicate the speed and size of the gap to the entering vehicle so that it can adjust its motion in order to align itself with the gap at the entry point.

Information Flow

Description	From System	To System
Vehicle operation status info	Vehicle self state sensing system	Check-in control system
Vehicle check-in / reject	Check-in control system	Vehicle planning system
Hand-off control	Driver	Vehicle control system
Entry request	Vehicle planning system	Entry control system
Traffic flow information (AHS and non-AHS)	Roadside control systems, AHMC and ITS service providers	Entry control system
Gap determination on AHS	Entry sensing system	Entry control system
Gap negotiation on AHS	Entry control system	Vehicle planning systems of vehicles on the automated lane
Communication ID information	Entry control system	Vehicle coordination systems of vehicles on AHS and entry ramp
Available gap information	Entry control system	Entering vehicle planning system
Gap dynamic information : speed, size	Neighborhood sensing system or coordination from AHS vehicles	Entering vehicle regulation control system
Lateral velocity, acceleration, yaw rate	Self state sensing system	Entering vehicle regulation control system
Road geometry preview	Neighborhood sensing system	Entering vehicle regulation control system
Front vehicle distance and speed	Neighborhood sensing system or communication system	Entering vehicle regulation control system
Vehicle velocity & acceleration	Self state sensing system	Entering vehicle regulation control system
Vehicle actuation commands	Entering vehicle regulation control system	Entering vehicle actuation systems (steering, brake, throttle)

Highway Geometry Modifications: Necessary modifications depending on the technology used for lateral movement and sensing of vehicles by entry sensing system.

Vehicle Exit

General Description: This function is the exit of the vehicle from AHS to non-AHS environment. Again, there are two configurations that are supported, dedicated exit and

transition lane exit. Both of them are very similar in functionality. The exit consists of three functions, <u>vehicle exit,</u> <u>hand-off</u> and <u>check-out.</u>

<u>Vehicle-exit:</u> This function involves taking the vehicle from the automated lane to the exit ramp/transition lane. It is executed either as a regular lane change or as a highway split. The *vehicle planning system* gets the information about available gap on the transition lane/exit ramp from the *exit control system* on the road. The exit control system creates a gap (on the transition lane) if it does not exist and is possible to do so. Otherwise, either the vehicle is routed to the next exit or joins the queue on the ramp/transition lane which ultimately slows down the traffic on the automated lanes.

<u>Check-out:</u> The vehicle passes the check-out station where the driver status monitoring system checks that the driver is ready to take over control. If the driver is not ready an attempt is made to alert him/her, otherwise the vehicle is automatically parked at the parking lot where assistance is provided. The check-out can be done either on-the fly or while the vehicle is stopped. Many other functions such as toll collection can be performed at the check-out.

<u>Hand-off:</u> If the driver is alert, the vehicle control is turned over to the driver. The driver has to follow a certain procedure to take over control. If he/she fails to do so, the control is returned to the automated system and the vehicle is taken to the parking lot. After taking over control, the driver drives onto the non-AHS street/highway. An exit-metering light is provided for flow control onto manual highway.

As in the case of entry, the vehicle coordination and regulation control system needs all information necessary to execute speed tracking, inter-vehicle separation tracking and lane change maneuvers. The following table shows additional information flow requirements.

Description	From System	To System
Information about gaps/space on the exit ramp/transition lane	Exit control system	Exiting vehicle planning system
Traffic flow information (AHS & non-AHS)	Roadside controllers & AHMC and ITS providers	Exit control system
Exit gap information	Exit sensing system	Exit control system
Exit gap negotiation	Exit control system	Coordination system of vehicles on exit ramp/transition lane
Driver alertness report	Driver status monitoring system	Check-out control system
Wake up call	Driver status monitoring system	Driver
Hand-off control signal	Driver	Vehicle control system
Exit metering signal	Exit control system	Driver

Highway Geometry Modifications: Necessary modifications depending on the technology used for lateral movement and sensing of vehicles by exit sensing system.

Automated Highway Merging

General Description: This function is the movement of automated vehicles from one automated highway to another. As the neighborhood sensing system of the vehicles may not be able to detect gaps in the merging traffic because of difference in curvature, banking, elevation of the merging highway lanes, the *merge control system* on the roadside uses *merge sensing system* to sense the gap and communicate it to the vehicles on both highways. The system supports merging two streams of platoons. If the appropriate gaps do not exist, the merge control systems coordinates with the appropriate vehicles to slow them down and create gaps. The merge control system also receives upstream flow information on merging highways from the AHMC and adjacent stretch control systems.

Information Flow

The vehicle coordination and regulation control system needs all information necessary to execute speed tracking, inter-vehicle separation tracking and lane change maneuvers. The following table shows additional information flow requirements.

Description	From System	To System
Traffic flow on the merging highways	Roadside control systems and AHMC	Merge control system
Gap detection on merging lanes	Merge sensing system	Merge control system
Gap negotiation on merging lanes	Merge control system	Vehicle coordination system
Communication ID of vehicles that need to coordinate their maneuvers	Merge control system	Vehicle coordination systems
Gap info on merging lanes	Merge control system	Vehicle planning system

Highway Geometry Modifications: Necessary modifications to help vehicle detection by merge sensing system and lane change/merging lateral control system on the vehicles.

D.3 Local Tailorability

The Infrastructure assisted concept offers the following architectural options in its stage 6 deployment. A valid combination is one choice from each of the five pairs, i.e., there are 32 local options. All are compatible with the concept.

1.   platooning or free agent
2.   single or multiple lanes
3.   dedicated or transition lane entry and exit
4.   regular lane entry and regular lane exit with infrastructure support in entry and exit zones only or short lane entry and short lane exit with infrastructure assistance in entry and exit zones only
5.   global infrastructure supported flow control or static signage flow control

All 32 combinations are expected to be equally safe. In general, the different combinations will differ in the maximum throughput levels they can support and the sophistication of flow control they offer.

We highlight salient features of the architectural options by discussing two examples. Example 1 pertains to a rural area. This example is identical to example 1 for the Infrastructure Supported concept. Example 2 pertains to an urban area and is described here.

Example 2: An urban area with high volume traffic may choose to support platooned

operation, multiple lanes, dedicated entry and exit, short lane entry and exit with infrastructure assistance in entry and exit zones and global infrastructure supported flow control. This combination is expected to have the highest control and communication infrastructure costs, though also the lowest real estate requirements if new automated highways are to be built. It also has the maximal set of vehicle system requirements, though it is expected to deliver the highest level of benefit. The global infrastructure supported flow control can be used for fast and reliable incident identification and clearing, thus reducing trip time variance. It can be used for vehicle lane assignment to achieve transit priority, people priority (HOV), commercial vehicle lanes. The twin benefits of trip time reliability and priority lane assignment can support flexible pricing schemes to manage congestion and yield higher returns on investment. The tighter flow control capabilities can be used for the dynamic re-allocation of freeway capacity to balance congestion in different freeway/arterial corridors. This allows inter-jurisdictional coordination in the form of coordinated control of multiple transportation networks. Increased freeway trip time reliability and priority lane assignment to transit or other commercial traffic facilitates inter-modal planning and interfacing. The global dynamic flow control capability can be used to support time of day variations such as platooning during peak period congestion and free agent operation during lean congestion periods. It can be used to broadcast vehicle class specific separation policies for, e.g., special isolation of HAZMAT vehicles, creation of mixed class platoons or single class platoons.

Appendix E.   Adaptable Concept

E.1   Concept Introduction

Goals and Objectives of the Adaptable Concept

1) Maximize safety and throughput available during degraded operations by providing underlying layers which can stand alone and provide safety and throughput comparable to an early phase AHS system.

2) Provide a deployment path with steps whose costs and benefits make them credible end-state AHS systems.

3) Design an architecture with sufficient flexibility to meet the needs of urban, intercity, and rural users.

4) Ensure that transitions during phased deployment or degraded operation occur with minimum cost and disruption of services.

5) Design the concept family so that when a vehicle passes between regions of different population density with different AHS implementations, a smooth transition occurs.

6) Use redundant capabilities in different layers to enhance safety – higher layers override "competing" capabilities in lower layers.

Note: In many cases the layers of the Adaptable Concept have names similar to, or the same as, earlier AHS concepts. While they may resemble prior or current concepts to some degree, the layers do not correspond to other stand-alone AHS concepts, and "Adaptable" is a separate concept, not a scheme for integrating the other four core team-generated concepts.

E.2 Concept Reference State Description

The Adaptable concept may be viewed as having its functions embedded in one of four modules, or "layers."

E.2.1 Autonomous Layer (or Core)

The innermost, or "Autonomous" layer is located in the vehicle, and contains functions essential to the autonomous operation of the vehicle as part of an AHS system.
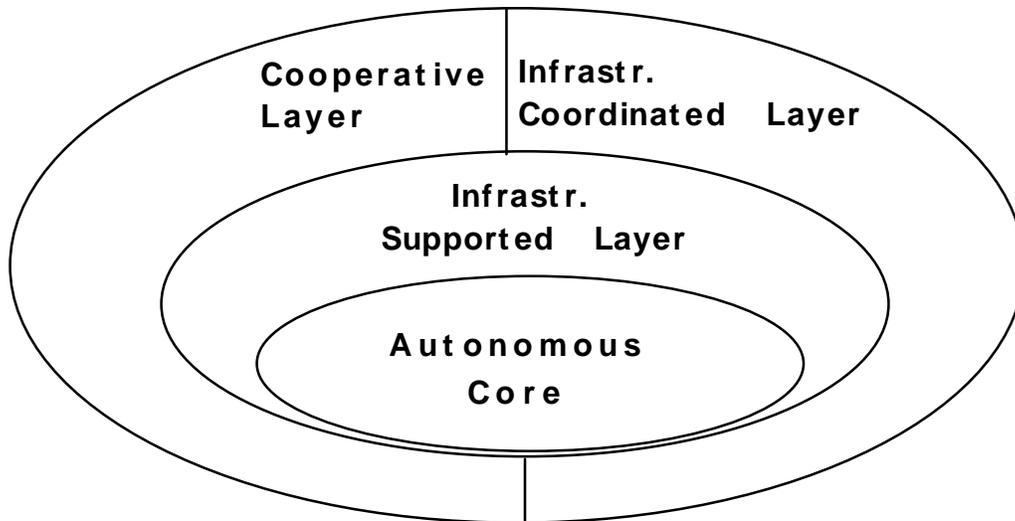
Autonomous layer functions include:

- Longitudinal position-keeping. This is regulation of the distance between the AHS vehicle and the vehicle ahead of it by acceleration and braking.
- Lane-keeping. This is steering the vehicle in order to keep it centered in the lane.
- Lane changing. Autonomous lane changing is steering the vehicle from a position centered in one lane to a position centered in an adjacent lane or exit ramp without actively seeking the cooperation of nearby vehicles.
- Obstacle detection and avoidance. The vehicle is capable of using on-board sensors to detect obstacles in the roadway, deciding whether it is best to stop or change lanes, and ordering the appropriate actions.
- Road condition sensing. A road surface condition sensor mounted on the vehicle senses water, snow, or ice on the roadway and adjusts stopping distance accordingly.
- Vehicle status monitoring. The Autonomous layer does self-checking of all important Autonomous layer functions. Failure of a non-critical function (or one with a back-up) will cause the driver to be alerted that the vehicle needs maintenance as soon as is practical and a system flag to be set. The vehicle will be permitted to proceed to its destination but cannot re-enter the AHS once it has exited until the problem is fixed. Failure of a critical function will cause an immediate action which will depend on the nature of the failure (and the results of the Driver Interaction cross-cutting study). Candidate actions include pulling onto the shoulder and stopping, handing over control of the vehicle to the driver, and stopping the vehicle in the lane.
- Driver status monitoring. Before a vehicle can enter the AHS, and before AHS can yield control of the vehicle to the driver (when exiting the system, or when manual intervention is required), the vehicle tests the driver's responsiveness. If the driver fails to respond appropriately, a vehicle ready to enter AHS will not enter automatic mode. A vehicle which is already in AHS will either exit at the next opportunity or pull to the right and stop depending on the situation requiring driver intervention.

Functions which may be supplied by ITS
- Navigation. The vehicle will know its position accurately enough to determine which exit or junction is approaching, and will have a (or will have access to a third-party) database with map information of sufficient resolution to determine the need for lane changes, merges, and exits.
- Emergency message set. The driver will have the ability to signal the need for emergency assistance if he sees an incident on the freeway, is suddenly taken ill, or other similar situations.

E.2.2 Infrastructure Supported Layer

The "Infrastructure Supported" (I/S) layer is distributed between roadside processors responsible for segment control, entry, and merging, and the Traffic Operations Center for the region. The I/S layer contains functions which allow the infrastructure to check vehicles in and out of AHS and to broadcast to groups of vehicles, and which allow the vehicles to report state information back to the infrastructure. The degree of infrastructure support may vary from region to region. If possible, the Infrastructure Supported layer will be "piggybacked" on ITS by using compatible technology.
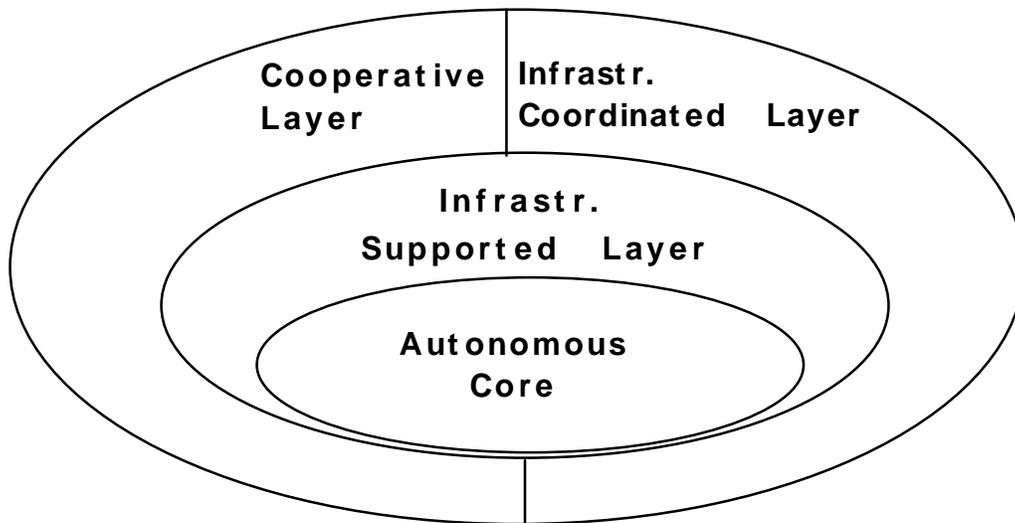
Infrastructure Supported layer functions include:
- Beacon-to-vehicle and vehicle-to-beacon broadcast. This is the most basic form of communication between the infrastructure and vehicles. It is described as "broadcast" because both the infrastructure and the vehicles send one-way messages to which no specific response is expected. Infrastructure broadcast messages can order groups of vehicles to report their status (see below), or to perform speed, spacing, and lane changes to support merging or obstacle avoidance. Vehicle broadcast messages report status (vehicle speed and type, following distance and driving lane), roadway condition, and obstacle location to the infrastructure. Beacons can be either fixed location, or be part of the equipment of an emergency vehicle (e.g., police car or fire truck).

- Infrastructure regulation of speed and spacing. Although the infrastructure cannot command individual vehicles using the capabilities of this layer, it can order groups of vehicles to change speed, lanes, or alter the spacing from the vehicle in front of them. This can be used to expedite merging, for flow control, or for limited incident management.
- Traffic condition monitoring. "Merge" controllers (roadside processors) will monitor traffic density and speed on entry ramps, and on lanes approaching ramps and merges. AHS vehicles will broadcast speed and following distance on request.
- Infrastructure roadway condition monitoring and obstacle detection. This layer permits condition monitoring (ice, snow, water) and obstacle detection sensors to be installed at trouble spots such as bridges which ice up, or stretches of roadway subject to rockfall. A beacon will warn approaching vehicles of dangerous conditions.
- Vehicle check-in/check-out. The vehicle will do a self-check, including driver status, and broadcast coded a "ready to enter" message including the vehicle ID and a password to the infrastructure, which will remove the access barrier. A radar reflector on the access barrier could signal the vehicle that the barrier is in place, or has been removed. The communications interface between entry processor and vehicle will be designed to make it difficult to intercept vehicle ID and password information. This will make it difficult (though certainly not impossible) for a non-AHS vehicle to enter the system.

E.2.3 Cooperative Layer

The "Cooperative" layer is located in the vehicle. It contains functions which support vehicle-to-vehicle coordination and cooperation.
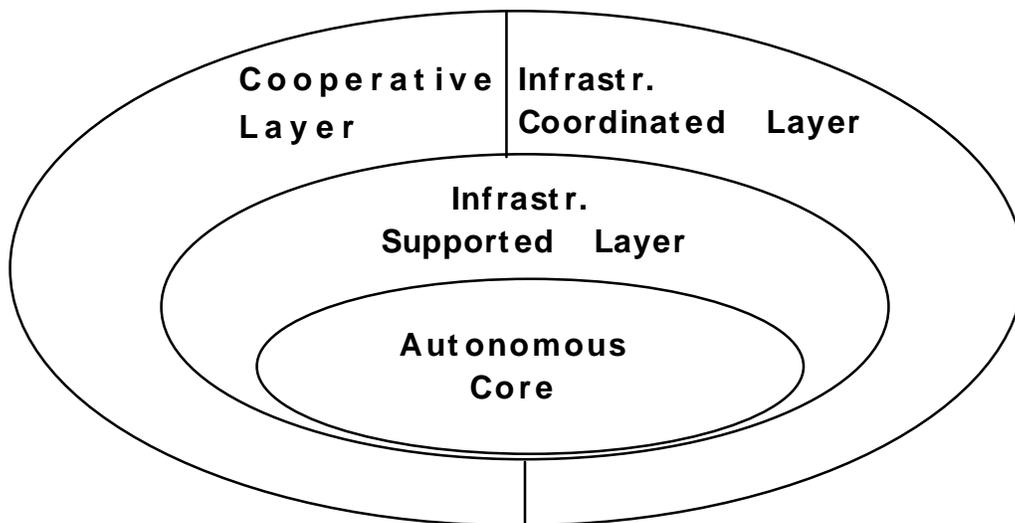
Cooperative layer functions include:
- Vehicle-to-vehicle communication. This is essential to inter-vehicle coordination, since it allows vehicles to make their intended actions known to nearby vehicles, and to negotiate cooperation for lane changing and merging maneuvers.
- Cooperative lane-changing and merging. The Autonomous layer contains basic lane-changing and merging functions which support lane-changing and merging in low to moderate density traffic. The cooperative functions adds the ability to warn nearby vehicles of own vehicle's intended maneuvers, to request action on the part of nearby AHS vehicles, and to use nearby AHS vehicles as remote sensing platforms.
- Recognition of rogue vehicles. This is a function for dedicated AHS lanes only. If own vehicle attempts to communicate with a nearby vehicle and receives no response, it designates the vehicle as a rogue (probably either an AHS vehicle with communication failure, or a manual vehicle which snuck onto a dedicated lane). A warning is broadcast to nearby vehicles and to the infrastructure that the rogue vehicle may behave uncooperatively or even erratically.
- Local incident warning. AHS vehicles detecting an accident or an obstacle will broadcast a warning to all nearby AHS vehicles giving the location and lane number, so that subsequent vehicles can minimize delays resulting from the incident.
- Platoon formation and dispersal. Platooning is an option which is supported by the cooperative layer, because vehicle-to-vehicle communication is used to coordinate vehicles which are underway. AHS vehicles will broadcast their availability to platoon and their destination. Nearby vehicles with similar destinations will respond, and a new platoon will be formed, or an existing one augmented.

E.2.4 Infrastructure Coordinated Layer

The "Infrastructure Coordinated" (I/C) layer is distributed between roadside processors and the Traffic Operations Center. It contains functions which allow the infrastructure to communicate with individual vehicles, and to order changes in their speed, spacing, routing, or lane use.
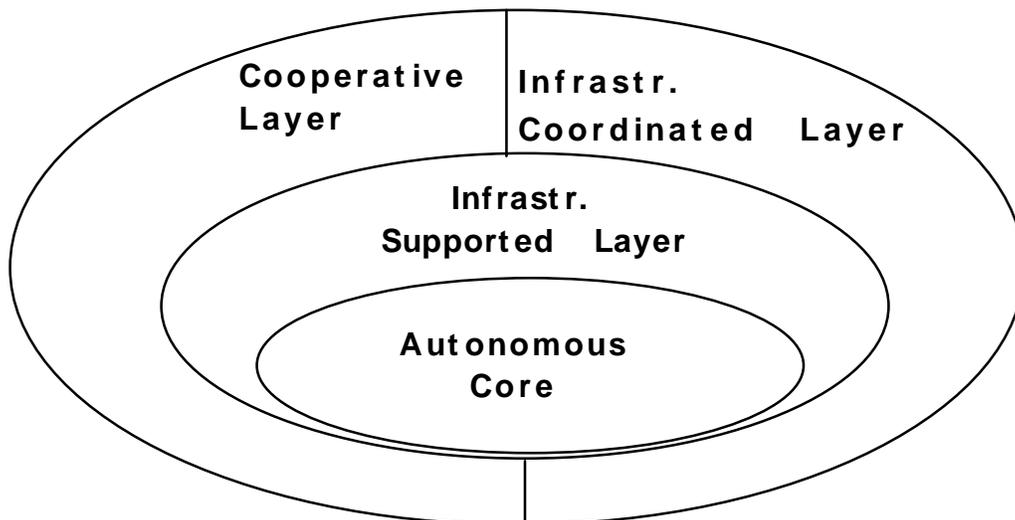
Infrastructure Coordinated layer functions include:

- Infrastructure-to-vehicle communication. This is the most sophisticated form of communication from the infrastructure to the vehicles. It allows the infrastructure to monitor vehicle position, spacing, and speed, and to order appropriate changes for individual vehicles.
- Monitoring of vehicle positions and speeds by the infrastructure. In order to take over management of traffic immediately upon being notified by one or more vehicles of a problem (e.g., obstacle in the roadway), the infrastructure must have some knowledge of vehicle positions, speeds (and perhaps other parameters such as vehicle class). How often this information must be updated is TBD.
- Infrastructure-directed lane changing and merging. Because it can direct individual vehicles, this layer has the capability to direct lane changes and merges using the position and speed information broadcast by individual vehicles on request. This can be used to support control of traffic flow in a region, or management of local traffic flow around an incident.
- Infrastructure-directed platoon formation. Since the infrastructure already has information on vehicle destinations, it can expedite platoon formation by identifying likely platooning partners for a vehicle or platoon in the upstream traffic flow. Once underway, platoons operate cooperatively.

E.3 Summary of Adaptable Concept Deployment Phases

Deploy-ment Phase	Distribution of Intelligence	Driver Engage-ment	Mixing Option	Platooning Option	Obstacle Detection & Avoidance	Comments
Urban 0	Pre-Autonomous	Partial (see comments)	Mixed	None	Automatic detection & driver warning	Manual lane changing, merging; selective deployment
Urban 1	Autonomous	Contingent (see comments)	Mixed	None	Automatic detection & avoidance	Driver takes over lane changing, merging in heavy traffic
Urban 2-	Infrastructure Supported	Disengaged	Dedicated	None	Automatic detection & avoidance	Infrastructure supports merging, entry by ordering increased vehicle spacing. Vehicle reports used to estimate density
Urban 2+	Infrastructure Supported/ Cooperative	Disengaged	Dedicated	Cooperative	Automatic detection & avoidance	Combined infrastructure and cooperative support for merging; cooperative lane changing
Urban 3	Infrastructure Coordinated/ Cooperative	Disengaged	Dedicated w/ separate AHS transit lane where practical	Infrastructure Coordinated/ Cooperative	Automatic detection & avoidance	Infrastructure coordination for platoon formation; cooperative support for platoon travel
Rural 0	Pre-Autonomous	Partial (see comments)	Mixed	None	Automatic detection & driver warning	Manual lane changing, merging; selective deployment

Deploy-ment Phase	Distribution of Intelligence	Driver Engage-ment	Mixing Option	Platooning Option	Obstacle Detection & Avoidance	Comments
Rural 1	Autonomous	Contingent (see comments)	Mixed	None	Automatic detection & avoidance	Driver takes over lane change, merge in heavy traffic
Rural 2 (where practical & econom-ically feasible)	Infrastructure Supported/ Cooperative	Disengaged	Dedicated	Cooperative	Automatic detection & avoidance	I/S support for merging, entry; roadway condition/ obstacle monitoring & beacon communica-tion in problem areas
Intercity 0	Pre-Autonomous	Partial (see comments)	Mixed	None	Automatic detection & driver warning	Manual lane changing, merging; selective deployment
Intercity 1	Autonomous with Cooperative Platooning	Contingent (see comments)	Mixed	Trucks having cooperative option	Automatic detection & avoidance	Driver takes over lane changing, merging in heavy traffic; truck platoons with contingent lead driver engagement
Intercity 2	Infrastructure Supported/ Cooperative	Disengaged	Dedicated	Cooperative	Automatic detection & avoidance	Infrastructure supports merging, ramp entry by ordering increased vehicle spacing. Vehicle reports used to estimate density

Deploy-ment Phase	Distribution of Intelligence	Driver Engage-ment	Mixing Option	Platooning Option	Obstacle Detection & Avoidance	Comments
Intercity 3	Infrastructure Coordinated/ Cooperative	Disengaged	Dedicated w/ separate AHS truck lane where practical	Infrastructure Coordinated/ Cooperative	Automatic detection & avoidance	Infrastructure coordination for platoon formation; cooperative support for platoon travel; infrastructure assisted merging at start & end of truck lane, highway junctions

Partial – Driver responsible for certain functions at all times.
Contingent – Driver has the option of taking over complete control of vehicle after hand-off.

E.4 AHS Functional Descriptions

E.4.1 Speed Tracking

This function is performed by the vehicle. The vehicle processor compares the ordered speed, the current speed, the maximum acceleration, and the acceptable longitudinal jerk, and generates an ordered acceleration or deceleration for the next time interval. This order goes to either the throttle or braking actuator, depending on the value.

Description	From System	To System
Ordered speed	Speed Decision, Inter-Vehicle Separation Tracking	This function
Current speed, acceleration	Vehicle speedometer, accelerometers	This function
Maximum acceleration, acceptable longitudinal jerk	Vehicle database	This function
Ordered acceleration	This function	Throttle actuator
Ordered deceleration	This function	Throttle/braking actuator

E.4.2 Inter-Vehicle Separation Tracking

This function is performed by the vehicle. The vehicle processor compares the measured separation fore and aft with the ordered separation forward, the safe separation fore and aft, and with any separation which has been agreed to as part of lane-change coordination. The measured lateral separation is compared with a design value.

Description	From System	To System
Ordered separation from vehicle ahead	Inter-Vehicle Separation Decision	This function
Measured separation, rate of change if available	Vehicle position sensors	This function
Minimum lateral separation	Vehicle database	This function
Agreed to separation from vehicle ahead or behind ("spacing change execute")	Lane Change Coordination	This function
Ordered speed	This function	Speed Tracking
Requested lateral bias in lane	This function	Lane Keeping
Vehicle proximity alert (if lateral bias cannot achieve required separation)	This function	Speed Decision, Lane Change Decision

E.4.3 Lane Keeping

This function is performed by the vehicle. Inputs from the lane-keeping sensors are compared with road curvature and any requested bias in the lane. If the vehicle is not positioned properly, a steering correction which takes speed into account is computed.

Description	From System	To System
Position of vehicle in lane	Lane-keeping sensors	This function
Lane keeping directions	Road Geometry Recognition	This function
Requested lateral bias in lane	Inter-Vehicle Separation Tracking, Obstacle Avoidance	This function
Own vehicle speed	Speedometer	This function
Steering commands	This function	Steering actuator

E.4.4 Lane Changing

This function will search for gaps in traffic which allow a lane change without the cooperation of other vehicles. It will also manage vehicle speed and direction during a lane change.

Description	From System	To System
Feasible lane changes query	Lane Change Decision	This function
Lane change opportunities	This function	Lane Change Decision
Position and velocity of own vehicle	Absolute position sensor, speedometer	This function
Acceleration capabilities of own vehicle	Vehicle database	This function
Position and speed of other vehicles	Vehicle position sensors	This function
Road geometry	Vehicle database	This function
Ordered vehicle speed and direction	This function	Steering, brake, throttle actuators

E.4.5 Road Geometry Recognition

This function is performed by the vehicle. The Road Geometry Recognition function supports lane keeping in cases where more than just following the white lines (or lane center marking) is required. Road geometry information for the upcoming section of roadway is transmitted to the vehicle from a roadside beacon at the beginning of the section. Merge points such as entry and exit ramps and junctions will have a dedicated beacon upstream.

Description	From System	To System
Stored road geometry	Vehicle database (from infrastructure via beacon)	This function
Upcoming entry and exit ramps, highway junctions, other features	Automated Highway Merging, vehicle database (from infrastructure via beacon)	This function
Sensed road geometry	Lane-keeping sensors	This function
Lane keeping directions (go straight, bear right, bear left, ...)	This function	Lane Keeping

E.4.6 Obstacle Recognition

This function is performed by the vehicle. The obstacle recognition function fuses the outputs of the vehicle detection sensors and the obstacle detection sensor, if one is present. Road geometry information in the vehicle's database is used to determine whether the object is on the roadway, or just close to it.

Description	From System	To System
Position and velocity of nearby vehicles and large objects	Vehicle detection sensors	This function
Position and size of objects located ahead of vehicle	Obstacle recognition sensor	This function
Road geometry	Vehicle database (from infrastructure via beacon)	This function
Position and velocity of potential obstacle	This function	Obstacle Avoidance, Emergency Detection/Monitoring, vehicle-to-infrastructure communication, vehicle-to-vehicle communication
Preliminary action ordered	This function	Speed Decision

E.4.7 Obstacle Avoidance

This function is performed in parallel by the vehicle and the infrastructure. The function is activated by the obstacle recognition function, which detects the probable presence of an obstacle, and estimates its position and speed. The function then uses information on vehicle dynamics, the relative position of surrounding vehicles, and estimated stopping distance to decide whether to try to steer around the obstacle or to stop. The function in the vehicle compares its chosen course of action with that recommended by the infrastructure, and uses pre-programmed logic to choose one or the other. If appropriate, the lane change coordination function is used to coordinate the maneuver with nearby vehicles.

Description	From System	To System
Position and velocity of obstacle	Obstacle Recognition	This function (vehicle and infrastructure)
Vehicle speed and heading, condition of pavement	Speedometer, compass, gyroscope, traction sensor	This function (vehicle and infrastructure)
Position and speed of nearby vehicles	Vehicle detection sensor	This function (vehicle and infrastructure)
Decision to stop, change lateral position in lane, or change lanes	This function (in vehicle)	None
Order to stop, change lateral position in lane, or change lanes	Infrastructure	This function (in vehicle)
Final sequence of actions to be taken	This function (in vehicle)	Speed Tracking, Lane Keeping, Lane Changing, Lane Change Coordination, Infrastructure

E.4.8 Speed Decision

This function is performed by the vehicle with input from the infrastructure. The infrastructure may order a maximum speed based on visibility, pavement condition, or the tightness of a turn. The maximum speed may also be chosen for the purposes of flow control, merging, or incident management. The vehicle will check the AHS maximum design speed against any limit set by the infrastructure, and check the required stopping distance (given vehicle type and pavement condition) against the separation to the vehicle in front and that vehicle's speed.

Description	From System	To System
Maximum design speed	Vehicle database	This function
Ordered speed	Infrastructure	This function
Distance to vehicle in front and back, speed	Vehicle detection sensor	This function
Ordered separation ("vehicle proximity alert")	Inter-Vehicle Separation Decision	This function
Obstacle Alert	Obstacle Recognition	This function
Change speed order (failure response)	Vehicle Operational Status Monitoring	This function
Enter AHS	Transition Lane Vehicle Entry	This function
Ordered speed	This function	Speed Tracking

E.4.9 Inter-Vehicle Separation Decision

This function is performed by the vehicle with input from the infrastructure. The infrastructure may order a minimum separation for safety reasons, or in the case of infrastructure supported merging. The function will calculate separation based on required stopping distance unless overridden by the infrastructure.

Description	From System	To System
Minimum lateral separation distance (design)	Vehicle database	This function
Minimum long. separation distance	Infrastructure via roadside beacon	This function
Pavement condition	Traction sensor infrastructure (if available)	This function
Vehicle speed	Speedometer	This function
Required stopping distance	Vehicle database	This function
Ordered separation	This function	Speed Decision, Inter-Vehicle Separation Tracking, Lane Change Decision

E.4.10 Lane Change Decision

This function is performed by the infrastructure using stationary or mobile controllers near entrance and exit ramps, highway junctions, and upstream of temporary obstructions such as accident scenes. At all other points the vehicle makes lane change decisions. The function will decide whether a lane change is to be performed, and which of the lane change possibilities is to be selected.

Description	From System	To System
Road geometry	Vehicle database (orig. infrastructure via beacon)	This function
Infrastructure order to change lanes	Infrastructure via beacon	This function
Emergency lane change request ("Vehicle Proximity Alert")	Inter-Vehicle Separation Tracking; Vehicle Operational Status Monitoring	This function
Feasible lane changes query	This function	Lane Changing
Feasible lane change alternatives	Lane Changing	This function
Lane Change Feasibility Reply	This function	Inter-Vehicle Separation Tracking; Vehicle Operational Status Monitoring
Notification of upcoming highway merge	Automated Highway Merging	This function
Lane Routing	Lane-to-Lane Routing within Highway	This function
Execute selected lane change	This function	Lane Change Coordination

E.4.11 Lane Change Coordination

Many lane changes will require coordination with nearby vehicles. The initiating vehicle will send out an inquiry to selected nearby vehicles (identifying them by their position) asking them to increase spacing from the vehicle ahead of or behind them. They will reply with a "can do" or "can't do," and the initiating vehicle will send out an "execute message" to one of the vehicles which replied positively. The Lane Change Coordination function of any vehicle agreeing to assist will send out the appropriate commands to change position.

Description	From System	To System
Execute Lane Change	Lane Change Decision	This function
Own vehicle position	Absolute position sensor	This function
Own vehicle speed	Speedometer	This function
Position, speed of nearby vehicles	Vehicle position sensor	This function
Feasible lane changes query	This function	Lane Changing
Feasible lane changes reply	Lane Changing	This function
Spacing change inquiry*	This function (own vehicle)	This function (nearby vehicle)
Spacing change reply*	This function (nearby vehicle)	This function (own vehicle)
Spacing change execute message*	This function (own vehicle)	This function (nearby vehicle)
Ordered speed change	This function	Speed Tracking
Execute Lane Change	This function	Lane Changing

* Senders and receivers are given from the point of view of the vehicle requesting the lane change. This function aboard the receiving vehicle will also handle that end of the communication, with sender and receiver reversed.

E.4.12 Platoon Formation and Dispersal

In Urban Phase 3, platoons are formed with infrastructure coordination, and they travel and disperse cooperatively. Vehicles passing a beacon are queried on their destination; the infrastructure then uses this information to choose groups of vehicles to be gathered into a platoon. The infrastructure orders existing platoons to accept additional vehicles; however, the lead vehicle manages any changes needed to accommodate the newcomer. Departures are coordinated entirely within the platoon with the lead vehicle giving the orders.

Description	From System	To System
Destination and platooning status query	Infrastructure via beacon	This function
Destination/platoon status reply	This function	Infrastructure via beacon
Proceed and join platoon order (platoon ID, speed, time)	Infrastructure via beacon	This function
Seeking platoon query (platoon ID)	Single vehicle	This function
Sought platoon reply (platoon ID, platoon position, speed)	Platoon leader	This function
Location and speed reply (vehicle position, speed)	This function	Platoon leader
Instructions for joining platoon (speed, lane, time)	Platoon leader	This function
Proceeding with intent to join platoon (platoon ID)	This function	Platoon leader

E.4.13 Vehicle Operational Status Monitoring

The AHS vehicle will perform an operational status check before entering automated mode, and at regular intervals (once every TBD minutes) during automated operation. Each subsystem (whether an AHS controller, or a critical vehicle component such as brakes) will be capable of reporting status as OK, non-critical failure, or critical failure. The AHS vehicle will not enter automated mode if any subsystems report failures, and the AHS check-in function, if present, will not allow a vehicle with failures to enter the Automated Highway System. A vehicle which is traveling in automated mode when it detects a failure will follow pre-programmed logic which will depend on the severity of the failure. The action dictated by the logic may be to get off at the next exit, move to the shoulder and stop, hand over control to the driver (depending on the results of this cross-cutting study), or stop in the lane.

Description	From System	To System
Request for subsystem status	This function	Critical AHS and vehicle subsystems
Subsystem status report	Critical AHS and vehicle subsystems	This function
Request feasibility of candidate responses to failure	This function	Lane Change Decision, Driver Status Monitoring, ...
Feasibility of candidate responses to failure	Lane Change Decision, Driver Status Monitoring, ...	This function
Ordered response to failure	This function	Lane Change Decision, Speed Decision, driver interface, ...

E.4.14 Driver Status Monitoring

The AHS vehicle will be able to perform a driver responsiveness check when appropriate. This status check is expected to be something as simple as pushing two buttons in sequence within a specified time interval. As a minimum, this check will be performed before the vehicle enters automated mode, before the vehicle exits automated mode and the driver resumes control, and before the driver of the lead vehicle is given control of a truck platoon (Intercity Phase 1). Driver status will also be checked in case of system failure if the logic dictates that having the driver resume control is the preferred option. Some sort of driver status check which can be performed while driving may be used as an alertness check for engaged drivers of truck platoons – this is TBD.

Description	From System	To System
Request for driver status	Dedicated Vehicle Exit, Transition Lane Vehicle Exit, Vehicle Operational Status Monitoring	This function
Driver interface test ordered	This function	Driver Interface
Test result	Driver Interface	This function
Driver status report	This function	Dedicated Vehicle Exit, Transition Lane Vehicle Exit, Vehicle Operational Status Monitoring

E.4.15 Vehicle Entry

In order to minimize rogue manual vehicles and malfunctioning AHS vehicles, entry into dedicated AHS lanes will be restricted, and vehicles will be checked in by the infrastructure.

E.4.15a Dedicated Vehicle Entry

The vehicle will broadcast its AHS ID, vehicle subsystem status, and driver status. The infrastructure entry controller will validate the ID, and will check account status. The vehicle will then be granted or denied entry to the AHS lane. A dashboard display will show that AHS entry has been approved, and the driver will be prompted to push a button putting the vehicle in automated mode. A physical barrier will block entry until permission is granted and the vehicle signals that it is in automated mode. A radar reflector on the barrier will allow the vehicle to sense that the barrier has been raised.

Description	From System	To System
Vehicle ID, vehicle and driver status	This function	Roadside entry controller
Permission to enter granted/denied (speed, lane)	Roadside entry controller	This function
Barrier status	This function	Vehicle position sensor
Barrier removed	Vehicle position sensor	This function
Enter AHS	This function	Speed Decision, Lane-to-Lane Routing within Highway

E.4.15b Transition Lane Vehicle Entry

The vehicle will broadcast its AHS ID, vehicle subsystem status, and driver status. The infrastructure will validate the ID, and will check account status. The vehicle will then be granted or denied entry to the AHS lane. A dashboard display will show that AHS entry has been approved, and the driver will be prompted to push a button putting the vehicle in automated mode. The vehicle will enter the dedicated lane in automated mode, and broadcast a message confirming AHS entry. Any vehicle which enters the dedicated lane without receiving permission and confirming entry will cause an alert.

Description	From System	To System
Vehicle ID, vehicle and driver status	This function	Entry controller
Permission to enter granted/denied (speed, lane)	Entry controller	This function
Enter AHS	This function	Speed Decision, Lane-to-Lane Routing within Highway
AHS entered (vehicle position, speed)	This function	Entry controller
Record of recent entries into AHS at this location	Entry sensors	Entry controller

E.4.16a Dedicated Vehicle Exit

The vehicle will enter the ramp in automated mode; driver status will be checked before entering the ramp. A roadside beacon will signal the vehicle to enter manual mode, and the driver will be prompted. If he signals by pushing a button that he is ready to assume control of the vehicle, the vehicle will confirm by signaling him and then enter manual mode. A signal will be sent to the infrastructure notifying it that the vehicle has left AHS. The vehicle will not drive onto the manual roadway in automated mode; if the handoff is not completed in time it will pull to the side and stop.

Description	From System	To System
Check driver status in prep. for entering manual mode	Roadside beacon	This function
Request driver status check	This function	Driver Status Monitoring
Driver status	Driver Status Monitoring	This function
Ready to assume control?	This function	Driver interface
Ready to assume control	Driver interface	This function
Transferring control	This function	Driver interface
Enter manual mode	This function	Main AHS processor
Confirm entry of manual mode	Main AHS processor	This function
Exiting AHS	This function	Roadside beacon

E.4.16b Transition Lane Vehicle Exit

The vehicle will enter the transition lane in automated mode; driver status will be checked before entering the lane. A beacon will signal the vehicle to enter manual mode, and the driver will be prompted. If he signals by pushing a button that he is ready to assume control of the vehicle, the vehicle will confirm by signaling him and then enter manual mode. A signal will be sent to the infrastructure notifying it that the vehicle has left AHS. The vehicle will not drive onto the manual roadway in automated mode; if the handoff is not completed it will stop at the next opportunity to do so without obstructing traffic.

Description	From System	To System
Check driver status in preparation for entering manual mode	Roadside beacon	This function
Request driver status check	This function	Driver Status Monitoring
Driver status	Driver Status Monitoring	This function
Ready to assume control?	This function	Driver interface
Ready to assume control	Driver interface	This function
Transferring control	This function	Driver interface
Enter manual mode	This function	Main AHS processor
Confirm entry of manual mode	Main AHS processor	This function
Exiting AHS	This function	Roadside beacon

E.4.17 Automated Highway Merging

Merging of the traffic streams from two AHS roadways will be performed jointly by the infrastructure and the vehicles. A "merge controller" will prompt vehicles to send their position and speed as they approach the intersection, and use this information to form a detailed picture of traffic flow near the junction. Commands will be sent by the controller to the vehicles ordering them to change speed or increase spacing. This will, in effect, match vehicles in one traffic stream to gaps in the other traffic stream. Final adjustments of speed and spacing required to interleave the two traffic streams will be negotiated cooperatively by the vehicles.

Description	From System	To System
Send position	Infrastructure via beacon	This function
Current position, speed	This function	Infrastructure via beacon
Ordered speed, spacing, or lane	Infrastructure via beacon	This function
Notification of upcoming highway merge	This function	Road Geometry Recognition, Lane Change Decision

E.4.18 Lane-to-Lane Routing Within a Single Highway

Lane selection on an AHS highway is done primarily by the vehicle, based on a map database for that section of highway downloaded from a roadside beacon at the start of the section. The infrastructure may override the vehicle's choice and order the vehicle to move into a lane for the purpose of flow optimization or traffic control around an incident or work site.

Description	From System	To System
Data on highway lanes	Map database for current highway section	Vehicle database
Data on highway lanes	Vehicle database	This function
Enter AHS	Dedicated Lane Vehicle Entry, Transition Lane Vehicle Entry	
Travel lane ordered	Infrastructure	This function
Current position	Vehicle position sensor	This function
Lane routing	This function	Lane Change Decision

E.4.19 Highway-to-Highway Routing

The choice of highways to get the vehicle from its AHS entry point to its AHS exit is made by the vehicle using information from a regional (or perhaps national) database, and information on speeds, closures, and anticipated conditions for each highway segment supplied by the infrastructure. The driver may express a preference for the fastest route, the most scenic route, or request specific waypoints.

Description	From System	To System
Current position of vehicle	Vehicle position sensor	This function

Highway vehicle is currently on	Vehicle database	This function
Requested destination, routing preferences	Driver interface	This function
Highway data	Vehicle regional or national highway database	This function
Average speed based on current conditions for highway segments along possible routes	Infrastructure via beacon	This function
Vehicle routing	This function	Vehicle database

E.4.20 AHS Flow Control

Flow control is performed by the infrastructure based on current average speed and throughput for the highway segments under control of the TOC, knowledge of usual daily, weekly and annual traffic patterns, and on reports from adjacent TOC's. The commands to implement the desired flow patterns are communicated to the vehicles from section controllers either through roadside beacons, or mobile beacons in the case of incidents.

Description	From System	To System
Link connectivities and capacities	Map database for area being managed	This function
Current average speeds and throughputs for highway segments under control	Infrastructure sensors and roadside beacons	This function
Usual daily, weekly, and annual traffic patterns	TOC Database	This function
Throughput and speed statistics, and incident reports from adjacent areas	Other TOC's	This function
Location and ID of mobile beacons	First responding emergency vehicles with beacon capability	This function
Traffic flow rules	This function	Roadside and mobile beacons

E.4.21 AHS Admission Control

Admission control is performed by the infrastructure based on current average speed and throughput for the highway segments under control of the TOC, knowledge of usual daily, weekly and annual traffic patterns, and on reports from adjacent TOC's. The commands to implement the desired flow patterns are communicated to the vehicles through a roadside beacon at the entry ramp.

Description	From System	To System
Link connectivities and capacities	Map database for area being managed	This function

Current average speeds and throughputs for highway segments under control	Infrastructure sensors and roadside beacons	This function
Usual daily, weekly, and annual traffic patterns	TOC Database	This function
Throughput and speed statistics, and incident reports from adjacent areas	Other TOC's	This function
Traffic flow rules	This function	Roadside beacons at entry ramp

E.4.22 Emergency Detection/Monitoring

Emergency detection is performed by the infrastructure using inputs from vehicles, beacons, and outside sources. Specifically, vehicles may send reports of critical subsystem failures, obstacles detected, or driver emergency messages. Roadside beacons may send reports that vehicle densities are very high or vehicle speeds are very low. When the infrastructure is alerted to a potential problem it can gather additional data by polling the vehicles in the vicinity of the problem (using cellular technology) on their speed and following distance.

Description	From System	To System
Report of critical subsystem failures	Vehicle self monitoring	This function
Probable obstacle detection	Obstacle Recognition (vehicle)	This function
Driver emergency message	Driver interface (vehicle)	This function
Vehicle density or speed report	Roadside beacon	This function
Incident reports via cellular phone or from news media	Entered by operator via keyboard at TOC	This function
Individual vehicle speed and following distance request	This function (via cellular)	Vehicles near suspected problem
Individual vehicle speed and following distance report	Vehicles near suspected problem (via cellular)	This function
Incident report	This function	TOC Active Incident Database
Additional information on incident including resources needed	Responders on scene	This function
Resources needed	This function	Emergency Response

E.4.23 Emergency Response and Incident Clearing

This function is triggered by the Emergency Detection function. It is performed in parallel by the vehicle and the infrastructure. It uses pre-programmed logic to decide on

the nature of the initial response, and displays the result for review by a human operator, who may override it, but whose input is not required for the response to proceed.

Description	From System	To System
Incident report including nature of incident	Emergency Detection/Monitoring	This function
Ordered actions by vehicles	This function	Vehicles in vicinity of incident
Request for response	This function	Appropriate agency - fire, police, tow truck contractor
Confirmation of arrival on scene	Responder on scene	This function
Additional resources needed	Emergency Response	This function

E.4.24 Driver Interrupt Handling

Deferred pending completion of the appropriate cross-cutting study.

E.5 Physical Architecture

Location	System Type	System Description	
Location	System Type	System Description	
Vehicle	Sensor	Name	Lateral position sensors
		Function	Identify lane/lane position
		Candidate Technologies	Vision system Magnetometer system Radar reflective stripe system
Vehicle	Sensor	Name	Vehicle detection sensors
		Function	Measure range, azimuth and range rate of large objects on roadway within 300 to 400 feet of vehicle
		Candidate Technologies	Doppler (EM) radar Laser radar Vision system
Vehicle	Sensor	Name	Obstacle detection sensor
		Function	Sense (small) objects and animals in the roadway ahead of the vehicle
		Candidate Technologies	Radar Doppler radar Laser radar Vision system
Vehicle	Sensor	Name	Vehicle state sensors
		Function	Sense vehicle speed, acceleration, heading, and traction
		Candidate Technologies	Speedometer, tachometer, accelerometers, gyroscope, compass. Hughes' Surface Condition Sensor (broadband microwave) for road surface
Vehicle	Sensor	Name	Absolute position sensors
		Function	Determine true vehicle position
		Candidate Technologies	GPS/Mapping system Count of encoded stripes Position from beacons/dead reckoning using vehicle state sensors
Vehicle	Sensor	Name	Road condition sensor
		Function	Detect water, snow, ice
		Candidate Technologies	Thermometer, barometer, hygrometer, vision system, traction sensor

Location	System Type	System Description	
Vehicle	Control System	Name	Speed Controller
		Function	Regulate vehicle speed
		Subsystems	Throttle controller, braking controller
Vehicle	Control System	Name	Steering Controller
		Function	Generate servo commands for steering actuator
Vehicle	Control System	Name	Throttle Controller
		Function	Generate servo commands for throttle actuator
Vehicle	Control System	Name	Braking Controller
		Function	Generate servo commands for braking actuator
Vehicle	Communi-cation System	Name	Vehicle-to-vehicle communication system
		Function	Transfer of vehicle maneuver information among nearby vehicles to support cooperative lane changing, merging, and platooning
		Candidate Technologies	Wireless mobile radio Infrared
Vehicle	Communi-cation System	Name	Vehicle-to-roadside two-way broadcast communication system
		Function	Transfer maneuver and obstacle information concerning local merge/entry/exit area. Roadside transmits general speed or lane change assignments to group; vehicle transmits position and speed
		Candidate Technologies	Wireless mobile radio RFID tag system

Location	System Type	System Description	
Vehicle	Communi-cation System	Name	Infrastructure-to-vehicle two-way addressed communication system
		Function	Provides continuous coverage of lanes to transfer maneuver and obstacle information to specific vehicles. Vehicles transmit ID, position and speed to the infrastructure.
		Candidate Technologies	Wireless mobile radio
Infrastructure	Sensors	Name	Roadway surface monitoring
		Function	Monitor hazardous areas for snow, ice, water on roadway surface
		Candidate Technologies	Hughes' Surface Condition Sensor (broadband microwave)
Infrastructure	Sensors	Name	Roadway obstacle monitoring
		Function	Monitor hazardous areas for avalanche, rockfall, mudslide, etc.
		Candidate Technologies	Vision system Laser radar
Infrastructure	Control System	Name	Entry processor
		Function	Check vehicle status, driver status, and AHS traffic conditions before allowing vehicle to enter. Control entry barrier
	Control System	Name	Roadside processor
		Function	Regulate flow of vehicles into merge point. Match vehicles in one traffic stream with "holes" in other traffic stream.
Infrastructure	Control System	Name	Region processor
		Function	Optimize traffic flow for region. Manage incident response

Location	System Type	System Description	
Infrastructure	Communi-cation System	Name	Vehicle-to-roadside two-way broadcast communication system
		Function	Transfer maneuver and obstacle information concerning local merge/entry/exit area. Roadside transmits general speed or lane change assignments to group; vehicle transmits position and speed
		Candidate Technologies	Wireless mobile radio RFID tag system
Infrastructure	Communi-cation System	Name	Infrastructure-to-vehicle two-way addressed communication system
		Function	Provides continuous coverage of lanes to transfer maneuver and obstacle information to specific vehicles. Vehicles transmit ID, position and speed to the infrastructure.
		Candidate Technologies	Wireless mobile radio
Infrastructure	Communi-cation System	Name	Roadside controller-to-TOC communication system
		Function	Transfer traffic flow information such as vehicle density and speed, local road conditions, and reports of incidents to the TOC. Receive traffic density and roadway status for adjacent regions, ID validation algorithm, and financial status for vehicles.
		Candidate Technologies	Land line Microwave link

E.6 Expected Stakeholder Role/Benefits vs Deployment Phase

Urban & Intercity	Phase 1	Phase 2	Phase 3
Rural	Phase 1	Phase 2	Not Applicable
Vehicle Electronics	Provide vehicle sensors and processors as original equipment and for retrofit	Provide vehicle-to-vehicle and infrastructure-to-vehicle communication equipment and vehicle processor upgrades	Upgrade vehicle and roadside communication equipment for 2-way communication with specific vehicles
Highway Design and Construction	Convert conventional lane to AHS by modifying for lane-keeping	Add pavement/obstacle sensors and roadside beacons. Convert/build dedicated lane where practical	Convert/build separate truck lane on intercity routes, separate transit lane on urban routes where practical
Trucking	Truck platoons on intercity routes increase driver productivity (non-lead drivers nap)	Platoons w/ disengaged drivers on urban and intercity routes	Separate AHS truck lane where practical on intercity routes
Transit	Lane keeping, longitudinal position keeping, collision avoid. features increase safety. More reliable travel times due to navigation	Driver can provide service to passengers en-route without delaying trip	Separate transit lanes reduce trip times, make travel times more reliable
Environmental Interests	Reduction in emissions per vehicle mile due to smoother driving	Reduction in emissions due to platooning and flow control; narrower lanes possible on urban and intercity routes	Better flow of truck and bus traffic further reduces emissions where separate lane is provided
Transportation Users	Driver need not concentrate on driving; less stress	Driver fully disengaged; can perform other tasks	Shorter, more reliable trip times, less chance of secondary accident due to better flow control, incident management
Government Agencies	Set roadway and vehicle standards; gain public confidence in and acceptance of automated vehicles	Set communication standards; gain public confidence in and acceptance of infrastructure control of vehicles	Better control of traffic. Help resolve privacy issues associated with communication with identified single vehicles
Insurance Industry	Help resolve liability issues concerning automated vehicles	Help resolve liability issues concerning infrastructure control of vehicles	Infrastructure coordination provides better information on accidents that occur

E.7 Degraded Function Description Table

E.7.1 Urban/Intercity Phase 3

The following table describes hardware failure responses for an AHS deployment which has both infrastructure coordinated and cooperative capabilities. It further assumes, pending communications hardware module definition, that the three types of communication systems aboard the vehicle are separate hardware modules.

Hardware Module Which Fails	Own Vehicle Actions	Infrastructure Actions/ *Other Vehicle Actions*
Vehicle lateral position sensor	Slow down Alert nearby vehicles and infrastructure Pull to right side of road and stop	Provide detailed road geometry to vehicle *Other vehicles provide steering guidance using on-board sensors*
Vehicle detection sensors	Slow down Alert nearby vehicles Request guidance from infrastructure	Order speed and lane changes to get vehicle off at next exit *Other vehicles increase space from failed vehicle*
Obstacle detection sensor	Notify driver Maintain "follower" position until exit	Prevent vehicle from re-entering AHS after it exits
Vehicle position sensor	Alert infrastructure; request guidance	Order speed and lane changes to get vehicle off at next exit
Road condition sensor	Notify driver Request roadway condition reports from other vehicles	Prevent vehicle from re-entering AHS after it exits *Other vehicles provide roadway condition reports*
Vehicle throttle, steering, or braking controllers	Alert infrastructure Alert other vehicles Use remaining controllers to stop vehicle out of lane if possible, in lane if necessary	Alert nearby vehicles *Other vehicles increase spacing from affected vehicle*
Vehicle-to-vehicle communication	Alert infrastructure Notify driver Get off at next service opportunity	Alert nearby vehicles Provide lane change orders as needed for affected vehicle
Vehicle-to-infrastructure broadcast communication	Request nearby vehicles to notify infrastructure Notify driver	Prevent vehicle from re-entering AHS after it exits

Hardware Module Which Fails	Own Vehicle Actions	Infrastructure Actions/ *Other Vehicle Actions*
Infrastructure-to-vehicle broadcast communication	No action required	Call in trouble report Use overlapping coverage if available (e.g., section controller to cover for merge controller)
Vehicle-to-infrastructure two-way communication	Notify driver Use vehicle-to-infrastructure broadcast to notify infrastructure, send high-priority messages	Do not expect replies to low priority messages sent to affected vehicle Prevent vehicle from re-entering AHS after it exits
Infrastructure-to-vehicle two-way communication	Use cooperative capabilities, broadcast communication to infrastructure	Call in trouble report Use I/S capabilities
Loss of all infrastructure-to-vehicle communication	Use cooperative lane-changing, merging, local hazard warning	None possible *Use cooperative lane-changing, merging, local hazard warning*
Infrastructure roadway surface monitoring and obstacle detection sensors	No action required	Order reduced speed on affected sections of road *Vehicles encountering hazards broadcast warning to nearby vehicles as usual*
Dedicated lane entry processor	Drive manually to next AHS on-ramp	Admit no vehicles at this on-ramp
Roadside processor	No action required	Redundant databases allow adjacent roadside processors to cover for defective one
Region processor	No action required	Region will use multiple processors working in parallel. If one or more fail, lower priority tasks will be postponed, wait for some services will be longer
Roadside controller-to- TOC communication system	No action required	Adjacent roadside processors will relay information to/from TOC during periods of low demand

E.7.2 Degraded AHS Function Description Table: Rural Phase 2

The following table describes hardware failure responses for an AHS deployment which
has both infrastructure supported and cooperative capabilities. It further assumes,
pending communications hardware module definition, that the three types of
communication systems aboard the vehicle are separate hardware modules.

Hardware Module Which Fails	Own Vehicle Actions	Infrastructure Actions/ *Other Vehicle Actions*
Vehicle lateral position sensor	Slow down Alert nearby vehicles and infrastructure Pull to right side of road and stop if possible, otherwise stop in lane	*Other vehicles (if present) provide steering guidance using on-board sensors*
Vehicle detection sensors	Slow down Alert nearby vehicles Request guidance from infrastructure	*Nearby vehicles send position relative to vehicle with sensor failure, increase space from failed vehicle*
Obstacle detection sensor	Notify driver Maintain "follower" position until exit	Prevent vehicle from re-entering AHS after it exits
Vehicle position sensor	Alert infrastructure and nearby vehicles	*Nearby vehicles compute and send position of vehicle with sensor failure*
Road condition sensor	Notify driver Request other vehicles send roadway condition	Other vehicles send roadway condition reports Prevent vehicle from re-entering AHS after it exits
Vehicle throttle, steering, or braking controllers	Alert infrastructure Alert other vehicles Use remaining controllers to stop vehicle in lane	Alert nearby vehicles *Other vehicles increase spacing*
Vehicle-to-vehicle communication	Alert infrastructure Notify driver Get off at next service opportunity	Alert nearby vehicles - notify them where disabled vehicle will exit *Nearby vehicles allow disabled vehicle room to change lanes and exit*
Vehicle-to-infrastructure broadcast communication	Send message to adjacent vehicles requesting them to notify infrastructure Notify driver	*Nearby vehicles relay message* Prevent vehicle from re-entering AHS after it exits

Hardware Module Which Fails	Own Vehicle Actions	Infrastructure Actions/ *Other Vehicle Actions*
Infrastructure-to-vehicle broadcast communication	Vehicle enters traffic flow and merges cooperatively	Call in trouble report *Cooperative merging*
Loss of all infrastructure-to-vehicle communication	Use cooperative lane-changing, merging, local hazard warning	None possible *Use cooperative lane-changing, merging, local hazard warning*
Infrastructure roadway surface monitoring and obstacle detection sensors	No action required	Order reduced speed on affected sections of road *Vehicles encountering hazards broadcast warning to nearby vehicles as usual*
Dedicated lane entry processor	Drive manually to next AHS on-ramp	Admit no vehicles at this on-ramp
Roadside processor	No action required	Redundant databases allow adjacent roadside processors to cover for defective one
Region processor	No action required	Region will use multiple processors working in parallel. If one or more fail, lower priority tasks will be postponed, wait for some services will be longer
Roadside controller-to- TOC communication system	No action required	Adjacent roadside processors will relay information to/from TOC during periods of low demand

E.8 Societal and Institutional Factors

Most of the AHS concepts include a number of vehicle and roadway types as part of their deployment plan. While there is a high degree of compatibility among them, there will be some situations where an AHS user, perhaps from a rural state, drives to a large city which has a more complex AHS deployment and finds that his vehicle is not compatible. It is important to the acceptance of AHS that those areas of the country which have less than the full-up AHS deployment not be made to feel like second-class citizens. The Adaptable concept starts with a basic autonomous vehicle and then adds communication modules and associated processing for the I/S, Cooperative, and I/C layers. This approach promotes modularity, and will tend to reduce the cost for someone who wants to drives his "rural-deployment AHS-mobile" in a big city with a fully-developed urban deployment of AHS. It is even possible that the required modules will be able to be rented by the day or week, like a cellular phone.

As anyone who reads the newspapers knows, there is in this country at present a trend toward more regional control and decision-making authority. Among other reasons, this springs from the fact that this is a diverse country, with people in different regions having different problems and needs from any national program including, but not limited to, AHS. Some regions have little money to spend, or their transportation problems that can be addressed by an AHS are modest – they need a low-end, inexpensive solution. Other regions contain densely populated urban areas where delays, accidents, and the other shortcomings of the current highway architecture have costs in the billions of dollars per year. The AHS architecture must meet this need for diversity while maintaining a high degree of compatibility between types of vehicles and types of roadways. The Adaptable Concept, with its large menu of regional and deployment options, promotes regional acceptance of AHS.

E.9 AHS Functions vs. Urban Deployment Phases Adaptable Concept

AHS Function	Urban Phase 0	Urban Phase 1	Urban Phase 2-	Urban Phase 2+	Urban Phase 3
Speed tracking	Vehicle	Vehicle	Vehicle	Vehicle	Vehicle
Inter-vehicle separation tracking	Vehicle	Vehicle	Vehicle	Vehicle	Vehicle
Lane keeping	Vehicle	Vehicle	Vehicle	Vehicle	Vehicle
Lane changing	Driver	Vehicle; driver in heavy traffic	Vehicle; infrastructure support by ordering spacing	Coordination among vehicles	Coordination among vehicles
Road geometry recognition	Vehicle	Vehicle	Vehicle; some roadside beacons	Vehicle; some roadside beacons	Vehicle; some roadside beacons
Obstacle recognition	Driver	Vehicle	Vehicle initially; then mobile beacon + vehicle	Vehicle initially; then mobile beacon + vehicle	Vehicle initially; then mobile beacon + vehicle
Obstacle avoidance	Driver	Vehicle if traffic permits; otherwise stop	Vehicle if traffic permits; otherwise stop	Vehicle	Vehicle & infrastructure in parallel
Speed decision	Driver	Vehicle	Infrastructure or vehicle	Infrastructure or vehicle	Infrastructure or vehicle
Inter-vehicle separation decision	Vehicle, driver for exceptions	Vehicle	Infrastructure or vehicle	Infrastructure or vehicle	Infrastructure or vehicle
Lane change decision	Driver	Vehicle; driver in heavy traffic	Infrastructure or vehicle	Infrastructure or vehicle	Infrastructure or vehicle
Lane change coordination	Visual	None for vehicle; visual for driver	Infrastructure can order spacing	Infrastructure can order spacing; coordination among vehicles	Infrastructure + vehicle
Platoon formation & dispersal	None	None	None	Cooperative	Infrastructure coordination formation; cooperative dispersal

AHS Function	Urban Phase 0	Urban Phase 1	Urban Phase 2-	Urban Phase 2+	Urban Phase 3
Vehicle operational status monitor	Driver, vehicle components	Vehicle	Vehicle	Vehicle	Vehicle
Driver status monitoring	Periodic alertness check by vehicle	Vehicle	Vehicle	Vehicle	Vehicle
Vehicle entry	Driver	Vehicle or driver	Vehicle w/ support of infrastructure ordered spacing	Infrastructure & vehicle	Infrastructure & vehicle
Vehicle exit	Driver	Vehicle	Vehicle + beacon	Vehicle + beacon	Vehicle + beacon
Auto. highway merging	Driver	Vehicle; driver in heavy traffic	Vehicle w/ support of infrastructure ordered spacing	Coordination among vehicles with infrastructure support	Infrastructure + cooperation among vehicles
Lane-to-lane routing	Driver w/ ITS information	Vehicle	Vehicle using info from beacon	Vehicle using info from beacon	Infrastructure or vehicle
End-to-end routing	Driver w/ ITS information	Vehicle	Vehicle	Vehicle	Vehicle
AHS flow control	None	None	Infrastructure, broadcast mode	Infrastructure, broadcast mode	Infrastructure assisted
AHS admission control	None	None	Infrastructure	Infrastructure	Infrastructure
Emergency detection/monitoring	Driver	Driver & vehicle; infrastructure notified	Driver & vehicle; infrastructure notified	Driver & vehicle; infrastructure notified; nearby vehicles warned	Driver & vehicle; infrastructure notified; nearby vehicles warned
Emergency response/incident handling	Present capabilities	Present capabilities	Vehicle initially; infrastructure support for flow control and emergency vehicles; mobile beacons	Vehicle initially; infrastructure & cooperative support for flow control and emergency vehicles; mobile beacons	Infrastructure & vehicle in parallel; infrastructure & cooperative support for flow control and emergency vehicles; mobile beacons
Driver interrupt handling	Driver override on all functions	Driver override on all functions	Interrupt trip, change destination, choose route	Interrupt trip, change destination, choose route	Interrupt trip, change destination, choose route

E.10 AHS Functions vs. Rural Deployment Phases

AHS Function	Rural Phase 0	Rural Phase 1	Rural Phase 2
Speed tracking	Vehicle	Vehicle	Vehicle
Inter-vehicle separation tracking	Vehicle	Vehicle	Vehicle
Lane keeping	Vehicle	Vehicle	Vehicle
Lane changing	Driver	Vehicle; driver in heavy traffic	Coordination among vehicles
Road geometry recognition	Vehicle	Vehicle	Vehicle; some roadside beacons
Obstacle recognition	Driver	Vehicle	Vehicle initially; then mobile beacon + vehicle
Obstacle avoidance	Driver	Vehicle if traffic permits; otherwise stop	Vehicle cooperatively
Speed decision	Driver	Vehicle	Infrastructure or vehicle
Inter-vehicle separation decision	Vehicle, driver for exceptions	Vehicle	Infrastructure or vehicle
Lane change decision	Driver	Vehicle; driver in heavy traffic	Infrastructure or vehicle
Lane change coordination	Visual	None for vehicle; visual for driver	Infrastructure orders spacing + cooperation among vehicles
Platoon formation & dispersal	None	None	Cooperative

AHS Function	Rural Phase 0	Rural Phase 1	Rural Phase 2
Vehicle operational status monitor	Driver, vehicle components	Vehicle	Vehicle
Driver status monitoring	Periodic alertness check by vehicle	Vehicle	Vehicle
Vehicle entry	Driver	Vehicle	Infrastructure orders spacing + cooperation among vehicles
Vehicle exit	Driver	Vehicle	Vehicle + beacon
Auto. highway merging	Driver	Vehicle; driver in heavy traffic	Infrastructure orders spacing + cooperation among vehicles
Lane-to-lane routing	Driver w/ ITS information	Vehicle	Vehicle
End-to-end routing	Driver w/ ITS information	Vehicle	Vehicle
AHS flow control	None	None	Infrastructure, broadcast mode
AHS admission control	None	None	Infrastructure
Emergency detection/monitoring	Driver	Driver & vehicle; infrastructure notified	Driver & vehicle; warning broadcast by vehicle & infrastructure notified
Emergency response/incident handling	Present capabilities	Present capabilities	Vehicle initially; infrastructure broadcast support for emergency vehicles; mobile beacons
Driver interrupt handling	Driver override on all functions	Driver override on all functions	Interrupt trip, change destination , choose route

E.11 AHS Functions vs. Intercity Deployment Phases

AHS Function	Intercity Phase 0	Intercity Phase 1	Intercity Phase 2	Intercity Phase 3
Speed tracking	Vehicle	Vehicle	Vehicle	Vehicle
Inter-vehicle separation tracking	Vehicle	Vehicle	Vehicle	Vehicle
Lane keeping	Vehicle	Vehicle	Vehicle	Vehicle
Lane changing	Driver	Vehicle; driver in heavy traffic	Coordination among vehicles	Coordination among vehicles
Road geometry recognition	Vehicle	Vehicle; some roadside beacons	Vehicle; some roadside beacons	Vehicle; some roadside beacons
Obstacle recognition	Driver	Vehicle	Vehicle initially; then mobile beacon + vehicle	Vehicle initially; then mobile beacon + vehicle
Obstacle avoidance	Driver	Vehicle if traffic permits; otherwise stop	Vehicle	Vehicle & infrastructure in parallel
Speed decision	Driver	Vehicle	Infrastructure or vehicle	Infrastructure or vehicle
Inter-vehicle separation decision	Vehicle, driver for exceptions	Vehicle	Infrastructure or vehicle	Infrastructure or vehicle
Lane change decision	Driver	Vehicle; driver in heavy traffic	Infrastructure or vehicle	Infrastructure or vehicle
Lane change coordination	Visual	None for vehicle; visual for driver	Infrastructure can order spacing; coordination among vehicles	Infrastructure + vehicle
Platoon formation & dispersal	None	Cooperative for trucks only	Cooperative	Infrastructure assisted formation; cooperative dispersal

AHS Function	Intercity Phase 0	Intercity Phase 1	Intercity Phase 2	Intercity Phase 3
Vehicle operational status monitor	Driver, vehicle components	Vehicle	Vehicle	Vehicle
Driver status monitoring	Periodic alertness check by vehicle	Vehicle	Vehicle	Vehicle
Vehicle entry	Driver	Vehicle or driver	Infrastructure & vehicle	Infrastructure & vehicle
Vehicle exit	Driver	Vehicle	Vehicle + beacon	Vehicle + beacon
Auto. highway merging	Driver	Vehicle; driver in heavy traffic	Coordination among vehicles with infrastructure support	Infrastructure + cooperation among vehicles
Lane-to-lane routing	Driver w/ ITS information	Vehicle	Vehicle using info from beacon	Infrastructure or vehicle
End-to-end routing	Driver w/ ITS information	Vehicle	Vehicle	Vehicle
AHS flow control	None	None	Infrastructure, broadcast mode	Infrastructure assisted
AHS admission control	None	None	Infrastructure	Infrastructure
Emergency detection/monitoring	Driver	Driver & vehicle; infrastructure notified	Driver & vehicle; infrastructure notified; nearby vehicles warned	Driver & vehicle; infrastructure notified; nearby vehicles warned
Emergency response/incident handling	Present capabilities	Present capabilities	Vehicle initially; infrastructure & cooperative support for flow control and emergency vehicles; mobile beacons	Vehicle & infrastructure in parallel; infrastructure & cooperative support for flow control and emergency vehicles; mobile beacons
Driver interrupt handling	Driver override on all functions	Driver override on all functions except trucks following in platoon	Interrupt trip, change destination, choose route	Interrupt trip, change destination, choose route

E.12 Roadway vs. Vehicle Compatibility

	Roadway Characteristics (down column)	Manual	Pre-Autonomous	Autonomous	Receive Infrastructure Broadcast	Infrastructure/ Veh. Two-Way Comm.	Veh./Veh. Two-Way Comm.
Vehicle Characteristics (across row)		Vehicle has no AHS capability	Lane and longitudinal position-keeping; manual lane changing	Lane and longitudinal position-keeping; auto. lane changing when traffic permits	Autonomous plus ability to receive and execute commands from infrastructure, broadcast position and speed	Autonomous plus ability to exchange messages with infrastructure and execute orders	Autonomous plus ability to exchange messages and negotiate with other vehicles
Mixed traffic, no infrastructure	Current freeway lanes	Yes	Yes	Yes	Yes	Yes	Yes
Dedicated lane, no infrastructure	Roadway enhanced for lane keeping	No	No	Yes	Yes	TBD (see note)	Yes
Dedicated lane, one-way vehicle/infra-structure communication	Commands broadcast by infrastructure	No	No	No	Yes	TBD (see note)	TBD (see note)
Dedicated lane, two-way vehicle/infra-structure communication	Communication between infrastructure and individual vehicle	No	No	No	Must upgrade	Yes	TBD (see note)

Note: Subject to communications hardware module definition.

Appendix F.   Application Scenarios Description

F.1 Data Inputs for Selected Application Scenarios

At the beginning of work on the C2 Task, the objective was to select application scenarios and appropriately matched specific site locations for which needed data would be obtained from appropriate sources, such as Metropolitan Planning Organizations and/or district or state Departments of Transportation. A broad investigation of representative and promising candidate application scenarios and corresponding specific sites was conducted. It was decided that four application scenario types would be pursued, namely, urban, rural, inter-city or inter-urban and a transit application. The transit application involved the collaborative effort between the consortium and the Houston Metropolitan Transit Authority (METRO), the first NAHSC-sponsored Case Study. Actual site-specific locations were chosen for the urban and rural scenarios and a process was initiated to obtain the required data. The tradeoff that exists in working with actual data from site-specific locations is the concern over the representativeness of such a site for all sites of that type, as promising sites of the same type still have differences. This potential concern was overtaken by the more serious obstacle of data acquisition for the application scenarios due to time and resource limitations. A compromise approach was reached for the urban, rural, and inter-city scenarios in which hypothetical or generic scenario sites were chosen as a way to represent the general features of the highway transportation system for each of these three scenario types. The data, both geometric and travel demand, for these three hypothetical scenarios, while not actual, were characteristic of these three scenario settings.

Three representative scenario sites were selected on which to perform subsequent analysis, urban, inter-city, and rural which are described in sections F.2, F.3, and F.4, respectively.

F.2 Urban

One of the application scenarios was chosen to represent a "typical" urban area, that is, a heavily congested roadway network encompassing major activity centers, such as the Central Business District (CBD) and including numerous entry and exit points such as highway-to-highway interchanges. The implementation of AHS in an urban environment, though it may face challenges because of constraints to potential expansion of the right-of-way even in the case of manual to automated lane conversion, is of central importance because of its potential ability to have a beneficial impact on congestion, both recurrent and non-recurrent congestion.

F.2.1 Types of Information

The information obtained for the application scenarios are of the following two primary types: geometric/physical characteristics and travel demand data. Each of these two types is described in the following two sub-sections.

F.2.1.1 Geometric/Physical Characteristics

The hypothetical urban application scenario is a 24 mile linear corridor, traveling from the suburban portions of the region through the CBD, serving intra-city travel needs. The AHS application in this urban corridor is based on converting an existing manual lane into a new AHS lane for each travel direction. For purposes of the analysis based on this urban scenario, only the inbound (suburb to city) portion of the corridor was under study. In the following sections, all information refers to the inbound direction.

F.2.1.2 Existing Configuration

The 24 mile hypothetical urban corridor consists of 21 miles through the more suburban sections of the region and 3 miles through the CBD. The average segment length inside the CBD area is only 1600 feet. For the freeway in the suburbs, the segment length varies from 1.7 mile in the outer-suburb to an average of half a mile in the inner suburb.

Other geometric characteristics for the corridor include 2-foot inside shoulders, 10-foot outside shoulders, and a range in the number of 12-foot lanes from 3 to 6. The varying number of lanes depends on the geographic location of the freeway and its traffic flow. At the urban core, the freeway has a 6-lane cross section, and at interchanges with other urban freeways, the roadway generally has 5-lane cross-sections. Generally, the number of lanes decreases with increasing distance from major activity centers.

The inbound corridor has a total of 23 entries and 23 exits, with more densely distributed entries/exits on the portion of the roadway in the CBD. There are also two highway-to-highway interchanges. The highways use both over-crossing and under-crossing configurations for local arterials at entry/exit locations. The interchange configurations basically use the form of staggered diamond structure, including one diamond interchange, and one semi-diamond structure.

F.2.2 AHS Application

A dedicated AHS lane is applied for the urban application scenario. Because of potential physical constraints to adding an additional lane for automated use in an existing right-of-way in an urban environment, an automated lane on the urban freeway is implemented by means of converting the inside lane from manual to automated use. Two subscenarios were initially considered with respect to entry/exit facilities:

1. Dedicated entry/exit from local arterials to the automated lane via a overpasses

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2. Entry/exit to the automated lane from existing manual on- and off-ramps by weaving through manual lanes and transitioning to the automated lane.

Subscenario 1: Dedicated entry/exit from local arterials
- Continuous physical barrier separating automated and manual traffic.
- Distance between dedicated entry/exit is 2 miles outside the CBD, and inside CBD area is at most 1.2 miles.
- Cross section of the automated lane outside the exit/entry area: 1 12-foot automated lane, 1 8-foot inside shoulder, 2-foot horizontal clearance between automated lane and physical barrier.
- Access: 8 exits and 6 entrances for the automated lane. Among them, three pairs of exits/entries are located inside CBD area. The length of entrance ramp is approximately 820 feet; and the length of exit ramps is also approximately 820 feet plus an allowance for queues. The physical configuration for a dedicated entry/exit is via an overpass to an at-grade automated lane.
- Direct AHS highway-to-highway interchanges are part of physical configuration to facilitate the movement of automated vehicles between urban freeways, using a staggered diamond configuration. Incorporating new construction over current highway interchanges may add complexity to current interchange by way of requiring higher or more spread out configurations (See urban scenario figures in Chapter 4.3, Chapter 7, and Appendix L).
- Merge and de-merge: at the location of entry/exit and interchange, it requires a temporary second lane on the right side of the automated lane. This second lane could be the widening out of the freeway traveled way. The length of the merging/de-merging lane varies depending on concept attributes.

Subscenario 2: Entry/exit to automated lane from freeway mainlines via a transition lane.
- Non-continuous physical barriers separating automated and transition traffic, and transition and manual traffic.
- Average distance between entry/exit is outside the CBD is 2 miles, and within the CBD is at most 1.2 miles.
- Cross section for the automated lane outside the exit/entry area is 1 12-foot automated lane, 1 8-foot inside shoulder, and a 2-foot horizontal clearance between automated lane and physical barrier.
- Access: 8 exits and 6 entrances via the transition zone for the AHS lane. Among them, 3 of each are located in the CBD area. Automated vehicles access the automated lane using existing on/off ramps, weaving through manual lanes, and changing from manual to automated mode in the transition zone.
- Interchange: At the highway-to-highway interchanges, automated vehicles need to exit automated lane, access manual lanes, and utilize existing highway-to-highway interchange.
- Transition zone: it can be a continuous lane or a non-continuous lane with temporarily widened out areas for entrance and exit. In the section from manual to transition lane, the length of entry section from manual to transition is approximately

820 feet and the length of exit section is again approximately 820 feet plus queue allowance. In the transition area from transition lane to AHS lane, the length of merging/de-merging (entry/exit) lane also varies from about 300 feet to 500 feet depending on the concept attributes.

For the remainder of the development of the application scenarios, focus is placed on sub-scenario 1 based on (1) previous results from the PSA studies which indicated safety-related issues associated with the sharing of entry/exit facilities with manual traffic and weaving through manual lanes to transition to the automated lane and (2) resource constraints limiting the ability to analyze both subscenarios.

F.2.3 Travel Demand

This section describes travel demand level for the baseline or non-automated freeway lanes and for the automated lane. Focus is placed on simulating travel during the morning peak hour.

F.2.3.1 Baseline Level

The hypothetical urban highway is a heavily congested corridor. During the morning peak hour, only 35% of corridor segments, i.e. portions of roadway between entry/exit locations, handle flows no greater than 2,000 vehicles per hour per lane (vphpl) with an average flow of 1,834 vphpl. However, 40% of the segments are carrying in excess of 2,200 vphpl with an average of 2356 vphpl. Within the CBD, the freeway is serving a flow of 2,600 vphpl during the morning peak hour. Examination of access points also reveals that 40% of entries are serving a flow over 700 vphpl. These demand levels for the hypothetical urban corridor freeway are based on actual traffic volumes existing in current heavily congested urban corridors.

Traffic volumes were initially produced at each entry and exit point and then an origin-destination trip table or matrix was derived which provided the distribution of all entering traffic among all subsequent exiting traffic.

F.2.3.2 AHS Levels

Four different levels of automated vehicle traffic demand were developed for purposes of sensitivity analysis. The average segment demand levels during the peak hour on a single AHS lane vary between a low of approximately 2700 vehicles to a maximum of about 6800 vehicles. Details are shown in Table F-1. Traffic volumes were initially produced at each AHS entry and exit point and then an origin-destination trip table was derived which provided the distribution of all entering AHS traffic among all subsequent exiting AHS traffic. A vehicle class percentage distribution was derived consisting of 93% light-duty passenger vehicles, 1% buses, and 6% trucks on the urban corridor. This vehicle class distribution was based on previous work in References 2, 3, and 4.

F.2.4 Graphical Description of AHS Urban Scenario

Figures F-1–F-3 depict various views for the urban scenario.

Figure F-1 shows three views of the dedicated entry/exit ramp configuration. Figure F-2 shows the following three items: (1) existing cross-section of roadway in the case of four manual lanes, (2) modified cross-section of roadway under the configuration of converting the number 1 manual lane to automated use in conjunction with dedicated entry and exit facilities. The required right-of-way width (one direction) is 60 feet in the existing baseline case whereas the required width in the AHS case is 72 feet. Both of these widths excludes the one foot for the physical barrier. Thus, even when an existing manual lane is converted for automated use, additional right-of-way is required in the assumptions used here (primarily to accommodate the separate shoulder for the AHS lane). The bottom portion of Figure F-2 displays a birds'-eye-view of the roadway (one direction) indicating a solid barrier separating manual from automated vehicles.

Figure F-3 expands on the cross-section elements of Figure F-2 and depicts again in the top portion the manual/AHS cross-section for the case of converting one of four manual lanes to automated use. This cross-section is outside the access/egress area. The bottom portion shows a cross-section at the access point.

For a complete description of these figures as well as additional figures see Chapter 6.

Table F-1. Traffic Demand on Automated Lane in an Urban Setting

Urban							
	AHS Volume				Access Volume		
	Total Traffic Volume	Avg. Segment Volume	Min. Segment Volume	Max. Segment Volume	Avg. Access Volume	Min. Access Volume	Max. Access Volume
Level 1	5530	2728	820	3210	426	70	640
Level 2	8295	4093	1030	4500	639	105	960
Level 3	11060	5457	1240	6000	852	140	1280
Level 4	13825	6821	1450	7500	1065	175	1600

ACCESS / EXIT   MERGE

ACCESS / EXIT   MERGE   TAPER
    (D1)   (D1) - ENTER   (D4)
                      (D3) - EXIT
                      (D2) - D3

PLAN

D1 - 1020'   D2 - ---   D4 - 780'

D3 - ---

ELEVATION
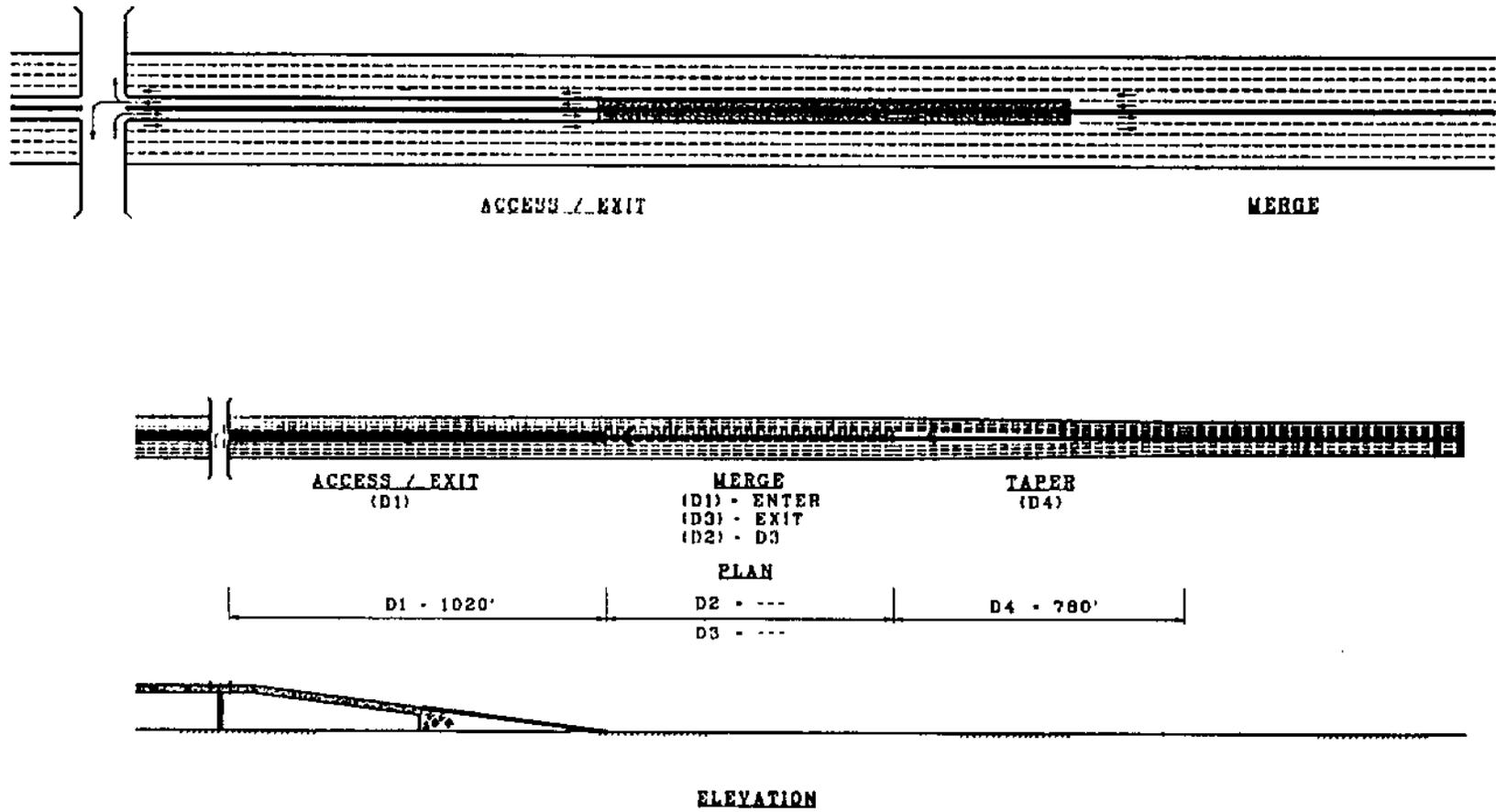
Figure F-1. Dedicated Entry/Exit Ramp.

EXISTING

MODIFIED
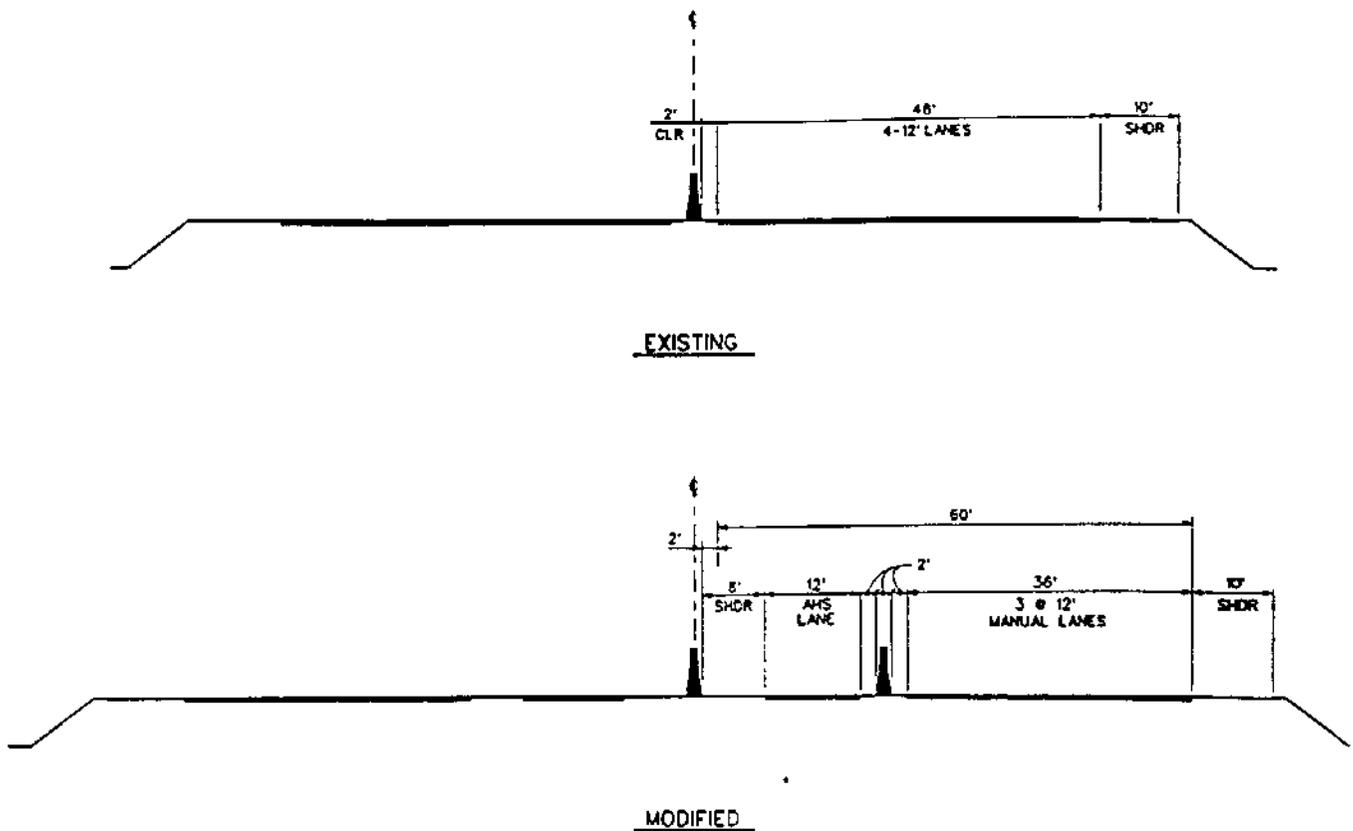
DEDICATED LANE -
DEDICATED ENTRY / EXIT RAMPS
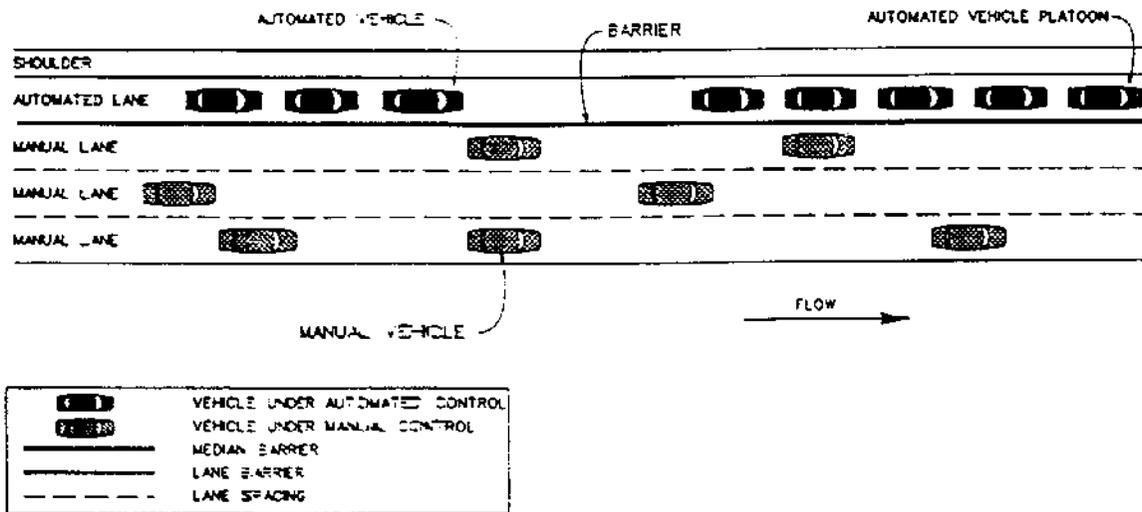
Figure F-2. AHS-Dedicated Lanes - Dedicated Ramps

73'

2'

8'	12'	36'	10'
SHDR	AHS LANE	3 @ 12' MANUAL LANES	SHDR

TYPICAL AHS / MANUAL CROSS SECTION

C/L SYMMETRICAL

79'

2'   2'

| 12'	12'	36'	10'
ACCESS RAMP	AHS LANE	3 @ 12' MANUAL LANES	SHDR
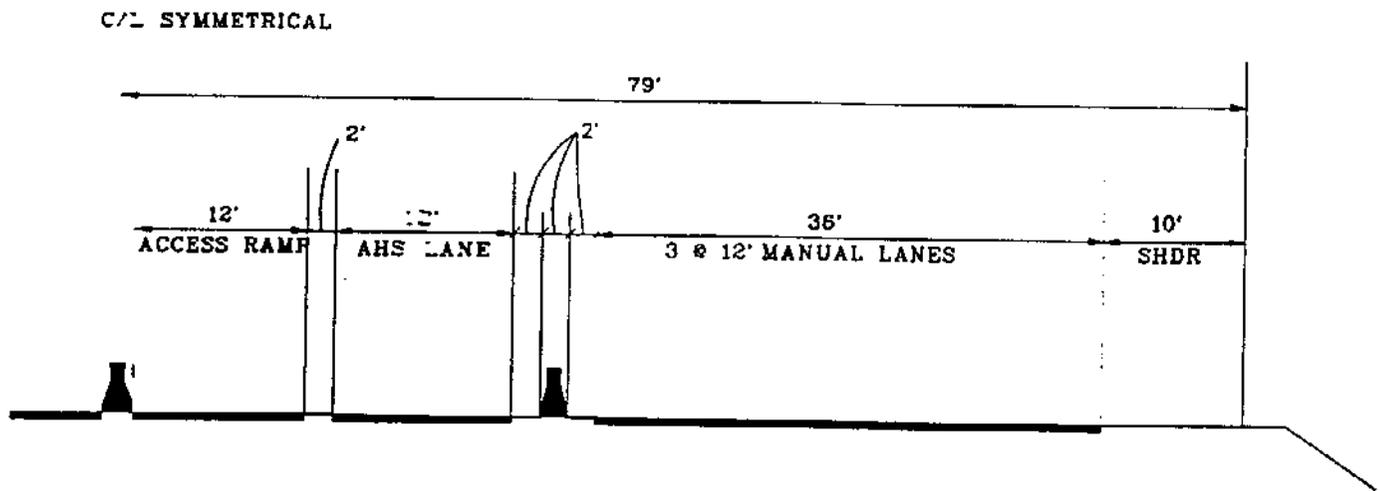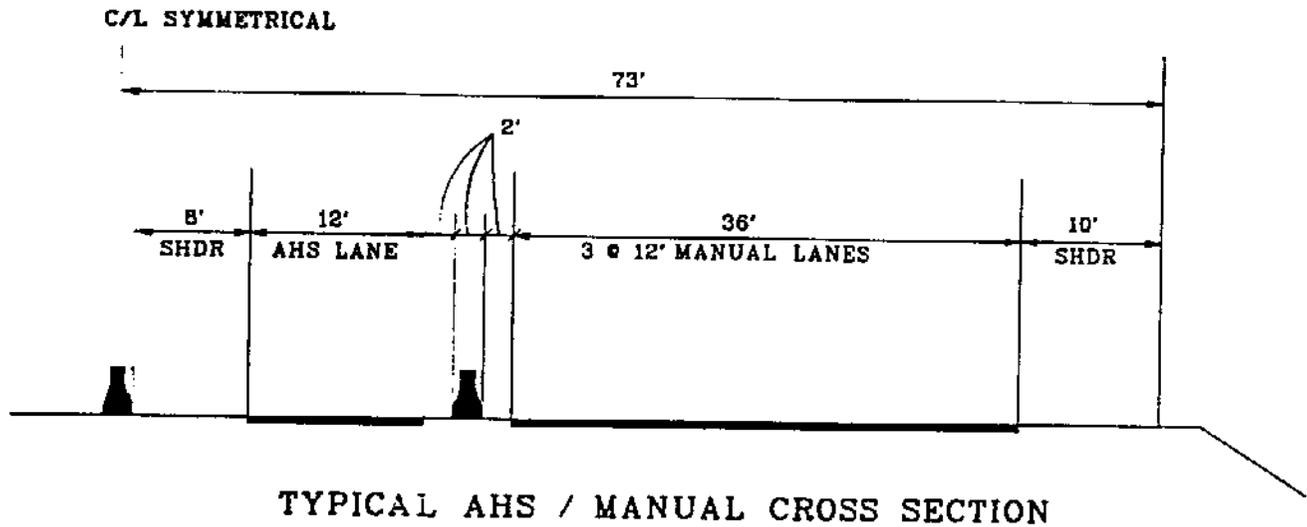
Figure F-3. Typical AHS Ramps/AHS-Manual Cross-Section

passenger movement.   Implementation of AHS in the intercity environment is primarily to assure the safety of driving over longer distances, and also to relieve congestion at particular locations.

F.3.1 Types of Information

The information obtained for the application scenarios are of the following two primary types: geometric/physical characteristics and travel demand data.

F.3.1.1 Geometric/Physical Characteristics

The hypothetical intercity highway connects two urban centers over a distance of 74 miles, starting and ending at the suburban edge of distinct urban areas. It consists of a six-lane linear corridor with three lanes for each travel direction. As in the case of the urban corridor, only a single travel direction is examined in further work.

F.3.1.2 Existing Configuration

The average segment length between access locations is 2.7 miles, with a maximum of 3.8 miles in the middle of the corridor and a minimum length of 1.2 miles at the outskirts of the urban area. The corridor has a standard 12 foot lane width, with 10-foot inside and outside shoulders. The median is considered to be a minimum of 22 feet and is generally not paved. There are 21 access and egress points which are evenly located along the highway, with a considerably smaller density than in the urban hypothetical corridor. Among these access and egress points, five pairs are highway to highway interchanges. Those highway interchanges are designed as clover-leaf interchanges, due to the relatively higher traffic volume at these locations.

F.3.2 AHS Application

The implementation of AHS in the intercity environment is to build a new automated lane. No dedicated entry/exit facilities are utilized for the automated lane due to the lower corridor traffic volume and generally improved access opportunity to the automated lane. Instead, a transition lane is used by converting a manual lane for the transition into and out of the automated lane.

- Non-continuous physical barrier separating automated and transition traffic, and the transition and manual traffic.
- Transition zone can be a continuous lane or a non-continuous area
- Cross section of AHS lane outside the exit/entry area: one 12-foot automated lane, an 8-foot inside shoulder, a 2-foot horizontal clearance between automated lane and physical barrier.
- Access to automated lane uses existing on/off ramps, weaving through manual lanes, and transfer of control between manual to automated mode through the transition zone.

- There are a total of 7 exits and entrances via the transition zone for the automated lane. The locations of the access points are spaced over a much longer distance varying between 7 and 11 miles.
- Configuration of transition: In the section of transition from manual to transition lane, length of entry section from manual to transition is approximately 820 feet and length of exit section is approximately 820 plus queue allowance. For the transition area, the merge and demerge of the vehicles require at least a widening out of the lane. The length of the merging/de-merging area depends on concept attributes.
- At the highway-to-highway interchanges, automated vehicles heading for the cross highways need to utilize existing highway-to-highway interchanges, by exiting the automated lane and accessing manual lanes.

F.3.3 Travel Demand

This section describes travel demand level for the baseline or non-automated freeway lanes and for the automated lane. Focus is placed on simulating travel during the morning peak hour.

F.3.3.1 Baseline Level

The hypothetical intercity corridor overall has a lower traffic flow with an average of 1500 vphpl. At locations close to urban areas, the flow reaches 1800 vphpl. The traffic flows on the entry/exit ramps vary widely, with a minimum of 100 vphpl and a maximum of 550 vphpl, depending on the access locations.

F.3.3.2 AHS Levels

Four different levels of automated vehicle traffic demand were developed for purposes of sensitivity analysis. The average segment demand levels during the peak hour on a single AHS lane vary between a low of approximately 2100 vehicles to a maximum of about 5100 vehicles. Details are shown in Table F-2. Traffic volumes were initially produced at each AHS entry and exit point and then an origin-destination trip table was derived which provided the distribution of all entering AHS traffic among all subsequent exiting AHS traffic. The vehicle classes on the intercity corridor are light-duty passenger vehicles and trucks, where the percentage of trucks may vary between approximately 10% and 35% based on data from Reference 3. While buses do travel on such routes, their percentage contribution is negligible.

Table F-2: Traffic Demand On Automated Lane In An Intercity Setting

Intercity							
	AHS Volume				Access Volume		
	Total Traffic	Avg. Segment	Min. Segment	Max. Segment	Avg. Access	Min. Access	Max. Access

	Volume	Volume	Volume	Volume	Volume	Volume	Volume
Level 1	4900	2053	1600	2900	379	200	450
Level 2	6950	2680	2000	3950	568	300	675
Level 3	9800	4107	3200	5800	757	400	900
Level 4	12250	5133	4000	7250	946	500	1125

F.4 Rural

The hypothetical rural highway represents an interstate highway, a corridor that is heavily used for commercial vehicle travel and recreational needs.   Safety is the most important issue for the study of AHS implementation in the rural environment.

F.4.1 Types of Information

The information obtained for the application scenarios are of the following two primary types: geometric/physical characteristics and travel demand data.

F.4.1.1 Geometric/Physical Characteristics

The generic rural interstate corridor covers a distance of 280 miles, linking two smaller size urban areas that are served primarily by a single highway. This hypothetical scenario has characteristics that are unique to its geometric layout. There are locations with steep grades (6%), structures of mid-length spans, and wider shoulders and medians, in addition to other geometric characteristics.

F.4.1.2 Existing Configuration

The distance between access locations is much longer than those in the intercity environment. Almost all access-to-access segments are greater than 12 miles in length. Access points to the rural freeway are widely spaced, with 21 pairs of entries and exits sparsely spaced over the entire corridor. The standard cross section for the corridor is 2 lanes for each direction, with a 10-foot outside shoulder and a 4-foot inside shoulder that are both paved. The median is, on average, 60 feet wide.

F.4.2 AHS Application

The implementation of AHS in the rural environment is to build a new automated lane. Only the transition lane scenario is applied since there is no need for dedicated entry/exits.

- Non-continuous physical barrier separating automated and transition traffic, transition and manual traffic.
- Transition zone can be a continuous lane or a non-continuous area

- Cross section of AHS lane outside the exit/entry area: one 12-foot automated lane, an 8-foot inside shoulder, a 2-foot horizontal clearance between automated lane and physical barrier.
- Access to automated lane uses existing on/off ramps, weaving through manual lanes, and transfer of control between manual to automated mode through the transition zone.
- There are a total of 7 exits and 7 entrances via the transition zone for the automated lane. The locations of access points are spaced over much longer distances (more than 30 miles).
- Configuration of transition: In the section of transition from manual to transition lane, length of entry section from manual to transition is approximately 820 feet and length of exit section is approximately 820 feet plus queue allowance. For the transition area from transition lane to automated lane, merges and de-merges of the vehicles require at least a widening out of the lane. The length of the merging/de-merging lane depends on concept attributes.

F.4.3 Travel Demand

This section describes travel demand level for the baseline or non-automated freeway lanes and for the automated lane. Focus is placed on simulating travel during the morning peak hour.

F.4.3.1 Baseline Level

Traffic demand in this scenario is very low. The average flow on mainline is 1500 vphpl and flow on the access ramp is below 200 vehicles per hour.

F.4.3.2 AHS Levels

Four different levels of automated vehicle traffic demand were developed for purposes of sensitivity analysis. The average segment demand levels during the peak hour on a single AHS lane vary between a low of approximately 680 vehicles to a maximum of about 1700 vehicles. Details are shown in Table F-3. Traffic volumes were initially produced at each AHS entry and exit point and then an origin-destination trip table was derived which provided the distribution of all entering AHS traffic among all subsequent exiting AHS traffic. The vehicle classes on the intercity corridor are light-duty passenger vehicles and trucks, where the percentage of trucks may vary between approximately 10% and 35% based on data from Reference 3. While buses do travel on such routes, their percentage contribution is negligible.

Table F-3: Traffic Demand on an Automated Lane in a Rural Setting

Rural							
	AHS Volume				Access Volume		

	Total Traffic Volume	Avg. Segment Volume	Min. Segment Volume	Max. Segment Volume	Avg. Access Volume	Min. Access Volume	Max. Access Volume
Level 1	1633	684	467	967	126	67	250
Level 2	2317	893	567	1317	189	100	375
Level 3	3267	1369	933	1933	252	133	500
Level 4	4083	1711	1167	2417	315	167	625

F.5 Actual Scenario Site

One scenario was based on actual data from the following real site: Houston Katy freeway on Interstate 10 west of the Houston CBD. The remainder of this section describes this corridor.

F.5.1 Houston Katy Freeway (I-10)

In early 1996, Houston Metropolitan Transit Authority (METRO), an associate member of the NAHSC, entered into a collaborative effort with the NAHSC to study the potential for AHS implementation on one of the Houston metropolitan area's High Occupancy Vehicle (HOV) lanes. METRO selected the HOV facility on Interstate 10 (I-10) known as the Katy Freeway as this corridor is currently part of a Major Investment Study (MIS) to select an alternative for this corridor to address growing travel demand.

All the criteria for scenario selection previously described were important for this application scenario. First, the Katy freeway is a representative urban corridor which connects the CBD at the corridor's eastern end with major employment generators along the length of the corridor. The freeway corridor, located between two heavily traveled north-south routes, carries a significant amount of traffic in both eastbound and westbound directions. There has been strong local public concern about the congestion on this part of the Katy Freeway. The HOV lane, a single reversible lane located in the median of the freeway, is approximately 12 miles long and operates seven days a week from 5 AM through noon in the eastbound direction (inbound toward the Houston CBD) and from 2 PM through 9 PM in the westbound direction (heading outbound from the Houston CBD). Secondly, METRO has a strong interest in the whole area of ITS and in particular, AHS. Thus, the institutional support is widespread. Thirdly, and linked with the institutional support, is the availability of the needed data.

F.5.2 Types of Information

The information obtained for the Katy Freeway scenario are of the following two primary types: geometric/physical characteristics and travel demand data.

F.5.2.1 Geometric/Physical Characteristics

Figure F-4 presents a graphical depiction of the Katy Freeway scenario. Five locations, within circles, are highlighted as follows:

1 =   Western Terminus
2 =   Flyover access/egress point for Park & Ride facility
3 =   Slip ramps providing access to the HOV facility from non-HOV lanes heading
         eastbound and exit from HOV lane to non-HOV lane heading westbound
4 =   HOV exit near Eastern Terminus
5 =   Eastern Terminus
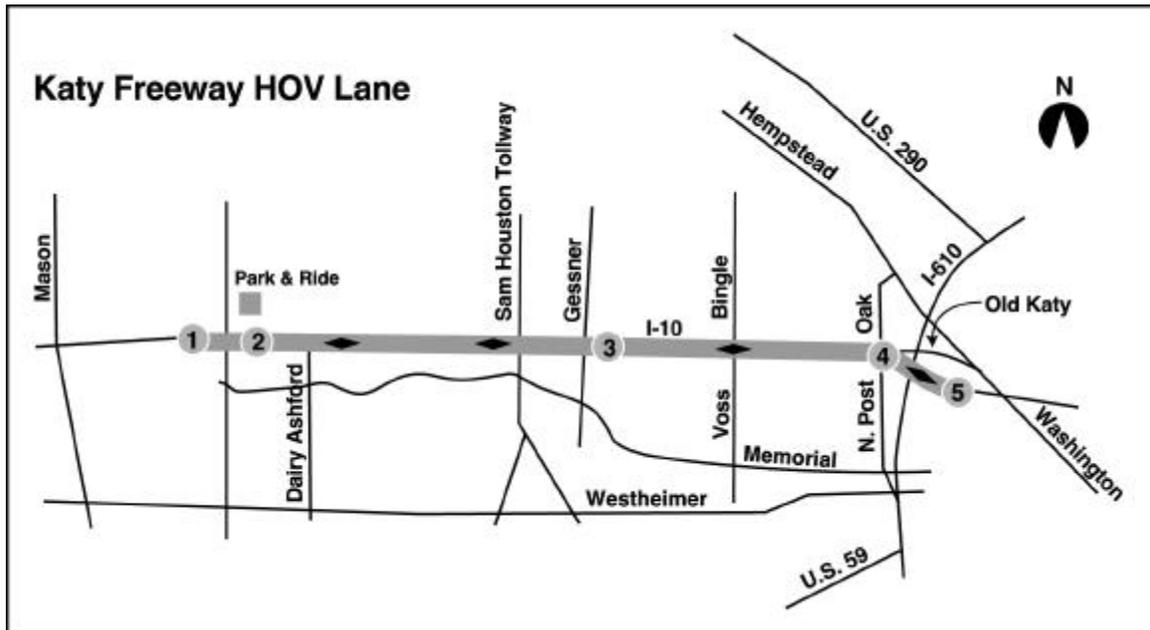
Figure F-4. Houston Case Study Site

F.5.2.2 Existing Configuration

The Katy Freeway HOV lane is a one-way reversible flow lane, separated from mainline traffic by concrete barriers. The average lane width is 19.5 feet, with 14-foot travel lane and lateral clearance of 2.75 feet on both sides. There are, however, several locations in which the lane width is 12 feet. The entry and exit facilities are limited on the HOV lane. Along the HOV lane, there are 5 entrance/exit facilities. These facilities alternate their direction in the morning and afternoon operating periods and keep closed during

non-operating hours. Table F-4 shows the locations and types of the entry/exit locations.
These locations correspond to the five highlighted areas on Figure F-4.

Table F-4. Configuration of Exit/Entry

Location/Function	Configuration	Direction	AM	PM
(1) State Highway 6/Western Terminus	Direct connection with mainline lanes	One-way	Entry	Exit
(2) Addicks/Park and Ride	At grade T-ramp to the Park and Ride lot	Two-way	Entry/ Exit	Entry/ Exit
(3) Gessner/Slip Ramps	Slipramp with direct connection with mainlines	One-way	Entry	Exit
(4) Off-ramp/North Post Oak	At grade flyover to the surface street	One-way	Exit	Entry
(5) I-610/East Terminus	Direct connection with mainlines	One-way	Exit	Entry

The operation is designed to facilitate the different travel needs in the morning and
afternoon. From 5 AM to 12 noon, it is used for the eastbound traffic heading inbound
to the CBD. A 2+ occupancy policy is enforced, except during the peak of the AM peak
period, that is, between 6:45 AM and 8 AM which requires a 3+ vehicle occupancy for
entry. During the 2 PM to 9 PM time period, the corridor accommodates westbound
traffic with a 2+ vehicle occupancy policy, except during the peak of the afternoon peak
period, that is, between 5 PM and 6 PM, when a 3+ policy is applied. Based on data
from the HOV facility, the vehicle class split on the HOV facility is approximately 4%
buses and 96% light-duty passenger vehicles.

F.5.3 AHS Application

The AHS application scenario on the Katy Freeway HOV lane has been developed into
three alternative sub-scenarios: near-term, mid-term and long-term. These three
alternatives correspond to development of an AHS system that correlates with the
growth in market penetration of automated vehicles. The three sub-scenarios have
differences in their physical characteristics, capacities and matching market demands for
AHS implementation. A major justification for developing these sub-scenarios, is that
the capacity of this AHS facility is limited by the capacity of the mainline freeway lanes
and the ability of the adjacent street system to feed and absorb the AHS traffic. Thus,
improvement on the mainlines is considered an important component for each of the
sub-scenarios, especially the widening of mainline lanes prior to the AHS entry location
and after the AHS exit location.

Sub-scenario 1 (Near Term):
- No major implementation on the existing HOV lane: one-lane, one-way operation.

- Provide feeder lane at western and eastern terminus. Feeder lane is a special auxiliary lane on the mainlines that serve to allow sufficient distance for automated vehicles weaving through manual lanes to enter the AHS lane or exiting automated vehicles enough distance to merge into mainline

    At western terminus: 3 mile feeder lane from west terminus to west of Mason Rd
    At eastern terminus: 1 mile feeder lane east of terminus.

- Entry/exit and transition lane:

    Extend transition lane to a length of 1100 feet at Park & Ride T-ramp and at Post Oak access/egress point.
    Move slipramps (at Gessner) eastward and provide an additional one mile of merge lane for eastbound and one mile de-merge lane for westbound flow, with corresponding freeway widening.

Sub-scenario 2 (Mid Term):
- Two way operations with one lane for each direction
- Provide feeder lane at western and eastern terminus over longer distance as compared to near-term scenario

    At western terminus: 6 mile feeder lane extending west from terminus
    At eastern terminus: 4 mile feeder lane extending east from terminus

- Entry/exit and transition lanes

    At Park & Ride T-ramps: extend transition lane length to 2200 feet in each direction
    At slipramps: replace slipramps with Park & Ride T-ramp facilities. Transition lane is 2000 feet long for each direction of traffic
    At Post Oak access/egress point: build another flyover to separate the use for entry and exit with transition treatment

Sub-scenario 3 (Long Term):
- Two way operations with one lane for each direction
- Provide 2-lane feeder lanes including transition at both of the termini

    At western terminus: 2 lanes , 4 miles feeder lanes extending west from terminus
    At eastern terminus: 2 lanes, 4 miles feeder lane extending east from terminus
- Replace transition lane facilities at Park & Ride and T-ramps built in mid-term with direct connectors (Y or wishbone design). These direct connectors allow flows between automated lane and mainlines, automated lane and frontage service roads. At Addicks Park & Ride (original), the direct connectors also link Park & Ride lot.

F.5.4 Travel Demand

The diverse urban economic and transportation activities along the corridor make the Katy Freeway significant in the region. Facing increasing demand over recent years, current Katy Freeway is operating at its designed capacity. During the peak periods of the day, certain portions of the freeway operate at an average speed lower than 20 miles

per hour. Thus, its ability to accommodate further demand is constrained. Even for the HOV lane which is still able to serve the speed around 50 miles per hour, the demand increases correspondingly with the total demand in the corridor. The access points to the HOV lane are already near their designed capacity. According to METRO's projection, by the year 2010, the demand in a 3+ mode is going to exceed the HOV lane operation capacity. By year 2020, the freeway /HOV lane demand is expected to double. On the portion of the Katy Freeway containing the HOV lane, the projected daily traffic flow for year 2020 varies between 8,000 and 9,000 vph for each traffic direction.

F.5.4.1 Baseline Level

METRO's existing operating capacity is 2000 vphpl for mainline and 1500 vphpl for HOV lane. Based on 1995 traffic flow data for the freeway, during the peak of the peak period (6 AM-7 AM), some segments operate over the designed capacity, with an average speed of 27 mph. In still other locations, congestion is worse, with an average speed of at most 20 mph. For westbound traffic in the afternoon peak periods, traffic is slightly better than that during the morning. During the peak of the afternoon peak period, 5 PM-6 PM, the same segments as operating beyond capacity during the AM peak are still operating beyond capacity. The HOV lane system performance is nevertheless better than for the mainline.

F.5.4.2 AHS Levels

The traffic capacity for AHS implementation on the Houston Katy Freeway is constrained by the design of its infrastructure. Consequently, different AHS infrastructure implementations serve different market demands and provide different capacities. At the near-term subscenario, the designed capacity on AHS is 1750 vphpl, the mid-term subscenario is 3000 vphpl, and long-term subscenario is 4000 vphpl. METRO's projected AHS traffic flow for the eastbound direction during the peak of the morning peak period, 6 AM - 7 AM, and its distribution along the HOV lane are shown in Table F-5.

Table F-5. HOV Facility Origin-Destination Tables
(6 AM - 7 AM/Eastbound)

NEAR TERM ALTERNATIVE			
	PARK & RIDE OFF-RAMP	POST OAK EXIT	EASTERN TERMINUS	ENTRANCE TOTAL
WESTERN TERMINUS	50	271	679	**1000**
PARK & RIDE ON-RAMP		143	357	**500**
SLIP RAMP		86	214	**300**
EXIT TOTAL	**50**	**500**	**1250**	**1800**

MID TERM ALTERNATIVE			
	PARK & RIDE OFF-RAMP	POST OAK EXIT	EASTERN TERMINUS	ENTRANCE TOTAL
WESTERN TERMINUS	100	633	1267	**2000**
PARK & RIDE ON-RAMP		200	400	**600**
SLIP RAMP		167	333	**500**
EXIT TOTAL	**100**	**1000**	**2000**	**3100**

LONG TERM ALTERNATIVE			
	PARK & RIDE OFF-RAMP	POST OAK EXIT	EASTERN TERMINUS	ENTRANCE TOTAL
WESTERN TERMINUS	100	487	1413	**2000**
PARK & RIDE ON-RAMP		256	744	**1000**
SLIP RAMP		256	744	**1000**
EXIT TOTAL	**100**	**1000**	**2900**	**4000**

F.6 References

(1)   Miller, Mark A., et al., *An Investigation of the Costs of Roadway Traffic Congestion: A Preparatory Step for IVHS Benefits' Evaluation*, California PATH Research Report UCB-ITS-PRR-94-15, California PATH Program Institute of Transportation Studies, University of California Berkeley, May 1994.

(2)   Grenzeback, Lance R. *Expanding Metropolitan Highways-Implications for Air Quality and Energy Use: Impact of Changes in Highway Capacity on Truck Travel-Appendix C*, Transportation Research Board Special Report 245, National Research Council, 1995.

(3)   California Department of Transportation, Office of Traffic Operations, 1994 Annual Average Daily Truck Traffic on the California State Highway System, September 1995.

(4)   Joint Architecture Team: Loral Federal Systems & Rockwell International, *ITS Architecture Evaluatory Design*, United States Department of Transportation Federal Highway Administration, June 1996.

Appendix G. Pipeline Capacity Analysis

G.1 Purpose

The purpose for computing pipeline capacity is to obtain upper-bound estimates of AHS throughput over three dimensions: (i) four distinct degrees of cooperation among vehicles, (ii) a range of AHS operating speeds, and (iii) a set of vehicle-class mixes. These estimates are used as inputs for planning and executing safety and throughput analyses.

A secondary aim is to verify, via systematic testing, the hypotheses about the sensitivity of AHS pipeline capacity to the following: the degree of inter-vehicle cooperation, speed, and vehicle class mix; platoon length and intra-platoon spacing; check-in policy governing minimum braking performance; and fixed and variable vehicle-space utilization[1], corresponding to uniform and non-uniform spacing policies, respectively.

G.2 Scope

AHS pipeline capacity[2] is defined as the maximum steady state vehicle flow per unit time on a lane dedicated for use by fully automated vehicles, subject to constraints on inter-vehicle spacing, intra- and inter-platoon spacing, vehicle jerk, vehicle speed, and the percentages of vehicles of each class flowing through the pipeline.

In this analysis, a hard braking malfunction scenario is used as the basis for determining the minimum following distances to be maintained between individual vehicles, between vehicles within a platoon, and between platoons. A hard braking scenario provides us the opportunity to address the following high-level requirement without having to make an explicit interpretation as to what malfunction occurred:

> "There will be no collisions in the absence of malfunctions"[3] or system intrusions.

For the purpose of this analysis, it is assumed that a malfunction or system intrusion is a necessary precondition for a hard-braking action to be initiated. The following definitions distinguish among four degrees of inter-vehicle cooperation, from the lowest to the highest level of cooperation:

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[1] *Vehicle-space utilization* is the sum of the length of the vehicle and the distance to the preceding vehicle, which may be of the same or different class. See Section G.4 for the full definition and explanation of this term.

[2] In this analysis, a *pipeline* is an AHS lane, consisting of a continuous single pathway over which all vehicles travel in the same direction, all vehicles travel at the maximum highway speed limit, and vehicles never exit the pathway.

[3] This policy statement appears in the *FHWA RFA for AHS*. The addition of "system intrusion" was made by the NAHSC System Requirements Team in 1996.

- *Autonomous individual vehicle[4] operation*: vehicles do not communicate with each other and do not form platoons.
- *Cooperative individual vehicles*: vehicles operate individually and inter-vehicle communication is allowed. A distinction is made between two kinds of communication:
  1. *Low cooperation*: vehicles communicate only during maneuver coordination and emergencies.
  2. *High cooperation*: vehicles continuously exchange state information such as vehicle speed, acceleration, in addition to maneuver coordination messages and emergency warnings (e.g., about hard braking).
- *Platoons*: automated vehicles can operate either in platoons or as individual vehicles. Vehicles exhibit low cooperation between different platoons or individual vehicles and high cooperation among vehicles within the same platoon.

In contrast to the pipeline capacity analysis, the throughput analyses (*vid.* Section 4.1 and Appendices H and I) account for mixed traffic operations[5], multilane highway configurations[6], spacing requirements for vehicle maneuvers (e.g., entry, exit, and merge), other constraints on AHS capacity, and the stochastic nature of traffic.

Whereas the pipeline capacity analysis is deterministic except for the use of a probability distribution to represent the maximum braking rates for the population of light-duty passenger vehicles, the safety analyses (*vid.* Section 4.2 and Appendix J) are based on probabilistic models of vehicle performance (e.g., braking and obstacle-detection capability), system and environmental events, and vehicle-to-vehicle interaction.

Simulation is used to test the hypotheses about pipeline capacity. There are an infinite number of cases that can be tested for each hypothesis; each case represents a different combination of input parameter values. Moreover, the computation of state trajectories – each of which represents the spacing required to guarantee for the given modeling assumptions that a collision will not occur between two individual vehicles or between two platoons – is intensive due to the structure and implementation of the optimal control spacing design algorithm, vehicle dynamics models, and models of vehicle communication.[7] Hence, to avoid the problems associated with combinatorial explosion of test cases and computational complexity, directed testing is applied in which a representative subset of the possible cases is selected for analysis.

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[4] In both the literature and engineering practice, there does not appear to be a commonly accepted definition of 'autonomous vehicles.' We append the term 'individual to 'autonomous' in order to emphasize to the reader that in this analysis we assign a narrow interpretation to the term.

[5] 'Mixed traffic operations' refers to operation of conventional and automated vehicles in the same lane.

[6] 'Multilane' is defined as to two or more adjacent lanes over which vehicles travel in the same direction and can move from one lane to another.

[7] The models and optimal control algorithm consist of a series of differential equations, which we solve as a matrix formulation implemented in MATLAB, an interpreted language developed by MathWorks, Inc., Natick, Massachusetts.

G.3 Questions and Hypotheses

The preceding questions are recast as hypotheses. Auxiliary assumptions are stated for each hypothesis. The hypotheses and auxiliary assumptions comprise the premises from which to deduce the pipeline capacity analysis results. The analysis results for the test cases are presented in Section G.6, in addition to a discussion of whether the observations provide confirming evidence for each of the hypotheses.

- *Hypothesis 1*. AHS pipeline capacity will increase as the degree of inter-vehicle cooperation increases.
    Auxiliary assumptions:
    1. Inter-vehicle communication is a prerequisite for a vehicle to cooperate with other vehicles in performing hard braking.
    2. If an automated vehicle has the ability to communicate with other vehicles, then it always cooperates with the other vehicles.
    3. An autonomous individual vehicle does not communicate with other vehicles. Rather, it relies on sensing the distance to the preceding vehicle and the difference between its speed and the preceding vehicle's speed.
    4. There is a delay between the time when the following vehicle receives a message from the preceding vehicle and the time at which the following vehicle commences hard braking.
    5. In case of autonomous vehicles, there is a delay between the time when the following vehicle detects, via sensory input, that the preceding vehicle has commenced hard braking and the time at which the following vehicle commences hard braking.
    6. Braking commences after a vehicle has processed a message or sensory data and actuates its brakes. Thus total delay in response to a hard braking emergency is the sum of the processing, sensing/communication, and actuation delays for a vehicle.
    7. The percentages of vehicles of each class remains constant. (*N.B.*: The pipeline is infinitely long.)

- *Hypothesis 2*. As highway speed increases, AHS pipeline capacity increases at a decreasing rate until it peaks and then decreases.
    Auxiliary assumptions:
    1. Same as for Hypothesis 1.

- *Hypothesis 3*. AHS pipeline capacity will decrease at an increasing rate as the ratio of trucks-to-light-duty-passenger-vehicles increases.
    Auxiliary assumptions:
    1. Same as for Hypothesis 2.
    2. The space utilized by each class of vehicle differs.

- *Hypothesis 4a.* AHS pipeline capacity increases as platoon length increases.
- *Hypothesis 4b*. AHS pipeline capacity decreases as intra-platoon spacing increases.

Auxiliary assumptions:
1. Same as Hypothesis 2.
2. An increase in platoon length results in a decrease in average vehicle-space utilization since there are fewer platoon leaders: platoon leaders use more space than the other members of the platoon.
3. Mixing of vehicles of different classes within a platoon is not allowed.

- *Hypothesis 5*. AHS pipeline capacity increases as the minimum vehicle braking capability on the AHS increases.
    Auxiliary assumptions:
    1. Same as Hypothesis 2.

- *Hypothesis 6*. Adjusting vehicle spacing based on real-time knowledge of vehicle braking capabilities can increase pipeline capacity.
    Auxiliary assumptions:
    1. Same as Hypothesis 2.
    2. For autonomous independent vehicles, no information is available about the capability of the preceding vehicle, so the worst case must still be assumed for the vehicle ahead, that is, the highest braking rate.
    3. For cooperative vehicles, self as well as preceding vehicle's braking capability information is available.

G.4 Method

G.4.1 Vehicle Model

Consider three vehicles (labeled A, B, and C) moving along a single lane highway. Assume that vehicles A and B have lengths L_A and L_B and let x_A and x_B denote their positions with respect to a fixed reference on the road. Assume that vehicle B is leading while vehicle C comes last, that is $x_B > x_A > x_C > 0$. We will primarily be interested in the interaction between vehicles A and B, vehicle C will be used only in certain cases, to isolate the system A-B from the rest of the highway. Assume that vehicle A can be modeled by a third-order system and that the acceleration of vehicle B cannot be measured by vehicle A. If we let $D = x_B - x_A - L_B$, the system A-B can be described by the state vector $x = \begin{bmatrix} x_A & \dot{x}_A & D & \dot{D} \end{bmatrix}^T$. After feedback linearization, the evolution of the state is described by

$$\dot{x} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & -1 & 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} u + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \ddot{x}_B$$

$$x(0) = x^0$$

where u is the jerk applied by the controller of vehicle A. The controller has access to full state information – velocity, acceleration, spacing, and relative velocity. The vehicle dynamics are constrained by the engine, tire, and road conditions. More specifically, it is required that

$$x(t) \in \mathbf{X} = \left\{ x \in \Re^4 \middle| x_1 \in \left[v_{\min}^A, v_{\max}^A \right], x_2 \in \left[a_{\min}^A, a_{\max}^A \right], x_4 + x_1 \in \left[v_{\min}^B, v_{\max}^B \right] \right\}$$

$$u(t) \in \mathbf{U} = \left[j_{\min}, j_{\max} \right]$$

$$\ddot{x}_B(t) \in \mathbf{D} = \left[a_{\min}^B, a_{\max}^B \right]$$

For highway operation, it is assumed that vehicles will not be allowed to go backwards, therefore $v_{\min}^A = v_{\min}^B = 0$ will be used. $v_{\max}^A$ and $v_{\max}^B$ are imposed by engine limitations and play no role in the safety calculations. The values of the remaining bounds will be parameters for the safety tools.

If vehicle B happens to collide[8] with the vehicle in front of it or vehicle C happens to hit vehicle A from behind the state of the system (in particular the velocities of the vehicles involved in the collision) will undergo an almost instantaneous jump. If the change in velocity induced by the above two kinds of collisions are $\boldsymbol{d}v_B$ and $\boldsymbol{d}v_C$ and the collisions take place at time T_B and T_C, respectively, then

$$x_4(T_B^+) = x_4(T_B^-) + \boldsymbol{d}v_B$$
$$x_1(T_C^+) = x_1(T_C^-) - \boldsymbol{d}v_C$$
$$x_4(T_C^+) = x_4(T_C^-) + \boldsymbol{d}v_C$$

T_B^- and T_B^+ denote the time right before and right after the collision of vehicle B (similarly for C). In the coordinate system considered here, $\boldsymbol{d}v_B \le 0$ and $\boldsymbol{d}v_C \le 0$. Assume that vehicle B can hit the vehicle ahead of it with relative velocity at most v_B and vehicle C can hit vehicle A from behind with relative velocity at most v_C. If one collision of each kind takes place in the time interval of interest, then the effect of vehicles B and C on vehicle A can be summarized as a disturbance

$$d \in D = \left\{ d \middle| \ddot{x}_B(t) \in \left[a_{\min}^B, a_{\max}^B \right], 0 \le T_B, \boldsymbol{d}v_B \in \left[\max\{v_B, x_4(T_B) + x_1(T_B)\}, 0 \right], 0 \le T_C, \boldsymbol{d}v_C \in \left[v_C, 0 \right] \right\}$$

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[8] Although our aim is to design inter-vehicle spacings for no-collision, we can not totally avoid collisions in vehicle following under all conditions. Particularly intra-platoon collisions due to emergency hard braking by the platoon leader and inter-platoon collisions during platoon join maneuvers can not be avoided. Platooning based AHS is based on the conjecture that these collisions will not be severe. We develop our model to take into account the possibility of collisions so that spacings can be designed to mitigate the effects of collisions.

The complicated bound on $\boldsymbol{d}\,v_B$ is dictated by the fact that $x_4(T_B^+) + x_1(T_B^+) \geq v_{\min}^B = 0$. This formalism can also be used to model the situation where no collisions take place by setting $v_B = v_C = 0$.

This model is adequate for the case where there is no communication of state information between the platoons and no sensing and actuation delays. To compare the various AHS concepts, three other models have been developed. These models explicitly take into account the sensing and actuation delays. Two of the models also consider use of inter-vehicle communication to exchange acceleration information (which can not be sensed) between vehicles. These models are described in detail in Datta N. Godbole and John Lygeros, "Safety and Throughput Analysis of Automated Highway Systems," *Proceedings of the American Control Conference*, 1997.

G.4.2 Spacing Design

We describe a methodology that can be used to design safe longitudinal vehicle following maneuvers. The methodology gives rise to the spacing tool that can be used to assess the safety of a given situation (Refer to [4] for details).

For the purposes of safety we would like vehicles to avoid collisions whenever possible. For vehicle A, this requirement can be encoded by a cost function

$$J(x^0, u, d) = -\inf_{t \geq 0} x_3(t)$$

If for a given initial condition x^0 and a given choice of u and d, $J(x^0, u, d) \leq 0$, vehicle A will never collide with vehicle B. (*N.B.*: It may still be hit from behind by vehicle C.) We would like vehicle A to remain safe in this sense whatever vehicles C and B decide to do. We therefore seek the worst possible action of vehicles B and C and the best possible action of vehicle A. In other words, we seek a pair (u^*, d^*) such that

$$J(x^0, u^*, d) \leq J(x^0, u^*, d^*) \leq J(x^0, u, d^*)$$

In the language of game theory, such a choice of inputs is called a saddle solution to the two-player, zero-sum game between u and d with cost function J.

For the vehicle model in the previous section, consider the candidate saddle strategy

$$u^*(t) = \begin{cases} j_{\min} & \text{if } t \leq T_1 \\ 0 & \text{if } t > T_1 \end{cases}$$

$$d^*(t) = \left\{ \ddot{x}_B^*, \left(T_B^*, \boldsymbol{d}\,v_B^*\right), \left(T_C^*, \boldsymbol{d}\,v_C^*\right) \right\}$$

where

$$\ddot{x}_B^*(t) = \begin{cases} a_{min}^B & \text{if } t \le T_2 \\ 0 & \text{if } t > T_2 \end{cases}$$

$$T_B^* = 0$$

$$d\,v_B^* = \max\left\{v_B, x_4^0 + x_1^0\right\}$$

$$T_C^* = 0$$

$$d\,v_C^* = v_C$$

T_1 is the time when the acceleration of vehicle A reaches a_{min}^A under j_{min} and T_2 the time when vehicle B stops under a_{min}^B. The candidate saddle solution is simply both vehicles A and B braking as hard as possible and both collisions (i.e., B colliding with the vehicle ahead and C hitting vehicle A) taking place at time $t = 0$ with the maximum allowable relative velocity. In [4] it was shown that

Lemma 1 (u^*, d^*) is globally a saddle solution for cost $J(x^0, u, d)$.

This lemma is used to calculate the optimum cost $J^*(x^0)$ for a given initial condition x_0. In particular, we can distinguish safe situations (i.e., $J^*(x^0) < 0$) from unsafe ones (i.e., $J^*(x^0) > 0$) and determine the boundary between them (i.e., $J^*(x^0) = 0$). Note that for all safe initial conditions, vehicle A is guaranteed not to collide with vehicle B as long as it starts decelerating if the state reaches the boundary (i.e., whenever $J^*(x(t)) = 0$). For unsafe initial conditions, on the other hand, there exist actions of vehicles B and C where a collision between vehicles A and B is unavoidable, whatever vehicle A does.

The above principle was used in the development of a computational spacing tool. The user of the tool is asked to provide a choice of one of the four vehicle models, the minimum acceleration (or maximum deceleration) rates, a_{min}^A and a_{min}^B, the minimum jerks j_{min}^A and j_{min}^B, sensing and actuation lag t, and the maximum allowable relative velocities at collisions of vehicle B with the vehicle ahead of it (v_B) and of vehicle C with vehicle A (v_C). Given the specific form of the dynamics, the differential equations characterizing vehicle motions can be explicitly solved to compute the state trajectories under the optimal control and disturbance. The tool then calculates the minimum spacing, x_3^0, required to guarantee no collisions between vehicles A and B, for a given initial condition x_1^0, x_2^0 and x_4^0.

G.4.3 Intra-Platoon Spacing Design Using String Stability Analysis

Application of the above methodology with the nominal parameter values shows that intra-platoon collisions under hard braking of the platoon leader cannot be completely avoided (unless we use platoons of large intra-platoon spacing thereby losing the

throughput advantage). Therefore, in case of platooning, we allow for low severity (low-impact velocity) collisions in case of hard braking of a platoon leader. We still do not allow any collisions within a platoon in the absence of malfunctions. In Reference [6] an intra-platoon vehicle following controller is developed to track the preceding vehicle at a constant distance, such as 1 to 4 m, at all speeds. The controller is designed so as to achieve string stability. Thus the vehicles in the string (platoon) do not amplify lead vehicle disturbances during normal mode so as not to result in a collision. Implementation of this controller requires each vehicle to have knowledge of acceleration of the preceding vehicle and the platoon leader. This information is obtained via intra-platoon communication.

The controller applies coordinated braking in order to achieve collision free operation in the absence of malfunctions. This strategy requires the followers within a platoon to progressively apply larger brake torque than the leader. This amplification of the braking force saturates beyond the fourth follower, in case of the control law developed in [6]. The ratio of the maximum braking force needed by any follower to the lead vehicle braking force is called braking amplification factor a. *Therefore, intra-platoon collisions can be avoided in a platoon of arbitrary length if the followers in a platoon are capable of braking at ($a \times$ a_lead) where a_lead is the deceleration applied by the platoon leader.* Based on the control law of [6] and the nominal parameter values, we calculate intra-platoon separation and braking amplification factor so as to attenuate the disturbance generated by the platoon leader along the length of the platoon, in the absence of malfunction. The braking amplification factor is used to derate the braking capability of the platoon leader when deriving the inter-platoon spacing, leading to longer spacings between platoons than between individual vehicles.[9] The derating of the platoon leader's braking ensures no collisions within the platoon even if the leader decelerates abruptly at the derated value.

Pipeline capacity is expressed in terms of the speeds of vehicles per the normalized weighted average of the space utilized by the respective vehicle classes: light-duty passenger vehicles, buses, and trucks. The space utilized by a vehicle is defined as the sum of the length of the vehicle and the distance to the preceding vehicle, which may be of the same or different class. Nominal vehicle lengths are given for each vehicle class and are shown in Table G.1. The values represent typical lengths which are given in the literature.[10]

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[9] Another method of coordinated braking involves first applying brakes by the rear vehicle of the platoon. Every vehicle starts braking a short time delay after its following vehicle starts to brake. This scheme will also result in additional inter-platoon spacing similar to the above.

[10] For example, for each bus manufacturer, *Jane's Urban Transport Systems 1995-96* (C. Bushell, ed., Fourteenth edition, Jane's Information Group, Alexandria, Virginia, 1995) specifies the types of vehicles manufactured, dimensions and seating-standing capacities, mechanical and electrical systems, prices, etc.

4.4 Calculation of Pipeline Capacity

4.4.1 Nominal Values

Table G.1. Nominal vehicle lengths

Vehicle Class	Vehicle Length (m)
light-duty passenger vehicle	5
bus	12
truck	20

The pipeline capacity is normalized in the sense that the denominator is expressed in terms of the percentages of each vehicle class in the traffic flow. Hence, the denominator is the average space utilized by a vehicle.

The analysis is deterministic in that it is based on an assumption that there is perfect knowledge about vehicle behavior, AHS characteristics, and system events. For each case under consideration, fixed percentages are assigned to each vehicle class to populate the pipeline, for example, ninety-three percent light-duty passenger vehicles, six percent trucks, and one percent buses. The weighted average refers to the sums of utilized space for the respective percentages of vehicles in each class. The space utilized by a vehicle can vary as a function of a vehicle class it follows, and its average space utilization is determined by the defined percentages of vehicles in the different classes.

The pipeline is assumed to always operate at maximum capacity. Maximum capacity is defined as the highest density of vehicles per unit of space as permitted by the space-utilization constraints.

G.4.4.2 Vehicle Spacing Constraints

The analysis of pipeline capacity is coupled to the safety analyses: minimum permissible vehicle spacing is couched in terms of hard braking by vehicles. Hard braking requirements are defined in the context of three spacing constraints:

1. *Minimum permissible inter-vehicle spacing*: the minimum separation distance between two vehicles such that if the preceding vehicle decelerates at its maximum achievable rate[11] until it comes to a full stop, then the following vehicle can come to a full stop and neither depart the lane nor collide with the preceding vehicle.

2. *Minimum permissible intra-platoon spacing*: the minimum separation distance between two vehicles within a platoon, such that spacing variations during normal maneuvering will not produce any collisions.

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[11] The uppermost limit on vehicle deceleration based on the vehicle's physical braking capability.

3. *Minimum permissible inter-platoon spacing*: the minimum separation distance between two platoons such that if the last vehicle of the preceding platoon decelerates at its maximum achievable rate until it comes to a full stop, then the following platoon can stop and neither depart the lane nor collide with the preceding platoon.

In addition, the model contains the following constraints on platoon operation:

- *Uniform composition*: Vehicles within a platoon are always of the same class.
- *Uniform nominal intra-platoon spacing*: Nominal intra-platoon spacing is homogeneous within a vehicle class.

The inter-vehicle and inter-platoon spacing values are calculated with the assistance of a deterministic vehicle-spacing design tool developed under NAHSC Task B5 (Acquire & Develop Tools). The nominal intra-platoon spacing values are derived with the assistance of a string stability analysis tool which was also developed as part of NAHSC Task B5, and the nominal values are shown in Table G.2. A discussion of the procedure used to derive inter-vehicle, intra- and inter-platoon spacing values is presented in Section G.5.

Table G.2. Nominal intra-platoon spacing

Vehicle Class	Nominal intra-platoon spacing (m)
light-duty passenger vehicle	2
bus	8
truck	8

G.4.4.3 Vehicle Jerk Constraint

The maximum permissible vehicle jerk[12] for each vehicle class is shown in Table G.3. These levels are known to cause discomfort to the occupants of conventional vehicles. These values are based on an assumption that the vehicle occupants are to be protected from being ejected from the vehicle during hard braking.

Table G.3. Maximum jerk

Vehicle Class	Maximum jerk (g/s)
light-duty passenger vehicle	7.5
bus	5
truck	3

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[12] Jerk is the rate of change of acceleration.

G.4.4.4 Pipeline Capacity Equations

Three types of inputs are required for the calculation of AHS pipeline capacity: (i) the minimum permissible inter-vehicle, intra- and inter-platoon spacing, (ii) the range of AHS operating speeds, and (iii) the percentage of vehicles of each class. We assume that vehicles of different classes – cars, buses, and trucks – are randomly (uniform) distributed along the AHS pipeline. The space utilized by an individual vehicle, denoted U_I, is given by Equation 1.

$$U_I = l + x \qquad \text{(Eq. 1)}$$

where

> l is the nominal vehicle length
> x is the inter-vehicle space, that is the distance from the rear bumper of the preceding vehicle to the front bumper of the following vehicle

The space utilized by a platoon is the sum of the space utilized by the member vehicles of the platoon and the distance to the preceding platoon. The space utilization of a platoon, denoted U_P, is given by Equation 2.

$$U_P = y + nl + zn - z \qquad \text{(Eq. 2)}$$

where

> y is inter-platoon spacing
> z is the intra-platoon spacing
> n is the nominal platoon size, that is the number of vehicles in a platoon

Equations 3 and 4 give the normalized-weighted average of the space utilized by individual vehicles, denoted C_I, and platoons, denoted C_P, respectively.

$$C_I = s / \left(\begin{array}{l} p_c^{\,2}\left(l_c + x_{c,c}\right) + p_b^{\,2}\left(l_b + x_{b,b}\right) + p_t^{\,2}\left(l_t + x_{t,t}\right) + \\ p_c p_b\left(l_b + l_c + x_{b,c} + x_{c,b}\right) + p_c p_t\left(l_t + l_c + x_{t,c} + x_{c,t}\right) + \\ p_b p_t\left(l_b + l_t + x_{b,t} + x_{t,b}\right) \end{array} \right) \qquad \text{(Eq. 3)}$$

$$C_P = s / \left(\begin{array}{l} p_c^{\,2}\left(y_{c,c} + n_c l_c + z_c - z_c / n_c\right) + p_b^{\,2}\left(y_{b,b} + n_b l_b + z_b - z_b / n_b\right) + \\ p_t^{\,2}\left(y_{t,t} + n_t l_t + z_t - z_t / n_t\right) + p_c p_b\left(l_b + l_c + y_{b,c} + y_{c,b}\right) + \\ p_c p_t\left(l_t + l_c + y_{t,c} + y_{c,t}\right) \end{array} \right) \qquad \text{(Eq. 4)}$$

where

> s is the vehicle speed
> p_c is the percentage of cars
> p_b is the percentage of buses

p_t is the percentage of trucks

l_c is the nominal length of cars

l_b is the nominal length of buses

l_t is the nominal length of trucks

$x_{c,c}$ is the inter-vehicle spacing between cars

$x_{b,b}$ is the inter-vehicle spacing between buses

$x_{t,t}$ is the inter-vehicle spacing between trucks

$x_{c,b}$ is the inter-vehicle spacing between a car and a bus (preceding vehicle)

$x_{b,c}$ is the inter-vehicle spacing between a bus and a car (preceding vehicle)

$x_{c,t}$ is the inter-vehicle spacing between a car and a truck (preceding vehicle)

$x_{t,c}$ is the inter-vehicle spacing between a truck and a car (preceding vehicle)

$y_{c,c}$ is the spacing between platoons of cars

$y_{b,b}$ is the spacing between platoons of buses

$y_{t,t}$ is the spacing between platoons of trucks

$y_{c,b}$ is the spacing between a platoon of cars and a platoon of buses (preceding)

$y_{b,c}$ is the spacing between a platoon of buses and a platoon of cars (preceding)

$y_{c,t}$ is the spacing between a platoon of trucks and a platoon of cars (preceding)

$y_{t,c}$ is the spacing between a platoon of trucks and a platoon of cars (preceding)

z_c is the nominal intra-platoon spacing for cars

z_b is the nominal intra-platoon spacing for buses

z_t is the nominal intra-platoon spacing for trucks

n_c is the nominal length of a platoon of cars

n_b is the nominal length of a platoon of buses

n_t is the nominal length of a platoon of trucks

The vehicle-spacing design tool's algorithm for computing spacing between two individual vehicles or two platoons can produce extremely small spacing values (e.g., on the order of much less than one meter for individual vehicles) when the maximum braking rate of the following vehicle is much greater than that of the preceding vehicle (e.g., a light duty passenger vehicle following a truck). Thus, to avoid the use of unrealistic spacing values, we apply the following spacing policy: if the braking capability of the follower is much greater than that of the preceding vehicle, then the following vehicle will follow at a distance from the preceding equal to the length of the follower. The two cases in which this occurs are when a car follows a bus or truck.
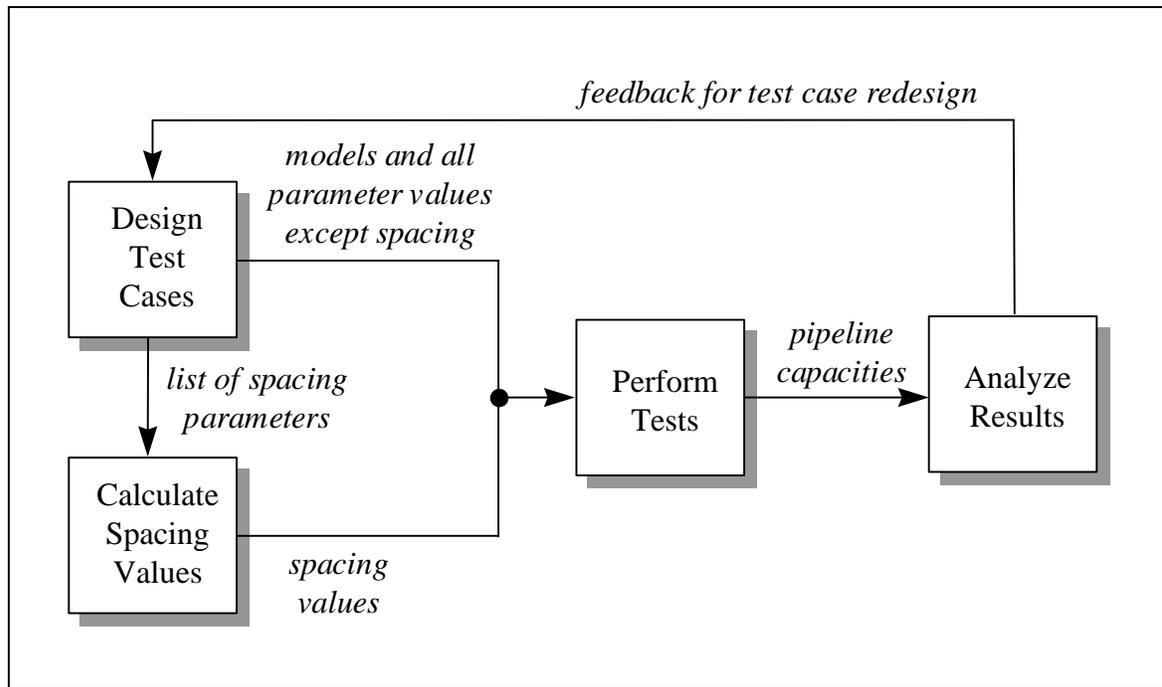
Figure G.1. Process for performing pipeline capacity sensitivity analysis

G.5 Procedure

The procedure for performing pipeline capacity analysis is shown in Figure G.1. The tasks 'Design Test Cases' and 'Calculate Spacing Values' are performed in series. A parametric model is given for each set of test cases: a test case defines the vehicle-following scenario to be analyzed, for example, one of the possible permutations of truck platoons and light-duty passenger vehicle platoons following each other. Each set of test cases corresponds to a hypothesis.

The dependent variable in the parametric equations is the pipeline capacity. Each of the independent variables – minimum permissible inter-vehicle, intra- and inter-platoon spacing, range of AHS operating speeds, and percentage of vehicles in each class – is assigned a fixed nominal value, or is allowed to vary for a range of values (i.e., computed during the simulation run).

G.5.1 Calculation of Inter-Vehicle Spacing for Individual Vehicles

For each vehicle-following scenario involving individual vehicles, the spacing-versus-speed values are generated using the vehicle-spacing design tool (*vid*. Section G.4.1), and stored and manipulated as matrices. The inputs to the vehicle-spacing design tool are
- braking amplification factor
- closed-loop lumped lag of the following vehicle (s)
- maximum deceleration of the lead vehicle (g)

- maximum deceleration of the following vehicle (g)
- maximum permissible jerk (g/s)
- speed tracking error

The braking amplification factor for the individual-vehicle scenarios is always set to one. Based on the information supplied by domain experts, simplifying assumptions are made about the sensing, inter-vehicle communication, and brake actuation delays for each of the four degrees of inter-vehicle coordination. The nominal lag values chosen for use in the derivation of spacing requirements are shown in Table G.4.

Table G.4a. Nominal lags and lumped lags for individual light-duty passenger vehicles

Type of Lag	Autonomous Individual Vehicle	Low-Cooperative Vehicle	High-Cooperative Vehicle
sensing	200 ms	NA	NA
communication	NA	50 ms	20 ms
actuation	100 ms	100 ms	100 ms
lumped (i.e., total)	300 ms	150 ms	120 ms
lumped, with overlapping actuation and communication delays	300 ms	50 ms	20 ms

Table G.4b. Nominal lags and lumped lags for individual buses and trucks

Type of Lag	Autonomous Individual Vehicle	Low-Cooperative Vehicle	High-Cooperative Vehicle
sensing	200 ms	NA	NA
communication	NA	50 ms	20 ms
actuation	1 s	1 s	1 s
lumped (i.e., total)	1.2 s	1.05 s	1.02 s

For this analysis and all three vehicle classes, braking rates for dry and good pavement conditions are used. The rationale for this is that these are the conditions for which braking rates are readily available in the literature. Maximum braking rates for 1995 model year new light-duty passenger vehicles are taken from Appendix B.1 of the NAHSC Task C1 Final Report[13]. The braking rate distribution for light-duty passenger vehicles is created by matching the North American production figures for each model for the time period January 1 through April 15, 1995 as reported in *Automotive News*. The resulting distribution is validated the stopping distance requirements mandated in the *Federal Motor Vehicle Safety Standard Number 105: Hydraulic Brake Systems* and

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[13] See *Automated Highway System (AHS): WBS C1 Final Report Appendices, Develop Initial Suite of Concept and Workshop No. 2*. National Automated Highway System Consortium, Troy, Michigan, 10 June 1996.

through consultation with the National Highway Traffic Safety Administration (NHTSA) Office of Crash Avoidance Research.

A factor of six percent per annum over five years is used to inject degradation (e.g., due to physical wear and tear) of braking performance into the braking distribution for light-duty passenger vehicles. The factor of six percent per annum is an estimate; we could not obtain data on the degradation of braking performance. The braking-rate data is shown in Table G.5, and the discrete probability distribution is shown in Figure G.2, representing the braking rates of the population of vehicles in the sample. A continuous probability distribution is built from this same data for use in the safety analyses (*viz*. Section 4.2 and Appendix J). (*N.B.*: A different distribution, representing more of the vehicle population, and with no derating for wear, will be used in Task C3.)

The choice of maximum braking rates for buses is based on the braking rates specified in the American Public Transit Association (APTA) document titled *Baseline Advanced Design Transit Coach Specifications: A Guideline for New 35- and 40-Foot Coach Designs*. The worst-case braking rate is used since the pipeline analysis is coupled to the safety analyses; in this case it is the hard braking rate for a transit coach design operating profile, from the high-speed duty cycle.[14]

Table G.5. Braking rate distribution for light-duty passenger vehicles, with a braking-performance-degradation factor of six percent per annum over five years

Model	Braking Rate (g)	Production (veh)	70% (g)	76% (g)	82% (g)	88% (g)	94% (g)
Toyota Corolla	0.65	26,403	0.46	0.49	0.53	0.57	0.61
Chevrolet Camaro	0.74	39,949	0.52	0.56	0.61	0.65	0.70
Chevrolet Blazer	0.77	76,441	0.54	0.59	0.63	0.68	0.72
Ford Explorer	0.81	127,207	0.57	0.62	0.66	0.71	0.76
Chrysler Sirrus	0.83	28,403	0.58	0.63	0.68	0.73	0.78
Honda Accord LX	0.84	109,132	0.59	0.64	0.69	0.74	0.79
Jeep Grand Cherokee	0.84	85,733	0.59	0.64	0.69	0.74	0.79
Nissan Sentra GXE	0.85	41,876	0.60	0.65	0.70	0.75	0.80
Mercury Mystique LS	0.86	18,160	0.60	0.65	0.71	0.76	0.81
Chevrolet Monte Carlo	0.87	44,692	0.61	0.66	0.71	0.77	0.82
Saturn SL2	0.87	93,206	0.61	0.66	0.71	0.77	0.82
Oldsmobile Aurora	0.88	11,650	0.62	0.67	0.72	0.77	0.83
Chevrolet Cavalier	0.90	48,960	0.63	0.68	0.74	0.79	0.85
Buick Riviera	0.90	9,968	0.63	0.68	0.74	0.79	0.85
BMW-3 series	0.90	2,310	0.63	0.68	0.74	0.79	0.85
Ford Thunderbird LX	0.92	24,844	0.64	0.70	0.75	0.81	0.86
Toyota Avalon XLS	0.93	23,022	0.65	0.71	0.76	0.82	0.87
Chevrolet Corvette	0.98	2,746	0.69	0.74	0.80	0.86	0.92
Ford Mustang Cobra	0.98	48,190	0.69	0.74	0.80	0.86	0.92

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[14] See p. II-3, Table II-1, "Transit coach design operating duty cycle," of the APTA document.
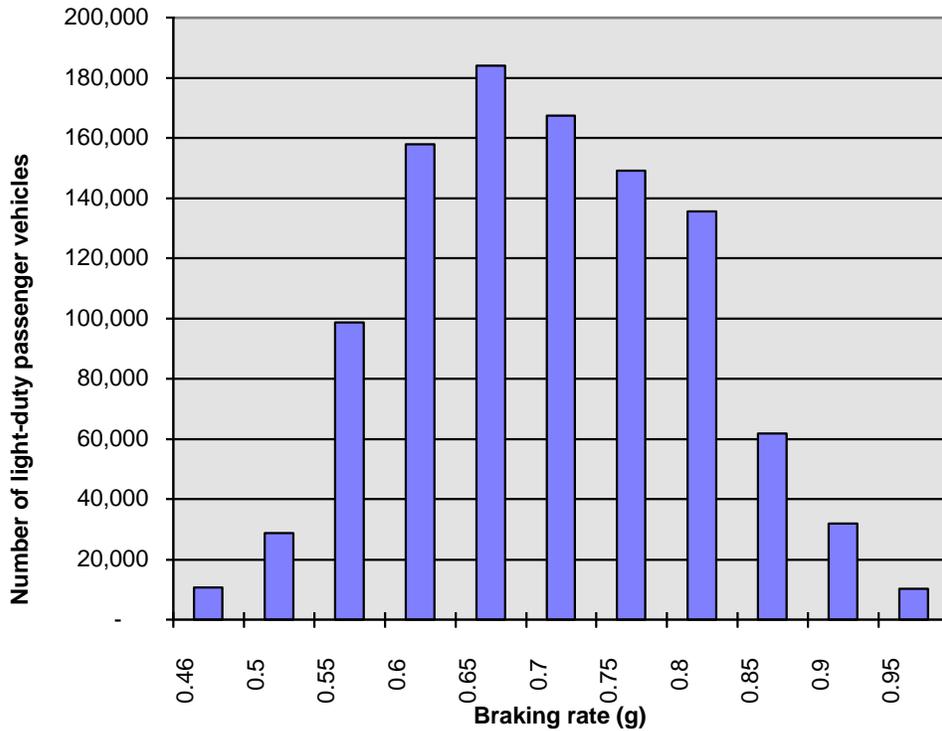
Figure G.2. Discrete probability distribution of light-duty passenger vehicle braking rates

The nominal values used for trucks are based on a synthesis of test track results published by NHTSA's Vehicle Test Center[15]. The test track results are reported in terms of required stopping distance for an initial speed of 60 mph from which the truck applies maximum braking. Equation 5 is used to convert the recorded stopping distances to their corresponding approximate braking rates.

$$a = \frac{v^2}{2s} \tag{Eq. 5}$$

where

a is acceleration
v is velocity
s is the stopping distance in feet

For example, the approximate braking rate for a recorded stopping distance is 232 ft is

$$a = \frac{\left(60 \cdot 1.47\,ft/s/mph\right)^2}{2 \cdot 232\,ft} = 17.45\,ft/s^2 \approx 0.54g \tag{Eq. 6}$$

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[15] See *NHTSA's Heavy Duty Vehicle Brake Research Program Report Number 9—Stopping Distances of 1988 Heavy Vehicles*, National Highway Traffic Safety Administration, Interim Report DOT HS 807 531, February 1990, pp. 17, 19, and 23.

Table G.6. Braking distances and rates for trucks

Type of Truck	Worst Stopping Distance (ft)	Worst Braking Rate (g)	Best Stopping Distance (ft)	Best Braking Rate (g)
Bobtail tractor	463	0.26	233	0.52
Empty tractor/trailer	319	0.39	225	0.54
Loaded tractor/trailer	273	0.44	230	0.52

Table G.7. Minimum and maximum values for the range of deceleration rates

Vehicle Class	Minimum Deceleration Rate (g)	Maximum Deceleration Rate (g)
Light-duty passenger vehicles	0.46	0.98
Buses	0.20	0.54
Trucks	0.26	0.54

These values are validated by referring to the *Federal Motor Vehicle Safety Standard Number 121: Air Brake Systems*, and through consultation with air brake system designers.[16] The worst and best braking rates, shown in Table G.6, are used in the analysis to facilitate consideration of cases in which the preceding truck can brake at a much greater rate than the following truck or bus.

Table G.7 is constructed from the preceding braking data, which defines the range of maximum deceleration rates on a per class basis. Given the minimum and maximum points in each range, denoted by *min* and *max*, respectively, the following rules are used to determine which deceleration values to use for the preceding individual vehicle, *PIV*, preceding platoon, *PP*, following individual vehicle, *FID*, and following platoon, *FP*, in order to guarantee safety under the worst case:

1. In test cases involving individual vehicles, use *max(PIV)* and *min(FID)*.
2. In test cases involving platoons, use *max(PP)* and *min(FP)*.

The speed tracking error is set to 1.5 percent for all test cases, including platoon test cases; that is, the following vehicle travels 1.5 percent faster than the preceding vehicle. The speed tracking error represents the maximum overshoot by the following vehicle.

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[16] We found that it is not enough to search for the braking performance of a particular truck model. When a truck is purchased, the buyer must select from among different braking, power, and transmission systems. Thus, two trucks of the same model can have different performance characteristics.

G.5.2 Calculation of Intra- and Inter-Platoon Spacing

In contrast, the generation of the spacing-versus-speed values for the platoon-based scenarios begins with the determination of the braking amplification factor and the intra-platoon spacing errors. These values are generated by the string stability tool, which takes the following inputs:

- communication processing delay (s)
- number of vehicles in the platoon (veh)
- closed-loop lumped lag (s)
- maximum deceleration of the lead vehicle (g)
- duration of the deceleration (s)
- simulation time (s)
- filter constant
- control system gains

The nominal values for communication processing delay and closed-loop lumped lag are shown in Table G.8. The nominal platoon lengths are given in Table G.9. The filter constant and control system gains are based on the results of tuning the tool's internal controller model for each class of vehicle, with these values being prescribed by the string stability and vehicle-spacing design tool developers.

Table G.8. Nominal lags and lumped lags for platoons of light-duty passenger vehicles, buses, and trucks

Type of Lag	Light-Duty Passenger Vehicle Platoon	Bus Platoon	Truck Platoon
sensing	NA	NA	NA
communication	50 ms (leader)	50 ms (leader)	50 ms (leader)
	20 ms (follower)	20 ms (follower)	20 ms (follower)
actuation	100 ms	1 s	1 s
lumped (i.e., total)	150 ms (leader)	1.05 s (leader)	1.05 s (leader)
	120 ms (follower)	1.02 s (follower)	1.02 s (follower)
lumped, with overlapping actuation and communication delays	50 ms (leader) 20 ms (follower)	NA	NA

Table G.9. Nominal platoon lengths

Vehicle Class	Platoon Length (veh)
light-duty passenger vehicles	10
buses	3
trucks	2

The braking amplification factor is used to account for the braking behavior of the vehicles following the platoon leader. For light-duty passenger vehicles, the braking amplification saturates beyond the third vehicle following the platoon leader. For example, consider the case in which the lead vehicle of a ten-vehicle platoon of light-duty passenger vehicles brakes at 8.5 m/s^2 (approximately 8.6 g). A plot produced by the String Stability Tool is shown in Figure G.3. In Figure G.3 the maximum acceleration is approximately 11 m/s^2 and the acceleration for the platoon profile at this same point in time is approximately 8.5 m/s^2. The braking amplification factor is computed as shown in Equation 7. (*N.B.*: this is a linear analysis to scale down to achievable braking rates.)

$$braking\ amplification\ factor = \frac{11m/s^2}{8.5m/s^2} \approx 1.3 \qquad \text{(Eq. 7)}$$

Given a braking amplification factor of 1.3, the maximum spacing error output by the String Stability Tool is ±0.4 m. Table G.9 shows the nominal braking amplification factors and intra-platoon spacing values used in the calculation of inter-vehicle and inter-platoon spacing. These nominal values represent the highest values per vehicle class generated by the String Stability Tool. Note that the braking amplification factor is used to increase the inter-platoon separation so that it is not necessary for vehicles to brake at physically unrealizable rates in order to avoid intra-platoon collisions.
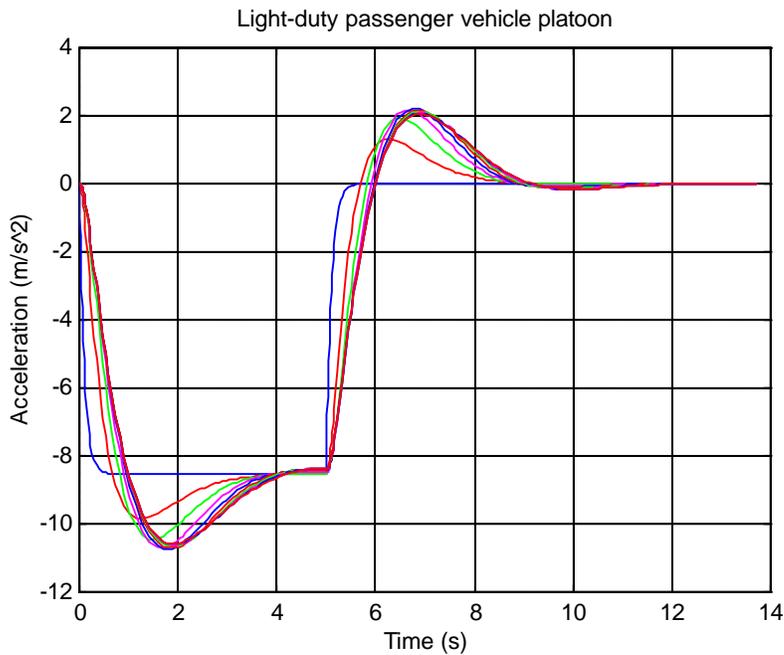
Figure G.3. Acceleration versus time for a platoon of ten light-duty passenger vehicles and the platoon leader braking at a rate of 8.5 m/s^2

Table G.9. Minimum permissible inter-vehicle and inter-platoon spacing for a vehicle-
highway speed of 30 m/s

Vehicle Class	Intra-platoon spacing (m)	Braking amplification factor
light-duty passenger vehicles	2	1.3
buses	8	1.5
trucks	8	1.5

Next the inter-platoon spacing is calculated. Sample Spacing Design Tool output for a
vehicle-highway speed of 30 m/s is shown in Table G.10. A sample plot generated by the
Spacing Design Tool is shown in Figure G.4. The input data used to calculate the spacing
values and to create the plot are shown in Figure G.5.

Table G.10. Minimum permissible inter-vehicle and inter-platoon spacing for a vehicle-
highway speed of 30 m/s

Preceding Vehicle [Following Vehicle]	Autonomous Individual Vehicle (m)	Low-Cooperative Individual Vehicle (m)	High-Cooperative Individual Vehicle (m)	Platoon (m)
light-duty passenger vehicle [light-duty passenger vehicle]	36	35	33	56
bus [bus]	129	128	127	129
truck [truck]	101	100	98	100
bus [light-duty passenger vehicle]	182	182	180	189
truck [light-duty passenger vehicle]	133	132	130	139
truck [bus]	79	79	77	79
bus [truck]	151	150	148	150
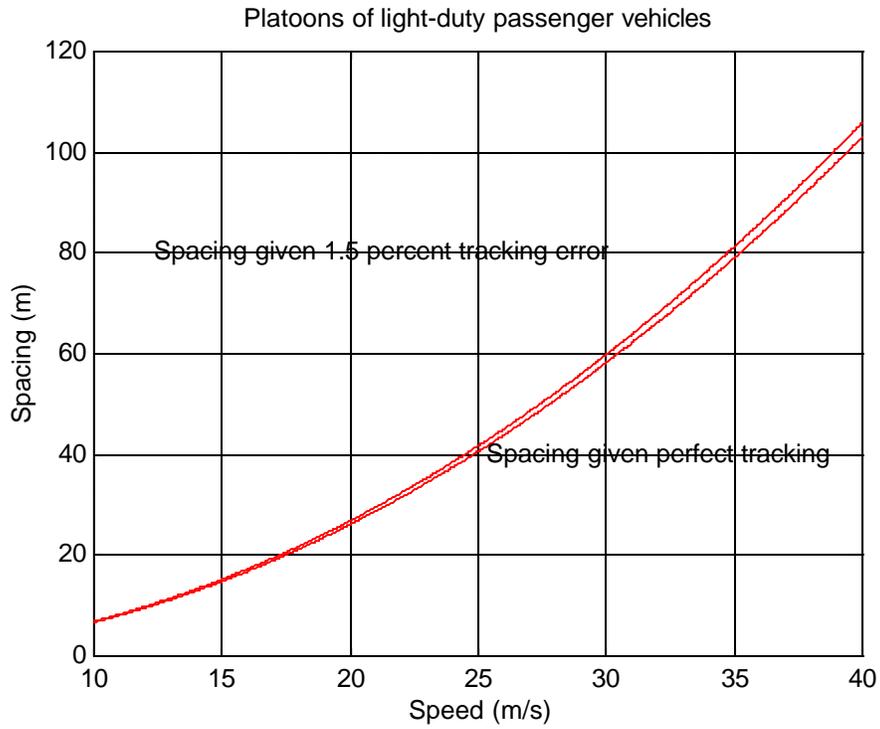
Figure G.4. Minimum permissible inter-platoon spacing for platoons of light-duty passenger vehicles following each other

```
% Parameter Specification

% Capabilities of the lead vehicle.
% dmax = maximum acceleration, dmin = maximum deceleration (m/s/s)
% jmind = minimum jerk, jmaxd = maximum jerk (m/s/s/s)
dmax=3.0;
dmin=-9.81*0.86;
jmind = -9.81*7.5;
jmaxd = 9.81*7.5;

% Capabilities of the following vehicle.
% amax = maximum acceleration, amin = maximum deceleration (m/s/s)
% jmax = maximum jerk, jmin = minimum jerk (m/s/s/s)
amin = -9.81*0.54;
amax=3.0;
jmin=-9.81*7.5;
jmax=9.81*7.5;

% Braking amplification factor due to coordinated braking. Used for
% calculating inter-platoon spacing. Default value = 1.
amplify = 1.3;

% Total delay (communication, sensing, actuation) tau, in seconds.
% The delay is modeled as a first order lag.
tau=0.15;

% Initial Conditions
% v0 = Initial velocity of the following vehicle (m/s)
% a0 = Initial Acceleration of the following vehicle (m/s/s)
% d0 = Initial spacing (m)
% dv0 = Initial relative velocity (m/s) = leader vel - follower vel
% da0 = initial relative acceleration (m/s/s) = leader acc - follower
% acc
v0=40.0;
a0=0.0;
d0=0.0;
dv0=-0.015;
da0 = 0.0;

% Allowable collision velocities for vehicles ahead, vallowL, and
% vehicle behind, vallowF (m/s). They are negative quantities.
vallowL = 0.0;
vallowF = 0.0;

% Safety Objective
% What is the closest, these two vehicles can ever get? specified in
% meters. Close = 0 refers to the limiting case of no collisions.
Close = 0.0;

% Output Format Specification
% Plot Number 1 {default plot}: Plots spacing vs. velocity with the rest
% of the variables assuming values as given above. Alternatively, you
% can get two different plots for two different relative velocities by
% setting the value of dv different than dv0. To view this plot, set
% vs = 1, otherwise set vs = 0. Enter the range of velocity for
% plotting. The data for the two plots is stored in the ASCII files
% vs1.mat & vs2.mat
vs = 1;
vlow=10;
vhigh=40;
dv = 0;
```

Figure G.5. Input data used to calculate the spacing values and to create the plot shown in Figure G.4

G.5.3 Validation of Relationship Captured by the Model

The relationships among vehicle-spacing design tool input parameters (i.e., the independent variables in the pipeline capacity model) and between these parameters and pipeline capacity are investigated prior to the execution of the test cases (i.e., computation of the pipeline capacity for each test case). The purpose for this exercise is to validate that the relationships between input parameters and pipeline capacity are those that are expected: the correctness of these relationships is judged in terms of how well they represent physical reality. The relationships explored are as follows:

- maximum spacing error versus regulation communication delay
- maximum braking amplification versus regulation communication delay
- pipeline capacity versus velocity error
- pipeline capacity versus lead vehicle jerk
- pipeline capacity versus communication lag
- pipeline capacity versus communication latency
- pipeline capacity versus acceleration sensing and processing lag

The results are given in Sections G.6.1 and G.6.2.

G.6 Results

G.6.1   Relationships Among Vehicle-Spacing Input Parameters

The results shown in Figure G.6 indicate that the maximum spacing error is sensitive to regulation communication delay. The spacing error doubles, from approximately 0.5 to 1 m as the regulation communication delay increases from 20 to 100 ms. In addition, the results show that the maximum braking amplification factor is not very sensitive to regulation communication delay; see Figure G.7. As the regulation communication delay increases from 20 to 100 ms, the maximum braking amplification for platoons of light-duty passenger vehicles increases by approximately 0.02 percent. Although it is not shown, it is known *a priori* that the intra-platoon control system becomes unstable for regulation communication delays greater than 150 ms.
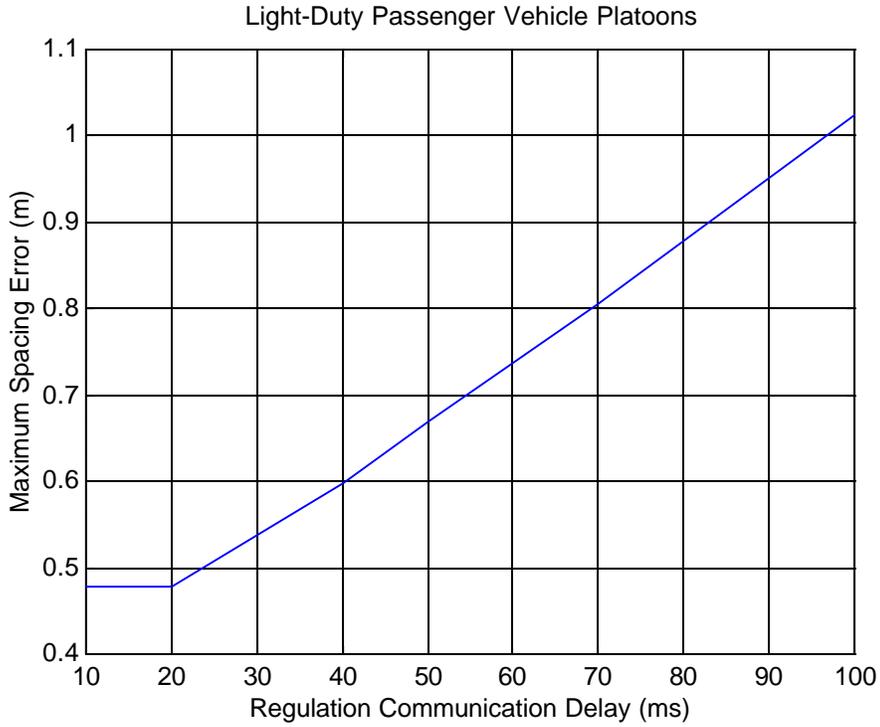
Figure G.6. Maximum spacing error versus regulation communication delay
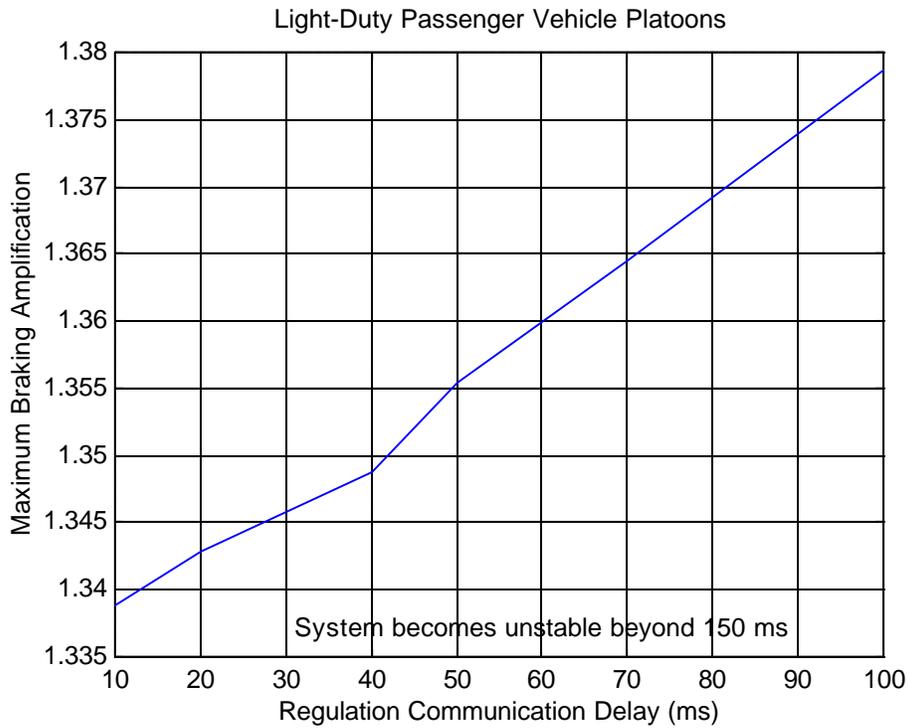
Figure G.7. Maximum braking amplification versus regulation communication delay

G.6.2 Relationships between Pipeline Capacity and the Vehicle-Spacing Tool Input Parameters

The next set of tests show that pipeline capacity is relatively insensitive to individual variations in the following vehicle-spacing input parameters: velocity error, lead vehicle jerk, communication lag, communication latency, and acceleration sensing and processing lag. Although this part of the model validation is only performed for light-duty passenger vehicles, the results should hold for buses and trucks; that is, the same relationships should be found since the only differences among these vehicle classes are the relative sizes of the parameter values. The results shown in Figures G.8 through G.12 are consistent with expectations. Note that the data in Figures G.10 and G.12 are identical, since the effects of communication lags for cooperative vehicles are the same as the effects of sensing and processing lags for autonomous vehicles.

In addition to showing that pipeline capacity is sensitive to vehicle speed, Figure G.13 shows the effect of varying the lag of the following individual vehicle braking response with respect to the initiation of braking by the preceding individual vehicle, for lags of 20 to 120 ms and light-duty passenger vehicles. The figure shows that pipeline capacity, which is a function of inter-vehicle spacing, changes approximately five percent between the lowest and highest lags, indicating the insensitivity of pipeline capacity to lags.

The result shown in Figure G.14 supports the finding regarding the relative insensitivity of pipeline capacity to lumped lag. The plot shows the relationship between inter-vehicle spacing and lag at a speed of 30 m/s. Thus, as long as the lags for individual vehicles are within the range of 20 to 120 ms, the effect on inter-vehicle spacing and pipeline capacity will be as estimated here. An explanation of the braking models for each level of inter-vehicle cooperation is given in Section 4.2.
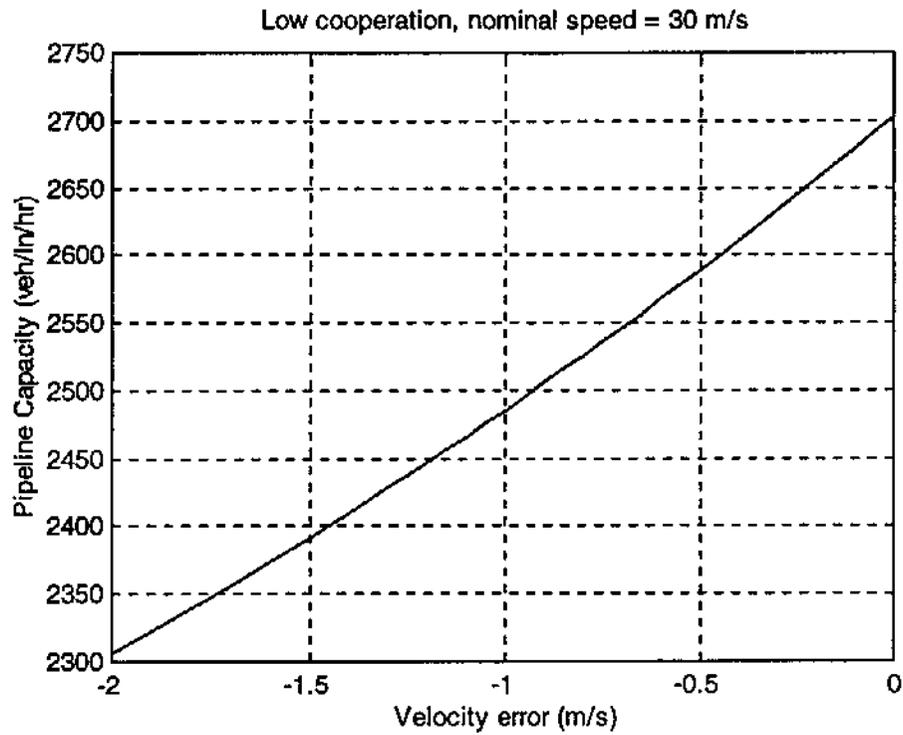
Figure G.8. Pipeline capacity versus velocity error for low-cooperative individual vehicles
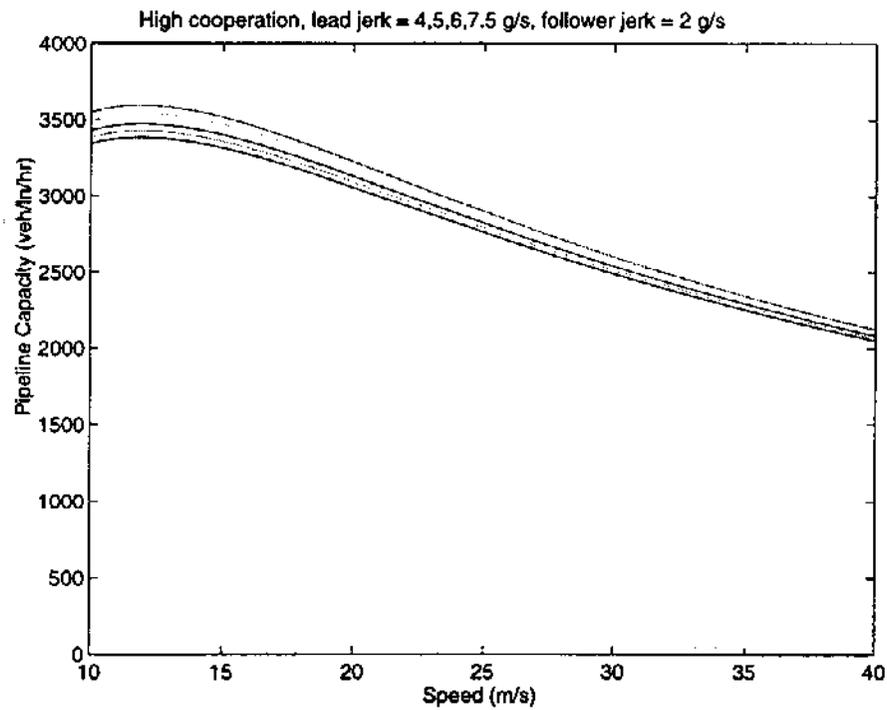
Figure G.9. Pipeline capacity versus lead vehicle jerk
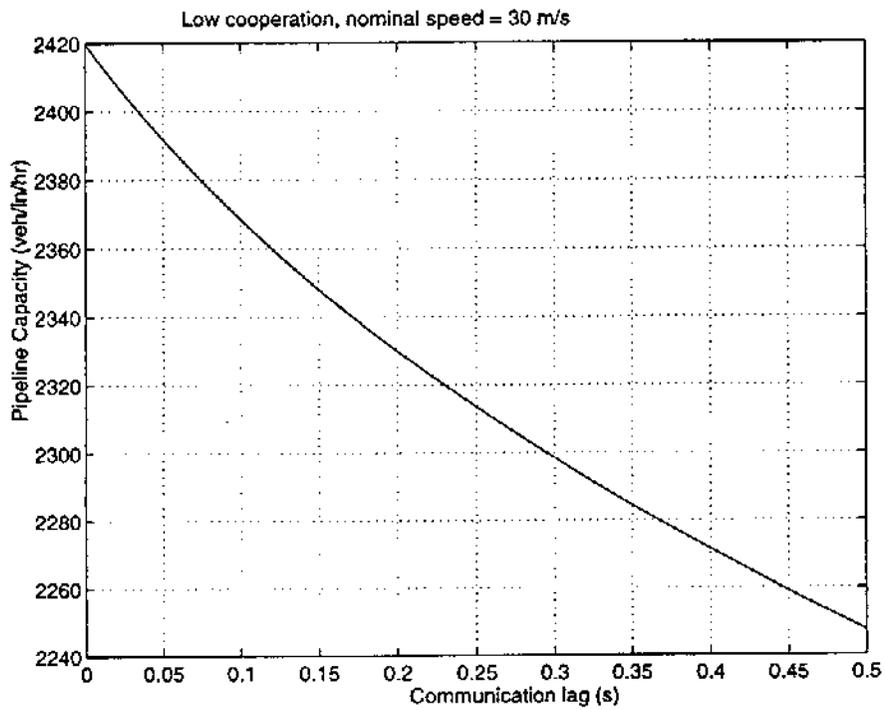
Figure G.10. Pipeline capacity versus communication lag
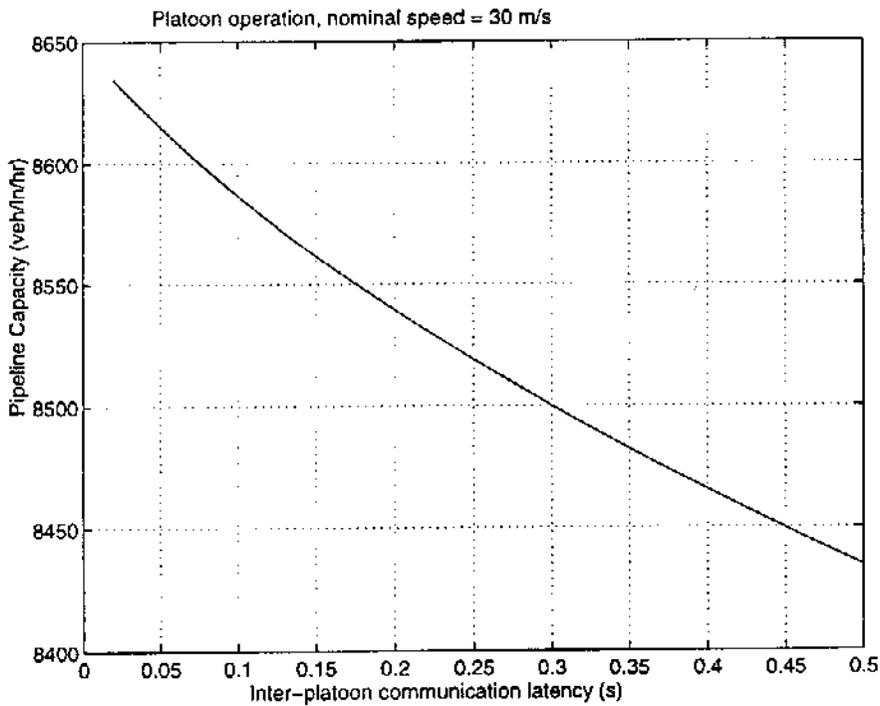
Figure G.11. Pipeline capacity versus inter-platoon communication latency
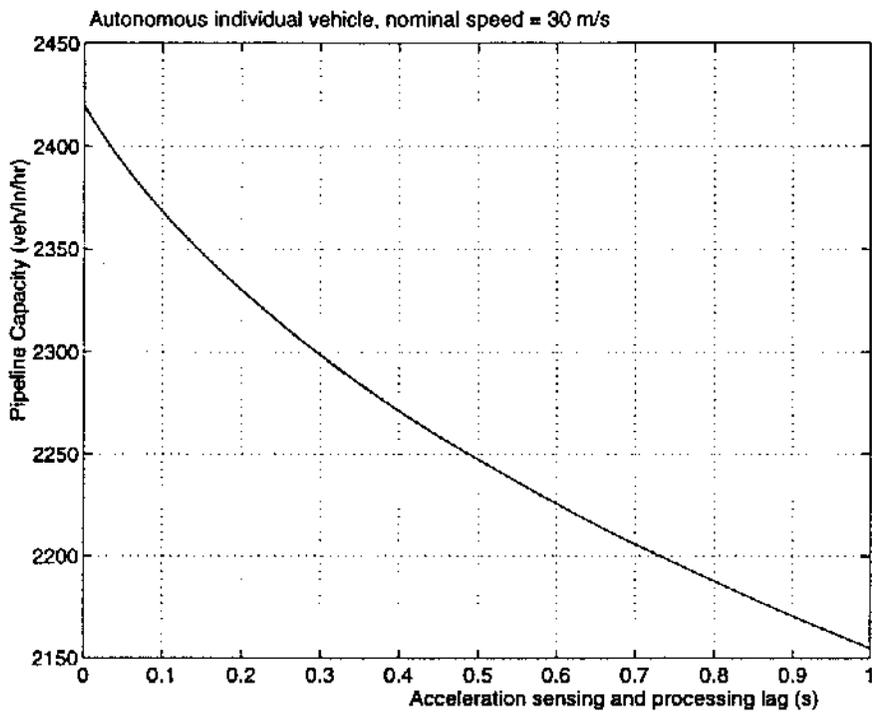
Autonomous individual vehicle, nominal speed = 30 m/s

Figure G.12. Pipeline capacity versus acceleration sensing and processing lag

Individual vehicles, lag = 20, 50, 80, 120 ms
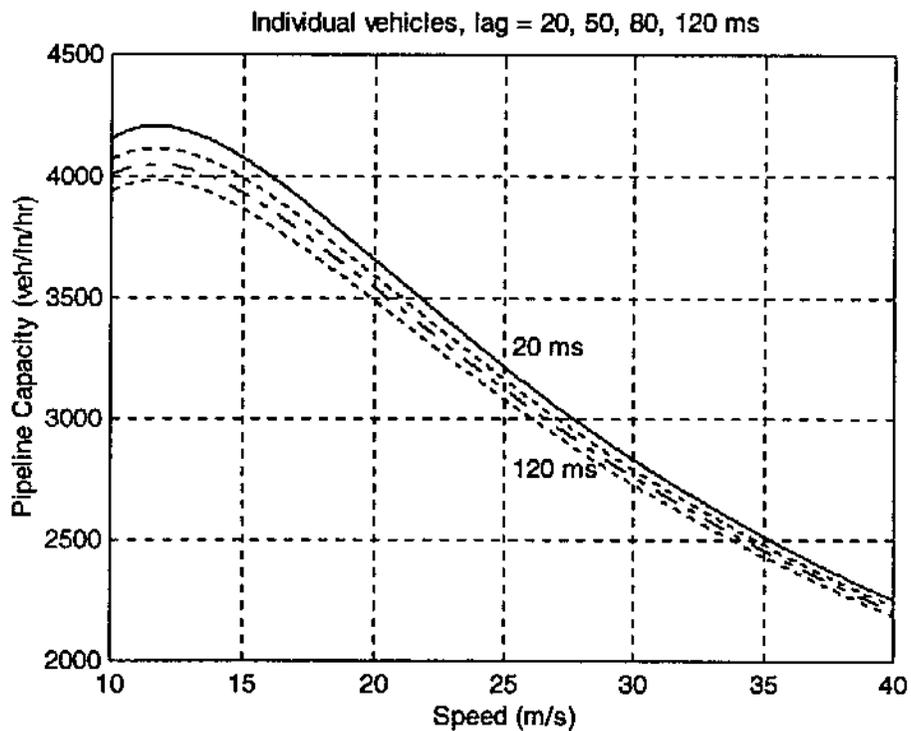
Figure G.13 Pipeline capacity versus speed for four different closed-loop lumped lags, light-duty passenger individual vehicles
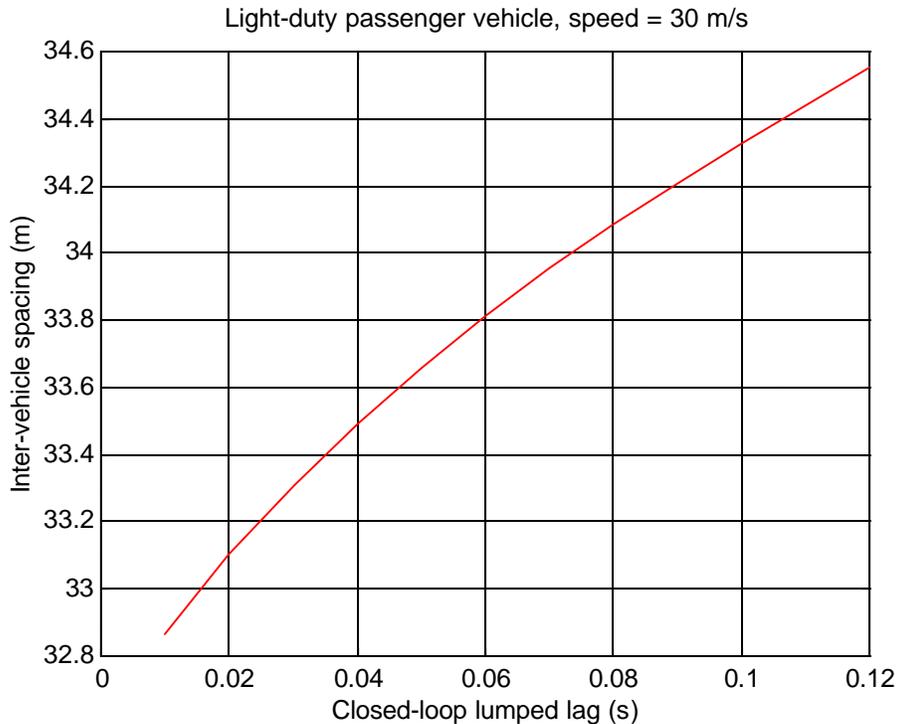
Figure G.14. Inter-vehicle spacing versus closed-loop lumped lag for light-duty passenger individual vehicles

G.6.3 Sensitivity of Pipeline Capacity to Degree of Inter-Vehicle Cooperation, Speed, and Vehicle Class Mix

Five test cases are used to test Hypotheses 1, 2, and 3. The first four test cases consist of varying the ratio of truck to light-duty passenger vehicles, from zero to 100 percent, for speeds between 10 and 40 m/s, for the different levels of cooperation among vehicles. The first three tests, shown in Figures G.15 through G.17, result in the same characteristic curves depicting pipeline capacity: after the peak in pipeline capacity, at approximately 12 m/s, pipeline capacity gradually decreases. In addition, the results show that the ratio of trucks to light-duty passenger vehicles increases (i.e., from zero to 100 percent trucks), the rate of decrease (i.e., the slope) of pipeline capacity is less pronounced. This can be explained by the fact that the inter-vehicle spacing between trucks and between trucks following light-duty passenger vehicles is much greater than that required between light-duty passenger vehicles.

In fourth test case – see Figure G.18 – the same trends are observed as found in the first three test cases, with two exceptions: (i) the peak pipeline capacity for platoons occurs at a speed greater than or equal to 20 m/s, as opposed to 12 m/s for the other test cases, and (ii) the platoon pipeline capacity attributed to 100 percent trucks is higher than that for the 90:10 ratio of trucks to light-duty passenger vehicles.

Moreover, the test case results show that as the level of inter-vehicle cooperation increases, there is a corresponding increase in pipeline capacity across the range of speeds. Figures G.19 and G.20 show the same finding, although from a different view of the data: pipeline capacity is plotted against the ratio of the two vehicle classes, rather than against speed.

The results of the fifth test case are shown in Figure G.21. For this test, the following percentages of light-duty passenger vehicles, trucks, and buses are applied: 93 percent, 6 percent, and 1 percent, respectively. The plot of pipeline capacity as a function of speed shows that platoon operation always results in the highest level of pipeline capacity. The dominance relation, abbreviated as *dom*, for the four levels of inter-vehicle cooperation with respect to pipeline capacity is

P dom HCIV dom LCIV dom AIV (Eq. 8)

where

        P is platoons
        HCIV is high-cooperation individual vehicles
        LCIV is low-cooperation individual vehicles
        AIV is autonomous individual vehicles
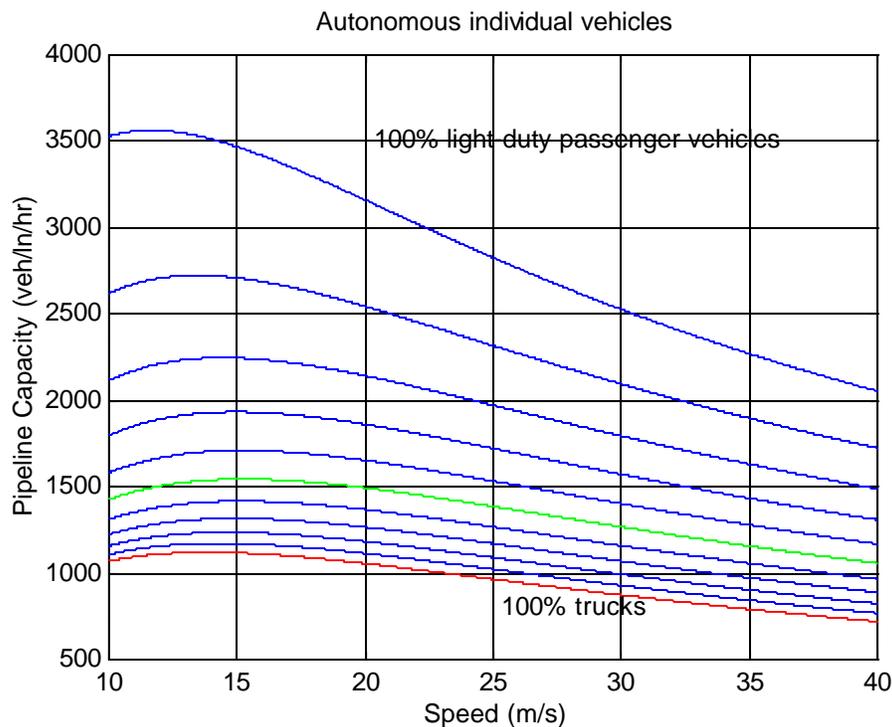
Figure G.15. Pipeline capacity versus speed for autonomous individual vehicle operation
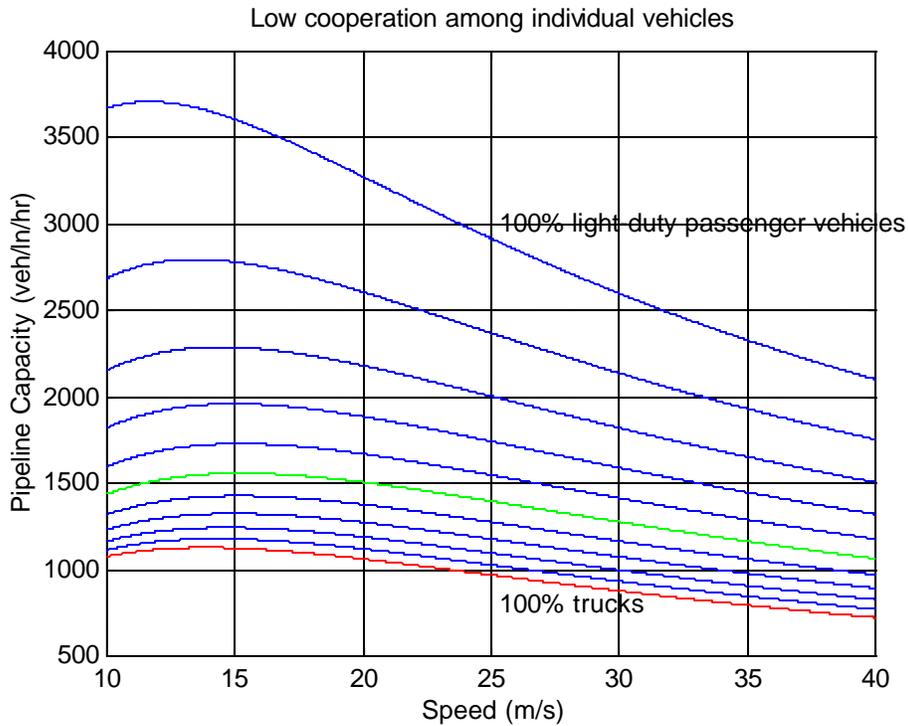
Figure G.16. Pipeline capacity versus speed for low cooperation among individual vehicles
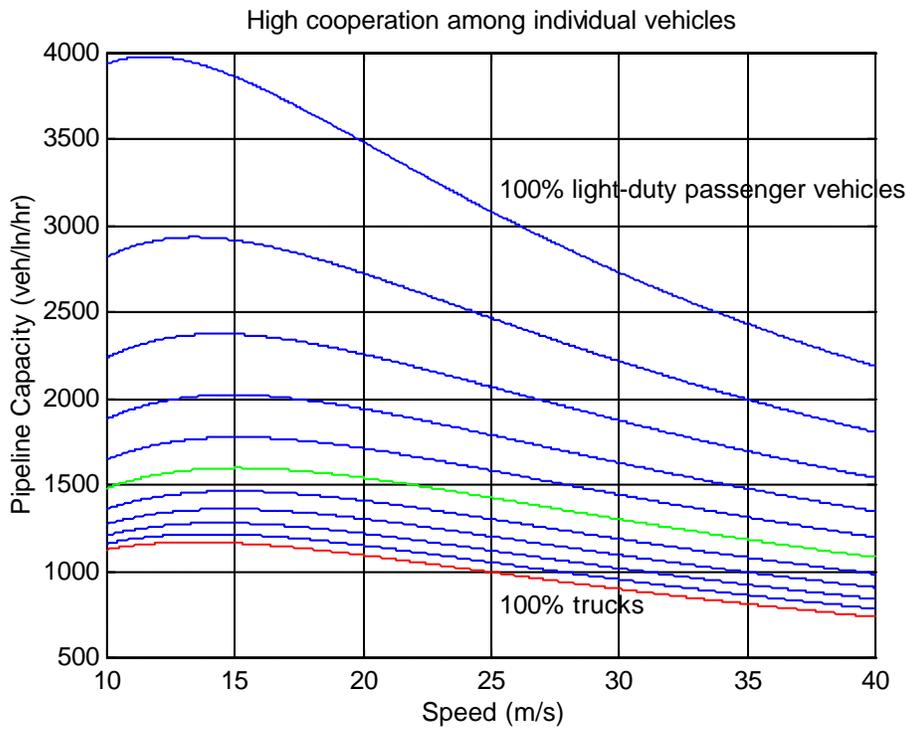
Figure G.17. Pipeline capacity versus speed for high cooperation among individual vehicles
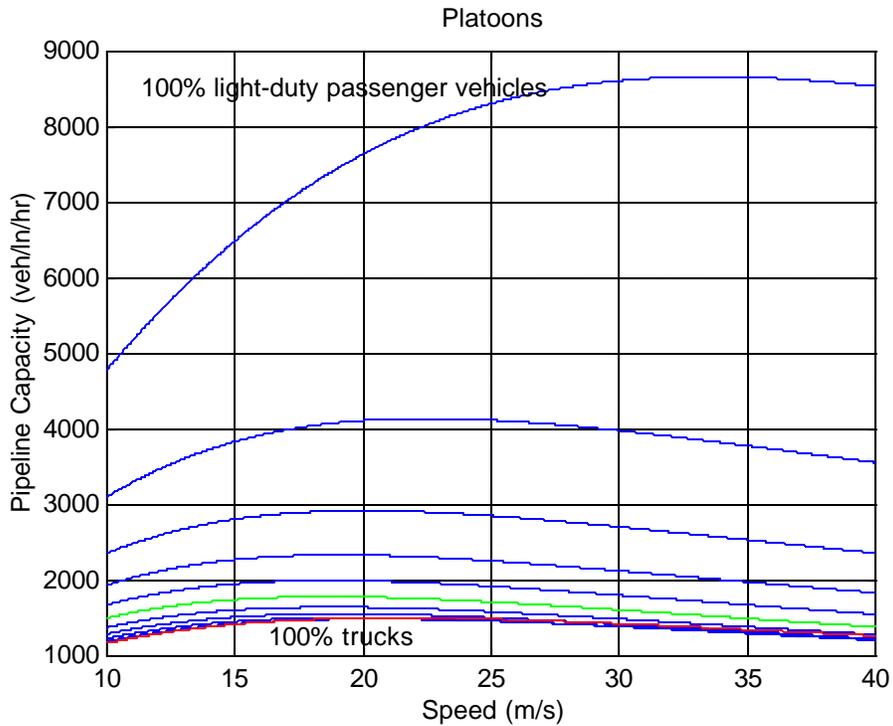
Figure G.18. Pipeline capacity versus speed for platoons
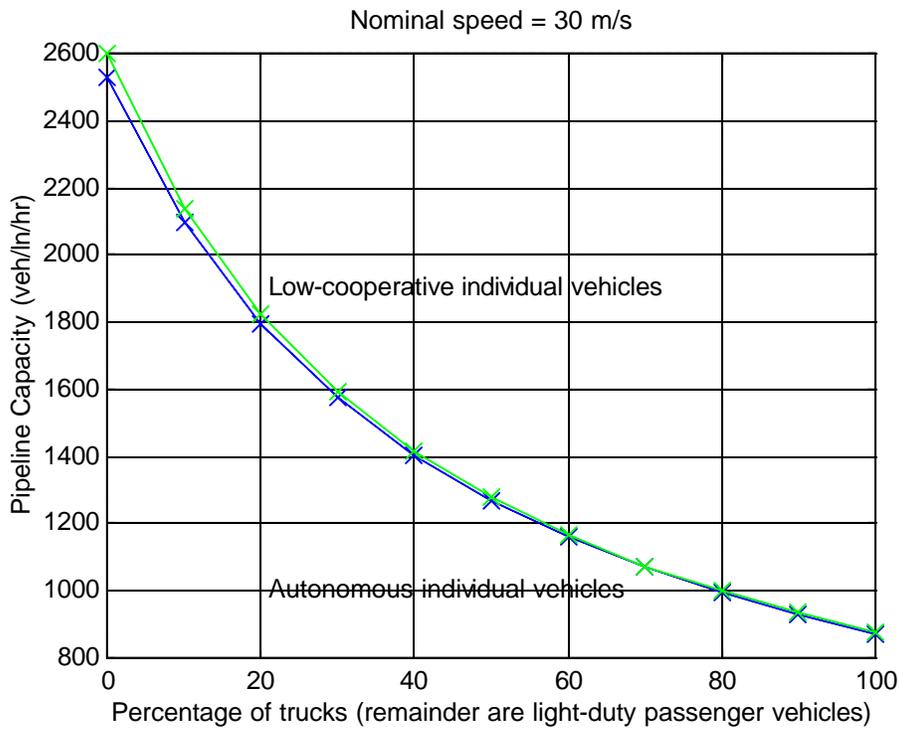
Figure G.19. Pipeline capacity versus percent trucks for autonomous and low-cooperative
individual light-duty passenger vehicle operation
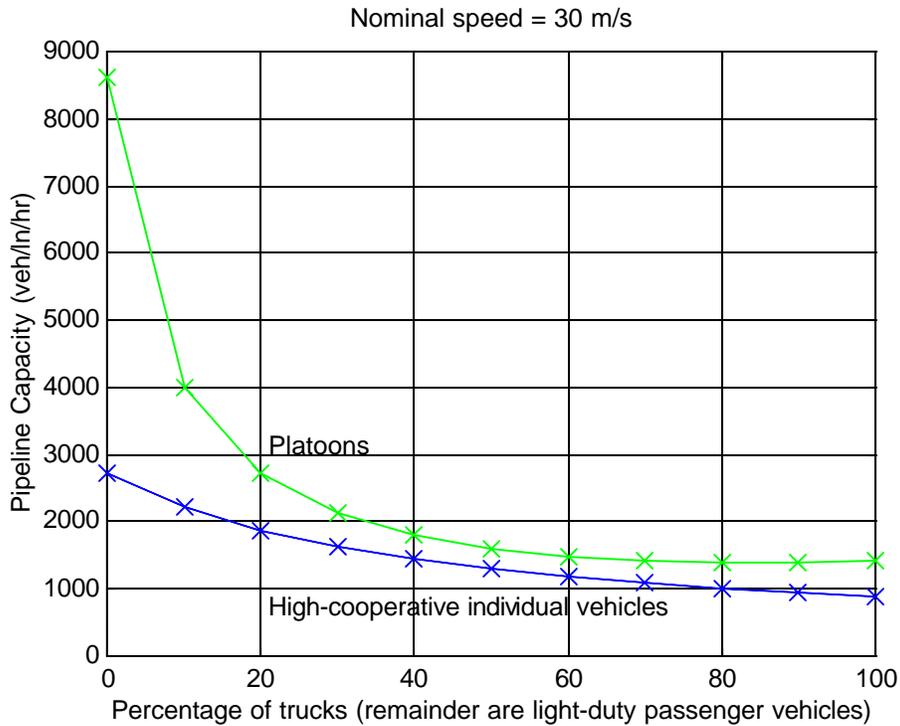
Figure G.20. Pipeline capacity versus percent trucks for high-cooperative individual light-duty passenger vehicle and platoon operation
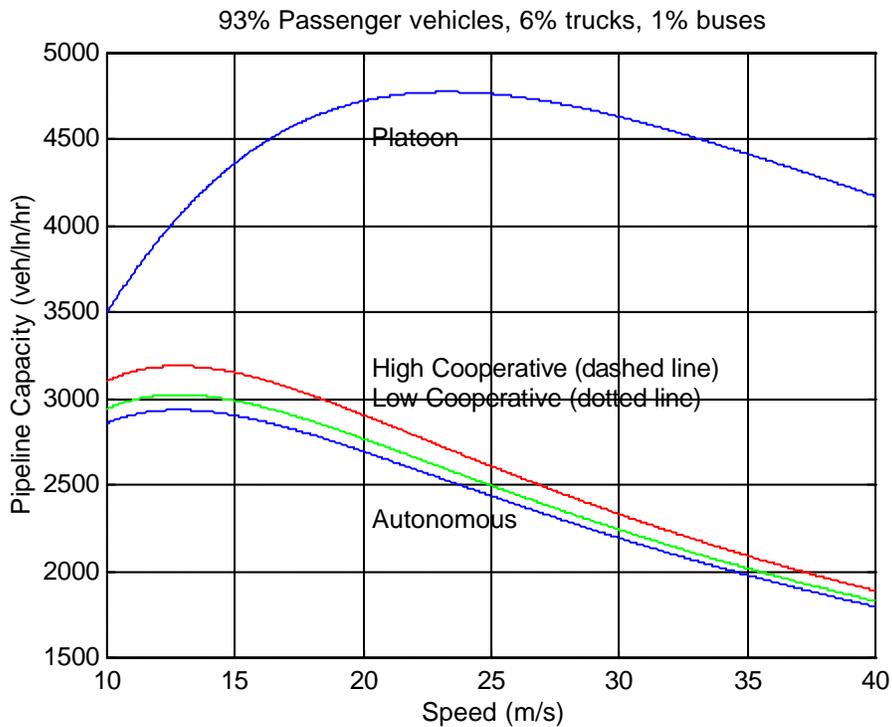

Figure G.21. Pipeline capacity versus speed for a mixture of all three vehicle classes and for all four degrees of inter-vehicle cooperation

G.6.4 Sensitivity of Pipeline Capacity to Platoon Length

The next set of test cases is used to test Hypothesis 4a. The platoon length is varied from one to ten vehicles for each of the three vehicle classes, with a step size of one vehicle, and plot pipeline capacity as a function of speed for each variation in platoon length. Intra-platoon spacing is held constant. Intra-platoon spacing for light-duty passenger vehicles is set at 2 m, while intra-platoon spacing for the other two vehicle classes is 8 m. Once the brake amplification factor reaches saturation (at platoon length of four vehicles), further increases in platoon length do not produce any increase in inter-platoon spacing.

The test case results are shown in Figures G.22 through G.24. The same pipeline capacity trends appear in all three cases, although the scales on the ordinate axes are different. In particular, note that pipeline capacity increases at a decreasing rate as the platoon length increases.

Moreover, for each of the pipeline capacity-speed curves, a peak pipeline capacity occurs followed by a gradual decrease in pipeline capacity. The point at which the peak pipeline capacity occurs is related to platoon length: as the platoon length increases, there is a corresponding increase in the speed at which the peak pipeline capacity occurs. Similarly, the rate of decrease in pipeline capacity is related to platoon size: as the platoon length decreases, there is a corresponding increase in the rate at which pipeline capacity decreases.
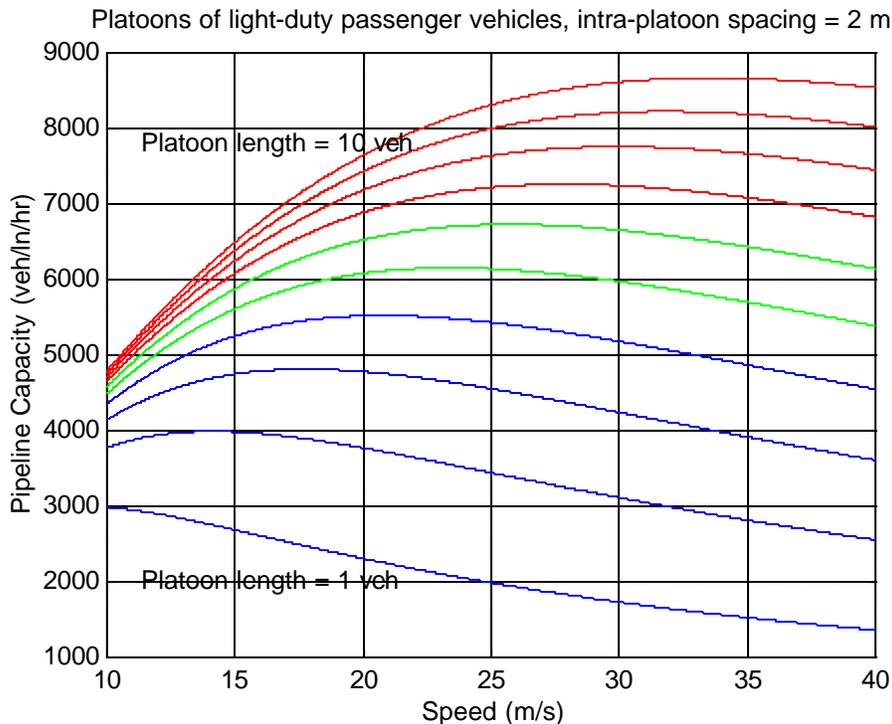

Figure G.22. Pipeline capacity versus platoon length for light-duty passenger vehicles
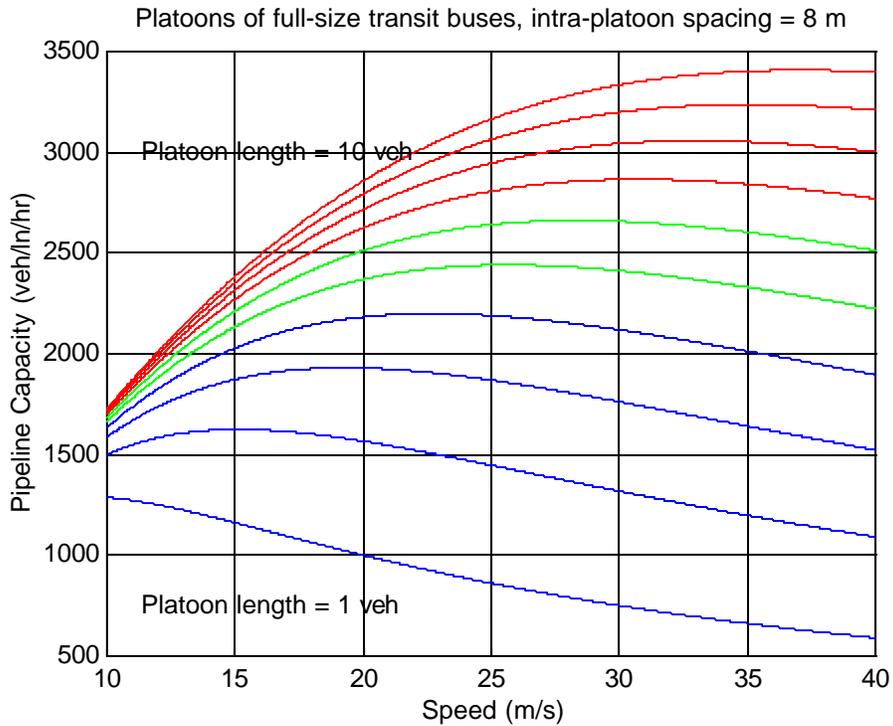
Figure G.23. Pipeline capacity versus platoon length for buses
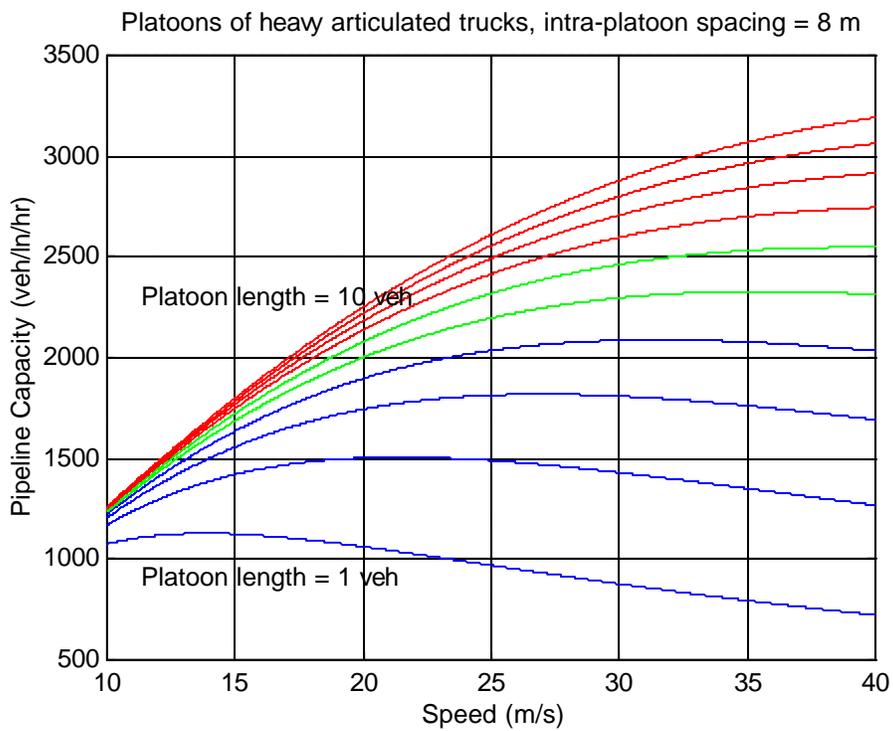

Figure G.24. Pipeline capacity versus platoon length for trucks

G.6.5 Sensitivity of Pipeline Capacity to Intra-Platoon Spacing

The test of Hypothesis 4b is performed by varying the intra-platoon gap from one to 15 m, while holding the platoon size constant. The nominal platoon sizes for light-duty passenger vehicles, buses, and trucks are ten, three, and two vehicles, respectively.

The results of the tests are shown in Figures G.25 through G.27. The trends are the same, although, as in the previous set of tests, the scales on the ordinate axes are different, with the highest level of pipeline capacity being given by light-duty passenger vehicles ($\approx$9300 vehicles at 30 m/s), followed by buses ($\approx$2250 vehicles at 16 m/s) and trucks ($\approx$1620 vehicles at 20 m/s).

The results indicate that as the intra-platoon gap increases, there is a corresponding decrease in pipeline capacity. As vehicle-highway speed increases, the rate of decrease in pipeline capacity after the peak decreases at an increasing rate for the full-size bus and truck cases. The light-duty passenger vehicle case shows a gradual degradation in pipeline capacity for the intra-platoon gap of 1 m between 30 and 40 m/s. However, all of the other curves on the plot of light-duty passenger vehicle pipeline capacity versus speed have a constant or positive slope at speeds between 30 and 40 m/s.
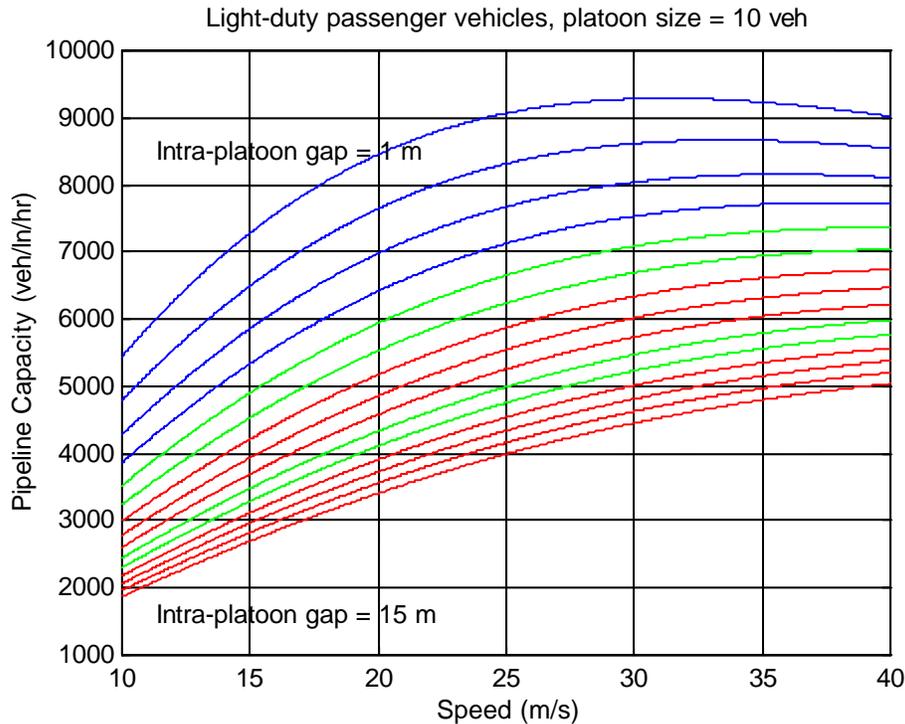

Figure G.25. Pipeline capacity versus intra-platoon spacing for light-duty passenger vehicles
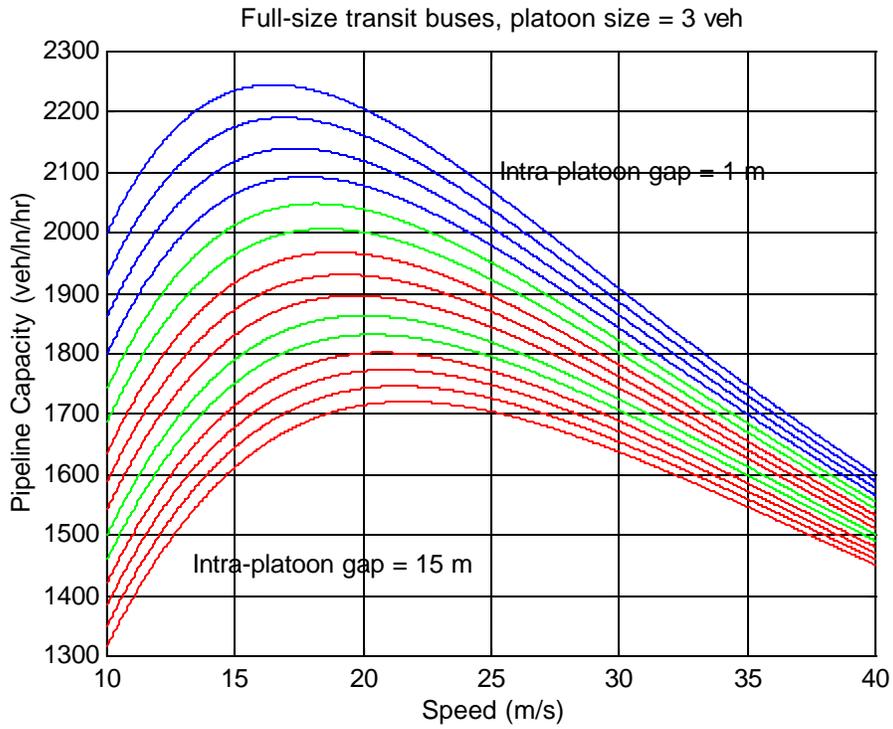
Figure G.26. Pipeline capacity versus intra-platoon spacing for buses
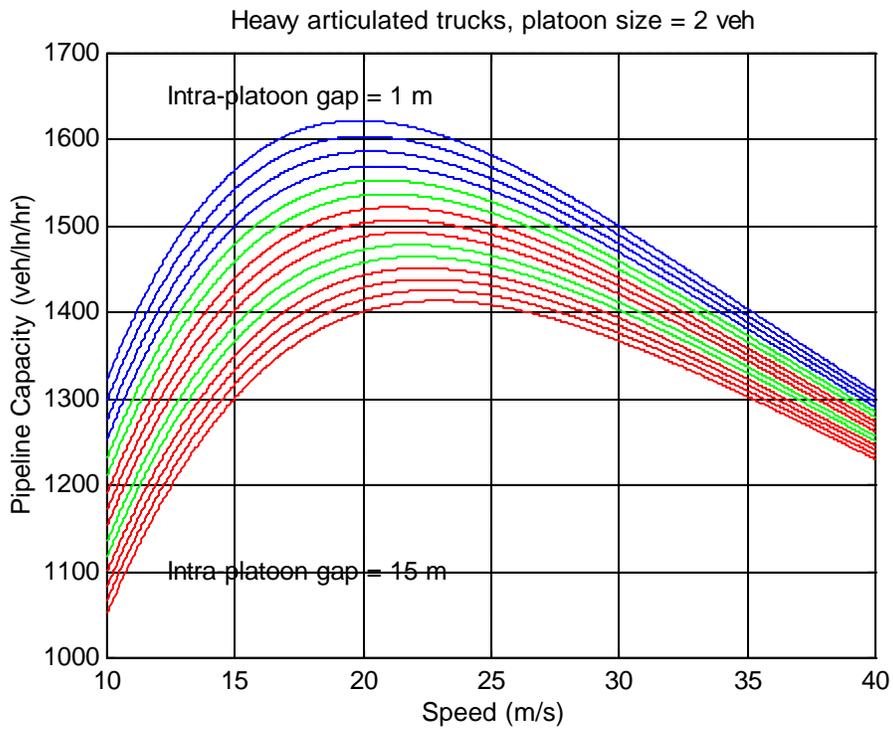
Figure G.27. Pipeline capacity versus intra-platoon spacing for trucks

G.6.6 Sensitivity of Pipeline Capacity to Check-In Policy on Minimum Braking Performance

Hypothesis 5 is tested by varying the coverage of the discrete probability distribution of light-duty passenger vehicle braking-rates shown in Figure G.2. The coverage is expressed as the percentage of the area under the distribution curve, measured from the right-hand tail of the distribution. For example, seventy-one percent refers to the portion of the vehicle-braking distribution which corresponds to a minimum check-in braking rate threshold of 0.65 g and a maximum braking rate of 0.95 g (i.e., the value located at the end of the right-tail of the distribution), representing a variation between the lowest and highest braking rates of approximately 34 percent. The range and variation in braking rates are shown in Table G.11.

Table G.11   Percentage difference in low and high braking rates for each percentage of the light-duty passenger vehicle braking distribution, permitted by check-in, from the right tail to the left

Percentage of vehicle braking distribution, permitted by check-in, as measured from the right tail to the left	*Lowest braking rate (g), light-duty passenger vehicle*	*Highest braking rate (g), light-duty passenger vehicle*	*Percentage difference between low and high values*
71	0.65	0.98	34
87	0.60	0.98	38
96	0.55	0.98	43
99	0.50	0.98	50
100	0.46	0.98	53

Figures G.28 through G.31 show the same trend: for all vehicle-highway speeds, pipeline capacity increases as the coverage of the braking-rate distribution decreases. A decrease in the braking-rate distribution coverage is equivalent to making the braking-rate performance requirement to travel on the pipeline more stringent. As the braking-rate performance requirement is relaxed, more vehicles with lower braking-rate capabilities are permitted to travel on the pipeline. As the number of vehicles with lower braking-rate capabilities increases within the pipeline, there is a corresponding increase in the minimum permissible inter-vehicle and inter-platoon spacing, which translates into a higher space utilization and lower capacity.

Table G.12 summarizes the results shown in Figures G.28 through G.31 for a highway speed of 30 m/s. For the individual vehicle cases, there is a decline in pipeline capacity of between 17 and 19 percent as the ratio of trucks to light-duty passenger vehicles increases from zero to 1:9. In contrast, the 55 percent decline in pipeline capacity for the platoon case is much greater than that of the individual vehicle cases. The increase in space-utilization requirements for separation of platoons of different classes of vehicles

accounts for the large difference in percentage decline in pipeline capacity between the individual vehicle and platoon cases – the braking capability of a platoon of trucks is much less than that of a platoon of light-duty passenger vehicles, *ceteris paribus*.

Table G.12. Pipeline capacity at 30 m/s for combinations of distribution of intelligence and ratios of trucks to light-duty passenger vehicles

	Pipeline Capacity (veh/ln/hr)		
	Ratio of Trucks to Light-Duty Passenger Vehicles		
Distribution of Intelligence	0	1:19	1:9
Autonomous individual vehicle	2527	2290	2096
Low-cooperative individual vehicle	2600	2345	2138
High-cooperative individual vehicle	2731	2446	2218
Platoon	8615	5399	3984

Pipeline capacity is sensitive to the absolute value of the difference between the lowest and highest vehicle deceleration rates for the population of vehicles permitted to enter and travel on the AHS lanes. The results from the analysis of the sensitivity of pipeline capacity to minimum check-in thresholds for braking rates, in terms of maximum achievable vehicle deceleration, are shown in Table G.13.

Table G.13. Pipeline capacity at 30 m/s for different assumptions about the rigor of braking performance requirement check-in

Distribution of Intelligence	*Pipeline Capacity (veh/ln/hr)*				
	Percentage of vehicle braking distributed permitted by check-in, as measured from the right tail to the left				
	100%	99%	96%	87%	71%
Autonomous individual vehicle	1702	1939	2270	2644	3069
Low-cooperative individual vehicle	1732	1980	2329	2728	3188
High-cooperative individual vehicle	1795	2064	2447	2892	3415
Platoon	8615	9189	9875	10527	11148

As the strictness of the minimum braking-rate check-in policy increases (i.e., from allowing all vehicles within the distribution entry to a policy of disallowing vehicles within the left tail of the distribution from entering the AHS lanes), the pipeline capacity increases. The magnitude of the increase varies between 45 and 47 percent for the independent vehicle cases, while the increase for the platoon case is 23 percent. The reason for the difference in magnitudes of increase between the independent vehicle and platoon cases is that as the difference in vehicle braking rates increases, both the intra-

and inter-vehicle and inter-platoon uniform spacing distances increase (to satisfy the constraint that there will be no collisions between platoons), but the intra-platoon distance remains fixed.

Figures G.32 and G.33 provide a different view of the same results. Instead of braking-rate coverage, the abscissa is expressed as minimum acceptable check-in vehicle braking capability. These plots shows how sensitive the capacity is to the minimum braking capability, reinforcing the importance of the check-in function.
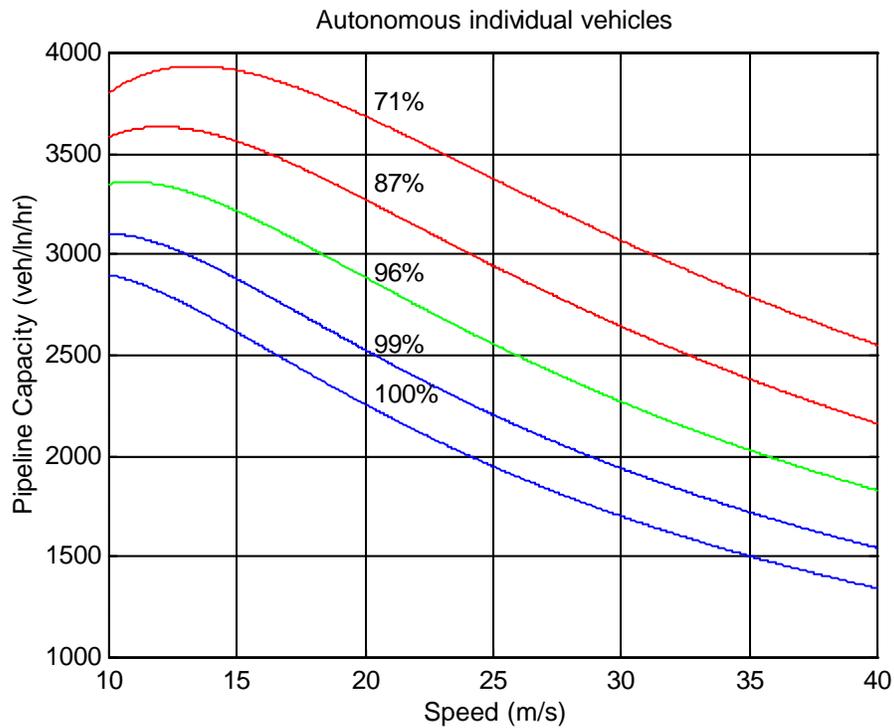

Figure G.28. Pipeline capacity versus braking rate for autonomous individual vehicle operation
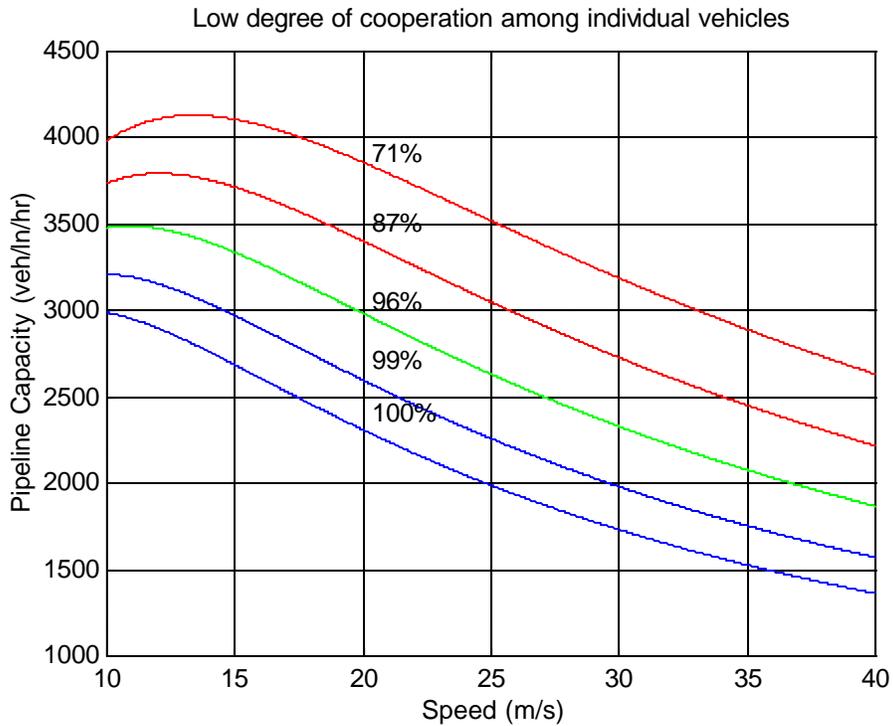
Figure G.29. Pipeline capacity versus braking rate for low cooperation among individual vehicles
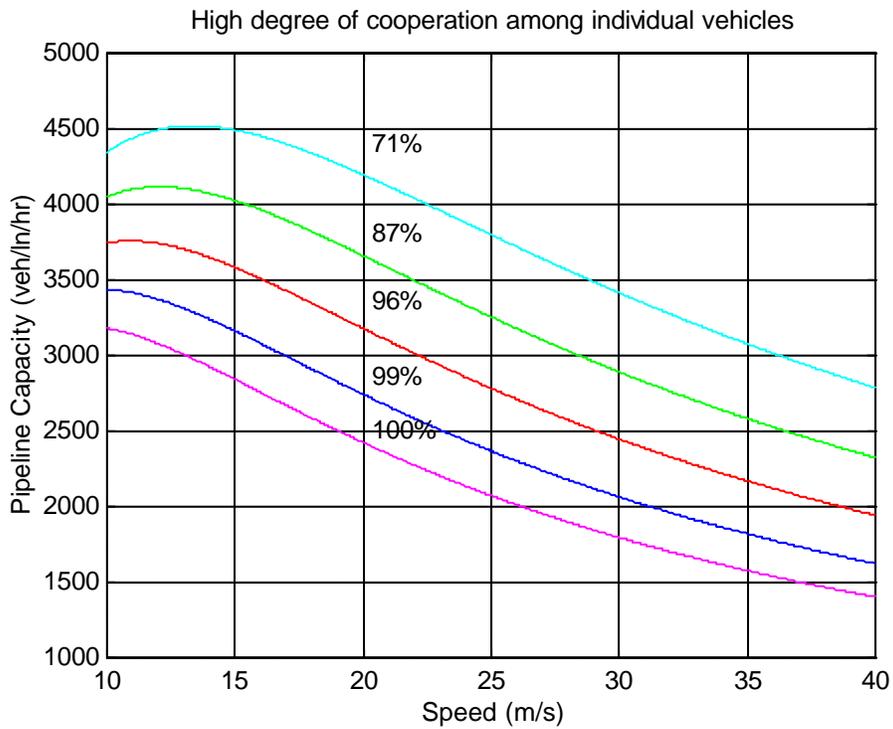

Figure G.30. Pipeline capacity versus braking rate for high cooperation among individual vehicles
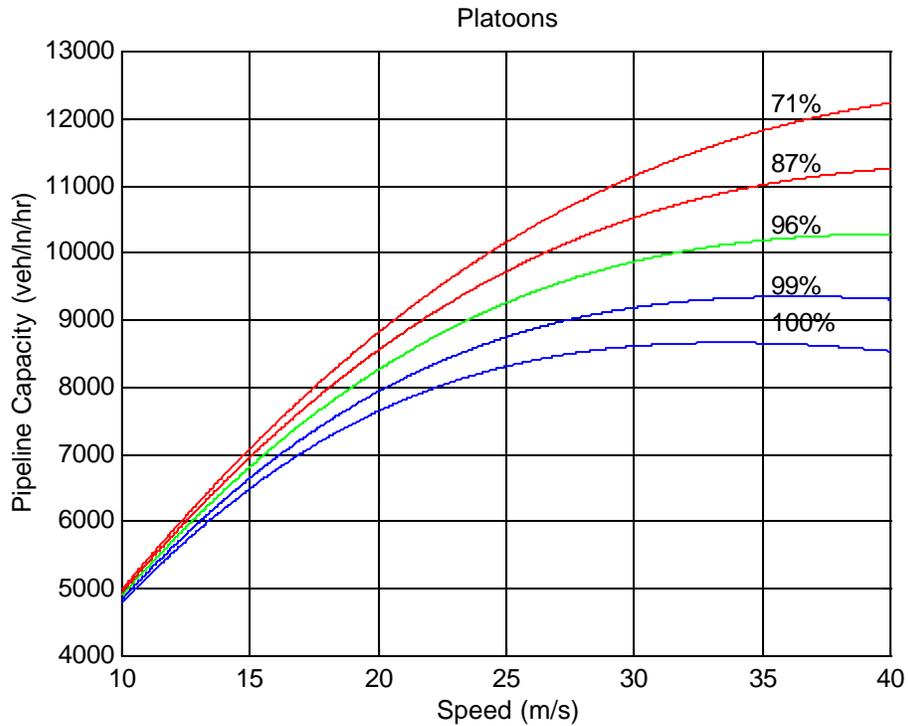
Figure G.31. Pipeline capacity versus braking rate for platoons
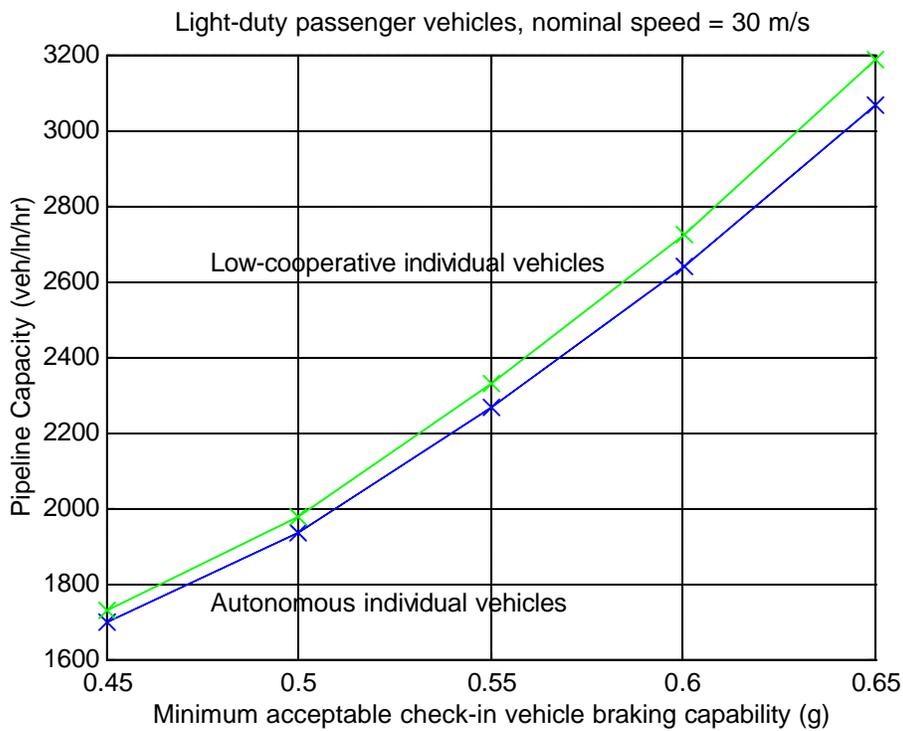

Figure G.32. Pipeline capacity versus minimum acceptable check-in vehicle braking capability: autonomous and low-cooperative individual vehicle operation
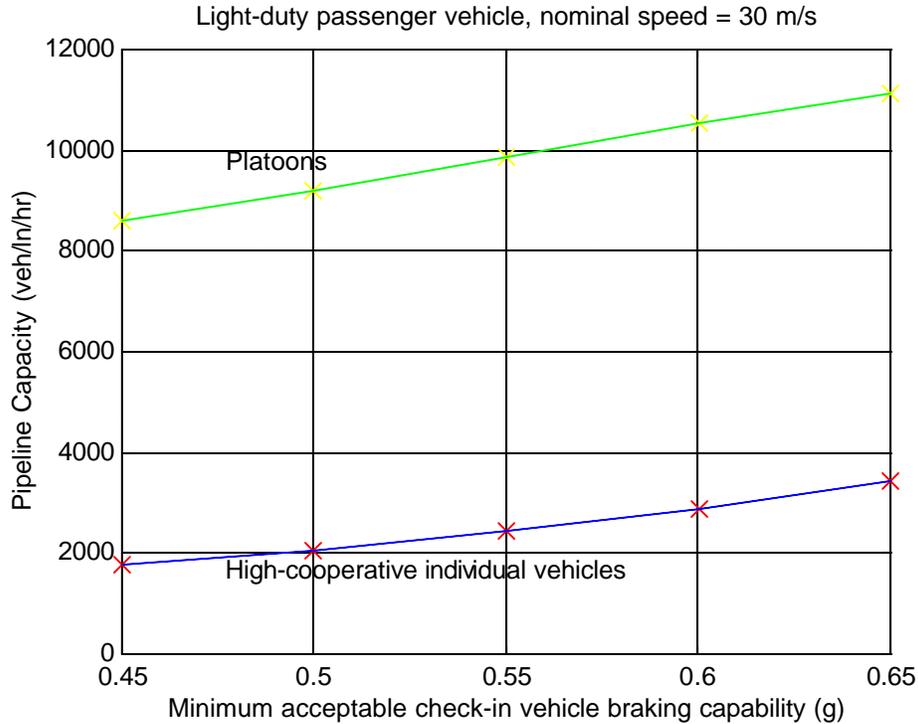
Figure G.33. Pipeline capacity versus minimum acceptable check-in vehicle braking
capability: high-cooperative individual vehicle operation and platoons

G.6.7 Comparison of Fixed and Variable Vehicle-Space Utilization

The test for Hypothesis 6 is performed by comparing the pipeline capacities resulting
from uniform and non-uniform spacing policies, that is, adjusting vehicle spacing based
on real-time knowledge of vehicle braking capabilities can increase pipeline capacity.
Pipeline capacity versus speed is shown in Figure G.34. The results of the test show that
if individual cooperative vehicles operate under a non-uniform spacing policy, the
resulting pipeline capacity exceeds that afforded under uniform spacing policies
implemented by individual vehicles for vehicle-highway speeds between 12 and 40 m/s.
Moreover, the divergence between the pipeline capacity curves corresponding to uniform
and non-uniform spacing policies initially increases with speed, and then distance
between the curves is approximately constant.

In addition, the difference in pipeline capacity between uniform spacing platoon operation
(4632 vehicles) and operation of cooperative individual vehicles under non-uniform
spacing (3397 vehicles) is approximately twenty-seven percent,

$$percentage\ difference = \frac{4632 - 3397\ veh}{4632\ veh} \approx 27\ percent \qquad \text{(Eq. 9)}$$

whereas the difference between platoon operation and individual vehicles with uniform spacing is much greater than that of the non-uniform case, as shown in Table G.14. Based on this observation, one can conclude that the availability of information about the braking capabilities of the following and preceding vehicle can result in an increase in pipeline capacity over that of individual vehicles operation in which vehicle braking capability information is not exchanged among vehicles; that is, the results provide confirming evidence for Hypothesis 6.
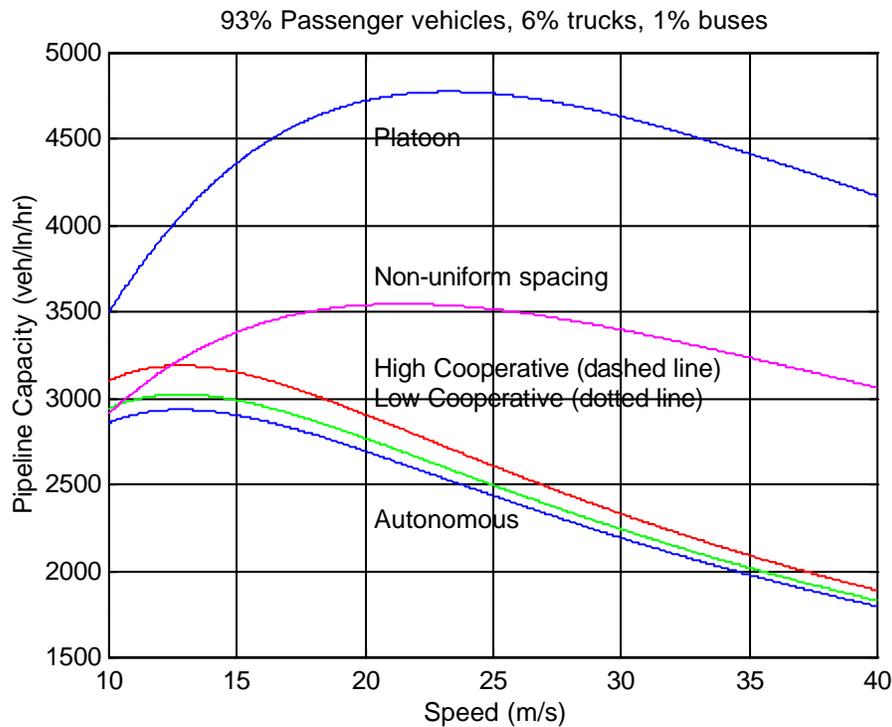
Figure G.34. Comparison of pipeline capacity versus speed for non-uniform and uniform spacing policies

Table G.14. Percentage difference in pipeline capacity at 30 m/s between each level of individual vehicle cooperation and platoon operation

Level of cooperation	Spacing policy	Difference in pipeline capacity from platoon operation (percentage)
Autonomous individual vehicle	uniform	53
Low-cooperative individual vehicle	uniform	52
High-cooperative individual vehicle	uniform	50
Cooperative individual vehicle	non-uniform	27

Combining the effects of non-uniform spacing design with overlapping of brake actuation time and narrowing the range of braking capabilities in the AHS vehicle population

provides some increase in throughput, as shown in Figure G.35. Note that the effects of these three capacity-enhancing assumptions are not additive because the harmonization of braking capabilities means that the non-uniform spacing design offers less of an advantage relative to uniform spacing design. This figure shows that the capacity is very insensitive to the variation between 50 and 150 ms in the total lag, representing the difference between whether or not braking time is overlapped with communication time.

On the other hand, the capacity is very sensitive to the variability in the braking capabilities of the two vehicles, particularly when uniform spacing policies are applied. If the entire braking rate distribution is permitted (0.46 g for follower and 0.98 g for leader), the pipeline capacity at 30 m/s is only 1700 vehicles per hour. When this distribution is truncated from both ends (0.54 g for follower and 0.86 g for leader), that increases to about 2600 and if it is truncated at the low end, by imposing strict check-in requirements that will disqualify more vehicles from entering, (0.65 g for follower and 0.98 g for leader) it increases to about 3200, even with the upper end not truncated. Cooperative non-uniform spacing can permit significantly higher capacities than uniform spacing, but the advantage decreases as the braking distribution is truncated. If the complete braking distribution is permitted, non-uniform spacing permits a 180 percent capacity increase at 30 m/s, but if the narrowest of the three braking distributions is used, this increase is only about 60 percent (but relative to a much larger starting value).
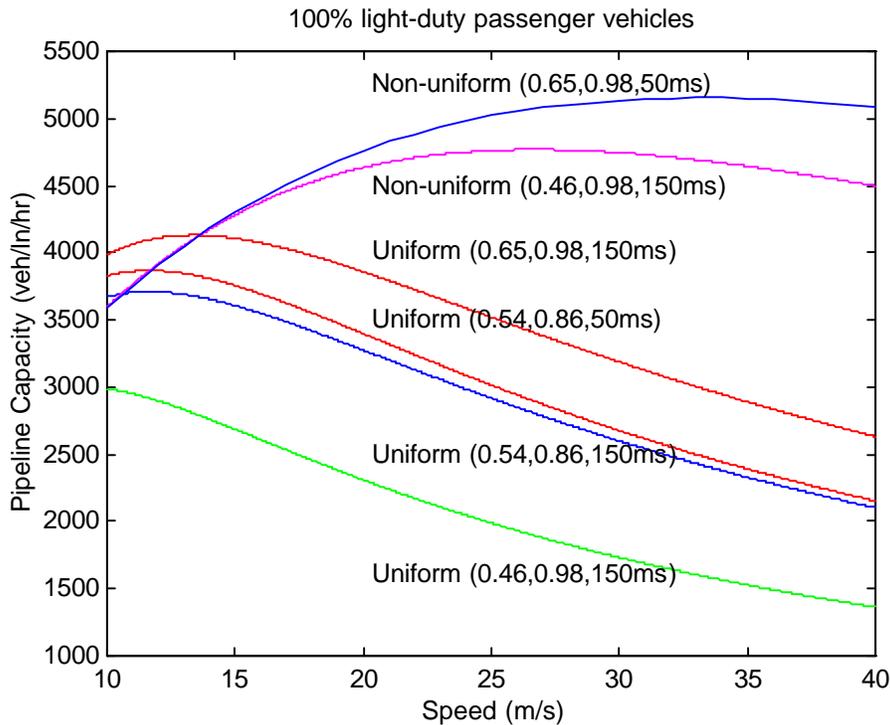

Figure G.35. Comparison of pipeline capacities for non-uniform and uniform spacing policies, given wide and narrow ranges of braking capabilities and lags

G.7 Summary

The results of the analysis provide confirming evidence for the six hypotheses (*viz.* Section 3). For the modeling assumptions and range of parameter values used in this analysis, one can conclude that the following relationships hold:

- AHS pipeline capacity increases as the degree of inter-vehicle cooperation increases.
- As highway speed increases, AHS pipeline capacity increases at a decreasing rate until it peaks and then decreases.
- AHS pipeline capacity decreases at an increasing rate as the heterogeneity of the vehicle class mix increases.
- AHS pipeline capacity increases as platoon length increases.
- AHS pipeline capacity decreases as intra-platoon spacing increases.
- AHS pipeline capacity is very sensitive to the variability of vehicle braking capabilities and to the degree of knowledge that each vehicle has of its own braking capability and that of its immediate predecessor.
- AHS pipeline capacity increases as the minimum vehicle braking capability requirement for entry to the AHS increases.
- Adjusting vehicle spacing based on real-time knowledge of vehicle braking capabilities (i.e., non-uniform spacing design) increases pipeline capacity significantly.
- Combining the effects of non-uniform spacing design with overlapping of brake actuation time and narrowing the range of braking capabilities in the AHS vehicle population provides a potentially significant increase in throughput, but the effects are not additive.

APPENDIX H: Merging Throughput Analysis Methods and Detailed Results

H.1. Introduction

H.1.1 Purpose

The definition of capacity and its calculation for AHS with traffic needing no lane changing or merging, i.e., the pipeline capacity, has been the subject of Section 4.1.3 and Appendix G. Lane-changing and merging will cause disturbance to AHS traffic flow and hence reduce the capacity of an AHS lane from the pipeline capacity to a derated capacity. Since merging can be viewed as location-constrained lane-changing, it imposes more impediment to the longitudinal flow and reduces more traffic flow from the pipeline capacity than lane-changing. In this Appendix, we study the impact of merging on the pipeline capacity for a set of well-defined operating assumptions. Alternate assumptions could be made about some conditions and may lead to a wide range of results.

H.1.2 Scope

We focus on on-ramp merging in this Appendix. In addition, we study only those merging protocols which require all vehicles entering from an on-ramp to stop at the on-ramp for check-in, metering and/or waiting for merging opportunities before their mering into the mainline traffic. Merging at highway-to-highway interchanges where the traffic from one highway to a crossing highway is not first stopped is beyond the scope of the present study. Merging at a location where two mainline AHS lanes merge into one as well as merging of entering traffic with the AHS mainline traffic at the end of the transition lane are also beyond the scope of the present study.

We consider the merging process from an on-ramp into an AHS with one single mainline lane. This is an important configuration because it is likely that initial AHS deployment, in most locations, would involve only one lane dedicated to AHS. Note that the derating of AHS capacity from its pipeline capacity in such a single-mainline-lane configuration is likely higher than for its multiple-lane counterparts because, with multiple lanes, the traffic on the mainline lane receiving the entering traffic may be diverted onto the other lanes before the merge point so as to minimize the disturbance to the mainline traffic and maximize the total throughput.

Since derating of the mainline pipeline capacity depends on the on-ramp flow, there is no single measure of derating due to merging. In other words, derating is a function of the on-ramp flow. However, it has been our observation that, in many cases, the sum of on-ramp flow and the resulting derated mainline capacity, i.e., the maximum combined flow after the merge area corresponding to the on-ramp flow, is not very sensitive to the on-ramp flow. Therefore, for ease of conveying the effect of merging on the pipeline capacity, we will use the term "the derated capacity" to mean the "approximately common" maximum combined flow. This analysis does not address the possible interaction between the merging process occurring at an on-ramp and the diverging process occurring at a near-by off-ramp. It also does not address the

possible effects of the interaction between the merging processes at two consecutive on-ramps, e.g., the effects of different spacings between two consecutive on-ramps.

H.1.3 Concept-distinguishing Attributes

Both the pipeline and the derated capacity depend on the vehicle-following rule. The reduction from the pipeline capacity due to merging, i.e., the derated capacity, also depends on the merging discipline. In this Appendix, we study three basic vehicle-following approaches: autonomous individual vehicle, cooperative individual vehicle and cooperative platooning. The autonomous vehicles are not equipped with any capability of electronic communication, although they may still be able to co-operate with one another through means other than electronic communication. The cooperative individual vehicles and platoons use electronic vehicle-to-vehicle communication and hence support real-time cooperation among vehicles.

The merging disciplines considered are as follows. None of the disciplines call for any conditioning of the mainline traffic (e.g., gap management) except that all the disciplines for the autonomous individual vehicle call for the closing of useless (small) gaps to save space for merging maneuvers.

<u>Merging Disciplines for Autonomous Individual Vehicles</u>

Several different disciplines are considered. They include:

(i) Non-cooperative with Conventional Metering
- no mainline slowdown (100% mainline right-of-way),
- conventional metering at on-ramp (to smooth out burstiness of the arrival stream of vehicles),
- on-ramp vehicle (after release by metering and after reaching the merge point) traveling on an extended merge lane that is parallel to the mainline lane,
- entering vehicle waiting (while traveling at a constant speed on the merge lane) for a sufficiently large gap between two mainline vehicles; entering vehicle merging into mainline traffic by changing lanes into the gap on the mainline lane,
- a positive and constant speed differential between the mainline lane and the parallel merge lane, with the mainline traffic being faster

(ii) Non-cooperative with Microscopic Metering:
- same as (i) except that microscopic metering is supported, where the infrastructure monitors the position of gaps and vehicles and releases on-ramp vehicles accordingly so as to align the entering vehicle with a gap at the merge point,
- microscopic metering is subject to monitoring inaccuracy; due to inaccuracy, the entering vehicle and the intended gap may not be exactly aligned when the entering vehicle reaches the merge point; in such a case, the entering vehicle uses its sensors to identify the location of the gap and adjusts its speed to reach the gap

(iii) Cooperation by Yielding:

- same as (i) except that a mainline vehicle is required to slow down to accommodate an entering vehicle if the size of the gap between the mainline vehicle and its immediate predecessor is larger than a specified threshold and if the entering vehicle is next to the gap. This threshold will be referred to as the yielding threshold.

Merging Disciplines for Cooperative Individual Vehicles

We consider the merging discipline of "release to gap".

(i) Release-to-gap:

- made possible by cooperation among vehicles at or near the merge point through electronic vehicle-to-vehicle communication. When the entering vehicle reaches the merge point, the intended gap also reaches the merge point so that the entering vehicle and the gap are properly aligned at the merge point.

Merging Disciplines for Cooperative Platooning

We consider three different disciplines:

(i) release-to-gap (as defined earlier),

(ii) preplatooning, i.e., on-ramp vehicles forming into platoons before entry, and
(iii) "release to tag", i.e., releasing a vehicle or a platoon so that when it reaches the merge point, it is at the tail end of a platoon on the mainline. The entering vehicle or platoon tags along behind the mainline vehicle or platoon upon reaching the merge point (and the tail end of the mainline platoon).

H.1.4 Performance metrics

The following measures of effectiveness have been chosen for this study:

(MOE1) total throughput downstream of merge point, i.e., the combined flow from mainline upstream and from on-ramp

(MOE2) length of the parallel merge lane required for (virtually) all vehicles merging (at least 95 percentile) into the mainline

(MOE3) wait time or queue length at on-ramp, and

(MOE4) disturbance to mainline traffic, particularly the number of vehicles slowing down for a merging maneuver and the reduction of mainline speed.

H.1.5 Two different approaches: (special-purpose simulation and analytical

models)

We developed probabilistic simulation and analytical models for the study. A simulator has been developed to study the effect of merging on the pipeline throughput for the following vehicle-following/merging-discipline combinations: autonomous-individual-vehicles/ non-cooperative-with-conventional-metering, cooperative-individual-vehicles/release-to-gap and cooperative-platooning/all-disciplines. Simulation results obtained for the combination of cooperative-individual-vehicles/release-to-gap will be used as an input to the analysis of the combination of autonomous-individual-vehicles/non-cooperative-with-microscopic-metering. Unlike the previous combinations, autonomous-individual-vehicle/cooperation-by-yielding will be studied using an analytical model.

H.2 Simulation

A simulation model was developed to evaluate the capacity and delay at automated/dedicated entrances under a range of conditions. The model is intended for comparison of alternative automation concepts, including communication of vehicle and gap positions between vehicles, organization of traffic into platoons, and ramp metering rules. The model provides statistics on queuing time, queue lengths, and distance traveled during merge, all as a function of vehicle arrival rates. By varying the arrival rates on the mainline and ramp, the model can be used to determine the merging capacity of the highway. Unlike more detailed simulators, such as SmartPath, the model allows concepts to be evaluated without coding the specifics of the vehicle control rules and communication.

H.2.1 Overview of Models

The basic model assumes that it is undesirable to disrupt the flow of mainline traffic and that such traffic moves at constant velocity during the merge process. However, the model does allow mainline traffic to be organized into platoons of varying lengths, which can be used to improve the efficiency of merging. Ramp traffic is allowed to enter the mainline when gaps of sufficient length appear. The frequency at which these gaps appear and their size, along with the rate at which vehicles arrive on the ramp, dictate the extent of queuing on the ramp and the performance of the system.

As illustrated in Figure H-2.1, the model has four basic elements:
1) arrival generator for mainline
2) arrival generator for ramp
3) ramp meter for releasing vehicles from ramp
4) ramp/mainline merge

The model is fundamentally a single server queuing system, with the merge point acting as the server (or, with metering, two servers in series) as is the case for normal freeway ramp metering, metering of the arriving vehicles reduces bunching at the merge point and reduces the overall impact on the mainline traffic. However, service times and interarrival intervals are both correlated and behave according to non-standard distributions, making the system difficult to model analytically.

The model is designed to represent two physical configurations, as shown in Figures H-2.2 and H-2.3. In Figure H-2.2, traffic is released precisely to coincide with the arrival of gaps on the mainline (called "release to gap"). Traffic only waits in a single merge queue, as it is unnecessary to further meter entry. This case requires communicating precise gap locations to vehicles on the ramp prior to their release. In Figure H-2.3, gaps are not communicated to ramp vehicles. Instead, they are released from the ramp meter at a regulated rate and then, upon arrival at the mainline, sense the location of nearby vehicles. If a gap is immediately adjacent on the mainline, then the vehicle immediately moves into position. Otherwise, the ramp vehicle travels along the entrance lane until it
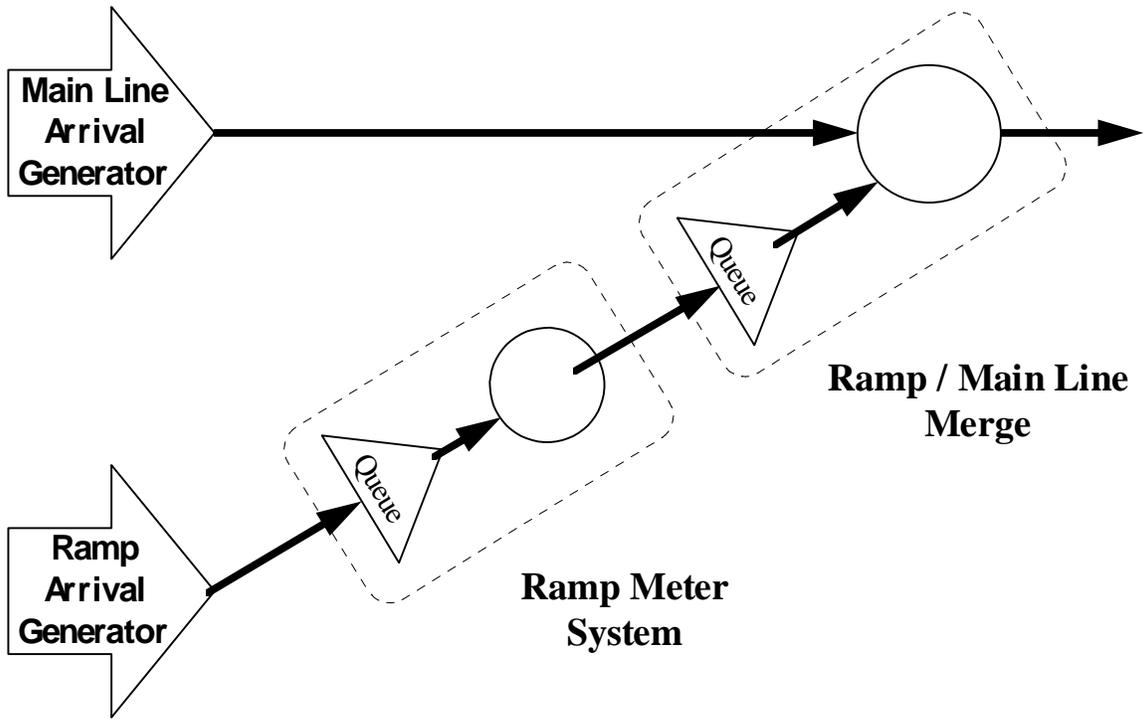
Figure H-2.1. Model Elements.
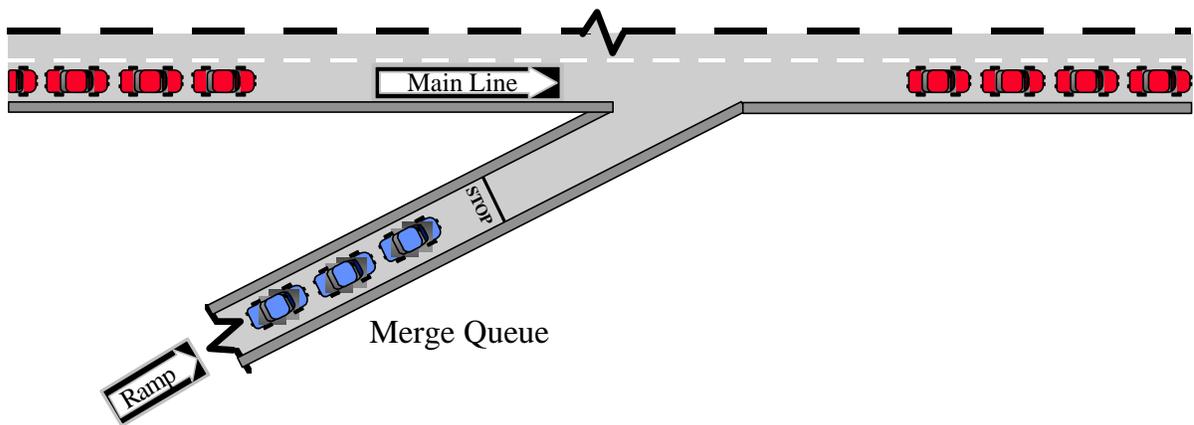
Figure H-2.2. Release to Gaps.
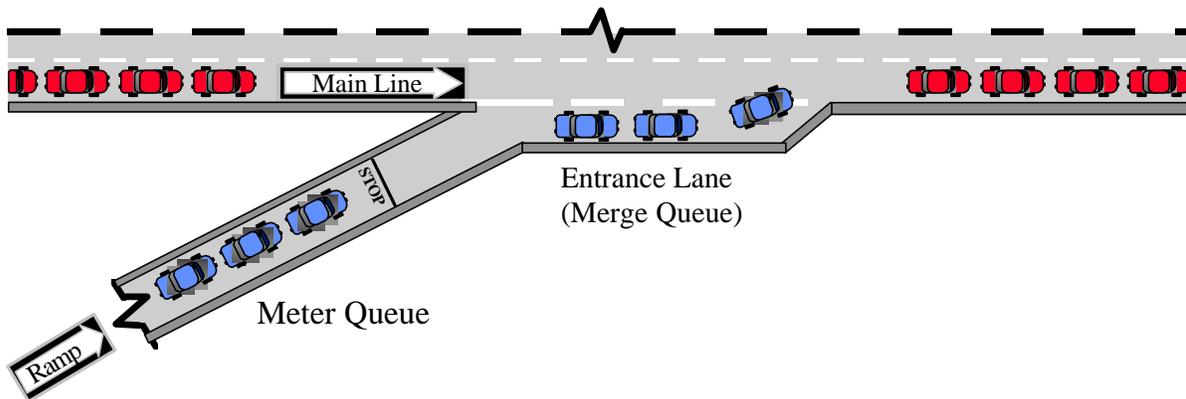
Figure H-2.3. Sensed Gaps (with Metering).

locates a gap and then moves over. In this case, the ramp vehicle is assumed to travel at a lower velocity than the mainline. With this lower velocity, the vehicle "waits" for a gap while in motion along the entrance lane.

H.2.2 Assumptions and Features

The individual model elements are described below:

Mainline Arrival Generator

Arrival times for mainline vehicles are generated by a stationary Poisson process with rate λ_m, reflecting arrivals from upstream. Upon arrival, a length (measured in time) is randomly generated for each vehicle according to a shifted gamma distribution: mean μ_l, standard deviation σ_l and shift parameter m_l . This process yields a data stream of arrival times for vehicle front ends and back ends, which are represented by (x_1, y_1), (x_2, y_2), ...

The arrival data must be modified to reflect the vehicle-following rules for the AHS concept (e.g., platooned or not), and to ensure that vehicles do not overlap (the Poisson process does not ensure that $y_i < x_{i+1}$ for all i.). The following four parameters depend on the AHS concept (Figure H-2.4):

s_1	=	intra-platoon spacing (end to front, in time)
s_2	=	minimum inter-platoon spacing (end to front, in time)
M	=	maximum platoon size
d	=	"sensing distance" (time)
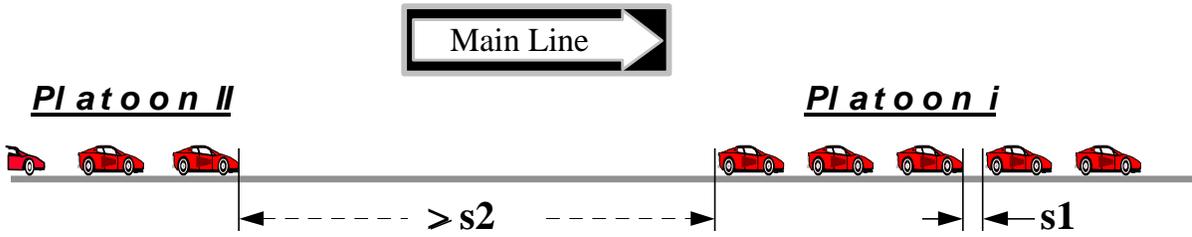
Figure H-2.4. Platoon Spacing Parameters.
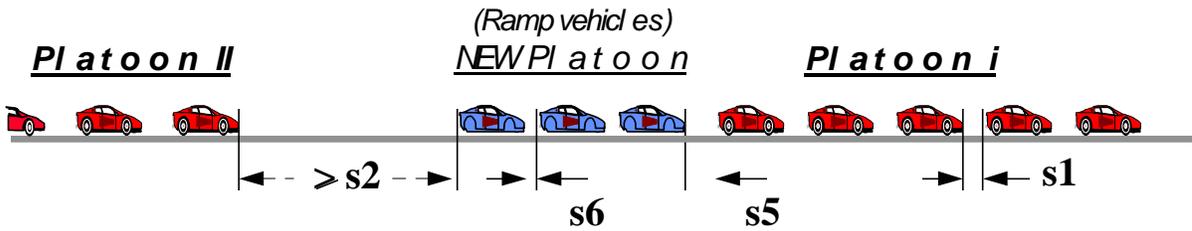
Figure H-2.5. Merge Parameters.

Note that the spacings are all measured in time. Because the model assumes that vehicles on the mainline move at constant velocity, distance spacing can be converted to time spacing by dividing by velocity.

Let:

p_i =   the position of vehicle i within its platoon (number between 1 and M)

Then vehicles are processed in order of arrival, making the following modifications:

If $p_{i-1} < M$ and $x_i \leq y_{i-1} + d$:

$$x_i = y_{i-1} + s_1 \tag{2.1a}$$

<u>If $p_{i-1} = M$ and $x_i < y_{i-1} + d$:</u>

$$x_i = y_{i-1} + s_2 \qquad\qquad\qquad (2.1b)$$

Otherwise, no adjustment is made. In the model, the sensing distance (d) is the maximum distance from where a vehicle can be "attracted" to the platoon in front of it. The parameter d affects the platoon size distribution, with larger d resulting in larger platoons. In non-platooned concepts, s_1 is set to the minimum inter-vehicle spacing and M is set to infinity (s_2 can be set to any value). In addition, if the system is purely non-platooned, then d should also be set equal to the minimum inter-vehicle spacing, meaning that vehicles will not be attracted to their leaders to form vehicle strings (acting as a virtual platoon). Hence, the model can be used to compare platooned to non-platooned concepts, and also to compare alternative high-level control rules for either.

Ramp Arrival Generator

Ramp arrival times are also generated as a stationary Poisson process, and ramp vehicle lengths are generated by a shifted Gamma distribution (identically distributed to mainline vehicle lengths), yielding the data set (x'_1, y'_1), (x'_2, y'_2), ... Vehicle positions are adjusted to ensure that they are separated by a minimum distance. Let:

$s_3 \qquad = \qquad$ minimum vehicle separation (back to front, in time)

Then ramp vehicles are processed in order of arrival to yield $x'_i = \max\{x_i, y'_{i-1} + s_3\}$.

Ramp Meter

The ramp metering feature is used to regulate traffic entering the highway from the ramp. It is only used in some concepts. The feature is bypassed if the concept releases vehicles to gaps (Figure H-2.1). Otherwise, metering is an option.

The ramp meter ensures that vehicle spacing equals or exceeds the minimum value:

$s_4 \qquad = \qquad$ minimum spacing between ramp vehicles (front to front, time).

The ramp meter acts as a single server, first-come-first-served (FCFS), queue with constant service time. Vehicles are processed in order of arrival, and if $x'_i < x'_{i-1} + s_4$, then x'_i is adjusted to equal $x'_{i-1} + s_4$. The adjustment represents the time in queue. The time in queue and the queue length at the ramp meter are calculated as performance statistics.

Ramp/Mainline Merge

Merging is the most complicated element of the simulator. It inspects the stream of traffic on the mainline to identify gaps that are suitably long to accept ramp vehicles (referred to as an "open gap" hereafter). A vehicle is released into an open gap if a vehicle is present in the "merge queue." Otherwise, the open gap passes the ramp unoccupied. The merge queue forms as vehicles arrive and wait to be served by an open gap. Vehicles are processed FCFS. The capacity of the merge depends on the ability to fill open gaps with ramp vehicles in the presence of stochastic variations in vehicle arrivals.

The simulator allows for two types of "open gaps":

1) open gaps at the end of a platoon that has not reached its maximum length
2) open gaps allowing the formation of a new platoon.

An open gap is defined by the parameters s_2 and M (already introduced) along with the following new parameters (Figure H-2.5):

s_5 = minimum spacing between mainline vehicle and entering ramp vehicle
(back to front, time)
s_6 = minimum spacing between adjacent entering ramp vehicles (back to front, time)

Let y_i represent the end of the last vehicle in a mainline platoon. A type 1 gap is present at the end of the platoon if the following conditions are satisfied:

$$p_i < M \qquad\qquad (2.2a)$$
$$x_{i+1} - y_i > s_5 + s_2 + l, \qquad\qquad (2.2b)$$

where:

l = length of vehicle at front of the ramp queue.

If both Eq. (2.2a) and (2.2b) are satisfied, and there is a vehicle in the merge queue, then the vehicle is released into the open gap. If one or more vehicles remain in the queue, the gap behind the entering vehicle is also inspected to check if the following conditions are satisfied:

$$p_i < M \qquad\qquad (2.3a)$$
$$x_{i+1} - y_i > s_6 + s_2 + l, \qquad\qquad (2.3b)$$

where the index i is now defined to represent the position of the newly entered vehicle and the index i+1 is defined to represent the vehicle at the front of the next mainline platoon. The substantive difference between Eqs. (2.2) and Eqs. (2.3) is that s_6

substitutes for s_5, allowing a different spacing requirement between entering ramp vehicles than between the ramp and mainline vehicles.

Eq. (2.3) is calculated iteratively until one of the following occurs: (1) there is no more space to add vehicles (Eq. (2.3b) no longer satisfied), (2) the platoon reaches its maximum number of vehicles (Eq. (2.3a) no longer satisfied), or (3) the ramp queue is exhausted.

If case 1 holds, there must also be insufficient space to form a new platoon in the gap, so the simulator finishes processing the gap and proceeds to the gap following the next platoon on the mainline. If case 2 holds, the gap must then be re-inspected to determine whether there is sufficient space to form a new platoon:

$$x_{i+1} - y_i > 2s_2 + l \tag{2.4}$$

If Eq. (2.4) is satisfied, the vehicle at the front of the ramp queue is released at time $y_i + s_2$. The trailing mainline gap is then inspected according to Eq. (2.4) to determine whether there is sufficient space to release additional ramp vehicles into the new platoon (iteratively, as above).

In case 3, the program waits until the next ramp arrival or until the arrival of the next platoon on the mainline (whichever comes first). In the former case, the remaining mainline gap is examined to determine whether sufficient space remains to form a new platoon, in which case the vehicle is released immediately. The program then proceeds to examine trailing vehicles and gaps to see whether additional vehicles can be released. In the latter case (platoon arrives before ramp vehicle), the program proceeds with processing the next mainline gap, following the steps above.

The merge element provides performance statistics on the merge queue, representing waiting time from vehicle arrival until entering the mainline as well as number of vehicles in the queue. The performance statistics directly represent concepts that release vehicles to gaps. The performance statistics can be modified to represent concepts that do not provide communication, as discussed in the following section.

Concepts That Do Not Release to Gaps

In some concepts, ramp vehicles are unable to detect the location of suitable gaps until they are close to or adjacent to the mainline. As a consequence, vehicles cannot be released from the ramp to precisely coincide with gaps. Instead, vehicles travel along the ramp until they are within their "sensing distance" of the mainline, and then travel adjacent to the mainline until a suitable gap is located. In such a system, ramp vehicles do not queue in the conventional sense, but instead queue while in motion, traveling along an entrance lane adjacent to the mainline (Figure H-2.3). The entrance lane must be sufficiently long to allow the great majority of vehicles to enter the mainline, under peak traffic conditions.

With some simplifying assumptions, the simulated merge queue time can be converted to an entrance travel distance, which can in turn be used to set requirements for the length of the entrance lane. We assume that both mainline and ramp vehicles travel at constant, but non-identical, velocities:

v_m =   velocity of mainline vehicles
v_r =   velocity of ramp vehicles ($v_m > v_r$)
Δ = $v_m - v_r$

Then the time in the merge queue for any vehicle, t_i, can be converted into a ramp travel distance as follows:

d_r =   distance traveled on ramp to merge
        = $(t_i v_m v_r)/\Delta$ (2.5)

The equation is based on calculating the distance separation between the ramp vehicle and the gap ($t_i v_m$), dividing by Δ to determine the time until reaching the gap, and multiplying by v_r to compute the distance traveled until reaching the gap. The equation indicates that d_r declines as v_r declines, suggesting that a large velocity differential reduces the entrance lane requirement. Nevertheless, small v_r also makes it more difficult to execute the lane change and increases spacing requirements due to the need to accelerate vehicles in the course of the lane change.

The entrance lane should be sized so that the vast majority of vehicles can gain entry to the highway. The following section presents a "3-sigma" requirement: entrance lane must equal or exceed the $E(d_r)$ plus three standard deviations. More or less stringent requirements can be set by changing the number of standard deviations, or setting the requirement based on a percentile of the d_r probability distribution. Absolute guarantees regarding the tails of the distributions cannot be provided, particularly because the distributions are already approximations to a messier reality.

It should be noted that $E(t_i)+3\sigma$ must be quite small to attain a reasonable design requirement. With $v_m = 30$ m/s (108 km/hr) the following requirements result for two different ramp velocities:

$v_m = 30$ m/s (108 km/hr) and $v_r = 27$ m/s (97.2 km/hr)

$E(t_i)+3\sigma$	.5 s	1.0 s	2.0 s	5.0 s	10 s
Entrance Lane Length	135 m	270 m	540 m	1350 m	2700m

$v_m = 30$ m/s (108 km/hr) and $v_r = 24$ m/s (86.4 km/hr)

$E(t_i)+3\sigma$	.5 s	1.0 s	2.0 s	5.0 s	10 s
Entrance Lane Length	60 m	120 m	240 m	600 m	1200m

Note that these values are for light-duty passenger vehicles only, not heavy vehicles.

Based on these results, a 3-sigma waiting time in excess of 5 s could lead to an unacceptable entrance lane requirement, which implies that *mean* waits as small as 1 to 2 seconds could be problematic. It should be noted that the standard deviation is sensitive to the queue discipline. Assuming that entering vehicles travel at a slower velocity than mainline vehicles, then queued vehicles would encounter gaps in a last-come-first-served sequence (i.e., gaps approach queued vehicles from the rear). This adds considerably to the variation in waiting time, consequently demanding even longer entrance lanes. On the other hand, in some concepts, the sensing might begin some distance before the ramp vehicle reaches the mainline. In such a case, the ramp requirement can be reduced by this distance.

A fundamental difference between communication and sensing based systems is that the former allows vehicles to queue at rest on the ramp, whereas the latter creates a queue in motion. The consequence is that sensing based systems require more lane length to accommodate vehicles waiting for entrance. This requirement can be moderated by utilizing ramp metering, with the result of somewhat longer total time in queue (counting both the meter and merge queues).

Alternative Simulator

If the autonomous concept allows for some cooperation, then it is possible to reduce the entrance lane requirement. This might be achieved by requiring mainline vehicles to slow to provide sufficient gaps for entering vehicles. This concept was simulated as an alternating service queuing system. Mainline and ramp vehicles enter separate queues, which are served on an alternating basis with deterministic service time (defined by the minimum spacing). In the event that one queue is empty, the other queue would be served continuously until the next arrival in the empty queue. The performance of the system was measured by the mean time in queue for each queue (mainline and ramp). Required entrance lane length was not calculated. This would require a more detailed simulator. Furthermore, no attempt was made to verify that mainline queues would not present safety or operational problems for mainline traffic.

H.2.4 Experimental Design and Parameter Values

A series of experiments was completed to compare the performance of the system for differing automation concepts. These concepts were defined by concept developers within NAHSC. Except where indicated, spacing values were generated by PATH through use of the safety evaluation tools. Concepts were defined in the following ways:

I. Infrastructure Supported or Assisted with Platoons

Modeled as "release to gap"

Maximum platoon size = 10
Intraplatoon Spacing = 2m
Velocity =   20 m/s: Interplatoon Spacing = 29 m; Attraction Distance = 50 m
               30 m/s: Interplatoon Spacing = 61 m; Attraction Distance = 80 m
               40 m/s: Interplatoon Spacing = 104 m; Attraction Distance = 120 m

    Ia: Platooned Entry:
        Vehicles enter the highway as platoons, with identical spacings to
        vehicles already on the highway

    Ib: Free-agent Entry
        Spacing of vehicles entering the highway cannot be less than the
        inter-platoon spacing.

    Ic: Modified Platooned Entry
        Vehicles enter the highway as platoons; however, spacing for first vehicle
        in a platoon cannot be less than the inter-platoon spacing.

II. Cooperative Vehicles

Modeled as "release to gap"

Interplatoon Spacing = Interplatoon Spacing (see spacing values below)
    Case 1 (conservative spacings, based on safety considerations)
    Velocity = 20 m/s: Spacing = 18 m; Attraction Distance = 50 m
    Velocity = 30 m/s: Spacing = 38 m; Attraction Distance = 50 m
    Velocity = 40 m/s: Spacing = 65 m; Attraction Distance = 80 m

    Case 2 (optimistic spacings)
    Velocity = 20 m/s: Spacing = 5 m; Attraction Distance = 50 m
    Velocity = 30 m/s: Spacing = 9 m; Attraction Distance = 50 m
    Velocity = 40 m/s: Spacing = 13 m; Attraction Distance = 50 m

III. Autonomous Vehicles

Modeled in two ways:
    a) Metered entry, with LCFS queue at entrance (rate = 1.05 x ramp arrival rate)
    b) Queue on mainline and ramp, with alternating service

Attraction Distance = 50 m
Interplatoon Spacing = Interplatoon Spacing =
   Case 1 (conservative spacings, based on safety considerations)
   Mainline Velocity = 20 m/s: Spacing =20 m; Ramp Velocity = 18 m/s
   Mainline Velocity = 30 m/s: Spacing = 41 m; Ramp Velocity = 27 m/s

   Case 2 (optimistic spacings)
   Velocity = 30 m/s: Spacing = 15 m; Ramp Velocity = 27 m/s

The experiments had the following common characteristics:

Minimum Vehicle Length: 4.0 m
Average Vehicle Length: 5.0 m
S.D. Vehicle Length: .5 m
Minimum Spacing on Ramp (s_3) .25 s

The primary performance measure for concepts I and II was average time in queue for entering vehicles (by assumption, mainline vehicles do not queue). The primary performance measure of concept IIIa was required entrance lane length. The primary performance measures for concept IIIb were average queue time on mainline and average queue time on entry.

In all of the experiments, the capacity of the highway is maximized when the entry ramp has zero flow. In this condition, the flow is bounded by:

$$\text{Capacity} \leq M/(Ms_1 + s_2) \tag{2.6}$$

Substituting the prior parameter values yields the following *nominal* pipeline capacities:

   Concept I: Capacity $\leq$ 7423 vehicles/hour (20 m/s)
                    Capacity $\leq$ 8372 vehicles/hour (30 m/s)
                    Capacity $\leq$ 8521 vehicles/hour (40 m/s)

   Concept II: Capacity $\leq$ 3130 vehicles/hour (20 m/s)
   (Safety   Capacity $\leq$ 2512 vehicles/hour (30 m/s)
   SPACINGS)   Capacity $\leq$ 2057 vehicles/hour (40 m/s)

   Concept II: Capacity $\leq$ 7200 vehicles/hour (20 m/s)
   (Optimistic   Capacity $\leq$ 7714 vehicles/hour (30 m/s)
   SPACINGS)   Capacity $\leq$ 8000 vehicles/hour (40 m/s)

   Concept III: Capacity $\leq$ 2880 vehicles/hour (20 m/s)
   (Safety   Capacity $\leq$ 2348 vehicles/hour (30 m/s)
   SPACINGS)   Capacity $\leq$ 1946 vehicles/hour (40 m/s)

Concept III: Capacity $\leq$ 5400 vehicles/hour (30 m/s)
(Optimistic
SPACINGS)

Any vehicle flow on the ramps decreases the nominal pipeline capacity in two ways: (1) because of the larger space requirement for vehicles during merging, (2) due to the stochastic element of vehicle arrivals on the ramp. Simulation experiments were completed for various combinations of ramp and mainline arrival rates to measure delays and estimate capacity. Each run covered one hour of operation, and each experiment covered 10 runs. A standard error was computed from the standard deviation among the 10 runs. This was converted to a 95% confidence interval using the t distribution. Simulation results are only provided for combinations of ramp and mainline arrival rates that are in the vicinity of capacity (many more runs were completed than shown).

H.2.5 Numerical Results

The capacity for each case is not defined crisply, but is rather an estimate based on the severity of the delays (or ramp lengths) derived from the analyses. Delays of the order of tens of seconds were considered tolerable, but hundreds of seconds were not. Table H-2.1a provides results for platooned with platooned merge. The sustainable capacity with the indicated attraction distances appears to be close to 7000 vehicles per hour (ramp and mainline arrival rates combined), roughly 80% of the nominal capacity. Capacity is somewhat less for 20 m/s, but still approximately 80% of the nominal capacity.

Table H-2.1b shows the effect of attraction distance on delay for a combined arrival rate of 6000 vehicles/hour. When the attraction distance is below the inter-platoon spacing, the system performs poorly. However, once it exceeds the inter-platoon spacing, the attraction distance seems to have little effect on delay. This result has not yet been verified for higher flow values, and it may be that increasing the attraction distance is more beneficial when approaching capacity.

Table H-2.2 evaluates platooned with free-agent merge. Capacity here is much less than platooned merge, due to much longer spacing required of entering vehicles. Here, higher velocities perform worse than lower velocities. This is because, with interplatoon spacing on entry, each entering vehicle requires more time on entry at higher velocities (e.g., 2.72 s at 40 m/s but just 1.7 s at 20 m/s).

Table H-2.3 evaluates platooned with modified platooned entry. Capacity is somewhat greater than concept Ib, but not nearly as large as platooned merge. At 30 m/s velocity, capacity is somewhat greater than 3000 vehicles/hour.

Table H-2.4 shows delays for cooperative vehicles with safety-determined spacings. Delays increase at larger velocities, as can be expected because nominal capacity decreases at higher velocity. At 30 m/s, capacity is on the order of 2250 vehicles/hour, comparable to conventional highways, and about 90% of nominal capacity. Capacity is

much greater with the optimistic provided spacings (Table H-2.5) -- in the 7000-7500 vehicles/hour range, in excess of 90% of nominal capacity.

Table H-2.6 provides results for autonomous individual vehicles. Here, performance is measured as the required entrance lane length. Under safety-determined spacings, capacity is very small, on the order of 1000 vehicles per hour at 30 m/s if ramps of 1.3 km length are sanctioned. With optimistic spacings, the capacity could be as large as 3000-3500 vehicles per hour (Table H-2.7) if ramps of 1.1 to 1.8 km length are sanctioned. These values place sustainable capacity in the range of 40-60% of nominal capacity. This low value is due to the strict requirement that virtually all vehicles be able to enter within a reasonable distance.

Finally, Table H-2.8 shows results for autonomous with safety-determined spacings and mainline queuing. As expected, the system performs much better than without mainline slowdown. The sustainable capacity is on the order of 2300 vehicles/hour, which is just a few percent below the nominal capacity. The simulation results are consistent with queue times from the Pollackek-Khintchine formula for the M/D/1 queue (Poisson arrivals, deterministic service, single server). Note that the highway being simulated does not have Poisson arrivals, but they are approximately Poisson.

The simulation analysis clearly indicates that some concepts will not provide substantial capacity increases in entry lanes compared to conventional freeways:

• Platooned concept combined with free-agent entry
• Autonomous concept without mainline slowdown
• Either the cooperative or autonomous concept with safety-determined spacings.

Further analysis is needed to study the interaction between entrance and exit processes, possibly allowing for sorting traffic by destination at entrance. Analysis is also needed on mixed vehicle classes and, eventually, more detailed simulation is needed on vehicle dynamics in and around the points of entrance and exit.

Table H-2.1a Platooned with Platoon Merge

Traffic Volume			Intra-p	Inter-p	Attraction	Average	95% Conf
Ramp	Mainline	Velocity	Separation	Separation	Distance	Delay	Interval
3000	3000	20 m/s	2 m	29 m	50 m	25.5 s	+ 46%
3000	4000	20 m/s	2 m	29 m	50 m	1010 s	+ 46%
3000	3000	30 m/s	2 m	61 m	80 m	2.66 s	± 8%
3000	4000	30 m/s	2 m	61 m	80 m	102 s	± 32%
3000	3000	40 m/s	2 m	104 m	120 m	4.6 s	± 10%
3000	4000	40 m/s	2 m	104 m	120 m	119 s	± 28%

Table H-2.1b Platooned with Platooned Merge: Effect of Attraction Distance

| Traffic Volume | | | Intra-p | Inter-p | Attraction | Average | 95% conf |
Ramp	Mainline	Velocity	Separation	Separation	Distance	Delay	Interval
3000	3000	30 m/s	2 m	61 m	50 m	169 s	$\pm$ 26%
3000	3000	30 m/s	2 m	61 m	80 m	2.66 s	$\pm$ 8%
3000	3000	30 m/s	2 m	61 m	110 m	3.82 s	$\pm$ 10%
3000	3000	30 m/s	2 m	61 m	140 m	3.56 s	$\pm$ 7%

Table H-2.2 Platooned with Free Agent Merge

| Traffic Volume | | | Intra-p | Inter-p | Attraction | Average | 95% conf |
Ramp	Mainline	Velocity	Separation	Separation	Distance	Delay	Interval
1000	1000	20 m/s	2 m	29 m	50 m	13.9 s	$\pm$ 23%
1000	1500	20 m/s	2 m	29 m	50 m	137 s	$\pm$ 33%
1000	1000	30 m/s	2 m	61 m	80 m	453 s	----
1000	1000	40 m/s	2m	104 m	120 m	926 s	----

Table H-2.3 Platooned with Modified Platooned Entry

| Traffic Volume | | | Intra-p | Inter-p | Attraction | Average | 95% conf |
Ramp	Mainline	Velocity	Separation	Separation	Distance	Delay	Interval
1000	2000	20 m/s	2 m	29 m	50 m	5.4 s	$\pm$ 8%
1000	3000	20 m/s	2 m	29 m	50 m	22.0 s	$\pm$ 18%
2000	2000	20 m/s	2 m	29 m	50 m	74.2 s	$\pm$ 33%
1000	2000	30 m/s	2 m	61 m	80 m	18.3 s	$\pm$ 13%
1000	3000	30 m/s	2 m	61 m	80 m	433 s	-----
2000	2000	30 m/s	2 m	61 m	80 m	496 s	-----
1000	2000	40 m/s	2 m	104 m	120 m	157 s	$\pm$ 37%
2000	2000	40 m/s	2 m	104 m	120 m	1010 s	-----
1000	3000	40 m/s	2 m	104 m	120 m	1150 s	-----

Table H-2.4 Cooperative: Safety-Determined Spacings

Traffic Volume		Velocity	Separation	Attraction Distance	Average Delay	95% conf Interval
Ramp	Mainline					
1000	1500	20 m/s	18 m	50 m	8.6 s	+ 14%
1000	2000	20 m/s	18 m	50 m	278 s	+ 71%
750	1500	30 m/s	38 m	50 m	99.3 s	± 24%
500	2000	30 m/s	38 m	50 m	738 s	± 39%
750	1500	40 m/s	65 m	80 m	919 s	-----
500	2000	40 m/s	65 m	80 m	1750 s	-----

Table H-2.5 Cooperative: Optimistic Spacings

Traffic Volume		Velocity	Separation	Attraction Distance	Average Delay	95% conf Interval
Ramp	Mainline					
3000	3500	20 m/s	5 m	50 m	8.6 s	± 15%
3000	4500	20 m/s	5 m	50 m	341 s	+ 9%
3000	3500	30 m/s	9 m	50 m	3.9 s	± 8%
3000	4500	30 m/s	9 m	50 m	96.9 s	± 23%
3000	3500	40 m/s	13 m	50 m	3.0 s	± 8%
3000	4500	40 m/s	13 m	50 m	45.4 s	± 36%

Table H-2.6 Autonomous: No Mainline Slowdown, Metered Entry, Safety-Determined Spacings

Traffic Volume		Velocity	Separation	Attraction Distance	Ramp Requirement
Ramp	Mainline				
250	1000	20 m/s	20 m	50 m	1.0 km
500	1000	20 m/s	20 m	50m	1.05 km
1000	1000	20 m/s	20 m	50 m	2.1 km
250	500	30 m/s	41 m	50 m	1.2 km
500	500	30 m/s	41 m	50 m	1.3 km
750	500	30 m/s	41 m	50 m	1.9 km

Table H-2.7 Autonomous: No Mainline Slowdown, Metered Entry, Optimistic Spacings

Traffic Volume				Attraction	Ramp
Ramp	Mainline	Velocity	Separation	Distance	Requirement
1000	1000	30 m/s	15 m	50 m	.36 km
1000	1500	30 m/s	15 m	50m	.63 km
1000	2000	30 m/s	15 m	50 m	1.1 km
1000	2500	30 m/s	15 m	50 m	1.8 km
500	3000	30 m/s	15 m	50 m	2.7 km
1000	3000	30 m/s	15 m	50 m	2.9 km

Table H-2.8 Autonomous: Mainline Slowdown, Safety-Determined Spacings

Traffic Volume				Attraction	Avg Ramp	Avg Main
Ramp	Mainline	Velocity	Separation	Distance	Delay	Delay
1250	1000	30 m/s	41 m	50 m	22.1 s	7.37 s
1150	1150	30 m/s	41 m	50m	21.3 s	30.3 s
750	1500	30 m/s	41 m	50 m	3.2 s	21.5 s

Pollackek Khintchine Formula: M/D/1 queue:
$\rho^2/2(1-\rho)$ = average delay

capacity = 2347.8 veh/hr

Traffic

Volume	ρ	average delay
2250	.9583	11 s
2300	.9796	24 s

Pollackek Khintchine Formula: M/D/1 queue:
$\rho^2/2(1-\rho)$ = average delay

capacity = 2347.8 veh/hr

Traffic

Volume	ρ	average delay
2250	.9583	11 s
2300	.9796	24 s

Note that such non-interaction is a major assumption of the single-entry model and proper metering is imposed to ensure the validity of results obtained with the single-entry model. Therefore, the derated capacity so obtained can be viewed as a lower bound of the derated capacity and the derated capacity could actually be higher. All four of the MOEs listed in Section H.1.4 are involved. We will identify combinations of mainline flow and on-ramp flow that jointly achieve a reasonable level of all four MOEs and will use the least upper bound of the combined flow as the derated capacity.

Given the speed, the safety spacing calculated by the Safety Evaluation Team, and a given flow level on the mainline, a probability distribution for the physical distribution of vehicles and gaps on the mainline is first estimated. Consider the entry of a particular vehicle from the on-ramp. Since the vehicle has no knowledge of the position of the vehicles and gaps on the mainline prior to reaching the merge point, the entering vehicle, upon arrival at the merge point, begins to look for a sufficiently large gap (catching up from behind) on the mainline lane while traveling at a constant speed on the merge lane. Without any cooperation from the mainline vehicles, the entering vehicle must wait for a gap that is longer than the sum of the length of a vehicle, the required safety spacing and a maneuvering space for adjusting the speed of the entering vehicle (to the speed of the faster traffic on the mainline). This severely limits the amount of traffic that can enter the mainline, i.e., throughput of the AHS lane. Note that this represents the case of complete mainline right-of-way. On the other extreme is complete on-ramp right-of-way, which stipulates that a mainline vehicle has to yield to the entering vehicle on the merge lane whenever the entering vehicle is next to the gap immediately in front of the mainline vehicle and is wanting to enter the mainline. This discipline is equivalent to one that calls for creating a gap for each and every the entering vehicle no matter how small the gap is between the adjacent mainline vehicle and its immediate predecessor.

Between these two extremes are many possible intermediate policies. This motivated the following idea of yielding threshold. When a mainline vehicle detects the presence of a vehicle in between itself and its immediate predecessor on the parallel merge lane, if the gap between itself and the immediate predecessor is larger than the yielding threshold, then it should create a gap to accommodate the entering vehicle into the mainline by slowing down and enlarging the gap. Note that safety spacing is considered as part of the space occupied by a vehicle and the gap refers to space that is not occupied by any vehicle. In fact, through the use of the yielding threshold, the two extremes are connected by a continuum of yielding policies. When the threshold is set at 0, then it represents the policy of complete on-ramp right-of-way. When the threshold is set at the sum of the length of a vehicle, the required safety spacing and a maneuvering space for adjusting the speed of the entering vehicle, then this threshold value represents the policy of complete mainline right-of-way. We will use half of this latter sum in this Appendix for easier numerical demonstration of the effectiveness of yielding. For convenience, we will refer to a gap that is larger than or equal to the yielding threshold as a "usable gap".

Associated with a yielding threshold is the length of the merge lane required to

enable all entering vehicles (or virtually all, e.g., 99-th percentile) to merge into the mainline. (Since mainline slowdown is supported, it can be stipulated that mainline vehicles should slow down to allow entry of an entering vehicle that has traveled to or near the end of the parallel merge lane. This way, all vehicles can merge before the end of the merge lane, although some additional traffic disturbance may result from yielding to such entering vehicles.) The larger the threshold, the longer the merge lane. If the threshold is set at 0, then there is no need for any length of merge lane. However, if the threshold is set to its least upper bound, then the ramp length will need to be as long as required for the autonomous/no-mainline-slowdown case. Also associated with a yielding threshold is the number of vehicles (or 95-th percentile) having to slow down to accommodate the merging of an on-ramp vehicle. This will dictate how far two entering vehicles must be separated from each other. This separation will then be used to calculate the maximum volume of on-ramp flow, as a function of mainline flow.

3.2 Assumptions and Features

We first develop a probablistic model for the physical distribution of the vehicles and gaps.

Assumption 3.1: All vehicles have a common length l and each occupies a space of length $b = d + l$, where d is the supplemental safety spacing.

For convenience, we refer to the space occupied by a vehicle as a slot. (Note that the space on an AHS lane is *not* being partitioned into such equi-length slots.) A vehicle can be thought of as being positioned in the middle of the slot so that one half of the safety spacing is "padded" at the front of the vehicle and the other half is padded on the rear. This way, any two longitudinally adjacent vehicle slots would provide a full safety spacing between the two vehicles.

Consider a segment of an AHS lane of length S_L with v vehicles. The gap length is defined to be the actual distance between two longitudinally adjacent vehicle slots. These v vehicles are randomly distributed on the segment. In the absence of evidence favoring any particular pattern of physical distribution, we make the following assumption:

Assumption 3.2: The v vehicles are at random positions on the lane in the following sense. After contracting the space occupied by a vehicle into a point, the segment length becomes $S_L - vb$ and each vehicle is represented as a point on the contracted segment. Vehicle positions are a random sample of size v of a uniform random variable on the interval of $[0, S_L - vb]$.

Based on Assumption 3.2, we can obtain the joint distribution of the $v - 1$ gap lengths. When v approaches infinity while $c \equiv v/S_L$ is kept constant, it can be shown that all the gap lengths are independent and identically distributed with an exponential distribution with a parameter of $c/(1 - cb)$. For details, the reader is referred to " Analytical Models for Vehicle/Gap Distribution on Automated Highway Systems" by Tsao, H.-S.J., Hall, R.W., and Chatterjee, I., (to appear in Transportation Science).

This demonstrates that the point process defined in Assumption 3.2 is a Poisson Process when the segment length tends to infinity and traffic density is kept constant. This can be viewed as the converse of the well-known fact that, given that n events ($n \geq 1$) of a Poisson process have occurred in time interval $[0,t]$, the set of n arrival times has the same joint distribution as a set of n random variables that are independent and uniformly distributed on the interval.

Assumption 3.3: Mainline vehicles travel at a preset constant speed except when slowing down to accommodate merging maneuvers. An entering vehicle travels at another preset constant but lower speed once it has reached the merge point.

Assumption 3.4: When a mainline vehicle detects the presence of a vehicle on the parallel merge lane that is between itself and its immediate predecessor, it enlarges the gap to accommodate the entering vehicle into the mainline if and only if the gap between itself and the immediate predecessor is larger than the yielding threshold δ but smaller than the sum of the vehicle length, the supplemental safety spacing and the maneuvering space.

3.3 Model Description and Derivation of Results

Let us focus on a particular vehicle entering from an on-ramp. The merging process starts at the time when the vehicle has just reached the merge point. Since the speed of the entering vehicle is slower than that of the mainline traffic, the entering vehicle will be caught up with by the vehicles and the gaps that are upstream from the entering vehicle on the mainline until the entering vehicle has merged into the mainline. The physical distribution of vehicles and gaps that are upstream from the merge point at the moment when the entering vehicle has just reached the merge point will determine, together with the merging protocol of course, the merging efficiency. Therefore, let us focus on these vehicles and gaps. We label these gaps, vehicles and vehicle-gap cycles upstream on the mainline with ascending numbers from 1 with the label 1 assigned to the vehicle, gap and vehicle-gap cycle that are the closest to the merge point at the time when the entering vehicle has just reached the merge point. To derive an equilibrium probability distribution for the physical distribution of the vehicles and gaps, we first consider a segment of AHS lane of finite length and then let the segment length go to infinity while keeping the density of traffic constant.

Notation

V_m : the preset constant velocity of mainline traffic, to be followed by all mainline vehicles except when slowing down to accommodate merging maneuvers.

V_o : the preset constant velocity of the entering vehicles having reached the merge point. Note that $V_m > V_o$ strictly.

δ : the yielding threshold.

G : the random length of a gap.

$F(x)$: the cumulative probability distribution function of the gap length G. Its

density is denoted by $f(x)$. Under Assumptions 3.1 and 3.2, the probability density function is given by:

$$f(x) = \mu e^{-\mu x}. \tag{H.3.1}$$

where μ, the parameter of the exponential distribution, is $c/(1 - cb)$ and c is the traffic density, i.e., the number of vehicles on the mainline per unit length.

G_i : the random length of the i-th gap .

G' : the random length of a gap, given that the gap is smaller than the yielding threshold δ.

G'': the random length of a gap, given that the gap is larger than the yielding threshold δ.

S_L : the length of the lane segment under consideration.

S_m : the length of additional space required to enable a merging vehicle to adjust its speed without affecting the speed of mainline traffic. (If one stipulates that the speed adjustment can take place only on the merge lane, then S_m can be set to 0. The theory to follow will be derived with explicit accommodation of S_m.))

S_D: the minimum gap length on the mainline required for beginning and completing a merge maneuver, which is equal to $b + S_m$. Note that whatever the value of the yielding threshold is, the existing gap has to be first lengthened to S_D before the actual lane-changing (for merging) can begin.

S: the length of a vehicle-gap cycle, i.e., $b + G$.

$S_i, i = 1, 2, \ldots,$: the length of the i-th vehicle-gap cycle on the mainline that an entering vehicle encounters (in the neighboring mainline lane), given that the gap length of that cycle is less than δ. In other words,

$$S_i = b + G'. \tag{H.3.2}$$

The expected value can be obtained as,

$$E[S_i] = b + E[G'] \tag{H.3.3}$$

where

$$E[G'] = \frac{\int_0^\delta x\,\mu\,e^{-\mu x}\,dx}{1 - e^{-\mu \delta}} = \frac{1}{\mu} - \frac{\delta\,e^{-\mu \delta}}{1 - e^{-\mu \delta}}. \tag{H.3.4}$$

Also,

$$E[S_1^2] = b^2 + E[G'^2] + 2bE[G'] \tag{H.3.5}$$

where

$$E[G'^2] = \frac{\int_0^\delta x^2\,\mu\,e^{-\mu x}\,dx}{1 - e^{-\mu \delta}} = \frac{2}{\mu^2} - \frac{\frac{2\delta}{\mu} + \delta^2}{1 - e^{-\mu \delta}}\,e^{-\mu \delta}. \tag{H.3.6}$$

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C : the random number of consecutive vehicle-gap cycles in the mainline with gaps smaller than the yielding threshold, i.e., the number of gaps passed by the entering vehicle before successfully merging into the mainline lane. Under Assumptions 3.1 and 3.2, C has the following geometric distribution:

$$p\{C = i\} = F(\delta)^i \, \overline{F(\delta)} \qquad i = 0, 1, 2, \ldots \text{ and} \tag{H.3.7}$$

$$E[C] = \frac{F(\delta)}{\overline{F(\delta)}}, \tag{H.3.8}$$

where $\overline{F(\delta)} \equiv 1 - F(\delta)$.

D : the distance traveled by an entering vehicle on the merge lane (before merging into the mainline traffic) relative to the mainline traffic. (This will be used to calculate the required ramp length R later in Equation (H.3.14).)

We have assumed that the vehicle slots on the mainline does not require any maneuvering space, i.e., S_m. It may be required only for beginning and completing a merge maneuver.

<u>Required Length of Merge Lane</u>

If the mainline gap beside which the entering vehicle appears is longer than the yielding threshold δ then the gap is enlarged and the vehicle merges into the mainline via a lane change. Otherwise, it waits till it encounters a gap longer than the threshold. Note that the maximum size of the threshold is equal to S_D.

The random variable D, i.e., the relative distance traveled by the entering vehicle before merging into the mainline lane (relative to the mainline traffic), can be determined by first conditioning on the number of vehicle-gap cycles on the mainline AHS traffic passed by the merge-vehicle (determined by the random variable C) and then by taking the weighted sum of the conditional cycle lengths (weighted by the probability of the number of vehicle-gap cycles passed by the entering vehicle). The distribution of "relative" distance can be defined as:

$$D|\{C = i\} = \sum_{j=1}^{i} S_j + S_m \qquad \text{for } i = 0, 1, 2, \ldots \tag{H.3.9}$$

In this Appendix, we use only the first two moments for numerical study. We have

$$E[D|C = i] = iE[S_1] + S_m \qquad \text{where } i = 0, 1, 2, \ldots \tag{H.3.10}$$

The expected value of D, $E[D]$, can then be calculated as,

$$\begin{aligned}
E[D] &= \overline{F(\delta)} \, S_m + F(\delta) \, \overline{F(\delta)} \, (E[S_1] + S_m) \\
&\quad + F^2(\delta) \, \overline{F(\delta)} \, (E[S_1] + E[S_2] + S_m) + \ldots \\
&= S_m + \overline{F(\delta)} F(\delta) E[S_1][1 + Z]
\end{aligned} \tag{H.3.11}$$

where

$$Z \equiv 2F(\delta) + 3F^2(\delta) + \ldots = \frac{2F(\delta)}{1 - F(\delta)} + \frac{F^2(\delta)}{(1 - F(\delta))^2}. \qquad \text{(H.3.12)}$$

To obtain the standard deviation of the distance traveled by an entering vehicle, relative to the mainline traffic, on the merge lane before merging into the mainline lane, we need to calculate the second moment of the variable D. We again condition on the number of vehicle-gap cycles passed by a merge-vehicle and obtain,

$$E[D^2|C = i] = E[(\sum_{j=1}^{i} S_j + S_m)^2] = S_m^2 + iE[S_1^2] + 2iS_m\, E[S_1] + 2\,C_2^i\, E^2[S_1]. \qquad \text{(H.3.13)}$$

Note that, due to the independence of the random variables $S_1, S_2, S_3, \ldots$, we know that $E[S_1] = E[S_2]$, $E[S_1^2] = E[S_2^2]$, $E[S_1\, S_2] = ES_1\, ES_2 = E^2[S_1]$, and so on. We uncondition the expected values mentioned above with the random variable C, which defines the number of consecutive vehicle-gap cycles passed on the mainline by a entering vehicle on the merge lane. Also note that the resulting equation for $E[D^2]$ is a sum of four series $T_1, T_2, T_3 \& T_4$ as defined below.

$$
\begin{aligned}
T_1 &\equiv S_m^2\, (\overline{F(\delta)} + F(\delta)\overline{F(\delta)} + F^2(\delta)\overline{F(\delta)} + \ldots) = S_m^2, \\
T_2 &\equiv E[S_1^2](F(\delta)\overline{F(\delta)} + 2F^2(\delta)\overline{F(\delta)} + 3F^3(\delta)\overline{F(\delta)} + 4F^4(\delta)\overline{F(\delta)} + \ldots) \\
&= E[S_1^2]F(\delta)\,\overline{F(\delta)}(1 + 2F(\delta) + 3F^2(\delta) + 4F^3(\delta) + \ldots) \\
&= E[S_1^2]F(\delta)\,\overline{F(\delta)}(\frac{1}{1 - F(\delta)} + \frac{F(\delta)}{(1 - F(\delta))^2}), \\
T_3 &\equiv S_m\, E[S_1]\sum_{i=1}^{\infty} i\, F^i(\delta)\overline{F(\delta)} \\
&= S_m\, E[S_1]\, F(\delta)\overline{F(\delta)}(2 + 4F(\delta) + 6F^2(\delta) + 8F^3(\delta) + \ldots) \\
&= S_m\, E[S_1]\, F(\delta)\overline{F(\delta)}(\frac{2}{1 - F(\delta)} + \frac{2F(\delta)}{(1 - F(\delta))^2}), \\
T_4 &\equiv E^2[S_1]\sum_{i=2}^{\infty} 2\, C_2^i\, F^i(\delta)\,\overline{F(\delta)} \\
&= 2E^2[S_1](C_2^2\, F^2(\delta)\overline{F(\delta)} + C_2^3\, F^3(\delta)\overline{F(\delta)} + C_2^4\, F^4(\delta)\overline{F(\delta)} + \ldots) \\
&= 2E^2[S_1]F^2(\delta)\overline{F(\delta)}(C_2^2\, F(\delta) + C_2^3\, F^2(\delta) + C_2^4\, F^3(\delta) + \ldots) \\
&= 2E^2[S_1]F^2(\delta)\overline{F(\delta)}(\frac{1}{1 - F(\delta)} + \frac{2F(\delta)}{(1 - F(\delta))^2} + \frac{F^2(\delta)}{(1 - F(\delta))^3}).
\end{aligned}
$$

Once $E[D^2]$ has been obtained, the standard deviation of D can easily be calculated. In this Appendix, we approximate the required length R of the merge lane by the expected value of D plus twice the standard deviation of D as follows:

$$R = \frac{E[D] + 2\sigma_D}{V_m - V_o}\, V_m. \qquad \text{(H.3.14)}$$

Note that the space requirement S_D of a merge maneuver includes the vehicle length, the safety distance d, and the maneuvering space S_m that is made available temporarily to enable the entering vehicle to change speed without disturbing traffic on either lane.

The random variable $\sum_{i=1}^{n} G_i$ has a gamma distribution with the following probability density function:

$$p_n(x) = \mu^n \frac{x^{n-1}}{(n-1)!} e^{-\mu x}, x \geq 0 \qquad (H.3.15)$$

Given that the gap beside which the vehicle appears is greater than the yielding threshold, the number V of vehicles slowing down can be calculated as follows. Let K be the gap length of the vehicle-gap cycle on the mainline AHS traffic that an entering vehicle eventually changes lanes into (for merging). Since $\delta \leq K \leq S_D$, the vehicle causes a slowdown in the mainline to create the additional space requirement of $S_D - K$. Note that K cannot be less than δ because a merge would not be possible. Now if V vehicles are slowing down in the mainline it implies that $V-1$ vehicles have slowed down to create an additional space of $S_D - K - y$, where $y > 0$ is a variable, and that the $V - th$ vehicle has slowed down to fulfill the remaining space requirement of y. Being able to fulfill a space requirement of y also implies that the gap length is greater than or equal to y.

Thus the probability that V vehicles are slowed down given that the gap length beside which the merge-vehicle appears equals K, where $\delta \leq K \leq S_D$, is ,

$$
\begin{aligned}
p(V|G'' = K) &= \int_0^{S_D - K} p_{V-1}(S_D - K - y) \, p(G \geq y) \, dy \\
&= \int_0^{S_D - K} p_{V-1}(S_D - K - y) \, \overline{F(y)} \, dy \\
&= \int_0^{S_D - K} \mu^{V-1} \frac{(S_D - K - y)^{V-2}}{(V-2)!} e^{-\mu(S_D - K)} \, dy \\
&= \frac{\mu^{V-1}}{(V-1)!} e^{-\mu(S_D - K)} (S_D - K)^{V-1}. \qquad (H.3.16)
\end{aligned}
$$

Alternatively, we have

$$p(V|G'' = K) = p\left\{ \sum_{i=1}^{V-1} G_i < S_D - K \text{ and } \sum_{i=1}^{V} G_i \geq S_D - K \right\} \qquad (H.3.17)$$

$$= \int_0^{S_D - K} p\left\{ \sum_{i=1}^{V-1} G_i < S_D - K \text{ and } \sum_{i=1}^{V} G_i \geq S_D - K \,\Big|\, \sum_{i=1}^{V-1} G_i = y \right\} p\left\{ \sum_{i=1}^{V-1} G_i = y \right\} dy$$

$$= \int_0^{S_D - K} p\left\{ V - th \; Gap \geq S_D - K - y \,\Big|\, \sum_{i=1}^{V-1} G_i = y \right\} p\left\{ \sum_{i=1}^{V-1} G_i = y \right\} dy.$$

Note that if y were greater than $S_D - K$, it would imply that the additional space requirement is being fully satisfied by the $V - 1$ vehicle-gap cycles. Since the gap length distributions are independent, we have

$$
\begin{aligned}
p(V|G'' = K) &= \int_0^{S_D - K} p\Big\{V - th\ Gap \geq S_D - K - y\Big\} p\Big\{\sum_{i=1}^{V-1} G_i = y\Big\}\, dy \\
&= \frac{\mu^{V-1}}{(V-1)!}\, e^{-\mu(S_D - K)}\, (S_D - K)^{V-1}.
\end{aligned}
$$

Note that this is exactly the same as Equation (H.3.16). Also note that the probability $p(V|G'' = K)$ implies that V vehicles must slow down to satisfy the additional space requirement $S_D - K$. Thus, for a given flow disturbance, we are also able to calculate the probability that V vehicles are slowed down.

The probability that V vehicles are slowed down, given that there is traffic disturbance in the mainline AHS traffic, is

$$
\begin{aligned}
p(V) &= \int_\delta^{S_D} p(V|G'' = K)\, p(G'' = K)\, dK \qquad where\ V = 1,2,\dots \\
&= \int_\delta^{S_D} \frac{\mu^{V-1}}{(V-1)!}\, e^{-\mu(S_D - K)}\, (S_D - K)^{V-1}\, \mu\, \frac{e^{-\mu K}}{e^{-\mu\delta}}\, dK \\
&= \frac{\mu^V}{V!}\, e^{-\mu(S_D - \delta)}\, (S_D - \delta)^V.
\end{aligned}
$$

Thus this conditional number of vehicles slowing down is a Poisson process with mean and variance of $\mu(S_D - \delta)$. Also the probability that there is slowdown in the mainline AHS traffic is given by the probability $p(G'' \leq S_D) = 1 - e^{-\mu(S_D - \delta)}$.

$$
\begin{aligned}
V &\sim\ Poisson((S_D - \delta)\mu) \quad &\text{with probability} \quad &p(G'' \leq S_D)\ and &\text{(H.3.18)} \\
V &= 0 \quad &\text{with probability} \quad &1 - p(G'' \leq S_D). &\text{(H.3.19)}
\end{aligned}
$$

The unconditional expected number of vehicles slowing down is:

$$
E[V] = [(S_D - \delta)\mu]\, p(G'' \leq S_D) + 0.(1 - p(G'' \leq S_D)). \tag{H.3.20}
$$

Using W to denote the binary random variable indicating whether there is slowdown in the mainline for accommodating a merging maneuver, the variance of V is simply:

$$
\begin{aligned}
Var(V) &= E[Var[V|Z]] + Var[E[V|Z]] &\text{(H.3.21)} \\
&= E[Var[V|Z]] + E[(E[V|Z])^2] - (E[E[V|Z]])^2 &\text{(H.3.22)} \\
&= E[Var[V|Z]] + E[(E[V|Z])^2] - E^2[V] &\text{(H.3.23)}
\end{aligned}
$$

Restrictions on On-Ramp Flow

As discussed earlier, the model described above deals with single-vehicle entry only and does not directly address the maximum allowable on-ramp flow that would lead to reasonable performance, in terms of the four main measures of effectiveness. We now link the single-vehicle model with the maximum on-ramp flow with explicit consideration of the four measures of effectiveness. By studying the relationships between the measures of effectiveness as a function of the yielding threshold, we select combinations of mainline-flow/yielding-threshold/on-ramp-flow that perform well with respect to the four measures of effectiveness as feasible combined flows and use the least upper bound as the derated capacity.

We have discussed (i) the length of the merge lane required to ensure that all entering vehicles merge into the mainline before the end of the merge lane vs. the mainline flow and yielding threshold, and (ii) the number of vehicles slowing down to accommodate a merging maneuver vs. the mainline flow and the yielding threshold. The main strategy of extending the single-vehicle model to estimate the maximum allowable on-ramp flow is to ensure that the on-ramp flow will not induce any interaction between the merging maneuvers between any two consecutive entering vehicles. To achieve this, we meter the entering vehicles at the on-ramp sufficiently apart so that (a) no single on-ramp vehicle would need to slow down twice to accommodate more than one merging maneuvers and (b) the entry flow is sustainable in the sense that there exists sufficient flow of gaps on the mainline that are larger than the yielding threshold. Item (a) can be studied with the help of the information on the number N_S of vehicles slowing down to accommodate a merging maneuver. Let n_S denote the maximum number of vehicles having to slow down to for accommodating a merging maneuver. If the on-ramp flow is such that only one on-ramp vehicle is released every n_S mainline vehicles or gaps that have passed by the merge point, no vehicle would slow down twice to accommodate more than one merging maneuver. Since the range of the random variable N_S is unbounded, we use the 95-th percentile of N_S. Item (b) can be studied by studying the (95-th percentile of the) number of consecutive gaps that a vehicle on the merge lane passes until it encounters a gap that is larger than the yielding threshold. When there is a gap larger than the yielding threshold every N_S gaps passing by the merge point (with 95 percentile confidence), then the corresponding on-ramp flow can be sustainable. An additional measure of effectiveness is the reduction of average speed due to accommodating merging maneuvers.

H.3.4 Experimental Design and Parameter Values

We select the following parameter values for the numerical study. Further study, using a variety of parameter values, will be conducted in Task C3.

V_m: 30 m/s (mainline speed)

V_o: 27 m/s (speed of vehicles traveling on the merge lane)

l: 5 m (vehicle length)

d: 15 m (optimistic distance between two mainline vehicles)

S_m: 0 m (maneuvering space)

With these parameter values, we vary (i) the mainline flow from 500 vehicles per lane per hour to 3800 vehicles per lane per hour and (ii) yielding threshold from 0 meter to 20 meters to estimate (a) the required length of merge lane (95-th percentile), (b) the number of vehicles slowing down to accommodate a merging maneuver (95-th percentile) and (c) the number of gaps (95-th percentile) passing by the merge point until the appearance of one that is larger than the yielding threshold. (Since the slowdown lasts for a short period of time and each vehicle slows down at least once per on-ramp, the reduction of average speed is actually negligible.) With the above sensitivity results, we will then identify the combinations of the yielding threshold and the mainline flow that lead to the highest on-ramp flow, while performing well with respect to the four measures of effectiveness. More precisely, (a) and (b) are used to screen out "infeasible" mainline flows and yielding thresholds. We use (b) and (c) to find the allowable on-ramp flow, for each of the "feasible" mainline-flow/yielding-threshold combinations. Finally, for each of the yielding threshold, we obtain the maximum combined flow downstream from the on-ramp, which is the maximum derated AHS lane capacity as a function of the yielding threshold. To simplify the discussion and to demonstrate the effectiveness of mainline slowdown, we select 10 meter (i.e., $S_D/2$) as the yielding threshold for detailed discussion.

H.3.5 Numerical results

Figure H.3.1 shows the 2σ value (i.e., approximately 95-th percentile) of the required ramp length as a function of the yielding threshold and the mainline flow. Figure H.3.2 shows the 2σ value (approximately 95-th percentile) of the number of vehicles slowing down to accommodate a merging maneuver, as a function of the yielding threshold and the mainline flow.

Figure H.3.3 shows the maximum combined flow as a function of the yielding threshold, assuming (i) that entering vehicles are released so far apart that virtually no two merging maneuvers will interact with each other and (ii) that the corresponding on-ramp flow can indeed be absorbed by the mainline gaps. This virtual non-interaction is ensured by using on-ramp metering rate calculated with 3σ value for the number of vehicles slowing down to accommodate a merging maneuver. Note that not all usable mainline gaps (i.e., those gaps that are larger than or equal to the yielding threshold) will be utilized by entering vehicles because there may be no vehicles at the on-ramp waiting to enter the AHS lane. Therefore, the 99-th percentile was used to account for possible "wasted" usable gaps and to approximate the sustainable actual on-ramp flow. (In addition to this way of accounting for the wasted usable gaps, 95-th percentile was used and some simple queueing analysis was also conducted. The resulting sustainable flow is very close to the one obtained with the use of 99-th percentile.) Note the above assumption that the corresponding on-ramp flow can be absorbed by the mainline, i.e., it is sustainable by the mainline. The substainability of a particular on-ramp flow hinges upon the arrival rate of the usable gaps on the mainline. We define a usable-gap cycle as an alternate sequence of gaps and vehicles that starts with a usable gap and ends before another usable gap. The

sustainability of a particular on-ramp flow, as a function of the mainline flow and the yielding threshold, can be studied and ascertained by Figure H.3.4, which shows the 95-th percentile of the size of the usable-gap cycle.

When the yielding threshold is set to 10 meters (i.e., half the sum of the vehicle length and the safety spacing), we made the following observations. In all of the following, any statement involving randomness and probability distribution, either 2σ values or 95-th or higher percentiles are used. First, the maximum length of merge lane (1.5 km) is no longer constraining. At the 10-meter yielding threshold, the required ramp length (again, a 2σ value) is less than 0.8 km, which is approximately half of the length required when no mainline slowdown or yielding is allowed. Second, the number of vehicles slowing down is well below 10. Third, the number of vehicle-gap cycles between two consecutive gaps that are larger than the yielding threshold is close to the number of vehicle having to slow down to accommodate a merging maneuver. The combined flows corresponding to the range of mainline flow from 500 to 4300 vehicles per lane per hour are at least approximately 4000 vehicles per lane per hour. This represents roughly 25% reduction from the pipeline capacity. Note that another important measure of disturbance to the mainline traffic is the speed reduction by any particular vehicle. As mentioned earlier, since a vehicle will be required to slow down at most once per on-ramp for accommodating merging maneuvers and the slowdown lasts only for a very short time (at most 2.5 seconds), the reduction in average speed turns out to be actually negligible (at most 1%).
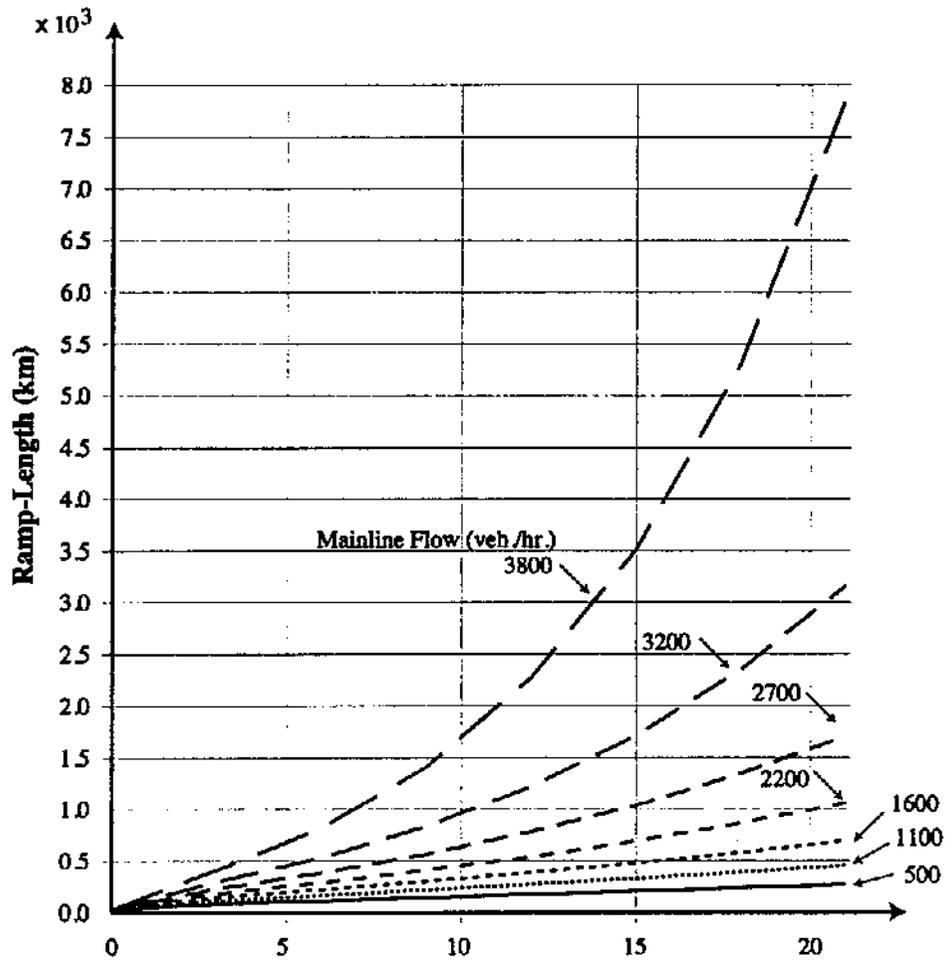
Figure H-3.1. Yielding Threshold (m).
Mainline speed 30 m/s, Merge-lane speed 27 m/s, Spacing 15m
Ramp length ≈ Average + 2 σ of distance traveled by an entering vehicle
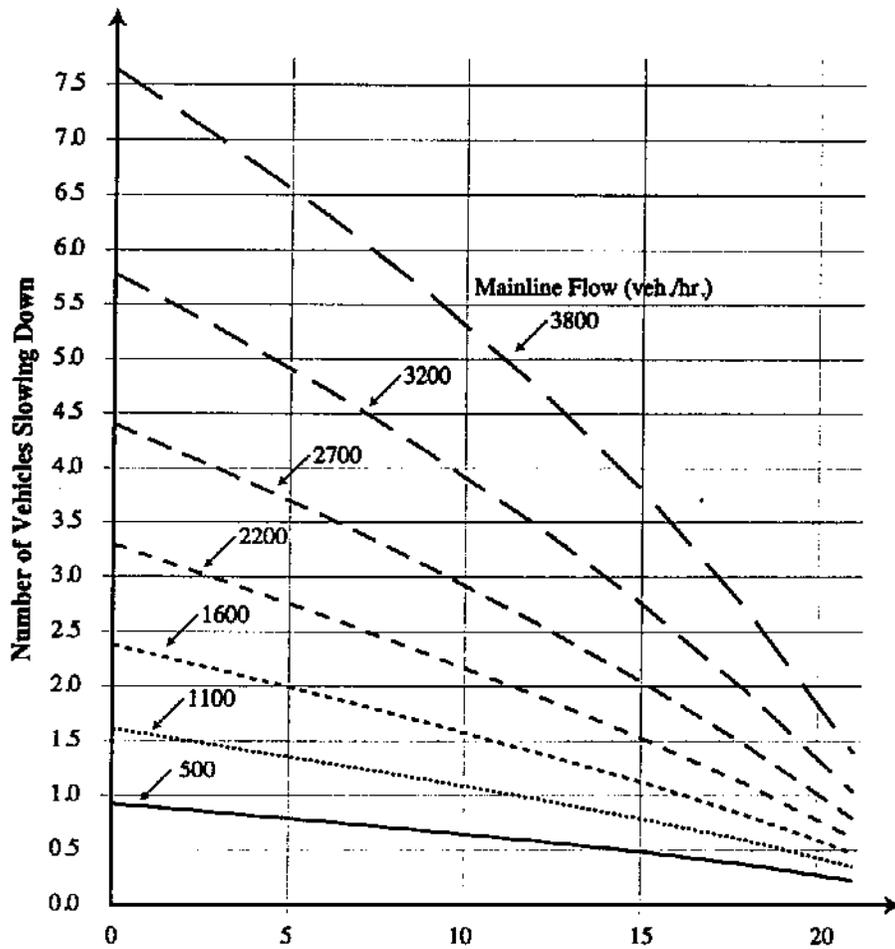
Figure H-3.2. Yielding Threshold (m).
Mainline speed 30 m/s, Merge-lane speed 27 m/s, Spacing 15m
Number of vehicles slowing down ≈ Average + 2 σ of distribution
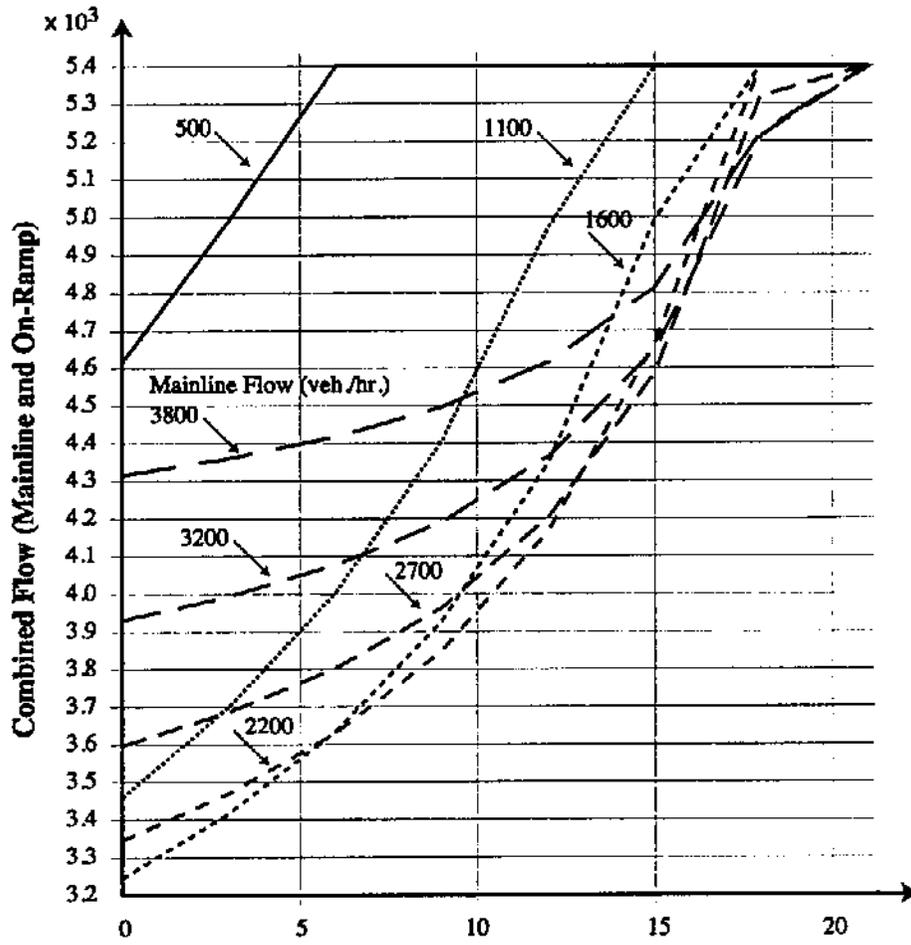
Figure H-3.3. Yielding Threshold (m)
Mainline speed 30 m/s, Merge-lane speed 27 m/s, Spacing 15m

H.4: Conclusion

H.4.1: Summary of Results

The parameters used in the study and the corresponding results are:
<u>Autonomous Individual Vehicles: two cases</u>
(1) inter-vehicle distance = 15m at 30 m/s, as requested by Bayouth (the developer of the Independent Vehicle Concept).

Results: 50%+ reduction from the max throughput (5400 → 2500).

(2) inter-vehicle distance provided by the Safety Evaluation Team: 20 m at 20 m/s; 41 m at 30 m/s; 69m at 40 m/s.

Results: 50%+ reduction from max (similar to case (1)).

Note: A major reason why the reduction is so large is due to the phenomenon of First-In-Last-Out, in terms of the queueing theory. After an entering vehicle (vehicle A) has reached the merge point, the best the vehicle can hope for is to merge into the next available gap upstream on the mainline lane. However, that gap may actually be encountered and used by a trailing vehicle (vehicle B) on the on-ramp. When this happens, vehicle A would have to wait for a gap further upstream, which would take a long time to catch up with vehicle A, if at all.

<u>Cooperative Individual Vehicle: two cases</u>
(1) the set of distance numbers requested by McKendree (the developer of the Cooperative Vehicle Concept): 5 m at 20 m/s; 9m at 30 m/s; 14 m at 40 m/s.

Results: typical reduction of 25-30%.

(2) Inter-vehicle distance provided by the Safety Evaluation Team: 20m at 20 m/s; 40m at 30 m/s; 68m at 40 m/s.

Results: typical reduction of 25-30% (similar to case (1)).

<u>Cooperative Platooning: one case.</u>

(1) Safety spacings provided by the Safety Evaluation Team: 27m at 20 m/s; 58m at 30 m/s; 101m at 40 m/s.

Results: typical reduction,
- with "release to gap", "preplatooning", and "release to tag": 25%;
- without "release to tag": 40% reduction;
- without "preplatooning" and "release to tag": 70% reduction.

<u>Autonomous Individual Vehicle with Mainline Slowdown: two cases</u>

(1) Inter-vehicle distance = 15m at 30 m/s, as requested by Bayouth, with a yielding threshold of 10m.

Results: capacity reduction = 25%.

H.4.2. Major Findings

Based on the reported analyses, for the chosen operating assumptions:

(1) Large reductions from the "pipeline" capacity will result if merging is not performed efficiently.

(2) Without some form of coordination, e.g., yielding, for autonomous individual vehicles, reduction from the pipeline capacity due to merging could be drastic, e.g., 50%+. Reasons include the First-In Last-Out phenomenon.

(3) With yielding, capacity associated with autonomous vehicles can be much improved at a reduction from the pipeline capacity of only 25% with negligible disturbance to the mainline traffic (at most 2% speed reduction). Note that all other merging disciplines assume no mainline slowdown, i.e., no yielding by any mainline vehicles.

(4) Cooperative individual vehicles with release-to-gap leads to a reduction of 25% from the pipeline capacity.

(5) Microscopic metering also works well for the autonomous individual vehicles (without mainline slowdown) at a reduction of only 25% from the pipeline capacity but with the need for some short parallel merge lane.

(6) Preplatooning together with release-to-gap lead to a 40% reduction from the pipeline capacity for cooperative platooning.

(7) Release-to-tag adds significant amount of efficiency for platooning, with only 25% reduction.

(8) Without release-to-tag and preplatooning, i.e., with only release-to-gap for a single vehicle, a reduction of 70%+ from the pipeline capacity has been observed.

(9) For all three vehicle-following approaches, merging disciplines have been identified that lead to 25% or less reduction from the theoretically maximum lane capacity, i.e., the pipeline capacity.

(10) Merging at highway-to-highway interchanges, at locations where one lane is being dropped, and merging at end of transition lane (without stopping vehicles on the transition lane prior to their "release" for merging) is more difficult, in terms of traffic management and model development.

Appendix I.   Mixed Traffic Throughput Analysis

I.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 here is on the derivation of throughput estimates for mixed traffic operations. The following sections discuss the assumptions used for the analysis, the method used to derive the throughput estimates, the results and an analysis of those results. The final section offers conclusions.

I.2   Assumptions

This section discusses the assumptions made during the analysis of mixed traffic operations.

I.2.1   Automated Vehicle Intelligence

The primary attributes for the automated vehicle represented in this analysis are that all the intelligence is concentrated within the vehicle and there is no communication of information among vehicles. This type of automated vehicle is referred to as an individual autonomous (or independent) vehicle.

I.2.2   Driver Behavior

It is assumed that manual driving behavior is unchanged from that of today.

I.2.3   Vehicle Class

The analysis is carried out for light-duty vehicles only, which are assumed to be approximately five meters long.

I.2.4   Placement of Automated and Manual Vehicles on the Roadway

It is assumed that the sequencing of manual and automated vehicles in the lane is random. This random sequencing requires a derivation of the likelihood of occurrence of the four possible pairs of manual/automated vehicle relative positions on the roadway, which will be discussed in Section I.3.2 on methodology. A listing of the four vehicle pair positioning possibilities are described in Table I-1.

Table I-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

I.2.5   Speed

Alternative operating speeds were used in the analysis to understand the impact of alternative speeds on the results. These speeds are: 20 meters per second (45 miles per hour) and 30 meters per second (67 miles per hour).

I.2.6   Merge Derating Factor

The merge derating factor is a percentage to represent the potential reduction in throughput experienced due to merging and lane changing. Because there is uncertainty in the appropriate value(s) for this parameter, alternative values were used in the analysis to understand the sensitivity of results to this uncertainty. Values for the merge derating factor are: 15%, 25%, and 35%.

I.2.7   Spacing

This sub-section discusses the relationships among the four vehicle pair positioning possibilities introduced in section I.2.4 and alternative ways of estimating spacing between two automated vehicles.

I.2.7.1 AM and MM Case

It is assumed that 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 significantly.

I.2.7.2 AA and MA Case

It is assumed that an automated vehicle follows a manual vehicle no closer than it, the automated vehicle, would follow another automated vehicle. This assumption is made since the spacing used for an automated vehicle following another automated vehicle has been calculated to be the minimum safe inter-vehicle spacing. In this case *safe* means that if the front vehicle applies maximum braking in response to a failure then the following vehicle should be able to stop. Such minimum safe spacing depends on the braking capabilities of the two vehicles, the type of information available for vehicle control, sensing delays, and operating speed. Full details for the estimation of these minimum safe spacings may be found in Appendix G-Pipeline Throughput Analysis Method and Detailed Results. 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.

I.2.7.3 Comparison of MM and MA Cases

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 another 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 36 drivers traveling around a 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 (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* (1), would not necessarily mean that such an automated vehicle was tailgating the manual vehicle. Thus, it was not assumed that the spacing between an automated vehicle and a preceding manual vehicle would have to be no smaller than the spacing between two manual vehicles. Care must be taken when the data, valuable though it may be, is very limited in size.

I.2.7.4 AA Case: Uniform and Non-Uniform Spacing

Appendix G provides a detailed documentation of the safe spacing design for the pipeline capacity analysis. Included in Appendix G is a discussion about the dependence of the minimum safe spacing and resulting capacity on differences in braking capabilities for the two automated vehicles. Braking capabilities are distributed over a wide range that results in conservative inter-vehicle following distances for a uniform spacing design since worst case fixed or uniform inter-vehicle spacings were utilized. Inter-vehicle

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spacing may be reduced and thus result in a capacity improvement by allowing dynamically changing or non-uniform spacing designs. For non-uniform spacing, it is assumed that each vehicle has the ability to identify and does in turn identify its own braking capability on-line. Full details about non-uniform spacing design for independent autonomous vehicles as well as for other distributions of automated vehicle intelligence may be found in Appendix G.

I.3   Methodology

This sections presents the methodological approach used in estimating lane throughput (vehicles/hour). The objective is to derive an estimate of lane throughput as a function of the percentage of automated vehicles in a highway lane.

I.3.1   All-Manual Throughput

The derivation of throughput was based on data available from a recently completed work (1) as well as from (2*)*. For the case of vehicles traveling at 20m/s, data available from (2) indicates that the throughput is approximately 1900 vehicles/hour. This translates into a headway of approximately 1.9 seconds and a spacing of 38 meters (including vehicle length).

The University of Michigan Transportation Research Institute (UMTRI) study [1] provided data on average speeds and spacings of vehicles traveling on a freeway loop in the metropolitan Detroit area to collect information about the following modes of driving: manual, cruise control, adaptive cruise control. Under manual control, the average speed traveled for all drivers was 30m/s, with speeds of 26.5m/s and 33m/s representing the smallest and greatest averages for different drivers respectively. The average spacing between vehicles, including an average vehicle length of 5 meters, was 67 meters. This spacing yields an average headway of 2.3 seconds, which in turn may be expressed as an average throughput of 1600 vehicles/hour.

I.3.2   Random Sequencing of Manual and Automated Vehicles

While operating in mixed traffic, four combinations of vehicle-to-vehicle pair positions are possible since each of the two vehicles of any pair may be automated or manual (Table I-1). Given these four possibilities or "outcomes" a simple probability calculation is used to estimate the likelihood that each of these four outcomes will occur, leading to an expression for throughput as a function of the market penetration of automated vehicles.

As previously stated, it is assumed that 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. In order to derive an expression for throughput as a function of market penetration, analytically and in closed form, it is also assumed that the

entire vehicle population is large relative to the number of vehicles on the roadway, that is, vehicles are being selected "with replacement," that is, with sequential "draws" independent of one another (3).

Let the market penetration of automated vehicles be expressed as α.

Let the probability of
an automated vehicle followed by an automated vehicle = P (A,A)
an automated vehicle followed by a manual vehicle   = P (A,M)
a manual vehicle followed by an automated vehicle   = P (M,A)
a manual vehicle followed by a manual vehicle   = P (M,M)

Probabilities must give the following values at the end point values for α :

$\alpha = 0\%$ yields
P (A,A) = 0
P (A,M) = 0
P (M,A) = 0
P (M,M) = 1

$\alpha = 100\%$ yields
P (A,A) = 1
P (A,M) = 0
P (M,A) = 0
P (M,M) = 0

Then the probability of any individual vehicle being
automated = α
manual   = $1-\alpha$

and the four probabilities are expressed as follows:
P (A,A) = $\alpha*\alpha$
P (A,M) = $\alpha*(1-\alpha)$
P (M,A) = $(1-\alpha)*\alpha$
P (M,M) = $(1-\alpha)*(1-\alpha)$

Throughput may therefore be expressed in terms of α as follows:

Throughput = $3600*v/(\alpha*\alpha*S(A,A) + (1-\alpha)*(1-\alpha)*S(M,M) + \alpha*(1-\alpha)*(S(A,M)+S(M,A)))$,

where

1. throughput is expressed in vehicles per hour per lane

2. 3600 is the conversion factor between seconds and hours
3. v equals the velocity expressed in meters per second
4. the spacing in meters for

an automated vehicle followed by an automated vehicle = S (A,A)
an automated vehicle followed by a manual vehicle = S (A,M)
a manual vehicle followed by an automated vehicle = S (M,A)
a manual vehicle followed by a manual vehicle = S (M,M)

I.3.3 Clustering Behavior

The potential for clustering or grouping of vehicles initiated by the drivers themselves was also considered and is presently described, including an expression for throughput, however, all subsequent analysis is focused on non-clustering behavior . If travel by both manual and automated vehicles is confined to a single lane, then no clustering could occur. So assume that travel is occurring on multiple lanes. In order for clustering to occur, there has to be an awareness by drivers of the vehicle type (manual or automated) of the vehicle in front of them. Secondly, there is a requirement that a vehicle prefers to follow a vehicle of its own type. A process of self -selection through weaving to separate the manual and automated vehicles would have to occur. This process of weaving, however, would exact its own cost of reducing throughput. With clustering, the AM and MA vehicle positioning possibilities would hardly ever occur (Table I-1), leaving the following approximate expression for the upper bound on the throughput:

$$3600*v/(\alpha*S (A,A) + (1-\alpha)*S (M,M))$$

I.4 Results

Results are presented in this section that show the relationship between throughput and automated vehicle market penetration as parameters such as maximum operating speed, merge derating factor, and spacing are allowed to vary in value. Two values for cruising speeds were used, 20m/s and 30m/s based on the available data from the UMTRI study. The merge derating factor is a percentage that is applied to all minimum spacings to represent the potential reduction in throughput experienced due to merging and lane changing. The following three values of the merge derating factor were used: 15%, 25%, and 35%. Alternative spacings between automated vehicles are used identifying both uniform and non-uniform spacing designs.

The throughput analysis results generally indicate that throughput increases with increasing market penetration, however, at different rates of increase. Results indicate a moderately large sensitivity to both operating speed and merge derating factor. For moderate values of market penetration, changes in throughput are small, however, either increases or reductions may occur. Based on this analysis, a fairly sizable market penetration of automated vehicles is required before appreciable throughput benefits appear.

I.4.1   Sensitivity Analysis: Inter-Vehicle Spacing Values

This section lists derived values for the four vehicle-pair positioning outcomes (Table I-1) under the following three alternative sensitivity analysis regimes, i.e. values for S(. , .) in meters (See I.3.2). One sensitivity analysis regime assumes a fixed merge derating factor of 25% and uniform inter-vehicle spacing and allows for the sensitivity to changes in maximum operating speed (Table I-2). The second regime assumes a fixed maximum operating speed of 30m/s and uniform inter-vehicle spacing and shows the sensitivity to changes in the merge derating factor (Table I-3). The third regime assumes a fixed maximum operating speed of 30m/s and a fixed merge derating factor of 25% and displays the sensitivity to spacing design, i.e. uniform vs. non-uniform (Table I-4).

Table I-2. Inter-Vehicle Spacing Values (in meters) under
Alternative Sensitivity Analysis Regimes
25% Merge Derating Factor & Uniform Spacing

Alternative Operating Speed Values	S(A,A)	S(A,M)	S(M,A)	S(M,M)
20m/s	30.0	38.0	30.0	38.0
30m/s	57.1	67.0	57.1	67.0

Table I-3. Inter-Vehicle Spacing Values (in meters) under
Alternative Sensitivity Analysis Regimes
30m/s Operating Speed & Uniform Spacing

Alternative Merge Derating Factor Values	S(A,A)	S(A,M)	S(M,A)	S(M,M)
15%	50.4	67.0	50.4	67.0
25%	57.1	67.0	57.1	67.0
35%	65.9	67.0	65.9	67.0

Table I-4. Inter-Vehicle Spacing Values (in meters) under
Alternative Sensitivity Analysis Regimes
25% Merge Derating Factor & 30m/s Operating Speed

Alternative Inter-Vehicle Spacings Values	S(A,A)	S(A,M)	S(M,A)	S(M,M)
Uniform Spacing	57.1	67.0	57.1	67.0
Non-Uniform Spacing	42.4	67.0	42.9	67.0

Table I-5 provides inter-vehicle spacing values that reflect spacings that are less than the spacing values calculated and displayed in Tables I-4 for S(A,A) and S(M,A). Spacing values for S(A,M) and S(M,M) remain unchanged for their merge derating factor and operating speed. These smaller values reflect a more optimistic viewpoint with respect to the inter-vehicle spacings. The values for S(A,A) are derived from their respective AA gap values by first adding in 5 meters (vehicle length) and then dividing by 0.75 to reflect the merge derating factor.

Table I-5. Inter-Vehicle Spacing Values in Meters Under Alternative Sensitivity Analysis Regimes for 25% Merge Derating Factor & 30m/s Operating Speed, with More Optimistic Safety Assumptions

Alternative Inter-Vehicle Spacings Values	S(A,A)	S(A,M)	S(M,A)	S(M,M)
AA Gap = 15 meters	26.7	67.0	26.7	67.0
AA Gap = 20 meters	33.0	67.0	33.0	67.0

I.4.2   Sensitivity Analyses' Impact on Throughput

This section presents the results of the analyses in graphical form to illustrate the impact of the sensitivity analyses on throughput as a function of the market penetration for automated vehicles.

I.4.2.1 Plots

Figures I-1 through I-3 correspond to the values of the four vehicle-pair positioning outcomes under the three sensitivity analysis regimes (Tables I-2–I-4), i.e. values for S(. , .).

I.4.2.2 Interpretation of Plots

Figure I-1 displays throughput as a function of market penetration and the sensitivity of this relationship to maximum vehicle operating speed, with fixed merge derating factor of 25% and uniform inter-vehicle spacing. Throughput varies with increasing market penetration with considerably larger throughput changes for the operating speed of 20m/s. Throughput is sensitive to changes in operating speed throughout the entire range of market penetration percentages.
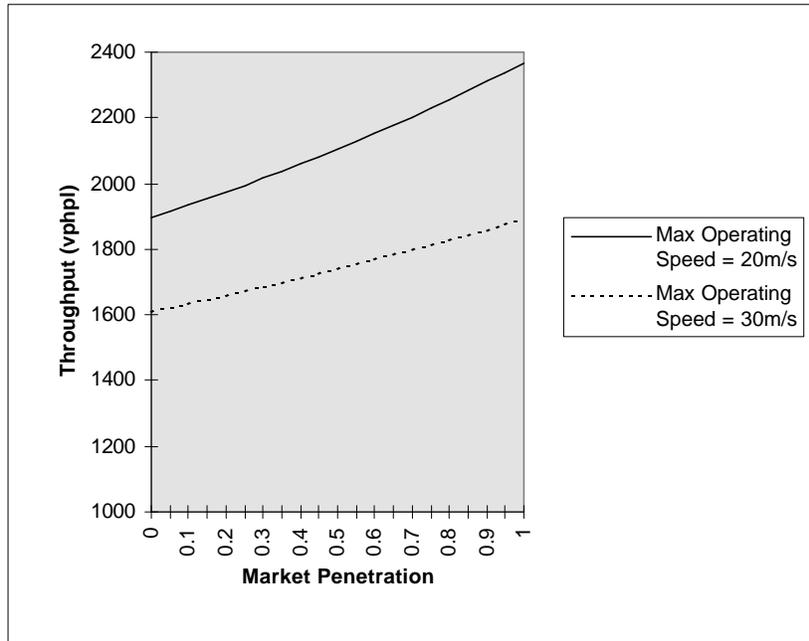
Figure I-1. Throughput vs. Market Penetration
Merge Derating Factor = 25% & Uniform Spacing

Note that even at a market penetration of 50% (which is high enough to provide strong justification for dedicating a lane for automated vehicles' exclusive use) the throughput increases are only 11.1% and 8.0% over the all-manual base case for the speeds of 20m/s and 30m/s, respectively.

Figure I-2 displays throughput as a function of market penetration and the sensitivity of this relationship to changes in the merge derating factor. A fixed operating speed of 30m/s and uniform inter-vehicle spacing are assumed for this sensitivity analysis. Throughput increases with increasing market penetration with considerably larger throughput increases corresponding to smaller values of the merge derating factor. Throughput is sensitive to changes in merge derating factor throughout the entire range of market penetration percentages and this sensitivity grows with market penetration.
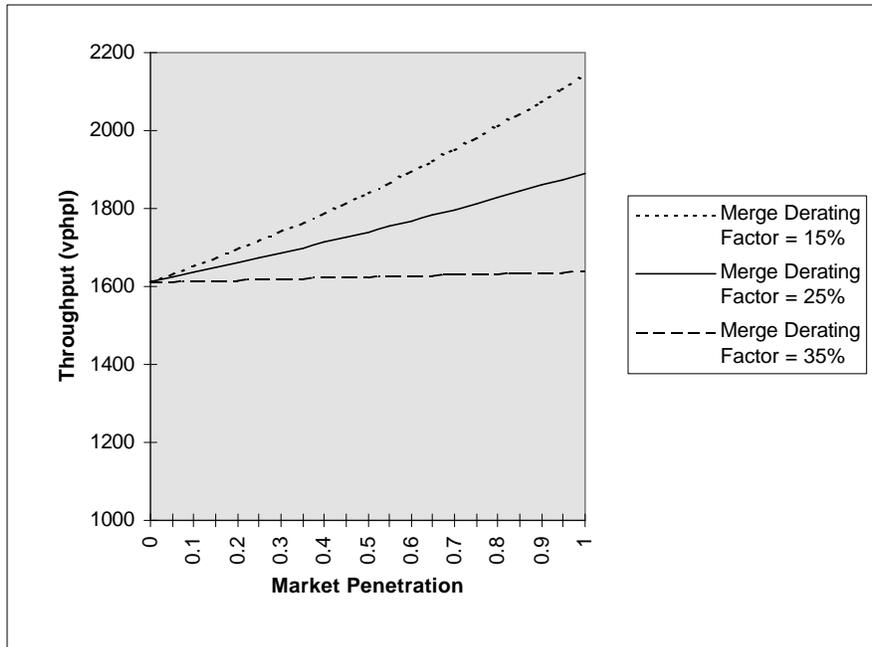
Figure I-2. Throughput vs. Market Penetration
Maximum Operating Speed = 30m/s & Uniform Spacing

The greater the merge derating factor, the smaller the throughput as seen in the positioning of the throughput curves relative to each other for each value of α. Note that even at a market penetration of 50%, the most optimistic case, with the derating factor of 15%, produces only a 14.1% throughput increase compared to the all-manual driving base case.

At the market penetration of 100%, with all vehicles automated, the throughput is about 1900 vehicles per hour per lane, based on the need to maintain the 57.1 m average safe spacing (including vehicle length and merge derating factor) for operations at 30 m/s with a 25% merge derating factor. If the merge derating factor were removed, this would be equivalent to a pipeline capacity of about 2500, which is consistent with the results derived in the pipeline capacity analysis for autonomous individual vehicles (see, for example, Figure G-15 for 100% LDPVs).

Figure I-3 displays throughput as a function of market penetration and the sensitivity of this relationship to changes in the inter-vehicle spacing. A fixed operating speed of 30m/s and merge derating factor of 25% are assumed for this sensitivity analysis. Throughput increases with increasing market penetration with considerably larger throughput increases corresponding to non-uniform inter-vehicle spacing. Throughput is
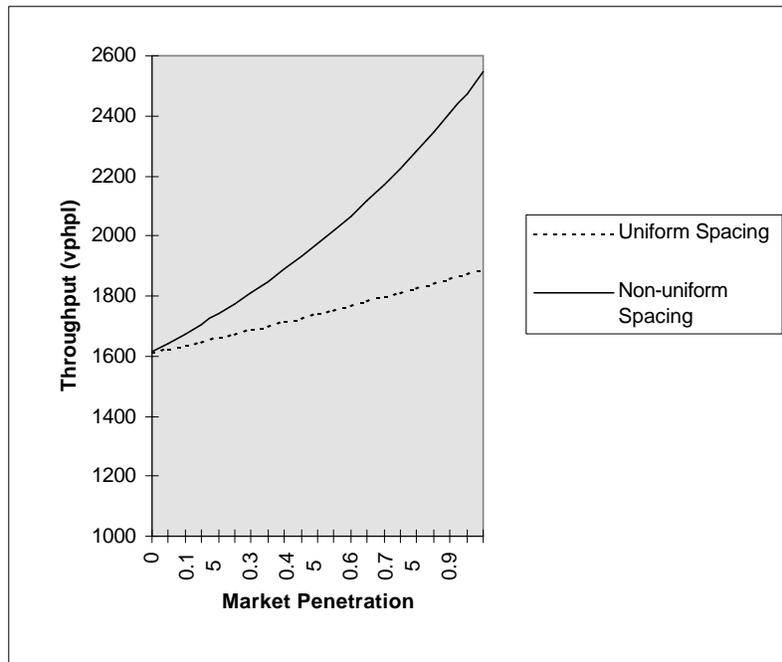
Figure I-3. Throughput vs. Market Penetration
Maximum Operating Speed = 30m/s & Merge Derating Factor = 25% for Uniform and
Non-Uniform Safe Spacings

sensitive to changes in inter-vehicle spacing throughout the entire range of market penetration percentages and this sensitivity grows with market penetration. For non-uniform spacing, the throughput is consistently higher than for uniform spacing. Note that even at a market penetration of 50%, for non-uniform inter-vehicle spacing, a 22.5% throughput increase is produced compared to the all-manual driving base case.

Figure I-4 displays throughput as a function of market penetration and the sensitivity of this relationship to changes in the inter-vehicle spacing. A fixed operating speed of 30m/s and merge derating factor of 25% are assumed for this sensitivity analysis. Throughput increases with increasing market penetration with larger throughput increases corresponding to the smaller of these two alternative inter-vehicle spacings. Throughput is sensitive to changes in inter-vehicle spacing throughout the entire range of market penetration percentages and this sensitivity grows with market penetration. For the 15 meter AA gap, the throughput is consistently higher than for the 20 meter AA gap. Note that the market penetration needs to reach a value of between 20% and 25% before the 15 meter AA gap achieves a 15.0% throughput increase compared to the all-manual driving base case.
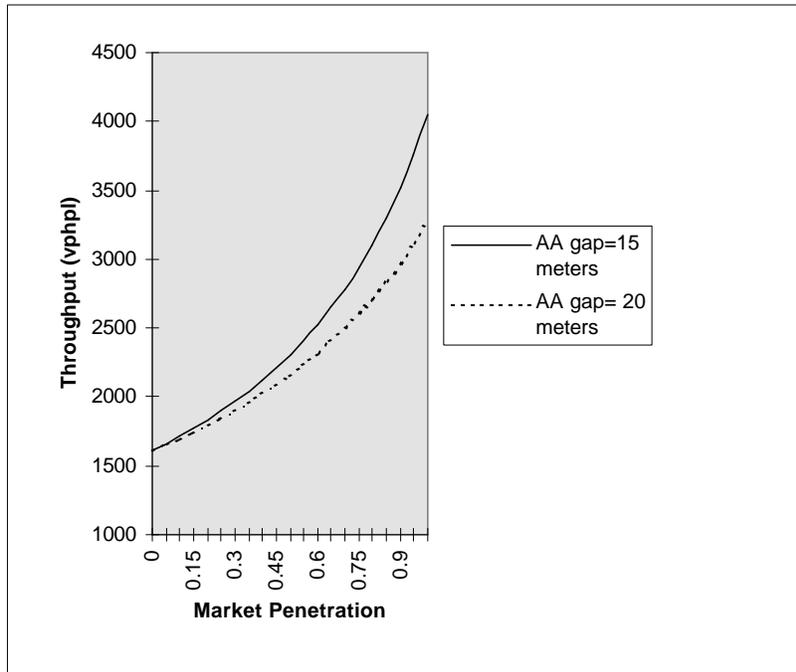
Figure I-4. Throughput vs. Market Penetration. Maximum Operating Speed = 30 m/s and Merge Derating Factor = 25% for Very Small Spacings Between Automated Vehicles

I.5   Conclusions

The throughput analysis results presented generally indicate that throughput increases modestly with increasing market penetration, however, at different rates of increase. The two primary parameters for which the sensitivity analysis was performed, speed and merge derating factor, showed some sensitivity. For relatively small values of α, changes in throughput are small. Based on this analysis, a substantial market penetration of automated vehicles is required before appreciable throughput increases can be achieved in mixed traffic operations.

I.6   References

(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.

(2)   Transportation Research Board, *Highway Capacity Manual*, 1985.

(3)   Larsen, Richard J., et al., *An Introduction to Mathematical Statistics and its Applications*, Prentice-Hall, Englewood Cliffs, NJ 07632, 1986.

Appendix J.   Hard-Braking Safety Analysis – Additional Results

This appendix consists of two sections. Section J.1 presents an example illustrating the hard braking analysis process when several of the input parameters are random variables. Section J.2 contains additional analysis results similar to those presented in section 4.2

J.1   Analysis Example

This analysis addresses the very rare, worst-case condition in which a malfunction or system intrusion causes a vehicle to abruptly apply maximum braking. Since each hard braking modeling parameter is a random variable, the collision velocity will also be a random variable. In order to calculate this collision velocity distribution, the vehicle parameter distributions are first discretized. For every combination of these discrete parameter values, a collision velocity is calculated. The probability of that collision velocity is incremented by the probability of the corresponding parameter value combination. Shown in Figure J.1 is an example set of parameter distributions. The resulting collision velocity distribution is shown in Figure J.2. Notice that parameters can also be modeled as deterministic values while calculating the collision velocity distribution.

J.2   Additional Results

This section presents analysis results similar to those presented in section 4.2 for AHS operating speeds of 20 and 40 m/s and intra-platoon spacings of 1 and 5m. Figures J.3 and J.4 are the collision velocity distributions for autonomous, low cooperative and high cooperative individual vehicles for AHS operating speeds of 20 m/s and 40 m/s respectively. Figures J.5 and J.6 show the collision velocity distributions at different operating speeds for autonomous and high cooperative individual vehicles. Figures J.7 and J.8 show the collision velocity distributions at different operating speeds of platoons operating at 1m and 5m intra-platoons spacing respectively. Figures J.9 and J.10 show the sensitivity of safety to intra-platoon spacing at speeds of 20 m/s and 40 m/s respectively. Figures J.11 and J.12 plot the safety capacity relationships for all attribute combinations at an operating speed of 20 m/s. Figure J.11 pertains to collision frequency and Figure J.12 to severity. Figures J.13 and J.14 plot the safety capacity relationships for all attribute combinations at an operating speed of 40 m/s. Figures J.15 and J.16 plot the relationship between the composite safety metric and capacity for all attribute combinations at operating speeds of 20 m/s and 40 m/s respectively.
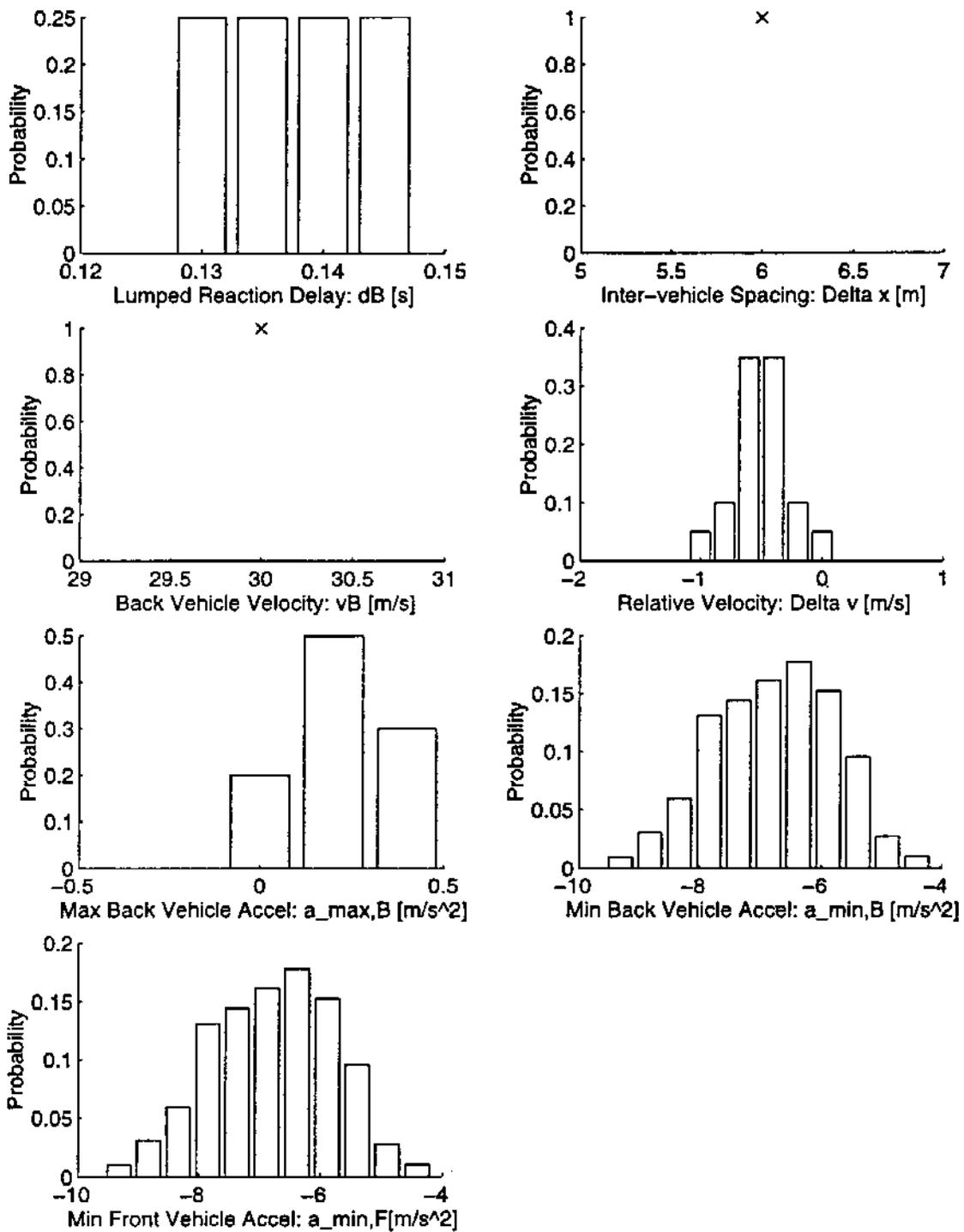
Figure J.1: Example Parameter Distribution Set
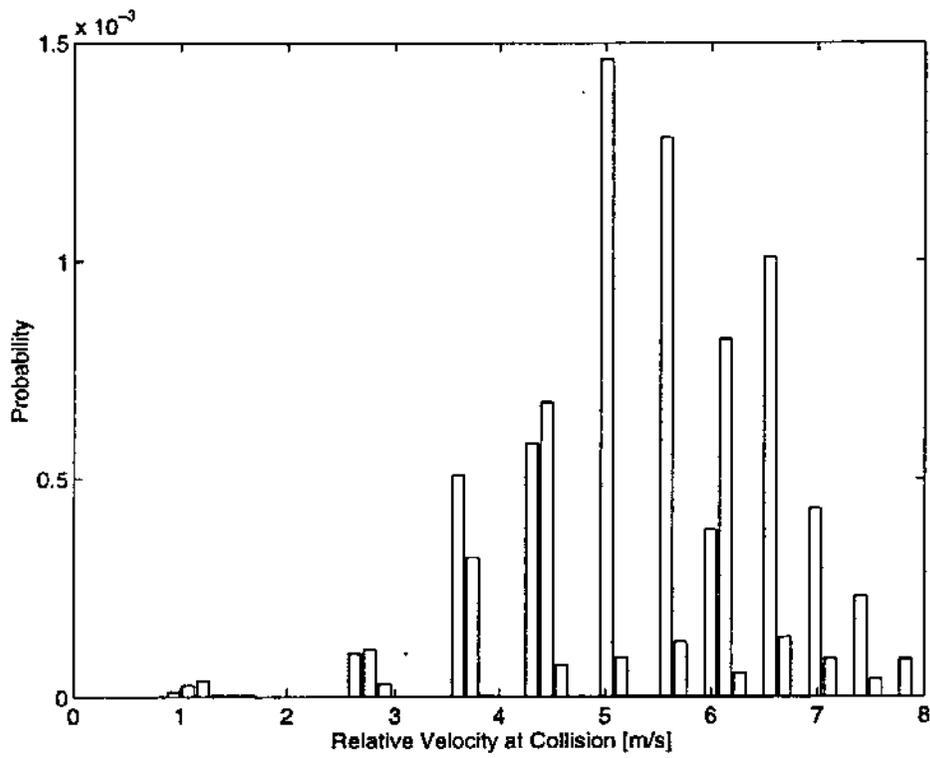
Figure J.2: Example $\Delta v_{collision}$ Distribution
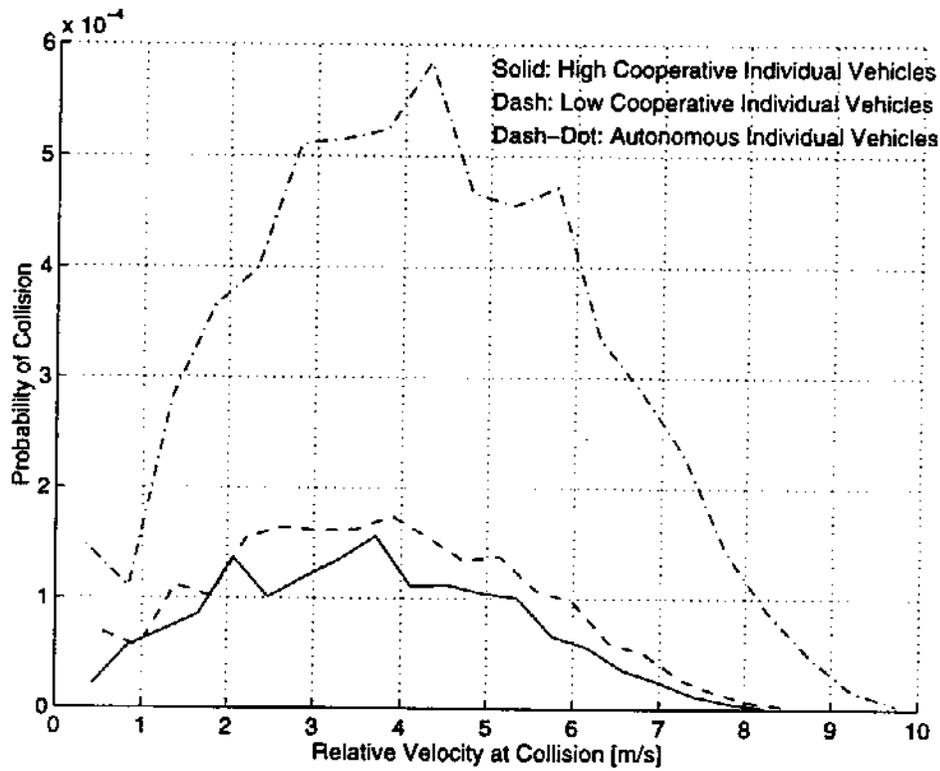
AHS Attribute	Capacity	Total Prob of Collision	Expected Δv_{coll}^2
Autonomous	2500 $vphpl$	0.006	21.6 m^2/s^2
Low Cooperative	2500 $vphpl$	0.0019	16.8 m^2/s^2
High Cooperative	2500 $vphpl$	0.0015	15.8 m^2/s^2

Figure J.3: Safety Comparison at Different Levels of Cooperation. 20 m/s AHS Operating Speed
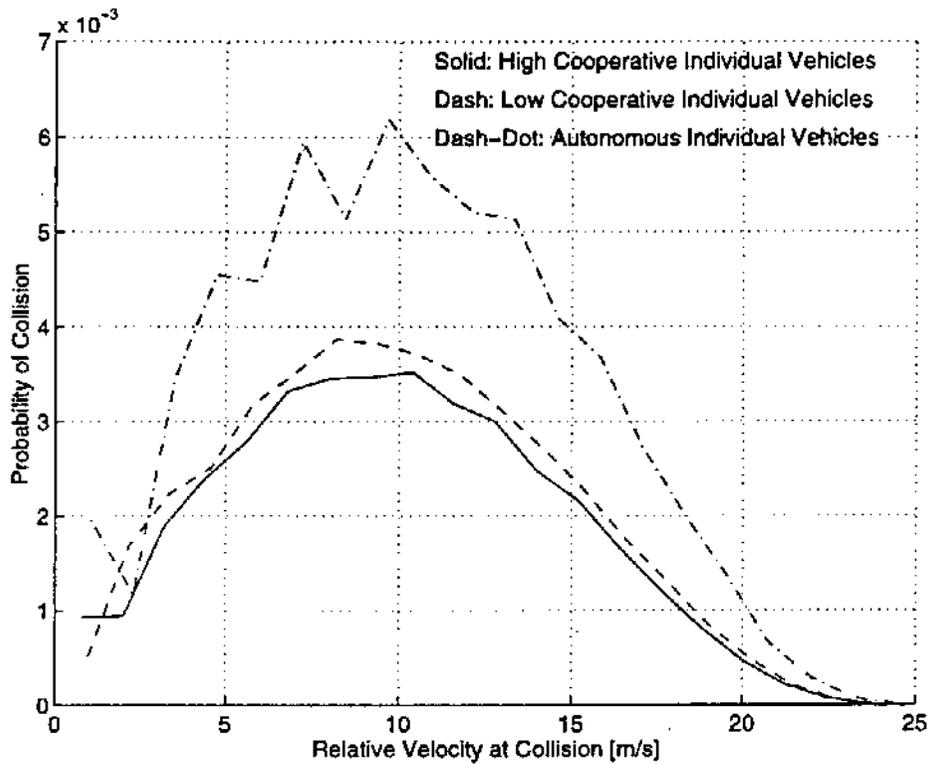
AHS Attribute	Capacity	Total Prob of Collision	Expected Δv_{coll}^2
Autonomous	2500 $vphpl$	0.064	128 m^2/s^2
Low Cooperative	2500 $vphpl$	0.041	121 m^2/s^2
High Cooperative	2500 $vphpl$	0.038	119 m^2/s^2

Figure J.4: Safety Comparison at Different Levels of Cooperation. 40 m/s AHS Operating Speed
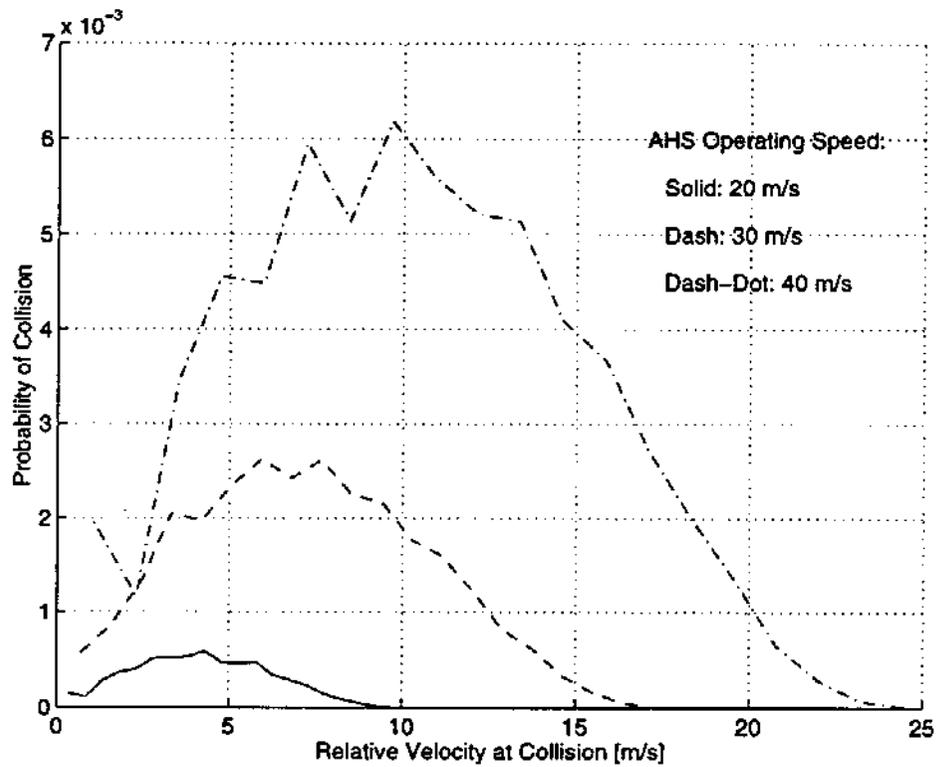
AHS Speed	Capacity	Total Prob of Collision	Expected Δv^2_{coll}
20 m/s	2500 $vphpl$	0.006	21.6 m^2/s^2
30 m/s	2500 $vphpl$	0.028	64.1 m^2/s^2
40 m/s	2500 $vphpl$	0.064	128 m^2/s^2

Figure J.5: Autonomous Individual Vehicles Safety at Different AHS speeds
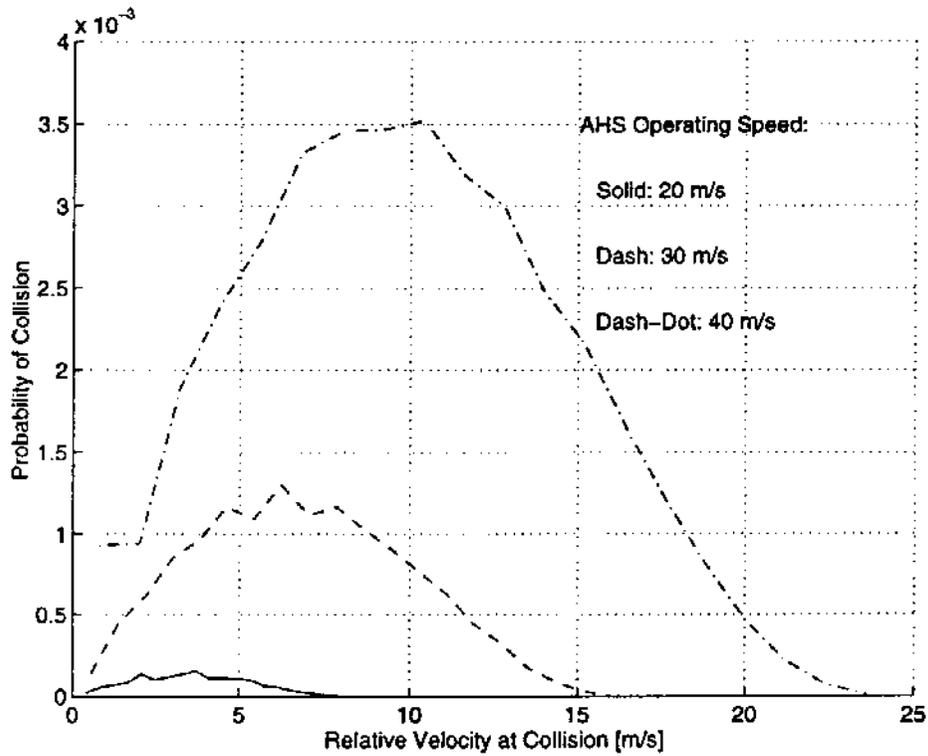
AHS Speed	Capacity	Total Prob of Collision	Expected Δv^2_{coll}
20 m/s	2500 $vphpl$	0.002	15.8 m^2/s^2
30 m/s	2500 $vphpl$	0.013	56.9 m^2/s^2
40 m/s	2500 $vphpl$	0.038	119 m^2/s^2

Figure J.6: High Cooperative Individual Vehicles Safety at Different AHS speeds
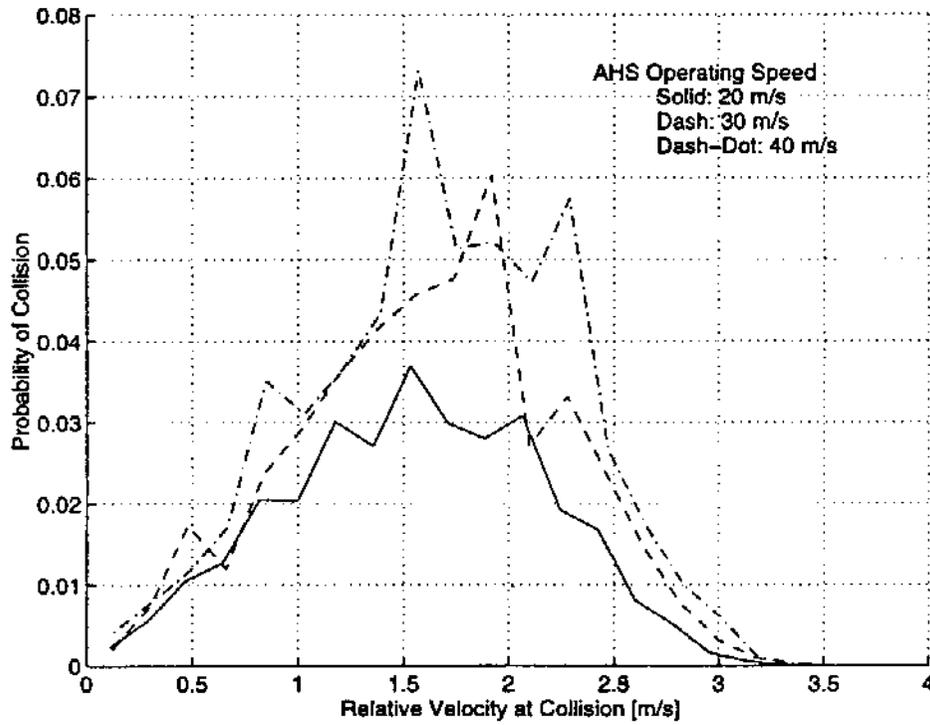
AHS Speed	Capacity	Total Prob of Collision	Expected Δv_{coll}^2
20 m/s	2500 $vphpl$	0.31	2.77 m^2/s^2
30 m/s	2500 $vphpl$	0.43	2.94 m^2/s^2
40 m/s	2500 $vphpl$	0.53	3.14 m^2/s^2

Figure J.7: Platoons with 1 m Intra-platoon Spacing: Safety at Different AHS Speeds
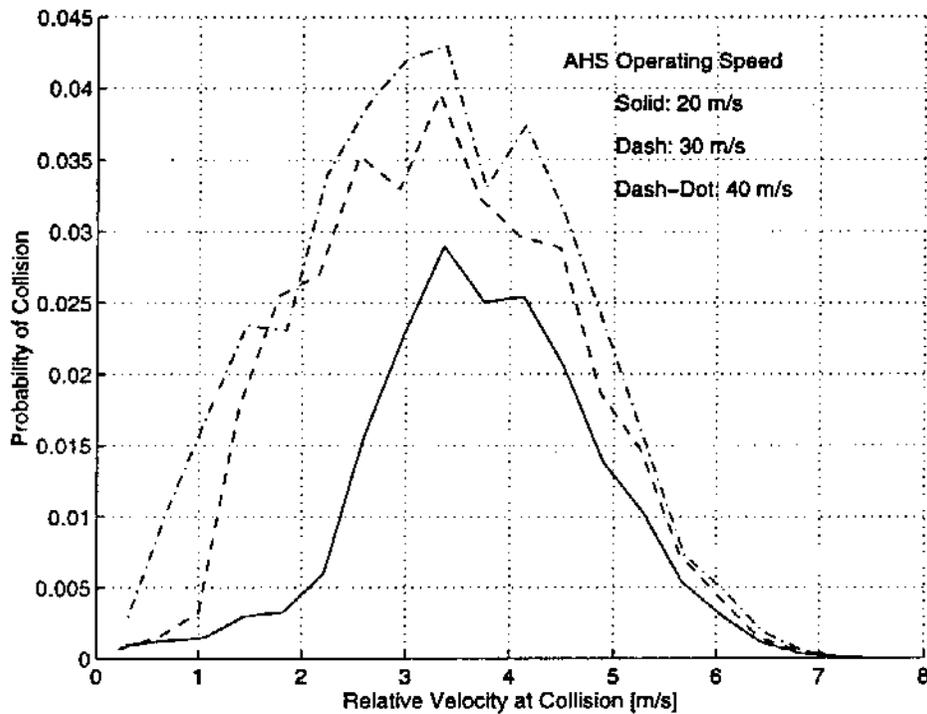
AHS Speed	Capacity	Total Prob of Collision	Expected Δv_{coll}^2
20 m/s	2500 $vphpl$	0.19	15.1 m^2/s^2
30 m/s	2500 $vphpl$	0.32	12.6 m^2/s^2
40 m/s	2500 $vphpl$	0.39	12.1 m^2/s^2

Figure J.8: Platoons with 5 m Intra-platoon Spacing: Safety at Different AHS Speeds
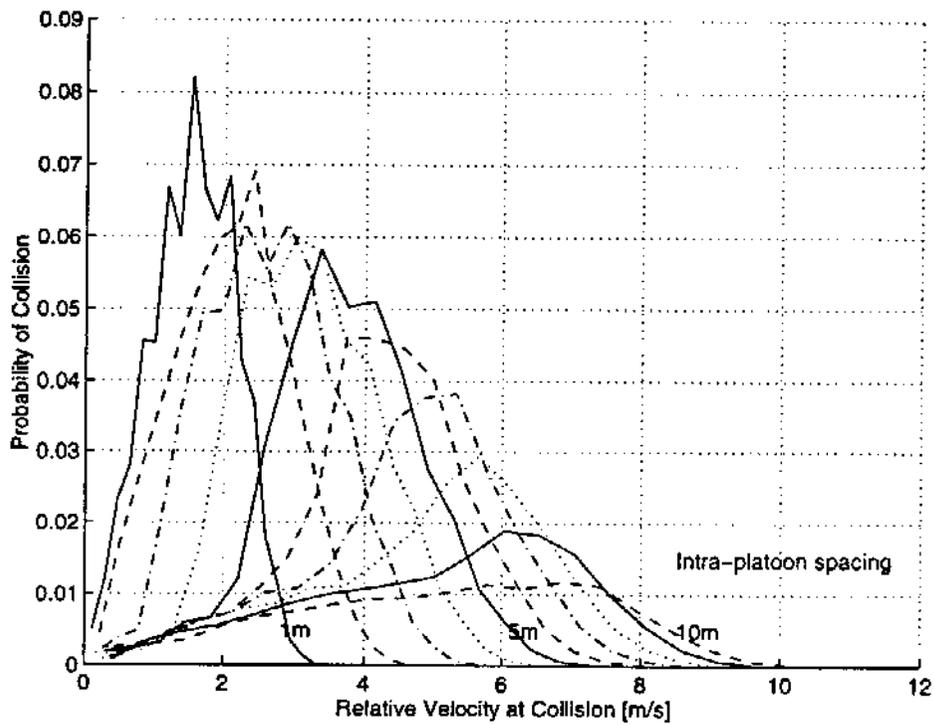
Intra-platoon spc	Total Prob of Collision	Expected Δv_{coll}^2
1 m	0.68	2.77 m^2/s^2
2 m	0.59	5.03 m^2/s^2
3 m	0.52	7.79 m^2/s^2
4 m	0.45	11.2 m^2/s^2
5 m	0.38	15.1 m^2/s^2
6 m	0.31	19.4 m^2/s^2
7 m	0.26	23.5 m^2/s^2
8 m	0.21	27.1 m^2/s^2
9 m	0.16	30.0 m^2/s^2
10 m	0.13	31.7 m^2/s^2

Figure J.9: Platoon Safety at Different Intra-platoon Spacings at 20 m/s
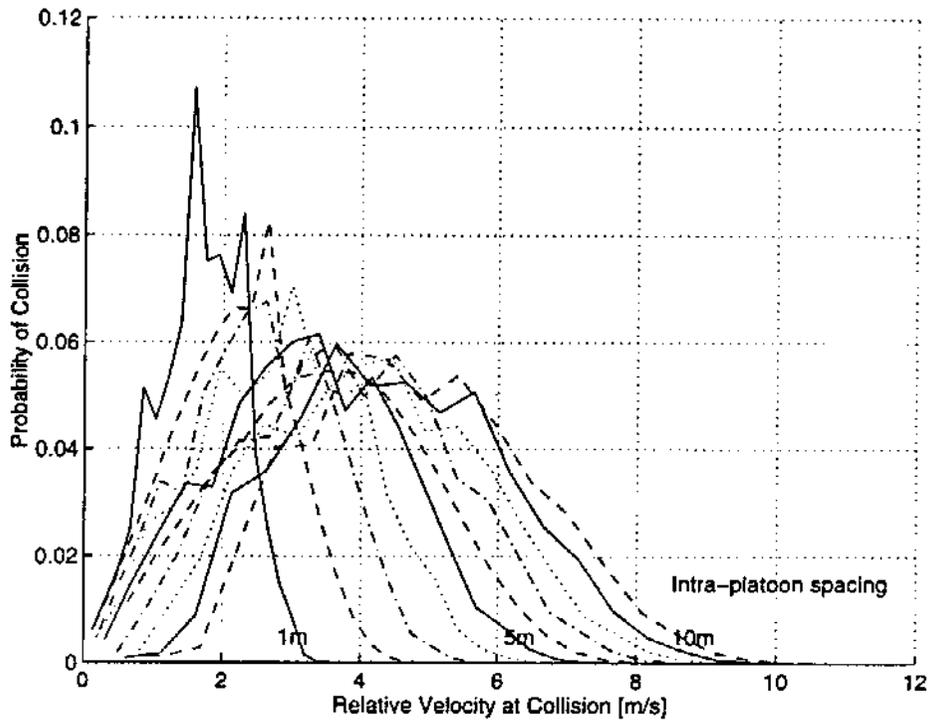
Intra-platoon spc	Total Prob of Collision	Expected Δv_{coll}^2
1 m	0.78	3.14 m^2/s^2
2 m	0.65	5.29 m^2/s^2
3 m	0.60	7.52 m^2/s^2
4 m	0.57	9.77 m^2/s^2
5 m	0.56	12.1 m^2/s^2
6 m	0.54	14.5 m^2/s^2
7 m	0.52	17.1 m^2/s^2
8 m	0.50	20.0 m^2/s^2
9 m	0.49	22.9 m^2/s^2
10 m	0.47	26.1 m^2/s^2

Figure J.10: Platoon Safety at Different Intra-platoon Spacings at 40 m/s
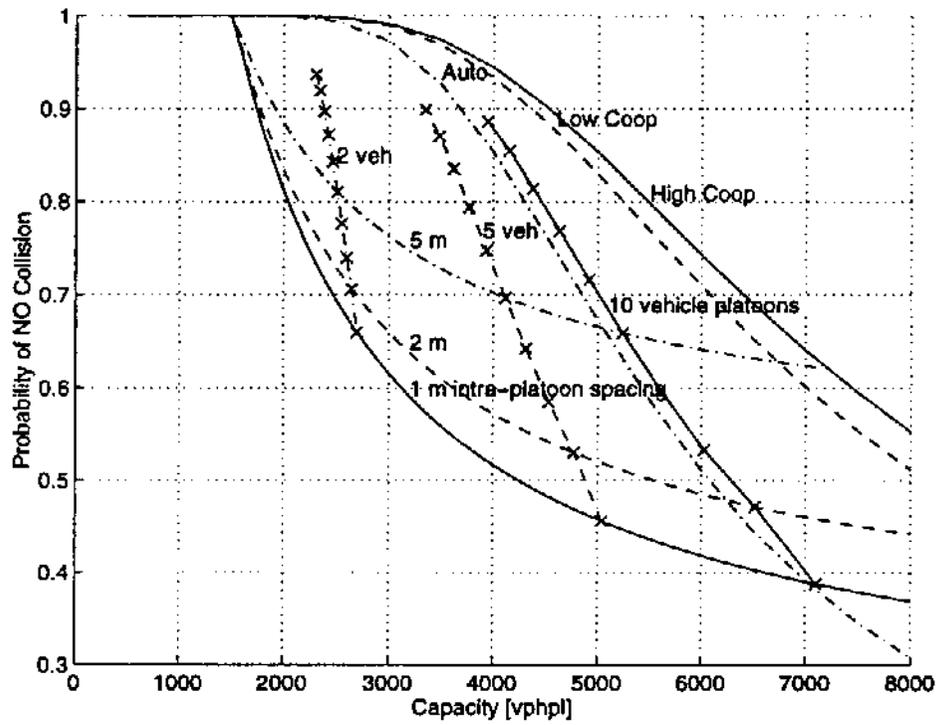
Figure J.11: The Safety/Capacity Relationship for all Attribute Combinations at 20 m/s: Frequency Metric
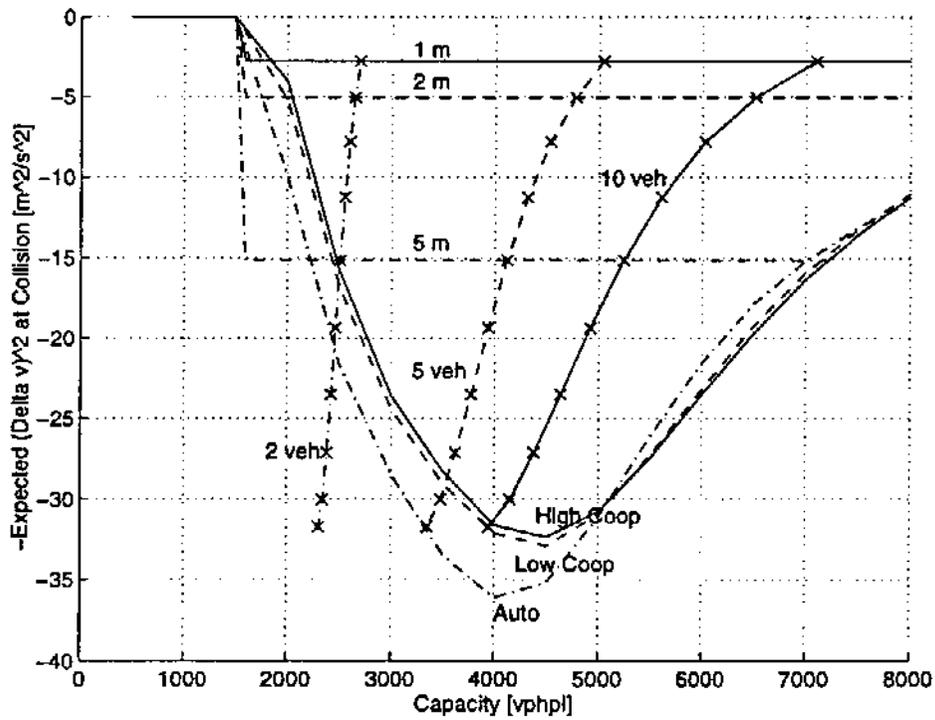
Figure J.12: The Safety/Capacity Relationship for all Attribute Combinations at 20 m/s: Severity Metric
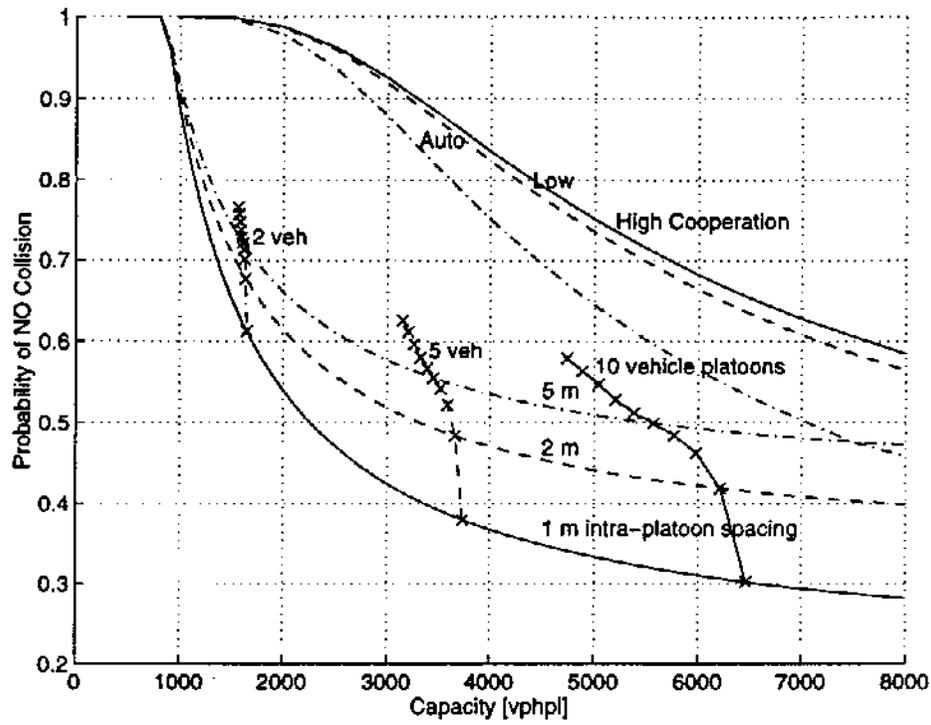
Figure J.13: The Safety/Capacity Relationship for all Attribute Combinations at 40 m/s: Frequency Metric
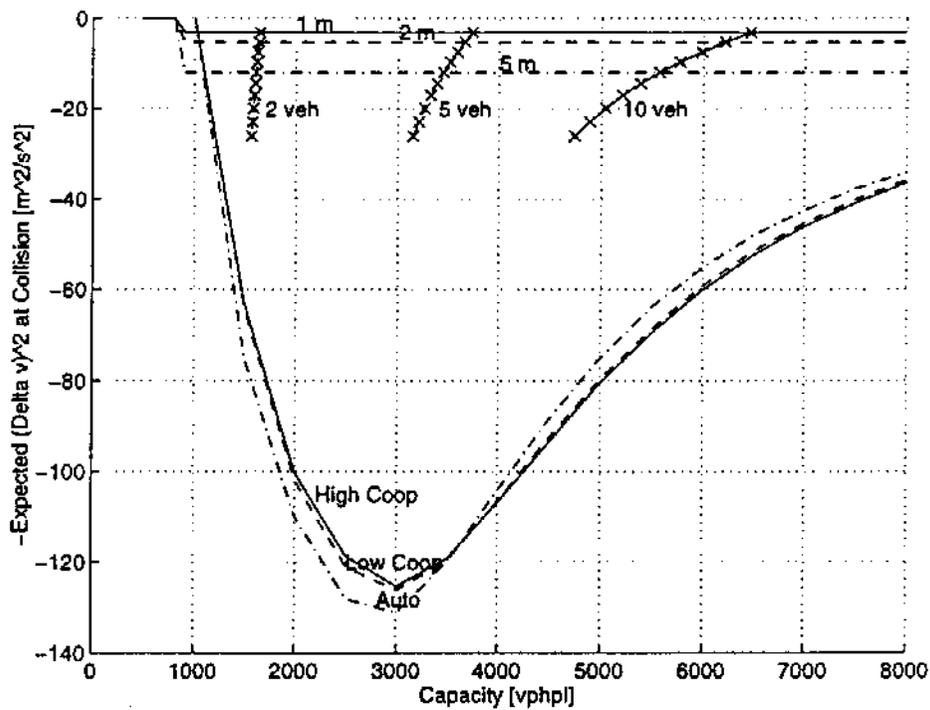

Figure J.14: The Safety/Capacity Relationship for all Attribute Combinations at 40 m/s: Severity Metric

Appendix K. Obstacle Avoidance Analysis Method and Detailed Results

K.1 Overview / Introduction

One of the more difficult issues in designing the Automated Highway System is what to do about obstacles. These range from mufflers, to tire treads from 18 wheelers, to vehicles with no communication which are stopped in traffic lanes. One approach is to attempt to exclude as many obstacles as possible using infrastructure enhancements such as barriers, chain link fences, and inspection of vehicles entering the system. This could potentially exclude many obstacles, allowing AHS vehicles to be designed with reduced obstacle detection and avoidance capabilities. Another approach is to give AHS vehicles the capability to detect, recognize and avoid any obstacle large enough to do unacceptable damage, and a third approach is to include obstacle detection sensors as part of the roadway infrastructure. Combinations are also possible.

Purpose of this Analysis

The purpose of this analysis is to determine the effect of increased vehicle cooperation on obstacle avoidance performance. The safety of two lane change techniques, one more and one less complex, as well as hard braking, is examined. The performance of the three techniques is analyzed as a function of speed, sensor update time, obstacle size, and range to the obstacle. A qualitative assessment of the communication bandwidth required to support the different obstacle avoidance techniques is also made.

K.2 Obstacle Avoidance Scenario

Roadway and Vehicles

The scenario which was chosen to evaluate obstacle avoidance strategies has two dedicated lanes with individual (not platooned) vehicles moving in the same direction. Traffic in the left lane moves 2.2 meters per second (5 mph) faster than that in the right lane due to vehicles entering into and exiting from the right lane. The AHS lanes are assumed to be operating at near capacity, with vehicles in both lanes separated by the minimum safe headway for braking, given the lane speed. Relative position of the vehicles in the right and left lanes, an important consideration for lane changing, is regarded probabilistically, with all geometries taken as equally likely. This is based on the assumption that the two lanes cannot be kept aligned due to the speed differential.

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Obstacle Characteristics

The obstacle is assumed to be stationary, with a specified diameter and mass. The relationship between size and mass is set by assuming that the obstacle is roughly spherical and composed of granite.

Vehicle Sensors and Communication

All vehicles are assumed to have forward-looking sensors capable of detecting a 0.3 meter (12 in) diameter obstacle at 100 meters (330 ft), and measuring range to the obstacle, azimuth of the obstacle, and size of the obstacle. All vehicles are assumed to have position information on all nearby vehicles, either from on-board sensors, or communicated from the infrastructure, or directly from the other vehicles.

K.3 Obstacle Avoidance Building Blocks

The three obstacle avoidance strategies discussed later in this paper have in common certain elements which might be thought of as "building blocks." This section introduces these elements, which are central to constructing an obstacle avoidance strategy for the AHS.

Braking

Two levels (or ranges) of braking are assumed to be available for obstacle avoidance. The first, referred to as "hard braking," is the maximum longitudinal deceleration of which the vehicle is capable, consistent with any lateral acceleration or deceleration which is required at the time. This typically ranges from 70% to 100% of the vehicle's maximum capability in the absence of lateral acceleration or deceleration. The second level of braking is referred to as "light braking." It is used when there is substantial uncertainty about whether the obstacle is in the path of the vehicle. Its purpose is to reduce vehicle speed in preparation for hard braking, while minimizing the discomfort to the passengers and the effect on throughput.

Gap Alignment

Gap alignment is the first phase of a lane change. It is done by the right lane vehicles accelerating or decelerating longitudinally, depending on whether they lead or lag the left lane vehicles, and the left lane vehicles either doing the opposite or maintaining speed. Gap alignment ends when the two vehicles are separated longitudinally by the minimum safe distance, or MSD (see Figure K-1). This minimum safe longitudinal distance is the smallest separation which is acceptable during an emergency maneuver, and is much smaller than the spacing required for safe braking during routine operation. If the vehicle in the right lane happens to be alongside a gap in the left lane when the maneuver starts, then gap alignment is already completed.
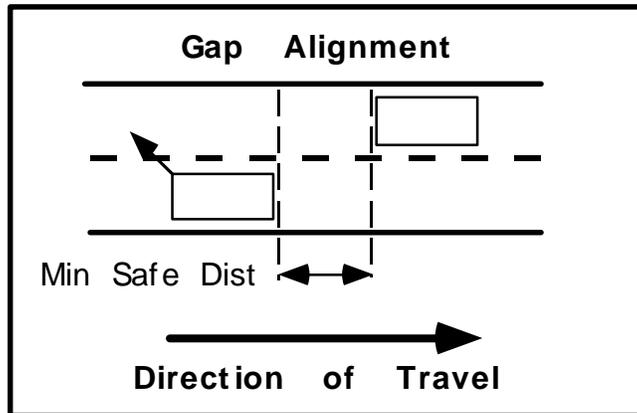
Figure K-1. Gap Alignment.

Merging

Merging is the second phase of a lane change. Merging begins while gap alignment is still taking place, and is timed so that gap alignment achieves the minimum safe distance between vehicles just as overlap occurs. Overlap is when the left edge of the right lane vehicle lines up with the right edge of the left lane vehicle (see Figure K-2). The merge phase ends when the left and right edges of the vehicles are aligned. Vehicle separation, however, is monitored in the model until the speed of the vehicle merged in from the right lane is the same as that of the left lane vehicles.
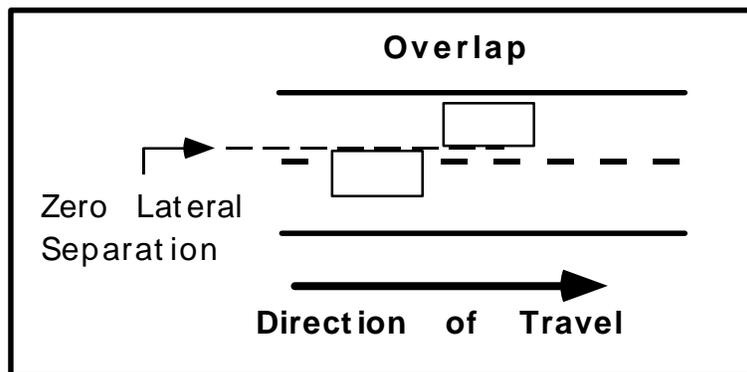
Figure K-2. Overlap.

Case 1 vs. Case 2 Lane Change

Lane changes are referred to as Case 1 or Case 2, depending on whether gap alignment is achieved by the right lane vehicles decelerating or accelerating (see Figures K-3 and K-4, respectively). The arrows on the vehicles in the diagrams indicate movement relative to the normal traffic flow. Case 1 is the more conservative maneuver if substantial uncertainty about obstacle position exists, since the right lane vehicles reduce speed, decreasing the ΔV of a collision should the maneuver fail (ΔV is the change in speed of a vehicle at the moment of collision). However, at most speeds and spacings a Case 1 lane change is not possible from all right/left lane geometries, so Case 2 must be used also. Whether Case 1 or Case 2 maneuvers predominate will depend on the relative speed of the two lanes in which the maneuver starts and finishes.
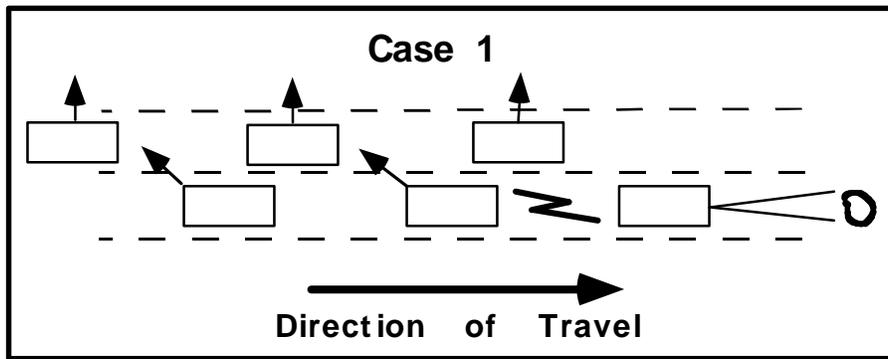
Figure K-3. Geometry of Case 1 Lane Change.
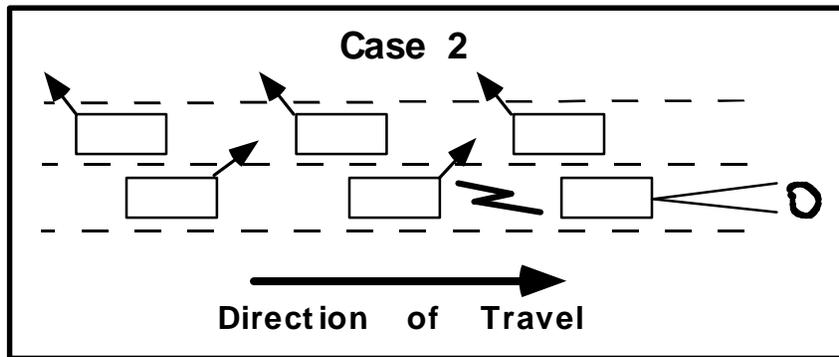
Figure K-4. Geometry of Case 2 Lane Change.

K.4 Obstacle Avoidance Strategies

Using the obstacle avoidance "building blocks" discussed in Section K.3, a set of three obstacle avoidance strategies was assembled for analysis. These range from full lane change, with relatively high coordination and data exchange between vehicles, to braking, where the vehicles can operate autonomously if needed.

Full Lane Change

"Full lane change" is a combination of Case 1 and Case 2 lane changes. In order for full lane change to be feasible at a specified range to the obstacle, it must be possible to do either a Case 1 or a Case 2 lane change from any right/left lane vehicle geometry (Figure K-5, darkest shading). If, for any given speed/spacing combination, there are ranges to the obstacle at which lane changing can be done from only a subset of vehicle geometries (Figure K-5, medium shading), then the obstacle avoidance function will select a combination of lane changing and braking as the obstacle avoidance strategy.
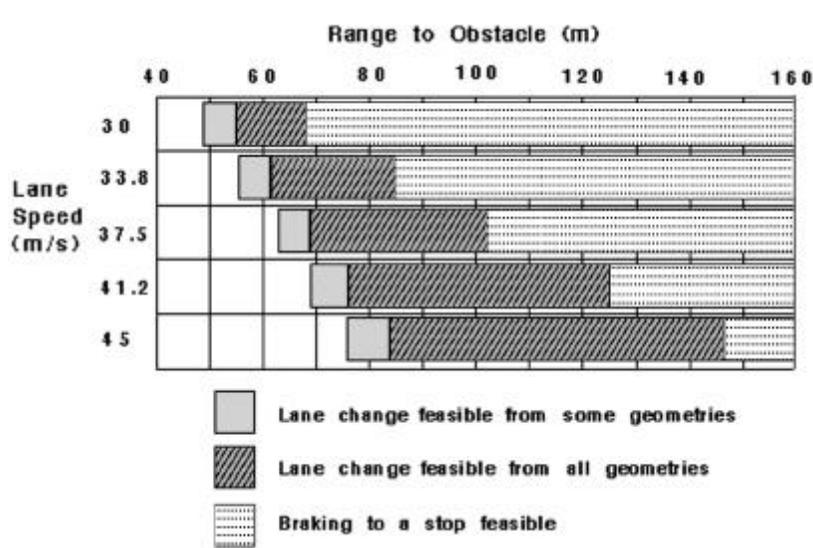
Figure K-5. Feasible Ranges for Lane Changing and Braking to Avoid Obstacle.

For most speeds and spacings, both Case 1 and Case 2 lane changes are needed to cover lane changing from all right/left lane geometries. When both are feasible, the system chooses the one with the lower expected ΔV.

Full lane change can require coordination and real-time decision-making among as many as seven vehicles – a maximum of three in the right lane executing the avoidance maneuver, and a maximum of four in the left lane being merged into. Obstacle position, vehicle positions, speeds, maximum acceleration and deceleration capabilities, and messages assigning and confirming each participant's role must be passed between vehicles and to/from the infrastructure, if it takes part, very quickly. Consequently, full lane change has the highest bandwidth requirements of the three obstacle avoidance techniques discussed here.

Braking

Braking is the simplest of the obstacle avoidance techniques. It requires no knowledge of adjacent vehicle positions and only limited coordination with other vehicles in the same lane. It is also less sensitive than lane changing to knowledge of obstacle position. Braking is also the most effective technique for reducing collision ΔV at ranges so short there is insufficient distance either to change lanes or to brake to a stop.

Hybrid Lane Change

"Hybrid lane change" uses a combination of Case 1 lane changing and braking, providing an alternative to a braking-only strategy for obstacle avoidance in AHS architectures which support low data rates. Since there may be insufficient distance to complete a Case 1 lane change, hard braking is done when it will result in a lower expected ΔV.

Hybrid lane changing requires only that vehicles know the position of other nearby vehicles and the range to the obstacle. The position of nearby vehicles is expected to be available from on-board sensors. Since a maximum of three right lane vehicles are expected to be involved, it is expected that each vehicle can receive the "range to obstacle" message sent by the prior vehicle, add its forward spacing, and rebroadcast the message without excessive delay. Because hybrid lane changing is not required to succeed from all right/left lane geometries in order to be considered feasible at a given range, it can be the strategy of choice at slightly shorter ranges than full lane changing.

K.5 Braking and Lane Change Protocols

Overview of Obstacle Avoidance Protocols

The obstacle avoidance function's knowledge of whether there is an obstacle in the roadway, and where it is located, is based on a series of sensor measurements. The longer the obstacle avoidance function (OAF) has to observe a potential obstacle, the better its information on whether the object represents a threat, and where it is located. This suggests that, rather than a single decision point at which the OAF decides to do obstacle avoidance or not, a decision tree is needed in which the OAF makes sequential decisions based on information which it continues to update even while executing the last action

chosen. This decision tree, and the geometric basis for choosing the next action, will be referred to here as the obstacle avoidance "protocol."

Protocol Zones

A series of longitudinal zones has been created on the two dedicated AHS lanes assumed for this study (see Figure K-6). These zones are imaginary subdivisions of existing lane width for the purpose of decision-making; they do not require the pouring of additional concrete. The three exclusion zones which have been added are buffers which reduce the likelihood that small position estimation errors will have high ΔV consequences. More information on how the zones are used is given in the Protocol Action Sequences section below. Note that the composition of the shoulders (e.g., sand, gravel, loose dirt) on some interstate highways makes them potential locations for an obstacle without necessarily providing safe access for a vehicle performing an avoidance maneuver at highway speeds.
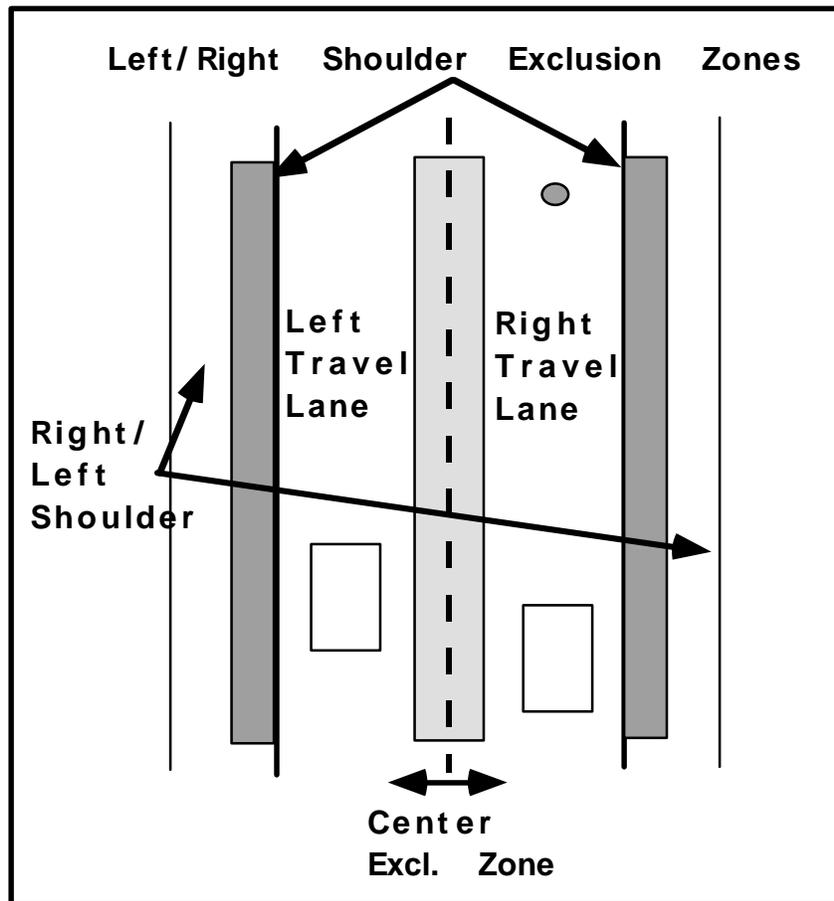
Figure K-6. Obstacle Avoidance Protocol Geometry.

Protocol Decision Times

The current protocol design uses three decision times. T_0 is the first of the three. At T_0, the obstacle has already been acquired and has been in track for about 15 meters. T_0 is defined as the last time at which lane changing can be initiated. Light braking (prior to the actual obstacle avoidance maneuver) may have already occurred.

T_1 is the last time at which a lane change maneuver can be safely aborted. T_1 usually falls about halfway through the time period available for obstacle avoidance. The current protocol supports the choice of three alternative actions at T_1 (see Figure K-7). T_1 is the last time at which lateral acceleration can be changed.

T_2 is the final decision time, and usually occurs about midway between T_1 and T_f, which is the time at which the vehicle reaches the obstacle position. Protocol options at T_2 are typically to continue the action chosen at T_1, or to do hard braking if the updated estimate of obstacle position makes the former a poor choice.
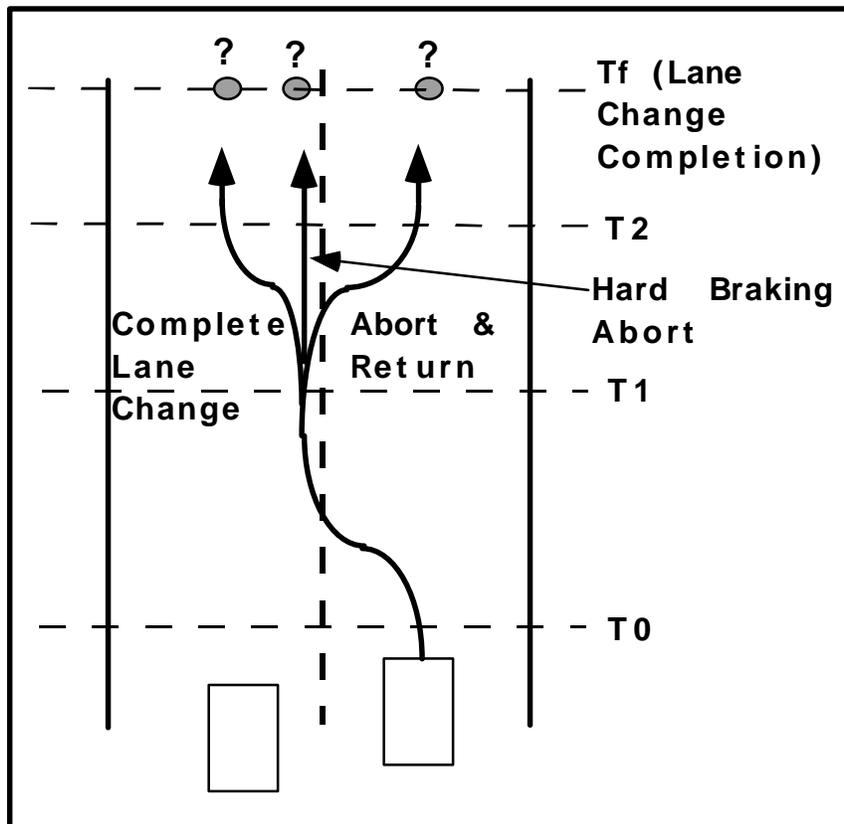
Figure K-7. Lane Change Decision Times.

Protocol Action Sequences

When viewed as a whole, the sequence of actions for each obstacle avoidance strategy (lane changing and hard braking) chosen successively at T_0, T_1, and T_2 form a decision tree with twelve branches (see Figure K-8). For any given scenario, each branch of the decision tree is characterized by a probability that this series of actions will be chosen, and by an expected ΔV if this series of actions is chosen. The probability is computed from the conditional probabilities of the sequence of actions given a particular obstacle location (zone), weighted by the likelihood of the obstacle being located in each zone. The conditional probability of an action, given a particular obstacle location (zone), is really just the probability that the estimated obstacle position will be in zone i, given that the true obstacle location is in zone j. The set of actions for which conditional probabilities are computed is derived from the Protocol Action Matrix, given the decision time and the estimated vehicle and obstacle position.
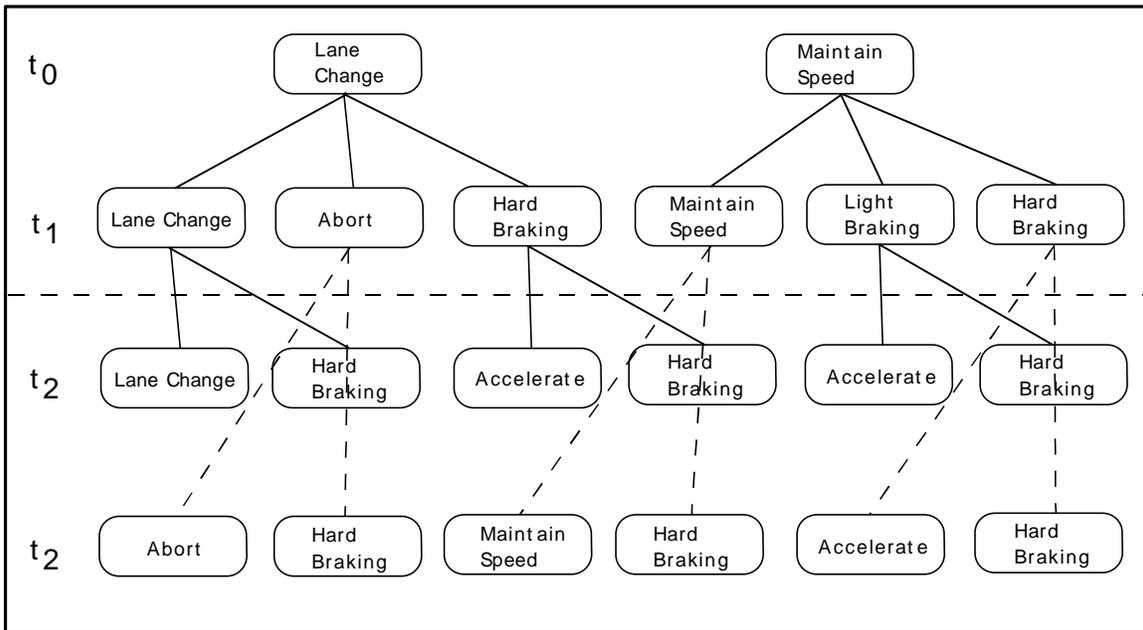
Figure K-8. Lane Changing Protocol Decision Tree
(dotted lines are for visibility of text only).

Figure K-9 gives the braking and lane changing protocol actions as a function of the decision time and the protocol zone in which the obstacle's estimated position falls. The action codes are as listed below:

MS – Maintain speed   AC – Accelerate
HB – Hard braking   LC – Lane change maneuver
LB – Light braking   AB – Abort (lane change maneuver)

Braking Protocol							
Time	Previous Activity	Left Shoulder	LS Excl Zone	Left Travel Lane	Center Excl Zone	Right Travel Lane	RS Excl Zone	Right Shoulder
t0	None	MS	MS	MS	MS/HB	HB	HB	MS
t1	MS or HB	MS	MS	MS	LB	HB	LB	MS
t2	LB or HB	AC	AC	AC	HB	HB	HB	AC
t2	MS	MS	MS	MS	HB	HB	HB	MS
Lane Changing Protocol							
Time	Previous Activity	Left Shoulder	LS Excl Zone	Left Travel Lane	Center Excl Zone	Right Travel Lane	RS Excl Zone	Right Shoulder
t0	None	MS	MS	MS	LC	LC	LC	MS
t1	LC	LC	AB	AB	HB	LC	LC	LC
t1	MS	MS	MS	MS	LB	HB	LB	MS
t2	LC	LC	HB	HB	HB	LC	LC	LC
t2	MS	MS	MS	MS	HB	HB	HB	HB
t2	AB	AB	AB	AB	HB	HB	HB	AB
t2	LB or HB	AC	AC	AC	HB	HB	HB	AC

Figure K-9. Protocol Action Matrix.

K.6 Modeling Assumptions

Physical Characterization of Vehicles

Vehicles are characterized as light passenger vehicles (car/pickup/van), trucks, or buses. Each type is characterized by a length, width, mass, maximum longitudinal acceleration and deceleration (two numbers), and maximum lateral acceleration/deceleration (one number). At any moment, each vehicle in the model has a position, speed and acceleration in the x and y directions. Accelerations are constant and can change instantaneously (there are no jerk limits). Vehicles in the model do not roll, pitch, or yaw.

Physical Characterization of Obstacle

A small, dense object like a granite boulder was chosen as the obstacle for this study because it represents the most challenging obstacle avoidance problem. While the expected ΔV's are fairly small numbers, even the smallest obstacle studied, which was .3 meters (12 in) in diameter, is large enough to disable most light passenger vehicles. Preliminary analyses using a stopped vehicle as the obstacle indicate that this is a less challenging problem for AHS (though the collisions are more destructive), and that the results are consistent with those for the smaller obstacles. The obstacle was characterized in the model by its mass and diameter. Mass and diameter are related by assuming that the obstacle is a sphere composed of granite.

Sensor Model

As mentioned above, the obstacle sensor was assumed to have sufficient range to acquire the object 15 meters (49 ft) before the range required for a full lane change, which was 100 meters (328 ft) or less for the speeds studied. By T_0, it is assumed that the object has been classified as an obstacle in the roadway, and that it has been in track for the amount of time the vehicle takes to travel 15 meters (49 ft). No missed detections are modeled, and the variation of signal-to-noise with object size and range to the object is ignored in this simple sensor model.

The sensor model is not specific to a particular technology. The sensor (or sensor suite) is assumed to measure range, azimuth, and object size. Measurements are assumed to be unbiased with known Gaussian measurement errors.

Tracker Model

For simplicity, the tracker model is one-dimensional (cross-range motion only). The object is tracked in position and velocity; acceleration is assumed to be zero. Tracking error estimates are based on the covariance errors for an alpha-beta filter. For those unfamiliar with alpha-beta filters, they may be described as a recursive implementation of least squares (see N. Levine, "A New Technique for Increasing the Flexibility of Recursive Least Squares Data Smoothing," *The Bell System Technical Journal*, May 1961).

Calculation of Expected DV

ΔV, or the change in speed of a vehicle at the moment of collision, was chosen as the safety metric for this analysis. ΔV is a good measure of the destructive force of a collision. The ΔV's included in the results are of two types. For the braking results, all the ΔV's represent the initial collision between the obstacle and the first vehicle to reach it. Because of the mass of the obstacles and the vehicle spacing used in the analysis, there are no secondary (vehicle-to-vehicle) collisions. For the lane changing results, the ΔV's represent the secondary collision between the vehicle striking the obstacle, and the

vehicle following it. In all the cases analyzed, this ΔV dominates the ΔV from the primary (obstacle-to-vehicle) collision. For example, with the right lane traffic moving at 30 meters per second (67 mph) and a range to the obstacle of 55 meters (180 ft) at the beginning of the maneuver, the initial collision with a .3 meter (12 inch) obstacle produces a ΔV of 0.6 meters per second (1.3 mph). If this is ignored, as is done in the model, but it is assumed that the lead vehicle does hard braking, then the collision between the first and second vehicles produces a ΔV of 4.8 meters per second (10.74 mph), which is modeled. There are no further collisions beyond the ones modeled, due to the mass of the obstacle and the vehicle spacings analyzed.

The expected ΔV's which are the performance measure of the obstacle avoidance techniques analyzed here are root mean squared (RMS) sums of the ΔV's for each protocol decision tree alternative, weighted by the probability of that alternative. This metric was chosen because it represents a less controversial alternative to the AIS injury model (see Anthony Hitchcock, "Intelligent Vehicle/Highway System Safety: Multiple Collisions in Automated Highway Systems," *California PATH Research Report UCB-ITS-PRR-95-10*, April 1995). The AIS model is a statistical relationship between collision ΔV, and the injuries and fatalities resulting from the accident. It is attractive because it is one of the few ways of translating the physics of a crash (i.e., speed differential) into the human consequences such as injury and loss of life. The problem with using the AIS model directly is that it is dated – it does not take into account the benefits of airbags and other recent safety improvements. Consequently, the figures produced by the AIS model would almost certainly be misleading. The RMS sums of ΔV's have an exponential structure similar to the AIS model. An added bonus for using this metric is that although it is somewhat complex computationally, it has an intuitive interpretation as a weighted average.

K.7 Results

This section presents the results of modeling runs showing the performance of the three obstacle avoidance strategies. Values of the input parameters most critical to the modeling are given in Table K-1, with the names of dependent parameters listed in italics.

Obstacle avoidance performance is modeled as a function of speed, sensor period, obstacle size, and range to the obstacle. In each run three of these four are held at their nominal value, and one of the four is varied. The nominal values of these four parameters appear in Table K-1 in bold type.

Table K-1. Important Modeling Parameters.

Parameter Name	Units English (metric)	Value in English Units	Value in Metric Units
Right lane speed	mph (m/s)	**67** to 100	30 to 45
Left lane speed	mph (m/s)	right lane + 5	right lane + 2.2
Spacing	ft (m)	**54** to 110 **	16.5 to 33.5
Throughput	veh/lane/hr	4600 to 5600	same
Range to obstacle	ft (m)	**180** to 492 **	55 to 150
Max. long. decel	g's	.75	same
Max. lateral accel./decel.	g's	.3	same
Max. long. accel.	g's	.1 to .15 **	same
Long. decel. for "light braking"	g's	.2	same
Vehicle mass	lbs (kg)	4405	2000
Obstacle diameter	in (m)	**12** to 22	.3 to .55
Obstacle mass	lbs (kg)	88 to 517	38 to 235
Sensor update rate	msec	25 to 150 (**50**)	same
Sensor range standard deviation	percent	1.0	same
Sensor azimuth standard deviation	degrees	0.5	same

** Varies with speed.

Because the resulting performance values will vary with changes in the scenario and assumptions, the conclusions accompanying each run are phrased in qualitative rather than quantitative terms to the extent possible. They necessarily remain somewhat dependent on the choice of scenario and on the assumptions chosen for this study, however.

Figure K-10 shows the performance of the three obstacle avoidance strategies as a function of speed. The x-axis (forward) is the speed of the right lane; the left lane is 2.2 meters per second (5 mph) faster. The z-axis (vertical) is the expected cost of collisions in the obstacle scenario described above expressed as ΔV^2; less is safer. The y-axis (right) lists the three obstacle avoidance strategies. The ΔV numbers are very small because they include the probability that no crash occurred. One can draw two conclusions from this plot – 1) At low to medium speeds braking is the preferred obstacle avoidance technique because it is just as safe as lane changing, and requires less coordination; 2) At higher speeds, the two lane changing techniques are substantially safer than braking.
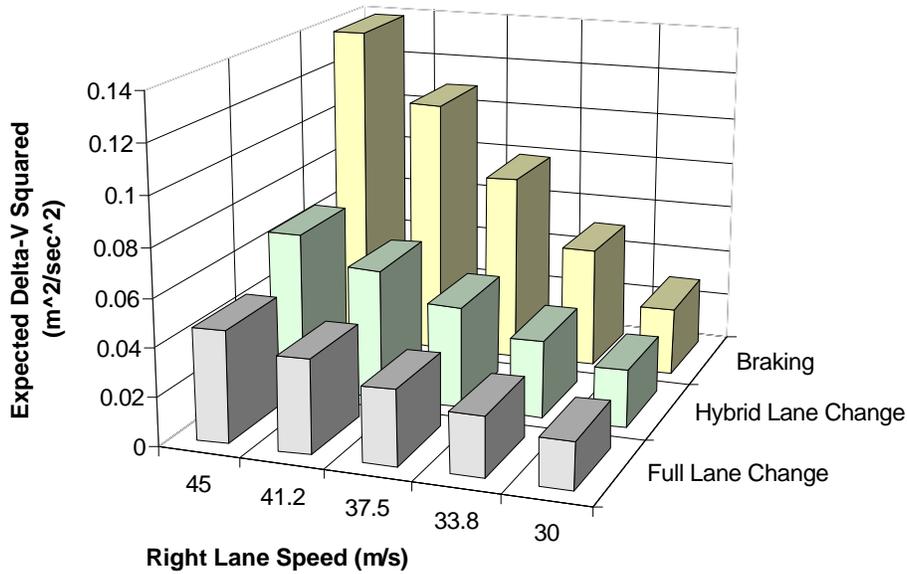
Figure K-10. Obstacle Avoidance Performance vs. Speed.

Figure K-11 shows the performance of the three obstacle avoidance strategies as a function of sensor update period. The x-axis (forward) is sensor period, or update rate. The z-axis (vertical) is the expected cost of collisions expressed as ΔV^2; less is safer. The y-axis (right) lists the three obstacle avoidance strategies. Braking safety performance is almost independent of sensor update rate, making braking a good choice for slower (or less accurate) sensors. Lane changing safety performance improves noticeably with sensor update rate. Although the exact crossover point between braking and lane changing will change with the scenario, full lane change does well with faster, more accurate sensors.
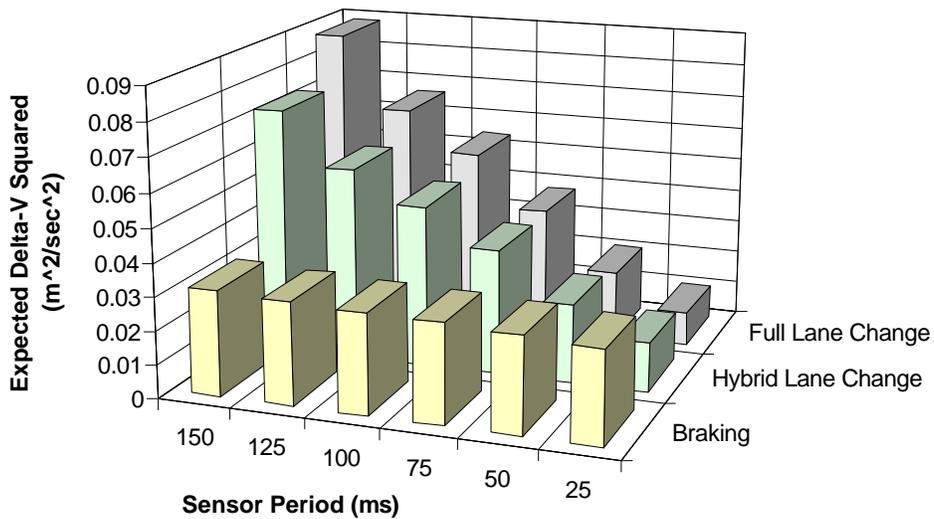
Figure K-11. Obstacle Avoidance Performance vs. Sensor Update Period.

Figure K-12 shows the performance of the three obstacle avoidance strategies as a function of obstacle size (diameter and mass). The x-axis (forward) is the obstacle diameter in meters. The z-axis (vertical) is the expected cost of collisions expressed as ΔV^2; less is safer. The y-axis (right) lists the three obstacle avoidance strategies. The analysis shows that lane changing is significantly safer against medium-sized obstacles. Against small obstacles, the performance of braking and lane changing is approximately equal.
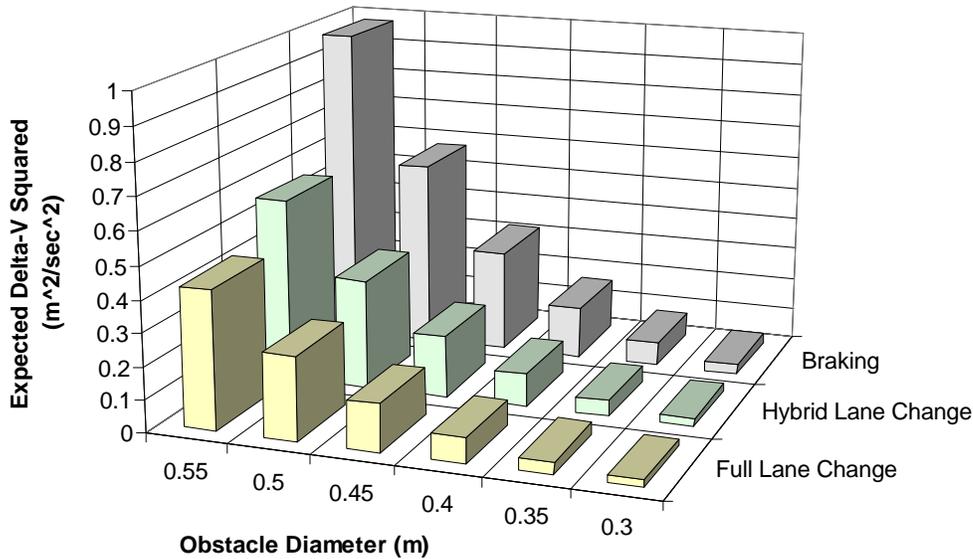

Figure K-12. Obstacle Avoidance Performance vs. Obstacle Size.

Figure K-13 shows the performance of the three obstacle avoidance strategies as a function of range to the obstacle at the initial decision time (T_0). The x-axis (forward) is the range to the obstacle. The z-axis (vertical) is the expected cost of collisions expressed as ΔV^2; less is safer. The y-axis (right) lists the three obstacle avoidance strategies. The magnitude of the ΔV numbers is very small because they include the probability that no crash occurred. This plot shows that although lane changing is frequently superior to braking in terms of safety, that advantage decreases as range to the obstacle increases. Consequently, lane changing is the preferred obstacle avoidance strategy when the obstacle is detected at (or at somewhat greater than) the minimum range required for lane changing; braking is the preferred solution if the obstacle is detected at substantially greater range. This optimal "range band" for lane changing does expand with speed, however, and at 45 meters per second (90 mph) encompasses several times the distance that it does at 30 meters per second (67 mph).
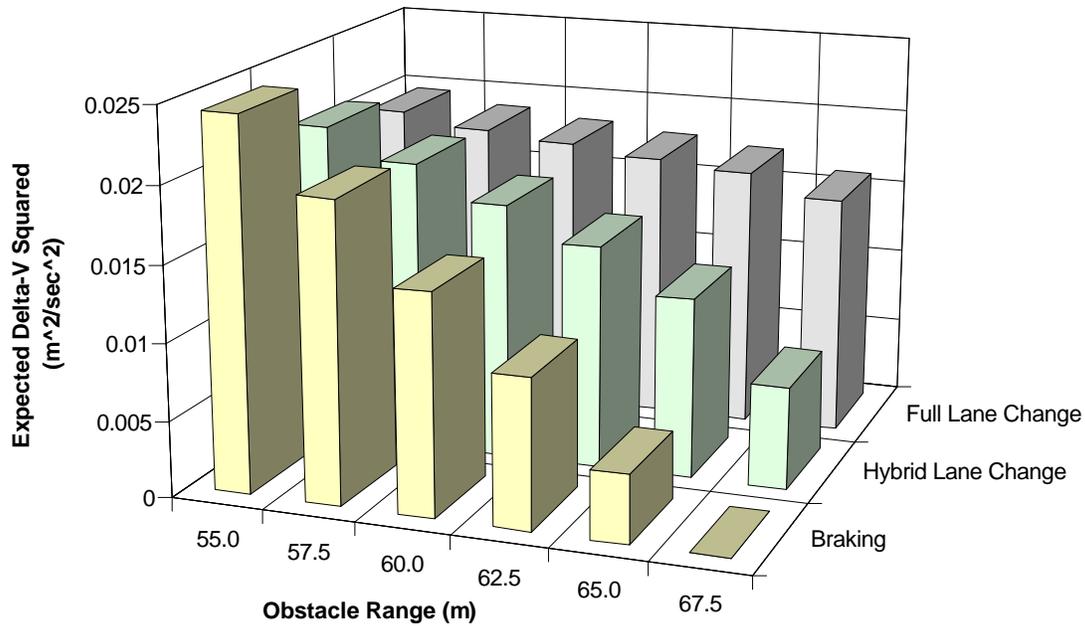
Figure K-13. Obstacle Avoidance Performance vs. Range to Obstacle.

K.8 Conclusions

The optimal choice of obstacle avoidance strategy for the Automated Highway System depends on speed, right/left lane geometry, range to obstacle, and other scenario-specific conditions. An obstacle avoidance function which is able to choose among full lane changing, hybrid lane changing, and hard braking in real time will be safer (have a lower expected ΔV) than one which is limited to a subset of these strategies.

One can also draw some general conclusions about the strengths of the three obstacle avoidance techniques which were analyzed:

Full lane changing is a good choice for obstacle avoidance –
        • against medium to large obstacles (or)
        • at medium to high speeds (or)
        • with more accurate sensing

Hybrid lane changing is a good choice for obstacle avoidance –
        • at ranges too short for full lane changing (or)
        • in architectures where communication capability is limited

Hard braking is a good choice for obstacle avoidance –
        • against small obstacles (and)
        • with less accurate sensing (and)
        • at low speeds (and)
        • at ranges to the obstacle too short for other techniques.

Appendix L.   Infrastructure Cost Analysis Method And Detailed Results

L.1   Introduction

This Appendix reports on the development of a general order-of-magnitude cost estimate for the addition of a dedicated AHS lane to an existing freeway infrastructure. Assessments were performed for generic application scenarios for AHS operation in the urban, inter-city, and rural environments. The same scenarios are also being used in other AHS modeling activities.

This report details the cost estimating methodology, the analyses, and the results.

L.2   Cost Estimating Premises

The scope of the analyses centers around hypothetical cases that were created for each of the three operating environments (urban, inter-city, and rural). Cost estimates were generated for each application scenario and include only standard civil and structural construction costs. Right-of-way (ROW) costs are also provided. These estimates, however <u>do not include</u> any systems infrastructure, communications, or control systems costs. Operations and maintenance costs are also not included.

L.2.1   Application Scenarios

Because of time constraints associated with gathering real site data, hypothetical application scenarios were created instead of using "real world" cases. At the same time, these hypothetical cases were based on "real world" data in several regions across the country.

It should be noted that, for simplification, the alignments for the hypothetical layouts are assumed to be linear, with no horizontal curves. The rationale is that most freeways are constructed with sufficient radii of curvature so that horizontal curvature is not a limiting factor in design. With regards to vertical curvature, grades were not fully developed on the assumption that it is not a concept discriminator. All vertical curvature is assumed to be of sufficient standard to ensure adequate sight distances and meet AASHTO (and state DOTs) recommended minimums for appropriate crossing structure, vertical clearance, etc. The following paragraphs describe the base conditions for each region.

l.2.1.1 Urban Base Conditions

The base case configuration for the urban application scenario consists of a 25-mile (40 km) corridor through a medium-dense urban environment with four lanes in each direction, with 21 arterial interchanges, and two regional (freeway-to-freeway) interchanges. The urban core is assumed to be near the center of the segment.

Average spacing between arterial interchanges is approximately 1 mile. Interchanges are standard AASHTO configurations with a mixture of diamonds, cloverleafs, and partial cloverleafs. Standard acceleration and deceleration rates and lengths are used. All interchanges have full movements. Every third arterial interchange has dual entry ramps, with dual exit ramps at the next interchange. The segment begins and ends with major freeway-to-freeway interchanges to other urban freeways. In the middle of the segment, another major interstate freeway interchanges with the alignment. This results in an average spacing between freeway-to-freeway interchanges of roughly 11 miles (17.6 km).

The eight-lane interstate highway has standard 12-foot lane widths with standard 10-foot outside shoulders and a 2-foot inside shoulder. Standard Jersey-type barriers are used to separate the two opposing directions. The various application cases for this urban alignment are detailed in Section L.2.2.

Due to the congested nature of most urban environments, it was assumed that room to expand within the existing ROW is not available, and 100 percent acquisition of new ROW would be necessary at a price of $15 per square foot. Sensitivity tests were performed for 50 percent ROW acquisition and for a ROW cost of $25 per square foot.

Investigated cases included converting an existing lane into a dedicated AHS lane as well as adding a new lane for AHS use without taking a lane away.

Figure L-1 depicts this base case alignment.

L.2.1.2 Inter-City Base Conditions

The inter-city corridor is an interstate highway that also links two major urban centers. The area of study starts and ends at the suburban edges of the urban areas. The corridor is heavily traveled, providing traffic flow for commerce exchange, long distance commuting, and recreational trips. The base case configuration for the inter-city application scenario consists of a 74-mile (119 km) freeway corridor with three lanes in each direction, 20 arterial interchanges, and two freeway-to-freeway interchanges. Average spacing between freeway-to-freeway interchanges is roughly 20 miles (32 km). A median width of 20 feet has also been assumed.

Inter-city traffic demand was assumed to be less than for the urban scenario. Interchange spacing ranges from 2 to 5 miles. The arterial interchanges have standard diamond configurations.

This six-lane facility has standard 12-foot lanes with an 8-foot inside shoulder and 10-foot outside shoulder.

A 50 percent ROW acquisition was assumed at cost of $7.50 per square foot.
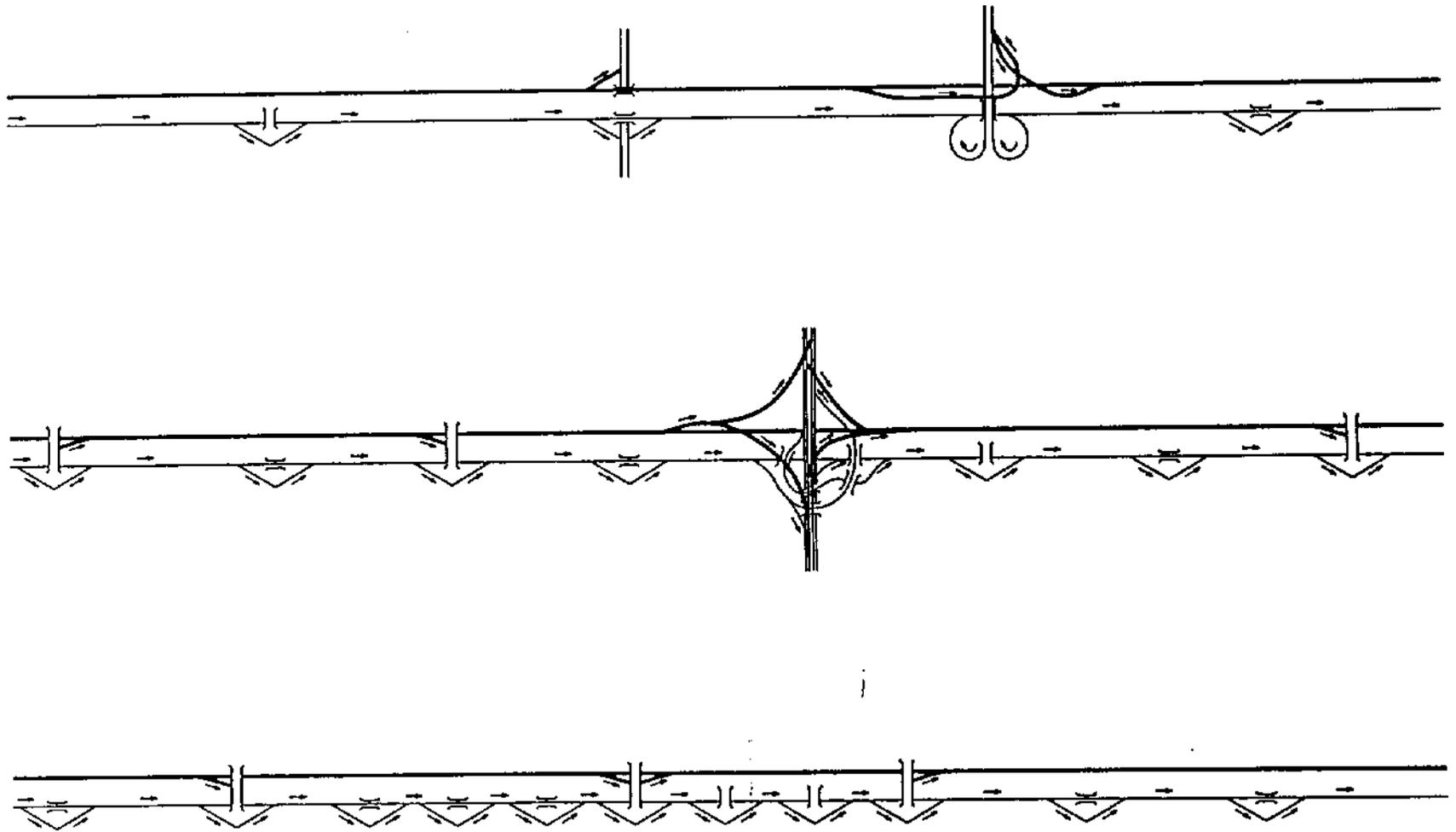
Figure L-1. AHS Urban Base Case Alignment.

L.2.1.3 Rural Base Conditions

The base case configuration for the rural application scenario consists of 296 miles (476 km) of a four-lane (two lanes in each direction) interstate rural highway with 20 interchanges. A 40-foot-wide median is also assumed. Both inside and outside shoulders measure 8 feet wide. Access is provided via existing interchanges, with spacings varying between 5 and 15 miles.

It was assumed that the existing ROW of this hypothetical facility would be wide enough to accommodate the addition of a dedicated AHS lane with no need for additional ROW.

L.2.2 Adaptation to AHS Operations

Various cases were generated for each of the three operating environments. These highway geometric configurations are based on current design standards. Section 7.0, Highway Configuration and Implementation Issues, documents the assumptions. Details regarding the configuration of each case follow for each operating environment.

L.2.2.1 Urban Cases

For the urban environment, five cases for retrofitting (either through replacement of a manual lane or the addition of a new lane) dedicated AHS lane operation were considered.

Urban Case 1. Convert one manual lane in each direction into an AHS-dedicated lane to be fed through seven new dedicated interchanges, with average spacing of 3.6 miles (5.7 km). Provide separate 8-foot breakdown lanes for each direction. Length of merge lane is assumed to be 1,400 feet (427 m) and the exit lane 500 feet (152 m). AHS traffic would utilize dedicated freeway-to-freeway interchanges. Figure L-2 depicts this cross-section.

Urban Case 2. Convert one manual lane in each direction into an AHS-dedicated lane to be fed through seven new dedicated interchanges, with average spacing of 3.6 miles (5.7 km). Provide a shared 12-foot breakdown lane in the median between the two AHS lanes. A variable barrier is used to separate the two opposing directions of travel (see Figure L-3).

Urban Case 3. Convert one manual lane in each direction into an AHS-dedicated lane where access is gained via existing interchanges and ramps, and using a "dedicated" transition lane between the manual and automated traffic. In addition, one 8-foot breakdown lane has been added in each direction to serve the AHS-dedicated lane.

EXISTING

MODIFIED

DEDICATED LANE -
DEDICATED ENTRY / EXIT RAMPS
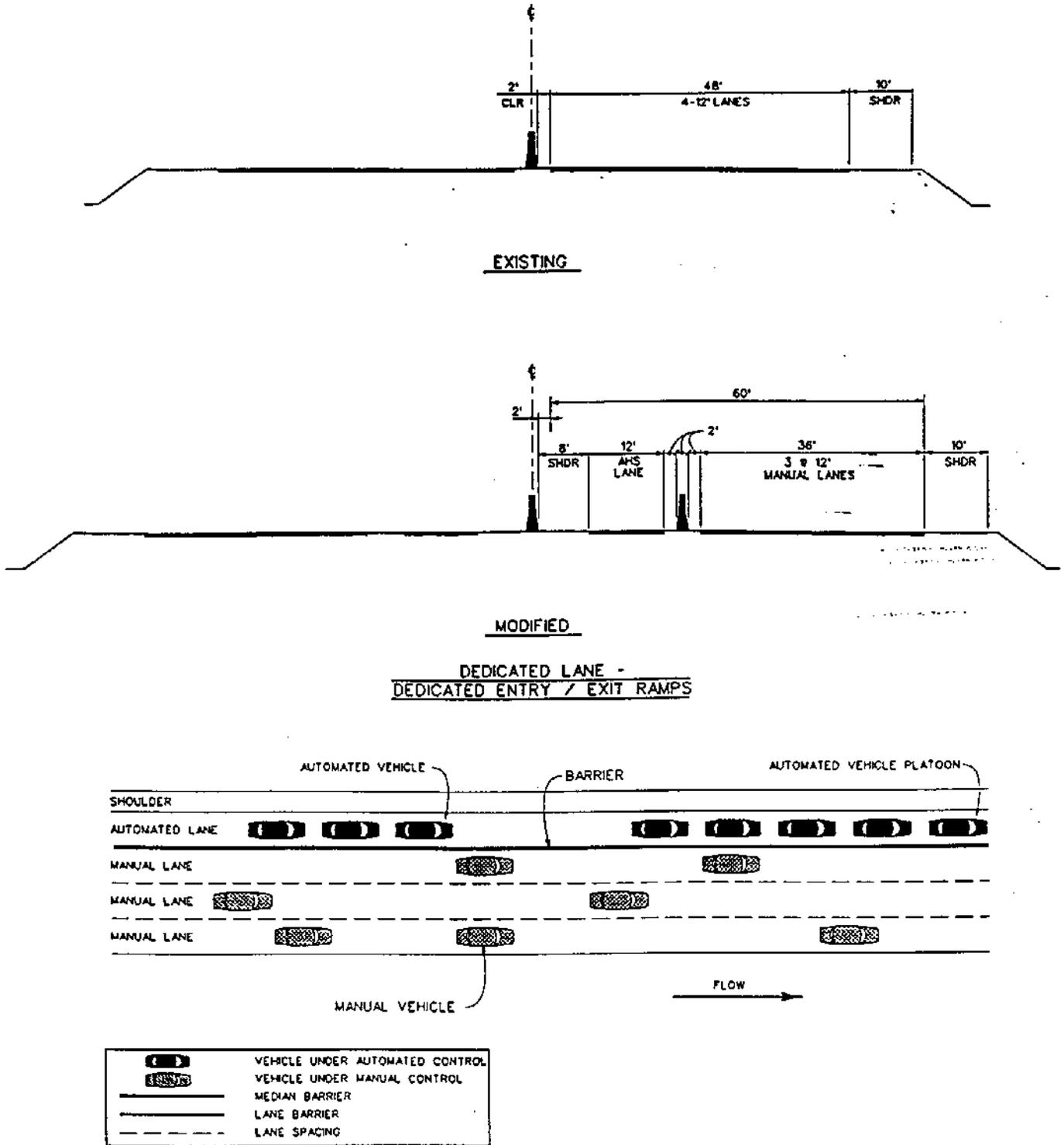
Figure L-2. AHS Operations - Urban Case 1.

EXISTING

MODIFIED

VARIABLE BARRIER
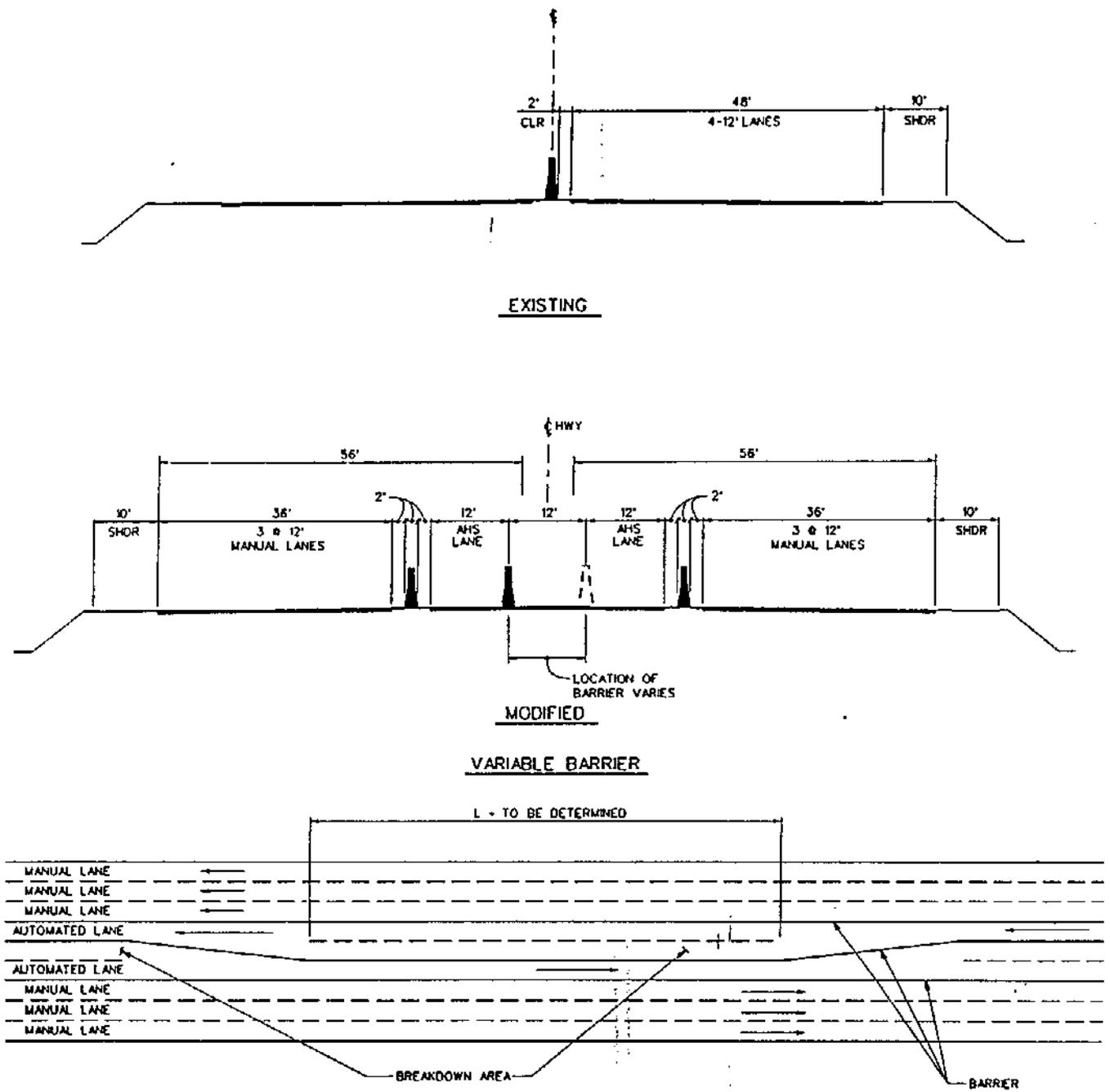
Figure L-3. AHS Operations - Urban Case 2.

Gaps are provided in the concrete barrier for access. These barriers run between the manual traffic lanes and the dedicated transition lane as well as between the transition lane and the dedicated AHS lane.

For access to another highway, special by-pass ramps are utilized prior to freeway-to-freeway interchanges (see Figure L-4) to accommodate the transition. These special ramps allow AHS traffic to merge with manual traffic before approaching the existing freeway-to-freeway interchanges. If an AHS vehicle wants to travel on the other freeway, it has to transition to manual operations via this special ramp and use the existing interchange. Once it completes travel on the interchange, another special ramp allows the vehicle to transition back into AHS mode. This eliminates the need to build a dedicated freeway-to-freeway interchange for AHS travel.

As seen in Figure L-4, the widening of the cross-section/ROW is necessary where these special by-pass ramps are located in order to accommodate the weaving AHS traffic. Figure L-5 depicts this roadway cross-section.

Urban Case 4. This case includes adding one dedicated AHS lane in each direction without taking away an existing manual traffic lane. Access is gained through seven dedicated interchanges at an average spacing of 3.6 miles (5.7 km). An 8-foot shoulder for breakdowns is also provided for each direction of travel.

Similar to Case 1, the length of the merge lane is assumed to be 1,400 feet (427 m) and the exit lane 500 feet (152 m).

Access to another freeway is gained via dedicated ramps through regional interchanges. Figure L-6 depicts this cross-section.

Urban Case 5. This is the same as Case 4, with the exception that 10-foot shoulders are maintained on either side of the dedicated AHS lane as well as the manual traffic lanes. (See Figure L-7).

Once again, access is gained through seven dedicated interchanges at an average spacing of 3.6 miles (5.7 km). An 8-foot shoulder for breakdowns is also provided for each direction of travel.

Similar to Case 1, the length of the merge lane is assumed to be 1,400 feet (427 m) and the exit lane 500 feet (152 m).

Access to another freeway is gained via dedicated ramps through regional interchanges.

DETAIL "A"

REGIONAL I/C

DETAIL "A"

DETAIL "A"

DETAIL "A"

URBAN APPLICATION

SHOWS EXIT OFF AHS

MANUAL

AHS

AHS

MANUAL

SHOWS ENTRANCE TO AHS
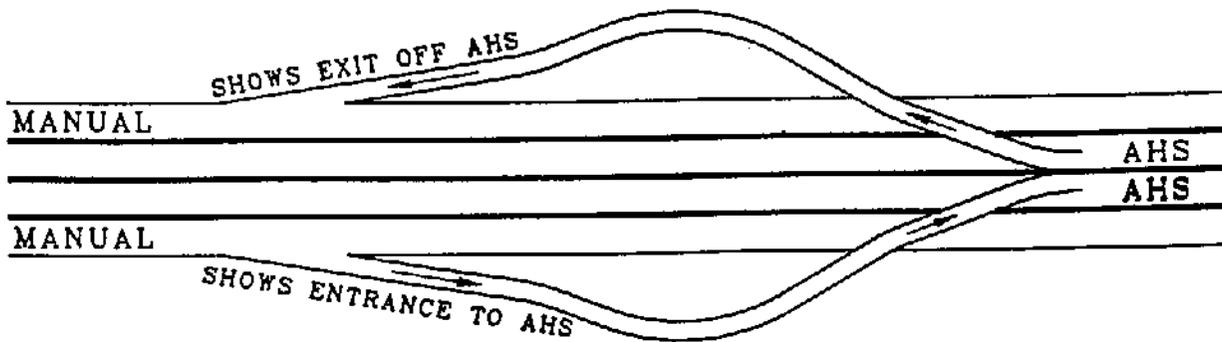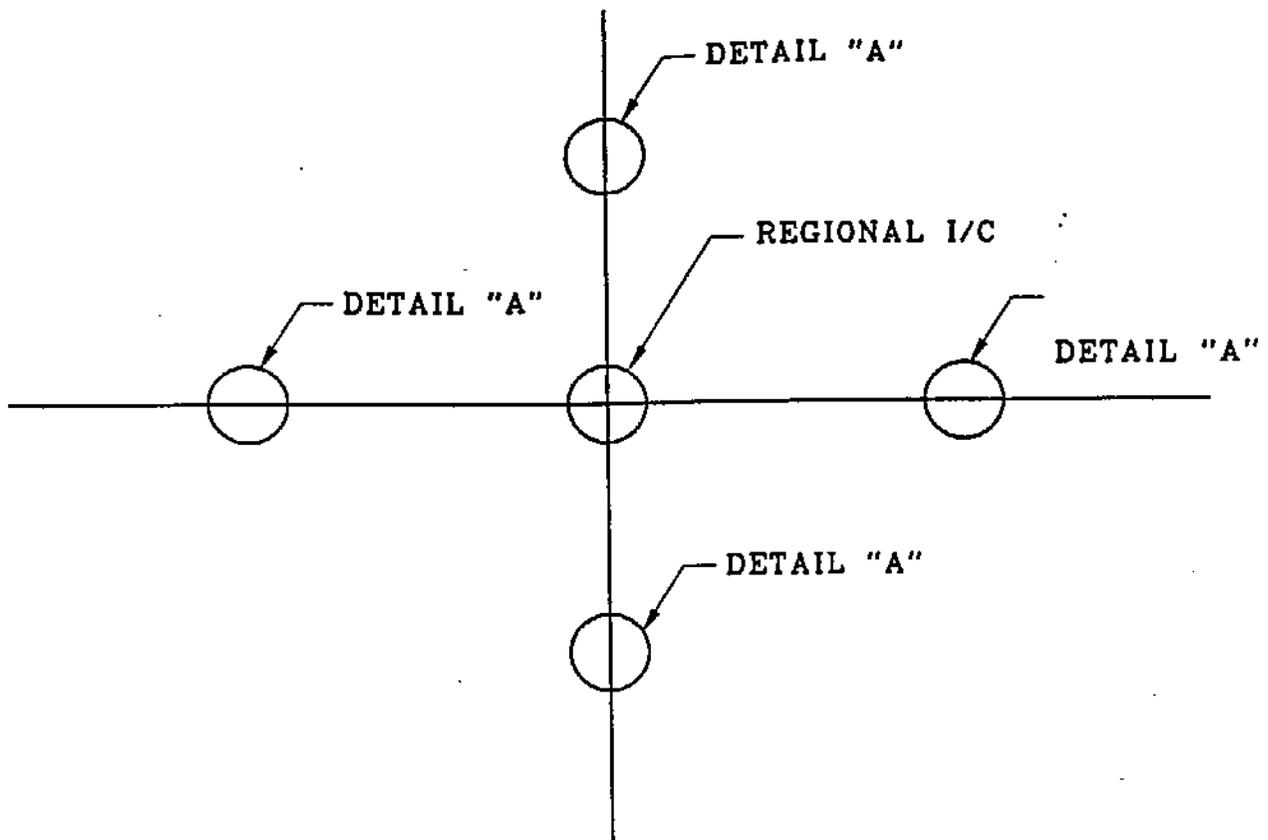
DETAIL A

Figure L-4. AHS Vehicles Changing Highways Merge with Manual Vehicles.

EXISTING

MODIFIED

DEDICATED LANE WITH TRANSITION LANE
COMMON ENTRY / EXIT RAMPS
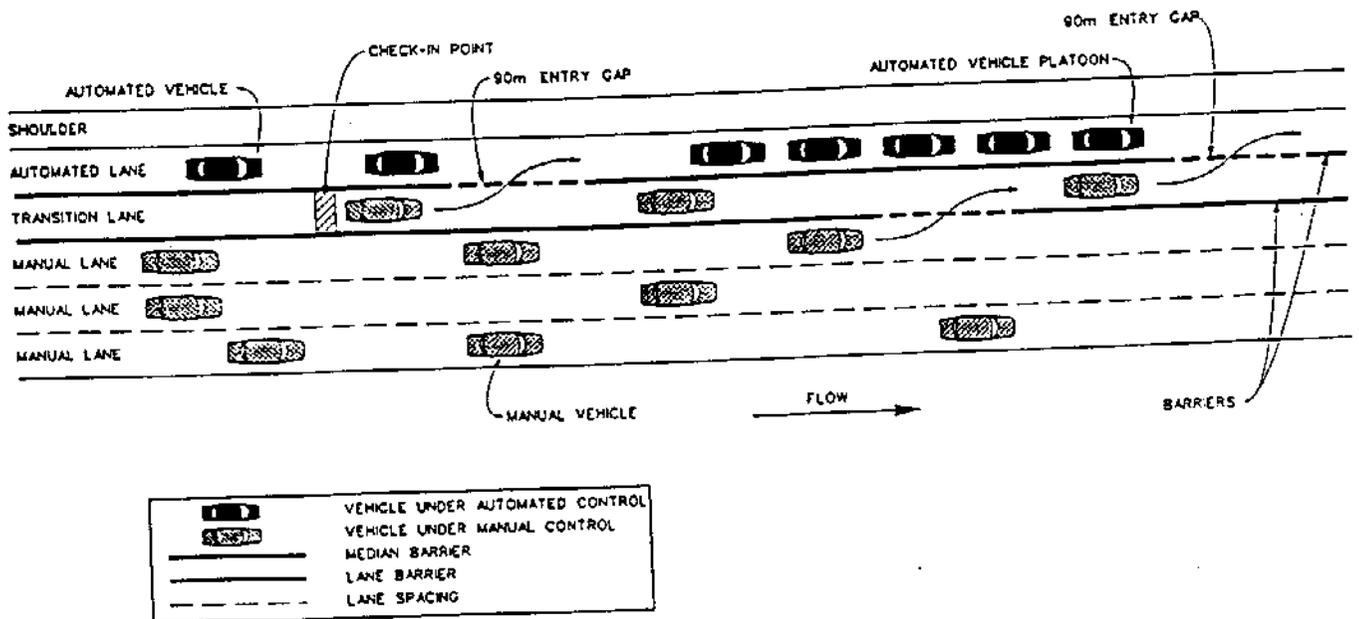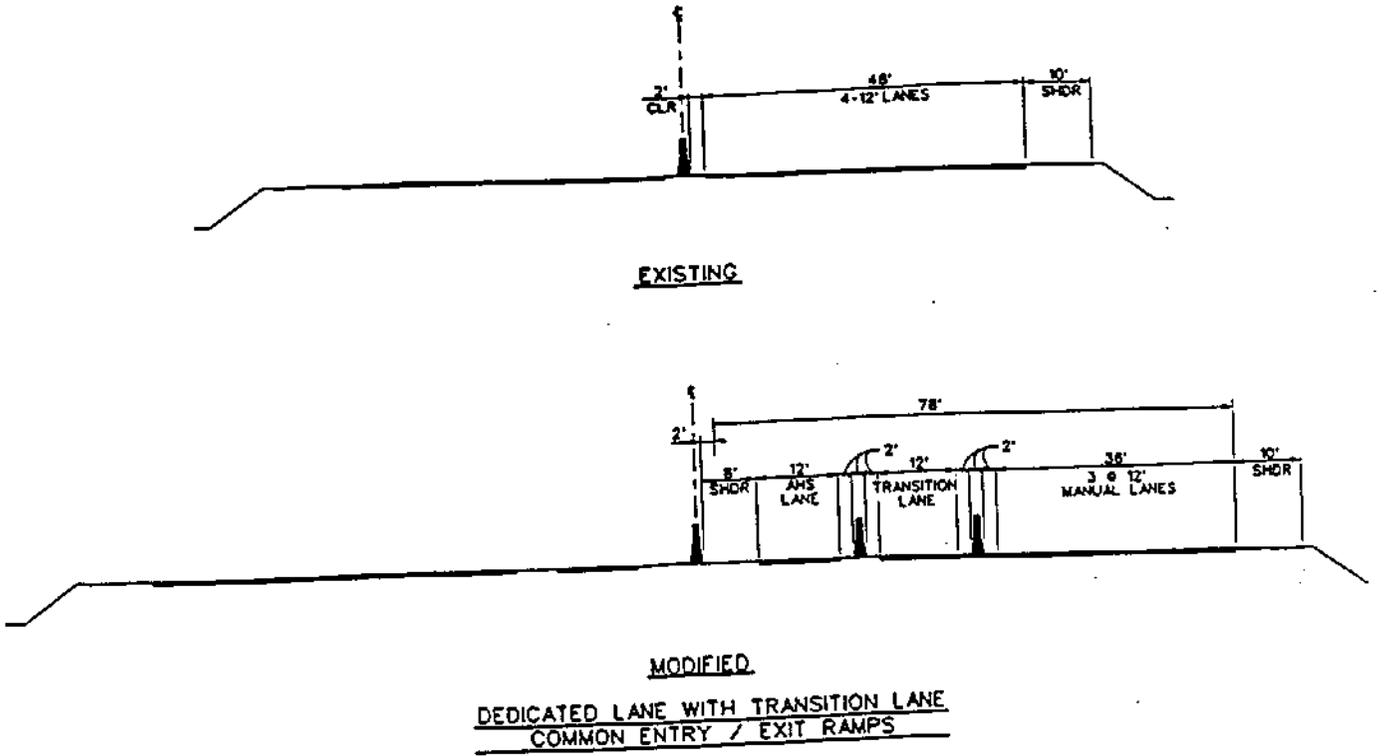
Figure L-5. AHS Operations - Urban Case 3.

EXISTING

MODIFIED
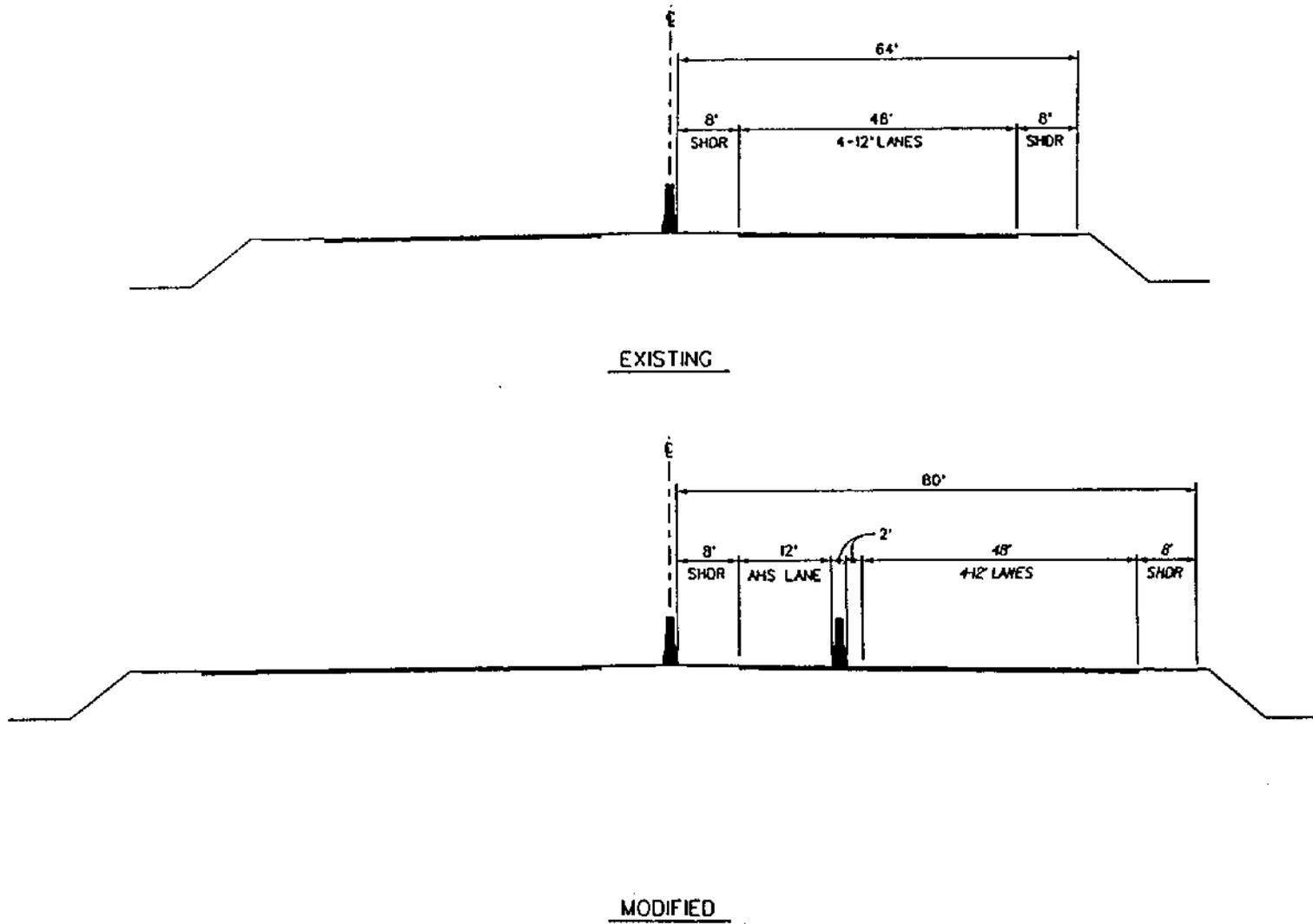
Figure L-6. AHS Operations - Urban Case 4.

EXISTING

61'

30'
ADD'L RIGHT OF WAY REQ'D

1' 2' 48'
CONVENTIONAL LANES
(4 EA X 12 FT)

10'
SHDR

MODIFIED

91'

1' 10'
SHDR

12'
AHS LANE

10'

2'
10'

36'
CONVENTIONAL LANES
(3 EA X 12 FT)

10'
SHDR
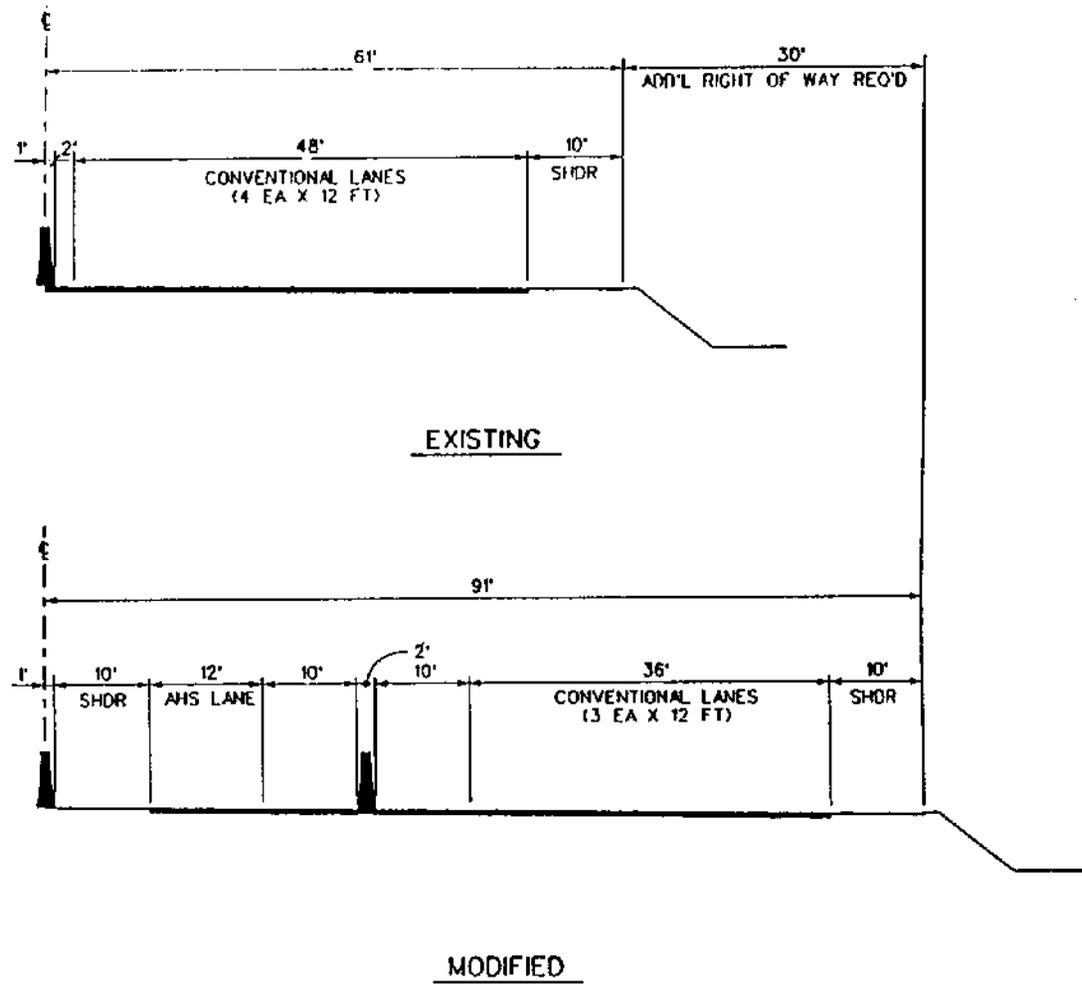
Figure L-7. AHS Operations - Case 5.

EXISTING

MODIFIED
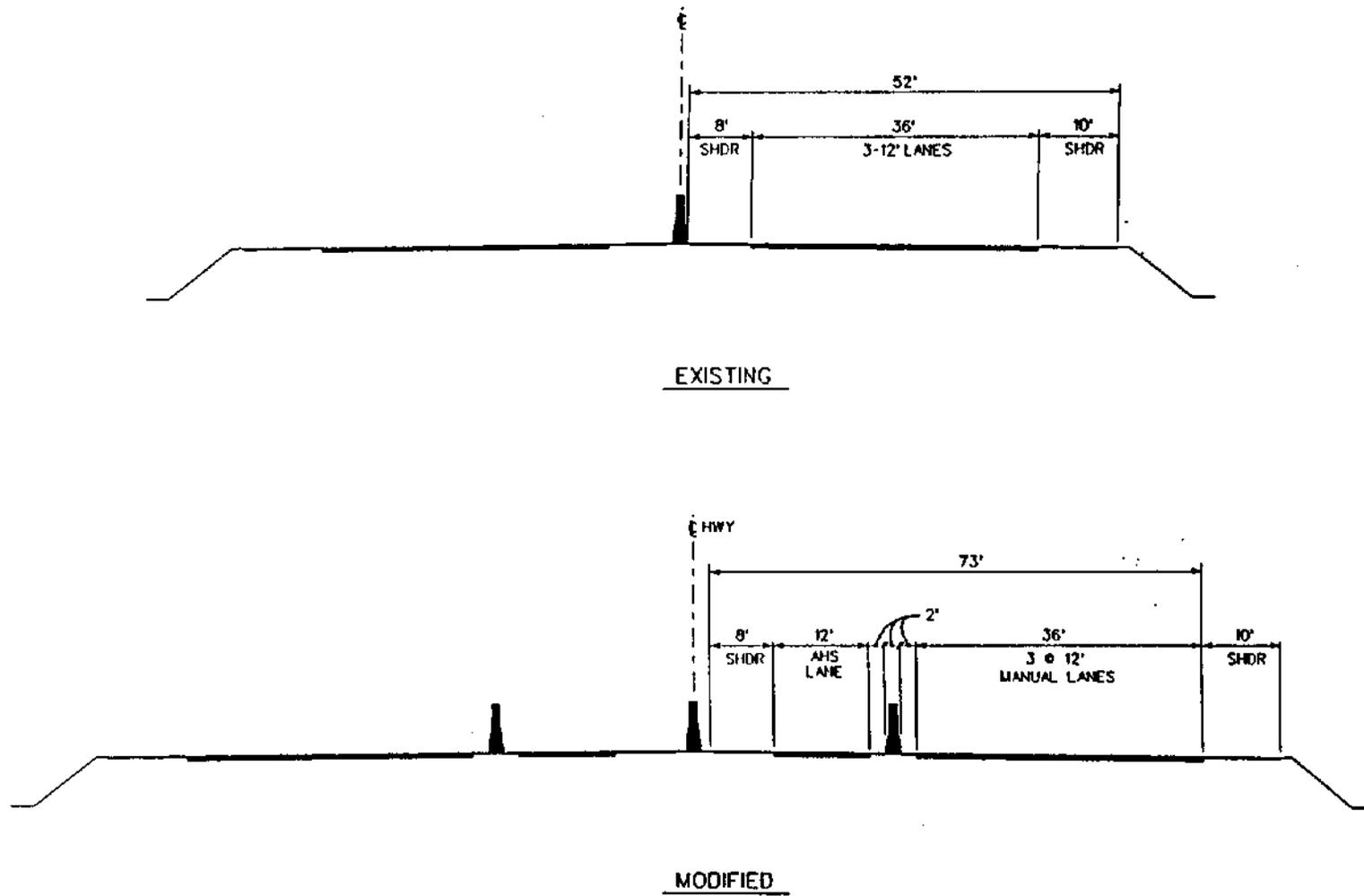
Figure L-8. AHS Operations - Inter-City Case.

EXISTING

8'	24'	8'
SHDR	2-12' LANES	SHDR

NO RIGHT OF
WAY REQUIRED

MODIFIED

8'	12'	4'	24'	10'
SHDR	AHS LANE		2-12' LANES	SHDR

ASSUME MEDIAN IS WIDE
ENOUGH THAT NO MEDIAN
BARRIER IS REQUIRED
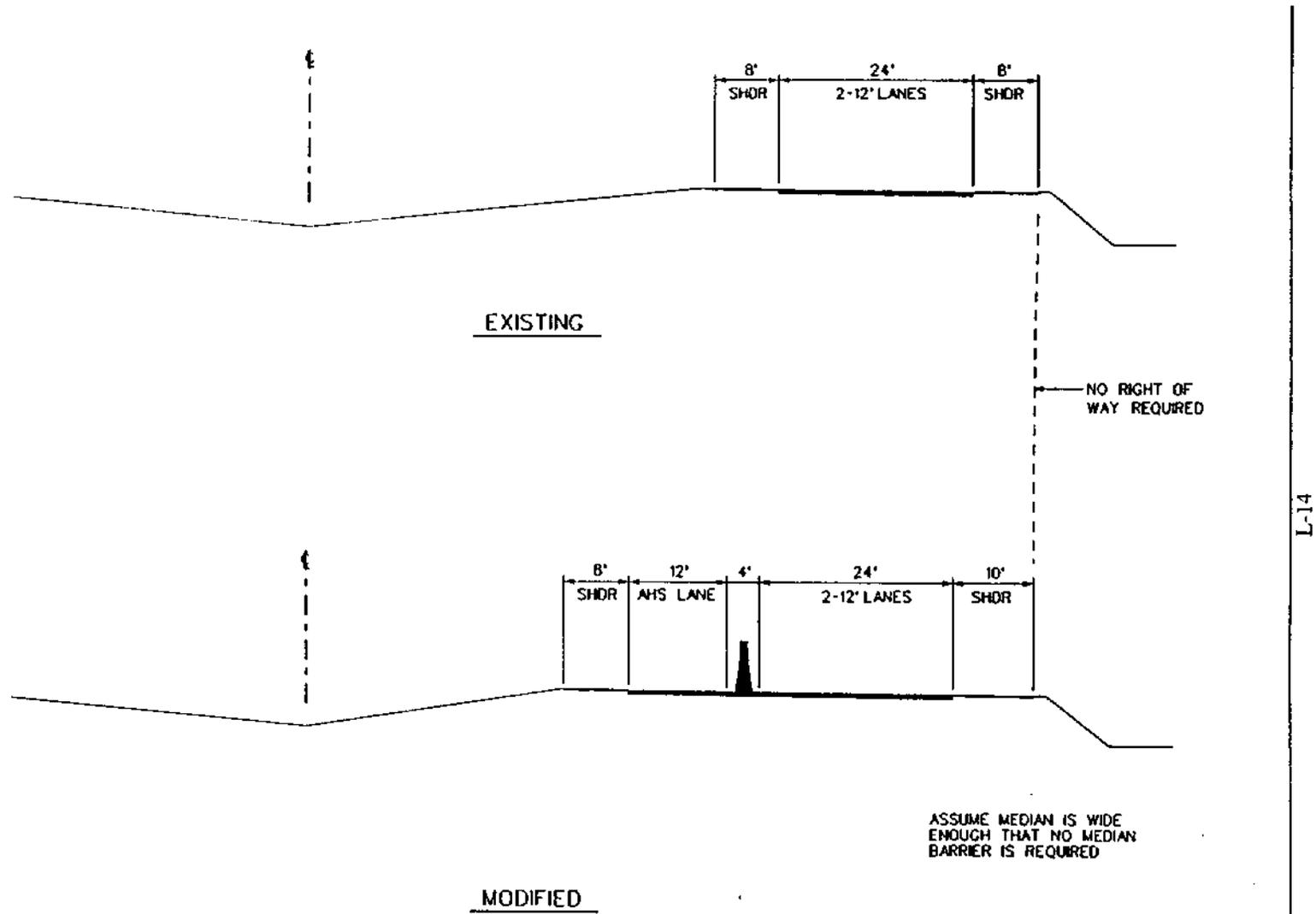
Figure L-9. AHS Operations - Rural Case

- **Items:** The fundamental building block of a cost estimate is the individual "item." Typical items are cubic yards of concrete, linear feet of culvert, pounds of rebar, or square feet of soundwalls. This is the level within the database where a unit cost is associated with an item of work. The unit cost of an item includes all the labor, material, equipment, and subcontracts required to put it into place. The estimating database developed for the AHS program included about 500 items, which closely follows the Caltrans Coded Contract Item List. These 500 items will cover over 95 percent of the work on any typical highway project, and specialty items can be added as necessary.

- **Work Packages:** Several items may be closely related to each other, and it becomes much more efficient to group them together into a "work package" in order to streamline the estimating process. For example, a typical retaining wall can be composed of many different items, including: excavation, backfill, rebar, and concrete. Published tables are available that specify the quantity of concrete and rebar required for a linear foot of retaining wall of a specified height. There are many other variables, such as piling, surface texture, barriers, fencing, and drainage, which may or may not be required. Work packages have been created to incorporate all of this information. A detailed list of individual item quantities may be generated by providing the wall length and height, and answering a few yes/no questions. In addition to retaining walls, work packages have been developed for masonry block soundwalls, structural pavement sections, and certain types of bridge structures. A work package can be developed for any group of items that are commonly associated with one another.

- **Models:** The third, and most sophisticated component of the estimate is the "model" A model may be made up of any number of items and/or work packages. For example, a model may be created to represent all the work shown on a freeway cross section. At which time, default values may be entered into the model for any of the work package variables – such as retaining wall height. Subsequently, a complete schedule of quantities can be generated, just as if the individual items had been input one by one.

L.3.3   Base Case Conditions

The cost model was built using a specific set of base conditions, including the following abridged version of the list of conditions:

- Defined set of units for each module and its items
- Construction season
- Traffic density
- ROW availability
- Noise mitigation requirements (e.g., soundwalls) and other environmental concerns
- Physical barrier separating AHS and manual vehicle lanes

- Existing construction practices (geometric and structural design standards)
- Productivity factors
- Special seismic requirements
- Pricing based upon first quarter 1996 levels; no escalation
- Costs consistent with a competitively bid, Caltrans administered highway project
- 10 percent for mobilization and 35 percent contingency
- 38 percent for engineering and construction management
- Lump sum allocations made for utility relocation, existing structure removal/relocation, drainage. signing and striping, traffic mitigation, etc.
- ROW costs varies between urban, inter-city, and rural locales

L.3.4   Variances from Base Case Conditions

Variances from the base case described above would be accommodated with a set of multipliers. The designer starts with the base case and then applies these factors where there are variances, such as cost of land, construction environment, and the terrain of a particular alignment. Such variances may include:

- Degree of complexity of civil/structural modifications
- Age of structure (crossings, cross-section, pavement, etc.)
- Local/arterial traffic mitigation (includes geometric, signalization, etc.)
- Labor costs
- Absence of physical barriers
- Land use (residential, commercial, or industrial)
- Setting (time of year, location, etc.)
- Project duration (length of time to complete the work)
- The difference between existing construction practices and those dictated by AHS: use of advanced construction technologies, techniques, and materials; more stringent quality control standards; and effect this may have on traffic management and construction sequencing.
- Degree of landscaping (light, medium, or heavy)
- Environmental mitigation
- ROW relocation (businesses, residents, etc.)

L.4   Assumptions

Several assumptions were made concerning the physical modification of the existing freeways to accommodate the addition of the AHS civil infrastructure. Examples of these geometric characteristics include lane widths, shoulder widths, ramp lengths and widths, barrier requirements, interchange requirements, etc.

The second set of assumptions used in this order-of-magnitude cost assessment is subject to engineering judgment, experience, and interpretations. Such assumptions include the following:

- Extent of ROW acquisition
- ROW acquisition cost
- Unit construction cost rates
- Percent of construction cost allotted to design
- Lump sum allowances for freeway-to-freeway interchanges
- Signing and marking
- Landscaping
- Traffic management during construction
- Planning, design, and construction management cost
- Contingency allowances

Since the cost assessment exercise dealt with hypothetical application scenarios (and not site-specific projects), these assumptions were based on experience with similar projects.

L.4.1   Right-of-Way

It was assumed that only in the urban and inter-city operating environments, the widening of a highway's cross-section would require the acquisition of additional ROW. Various assumptions in terms of percentages and cost per square foot were applied. Calculations were performed for each of the cases under the following requirements:

- **Urban application:**

The base case calculation for all urban applications assumed acquisition of 100% of the required ROW at a cost of $15/sq. ft. Sensitivity tests were made for other cases as follows:

- – 50 percent ROW required at $15 per square foot
- – 100 percent ROW required at $25 per square foot
- – 50 percent ROW required at $25 per square foot

- **Inter-city application:**

- – 50 percent ROW required at $7.50 per square foot

For the rural application environment, it was assumed that existing ROW would accommodate the addition of a dedicated AHS lane.

L.4.2 Barrier Separation

Concrete barriers (Type 50) were used for separation between manual and AHS lanes. Barriers were estimated at $20 per linear foot.

L.4.3 Unit Costs

The 500 items in the database each have a unit cost associated with them. These unit costs represent a reasonable bid level cost for a medium-sized ($5 to 50 million), competitively bid, Caltrans-administered project in the Silicon Valley area (one of the highest-cost areas of the country) in the first quarter of 1995. The unit costs are expressed in both English and metric units. Some sample item unit costs are as follows:

Caltrans Code	Description	Unit Cost English	Metric
129000	Temporary railing (Type K)	12.00 $/LF	40.00 $/m
190101	Roadway excavation	9.00 $/CY	$12.00 $/m^3
250401	Class 4 aggregate subbase	15.00 $/CY	20.00 $/m^3
290211	Asphalt treated permeable base	48.00 $/CY	63.00 $/m^3
390155	Asphalt concrete (Type A)	30.00 $/Ton	33.00 $/Tonne
401000	Portland cement concrete pavement	75.00 $/CY	100 $/m^3
510053	Structural concrete (bridge)	350 $/CY	460 $/m^3
510060	Structural concrete (retaining wall)	300 $/CY	400 $/m^3
518002	Soundwall (masonry block on pile cap)	11.00 $/SF	120 $/m^2
520102	Bar reinforcing steel (bridge)	0.50 $/LB	1.10 $/KG
650018	24" reinforced concrete pipe	60.00 $ LF	200 $/m
839481	Concrete barrier (Type 50)	20.00 $/LF	65.00 $/m
840656	Paint traffic stripe (2-coat)	0.25 $/LF	0.80 $/m

When these items are incorporated into work packages, the result is a higher level unit cost. Work package unit costs are not explicitly included as part of the database, but are derived from the item unit costs and the work package quantity information. The unit cost of a work package is usually expressed as a range, because it may vary depending on the input variables. Some sample work package unit costs are as follows:

Description	Unit Cost English	Metric
Retaining wall (Type 1, spread footing) $/m^2$	35-90 $/SF	375-950
Masonry block soundwall on pile cap $/m^2$	10.00-13.00 $/SF	110-140
Masonry block soundwall on barrier $/m^2$	12.00-15.00 $/SF	130-160
Pavement structural section (freeway trav.lane)	3.00-5.00 $/SF	32-54 $/m^2$
Pavement structural section (ramp or local street)	2.50-4.00 $/SF	27-43 $/m^2$
Pavement structural section (shoulder)	2.00-3.00 $/SF	22-32 $/m^2$
Bridge structure	60-100 $/SF	650-1,10

L.4.4 Lump Sum Allowances

There are some project costs for which it is either not possible or not necessary to develop an itemized cost estimate. These costs may be expressed as a lump sum dollar amount, with no associated quantities. The major lump sum allowances used for the cost estimates included in this report were for the two regional interchanges. The value used for the 3-legged interchange was $125 million, and the value used for the 4-legged interchange was $350 million. These allowances are assumed to include a 10 percent mobilization and a 35 percent contingency.

The cost estimates for many categories of work are often expressed as a dollars-per-mile allowance. These categories include lighting, drainage, signage, striping, construction support, existing facilities removal, and utility relocation. The values for these cost allowances are based on historical records for similar projects and on the engineer's judgment. As project definition evolves, these allowances will be replaced with actual quantities for the various items of work.

L.4.5 Contingency

Contingency is a percentage factor that is applied to the subtotal of all itemized costs and cost allowances. Contingency is a provision in the estimate for additional costs that cannot yet be defined, but that we know from experience will arise.

For the estimates included in this report, a contingency of 35 percent was applied to the construction costs. The unit costs for right of way acquisition are assumed to include contingency, so no additional contingency factor is applied. The costs for engineering and management services are expressed as percentages of the capital costs for construction and right of way, and these percentages are inclusive of any contingency.

L.5   Results

This section details the results of each case for each of the three operating environments. As noted earlier, these costs are only capital costs for civil infrastructure and <u>do not include</u> costs for vehicle or infrastructure systems, nor do they include operations and maintenance costs for the facility or equipment. The cost per mile and per kilometer are for both directions of the highway segment.

L.5.1   Urban Cases

Urban Case 1

Table L-1 shows costs for Urban Case, 1, based on:
- Replacing one manual lane with one dedicated AHS lane, fed by seven dedicated interchanges at 3.6 miles (5.7 km) average spacing
- Separate breakdown lane per direction
- Length of merge lane assumed at 1,400 ft (425 m), exit lane at 500 ft (150m)
- Carrying AHS lanes over dedicated ramps through regional interchanges
- Lump sum cost assumption for regional interchanges: $350 million for 4-leg and $125 million for 3-leg

Table L-1

Urban Case 1: Total Cost Breakdown ($ Millions)

Item	$M/mi	$M/km	%
Construction	18.20	11.38	48.27
ROW	3.81	2.38	10.10
Engineering/management	6.92	4.32	18.34
Contingencies	8.78	5.49	23.29
Total	37.71	23.57	100.00

Note: ROW – 100% acquisition required at $15 per sq.ft.

Urban Case 2

Table L-2 shows costs for Urban Case 2, based on:
- Replacing one manual lane with one dedicated AHS lane, fed by seven dedicated interchanges at 3.6 miles (5.7 km) average spacing
- Case 2 assumes a shared breakdown lane (modified variable barrier) for two opposing AHS directions
- Length of merge lane estimated at 1,400 ft (425 m), exit lane at 500 ft (150 m)
- Carrying AHS lanes over dedicated ramps through regional interchanges

- Lump sum cost assumption for regional interchanges: $350 million for 4-leg and $125 million for 3-leg

Table L-2

Urban Case 2: Total Cost Breakdown ($ Millions)

Item	$M/mi	$M/km	%
Construction	18.20	11.38	50.22
ROW	2.34	1.46	6.46
Engineering/management	6.92	4.32	19.08
Contingencies	8.78	5.49	24.24
Total	36.24	22.65	100.00

Note: ROW – 100% acquisition required at $15 per sq.ft.

Urban Case 3

Table L-3 shows costs for Urban Case 3, based on:
- Replacing one manual lane with one dedicated AHS lane fed by common entry/exit ramps and a dedicated continuous transition lane
- Barriers with gaps assumed between manual and transition lanes and between transition and AHS lanes
- Flexible placement of entrance/exit gaps for transition and AHS lanes on basis of local conditions
- Special by-pass ramp arrangement at freeway-to-freeway interchanges
- Need for local widening of manual lanes to accommodate weaving traffic

Table L-3

Urban Case 3: Total Cost Breakdown ($ Millions)

Item	$M/mi	$M/km	%
Construction	13.28	8.30	42.37
ROW	6.61	4.13	21.10
Engineering/management	5.05	3.15	16.10
Contingencies	6.41	4.00	20.44
Total	31.35	19.59	100.00

Note: ROW – 100% acquisition required at $15 per sq.ft.

Urban Case 4

Table L-4 shows costs for Urban Case 4, based on:

- Adding one dedicated AHS lane (without taking away a lane), fed by seven dedicated interchanges at 3.6 miles (5.7 km) average spacing
- Separate breakdown lane per direction
- Length of merge lane assumed at 1,400 ft (425 m), exit lane at 500 ft (150m)
- Carrying AHS lanes over dedicated ramps through regional interchanges

Table L-4

Urban Case 4: Total Cost Breakdown ($ Millions)

Item	$M/mi	$M/km	%
Construction	21.12	13.20	46.41
ROW	6.15	3.84	13.51
Engineering/management	8.03	5.02	17.64
Contingencies	10.21	6.38	22.44
Total	45.51	28.44	100.00

Note: ROW – 100% acquisition required at $15 per sq.ft.

Urban Case 5

Costs for Urban Case 5 (see Table L-5) are based on:

- Adding one dedicated AHS lane (without taking away a lane), fed by 7 dedicated interchanges at 3.6 miles (5.7 km) average spacing
- Separate breakdown lane per direction
- Length of merge lane assumed at 1,400 ft (425 m), exit lane at 500 ft (150m)
- Maintain 10-foot shoulders on both sides of both the manual and AHS traffic lanes
- Carry AHS lanes over dedicated ramps through regional interchanges

Table L-5

Urban Case 5: Total Cost Breakdown ($ Millions)

Urban Case 5	$M/mi	$M/km	%
Construction	22.68	14.18	45.50
ROW	7.61	4.76	15.27
Engineering/management	8.62	5.39	17.29
Contingencies	10.94	6.84	21.94
Total	49.85	31.17	100.00

Note: ROW – 100% acquisition required at $15 per sq.ft.

From these estimates, it can be concluded that changes in highway geometrics greatly affect construction and ROW cost as a percentage of total cost. For example, in Urban Case 2, where a shared breakdown area is utilized between both directions of AHS travel, ROW cost is significantly reduced (almost half the cost of Case 1) while construction costs are maintained.

In Urban Case 3, although there is substantial savings in construction costs, the ROW costs are almost double those in cases 1 and 2. The rationale is that in this case, a transition lane is required next to the dedicated AHS lane and thus results in two lanes dedicated for AHS use only. In this case, Construction costs are lower since there are no dedicated entry/exit ramps and the total cost per mile of highway is 17 percent lower than the previous two cases.

In Urban Case 4, where the number of existing manual traffic lanes is maintained, extra ROW is necessary to accommodate a new lane for AHS use, and construction costs are higher as compared to all the three previous cases. The total cost per mile is 20 percent higher than the previous three cases.

The last case, Urban Case 5, is the most expensive configuration due to the full 10-foot shoulder widths.

Although Case 3 is the least expensive case, it is solely in terms of civil infrastructure. It depends on the capabilities of AHS technologies to perform in these conditions. At this point in the program, it is too early to establish civil infrastructure design standards. The configuration is dependent on the results of the technological characteristics and needs of the final AHS concept (which are still under investigation).

L.5.2 Inter-City Case

Costs for the inter-city case (see Table L-6) are based on:
- 74 miles (119 km) inter-city freeway, three lanes each direction, 20 normal interchanges, and two freeway-to-freeway interchanges
- Adding one dedicated AHS lane fed through common ramps via a localized transition lane

Table L-6

Inter-City Case: Total Cost Breakdown ($ Millions)

Item	$M/mi	$M/km	%
Construction	3.18	1.97	47.96
ROW	0.71	0.44	10.71
Engineering/management	1.21	0.75	18.22
Contingencies	1.53	0.95	23.11
Total	6.63	4.11	100.00

Note: ROW – 50% acquisition required at $7.50 per sq.ft.

L.5.3   Rural Case

Table L-7 shows costs breakdown for the rural case, which are based on:

- 296 miles (476 km) rural freeway, two lanes each direction, 20 normal interchanges and two freeway-to-freeway interchanges
- Adding one dedicated AHS lane fed through common ramps via localized transition lanes
- No ROW acquisition required

Table L-7

Rural Case: Total Cost Breakdown ($ Millions)

Item	$M/mi	$M/km	%
Construction	1.77	1.10	53.68
ROW	0.00	0.00	0.00
Engineering/management	0.67	0.42	20.40
Contingencies	0.85	0.53	25.92
Total	3.29	2.05	100.00

L.6   Right-of-Way Sensitivity Analyses

For the urban operating environment, right-of-way sensitivity analyses were conducted to observe discrepancies in percentage of total cost. Calculations with a ROW cost of $25 per square foot as well as with a 50 percent ROW acquisition requirement were performed.

When the ROW acquisition requirement is decreased from 100 percent to 50 percent, the total cost per mile (or per kilometer) of highway decreases anywhere between 9 percent and 16 percent.

When the cost per square foot of ROW is increased from $15 in the base case to $25 per square foot, the total cost per mile of highway increases between 3 percent and 12 percent.

Several other sensitivity tests can be postulated once a final AHS configuration is defined. Section L-7. exhibits some configuration options and raises several issues that are still outstanding in the program's research and development phases. Once a better understanding of the technology capabilities of AHS is gained, civil infrastructure configurations will be further developed and tested.

L.7   Recent Highway Cost Experience in California

An attempt was made to gather cost data on recent highway expansion projects to test the reasonableness of the estimates above. The following details the information that was received from the various district offices of the California Department of Transportation. Some costs, such as engineering design costs or the amount of ROW acquired, were not available. From these figures, one can conclude that costs vary greatly from project to project. It can also be said that in congested urban areas, ROW can sometimes cost as much as the construction costs.

- **Santa Clara County Traffic Authority Freeway Improvement Program:** This $1.12 billion freeway project includes 18 miles of new freeway, 39 miles of widened freeway, and 29 interchanges to be built or upgraded. Construction cost is $572 million with a ROW cost of $341 million, and engineering cost of $206 million. The new freeway segment is a six-lane facility. Two lanes are being added to 20 miles of the existing freeway while only one lane is being added to the remaining 19 miles. This indicates that the cost per lane-mile of new freeway is approximately $3.3 million while cost per lane-mile of widened freeway is $14 million.

- **Cypress Freeway – I-880 (Oakland):**   This 19-mile freeway widening project has a total cost of $1.35 billion or $71 million per mile. This cost includes the price of complex interchanges in the area, as well as extensive environmental mitigation measures based on prior soil contamination.

- **Freeway/Transitway (Los Angeles):** This portion of the I-110 High Occupancy Vehicle (HOV) Transitway project consists of 10.3 miles of an at-grade, 4-lane segment in the middle of the existing freeway and a one mile stretch of an elevated viaduct above the existing I-110 freeway (see Figure L-10). The total construction cost is $360 million. This implies a cost of $35 million per mile or $8.75 million/lane-mile. This price does not include ROW costs. The elevated portion is $25 million per mile or $6.25 million per lane-mile.

- **I-880 East Shore Freeway from SR 4 to the San Francisco Bay Bridge:** This project involves 16.5 miles of widening, the addition of HOV lanes, interchange improvements, seismic upgrades, traffic operation improvements, and other elements.

The total project cost is $355 million (construction only). Minimal ROW acquisition cost is needed. This results in an average of $11 million per lane-mile cost.

- **Improvement Project (Orange County):** This project encompasses the widening of Interstate 5 in Orange County, California. A 9.5 mile segment will be widened from 6 to 10 lanes. The finished project will include one new HOV lane in each direction. A major interchange between I-5 and State Route 91 will be reconfigured. The estimated construction cost is $500 million, resulting in an average cost of $13 million per lane-mile. ROW is estimated at $600 million, resulting in an average cost of $16 million/lane-mile. Figure L-11 depicts the project area.

- **Route 24 /I-680 Interchange (Walnut Creek):** The construction cost for this interchange is approximately $275 million, including $14 million for traffic management. Additionally, ROW acquisition cost is approximately $60 million. Total project cost is $355 million.

- **I-105/I-110 Interchange (Los Angeles):** Total construction cost is $82 million. ROW is not included in this cost figure. This interchange includes HOV-to-HOV connector ramps analogous to AHS-to-AHS ramps under consideration.

72'

BUSWAY TRANSITWAY

AT GRADE SECTION

67½'

SOUNDWALLS
(Where required)

SOUNDWALLS
(Where required)

15'

EXISTING FREEWAY LANES

EXISTING FREEWAY LANES
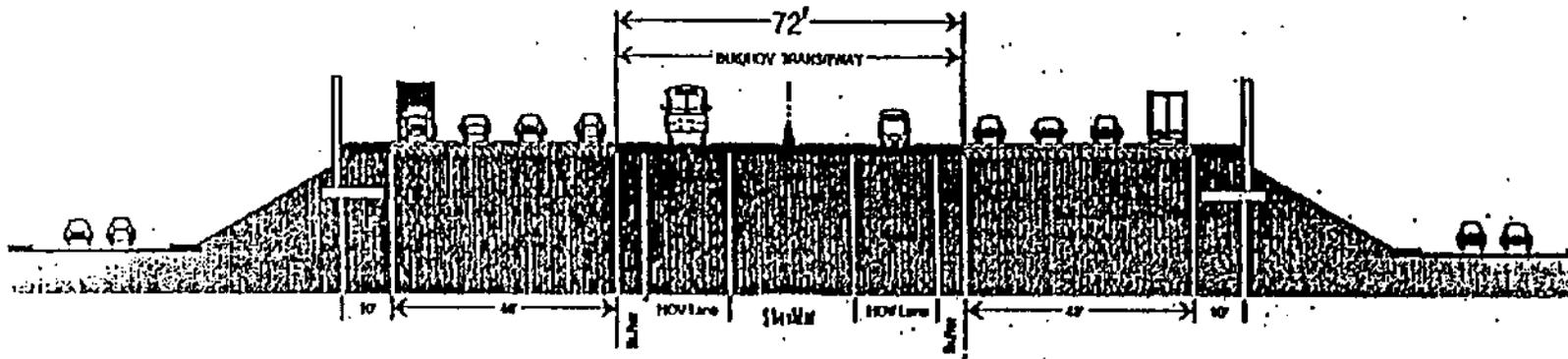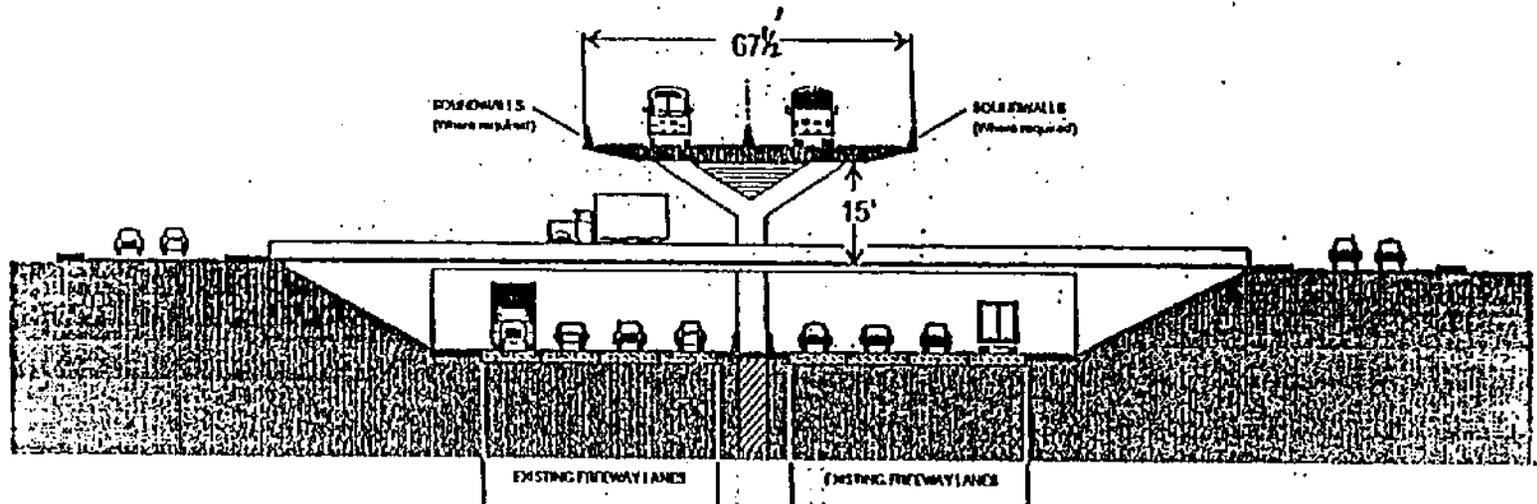
ELEVATED SECTION

Figure L-10. Los Angeles I-110 Freeway Transit Bay - Elevated Section.
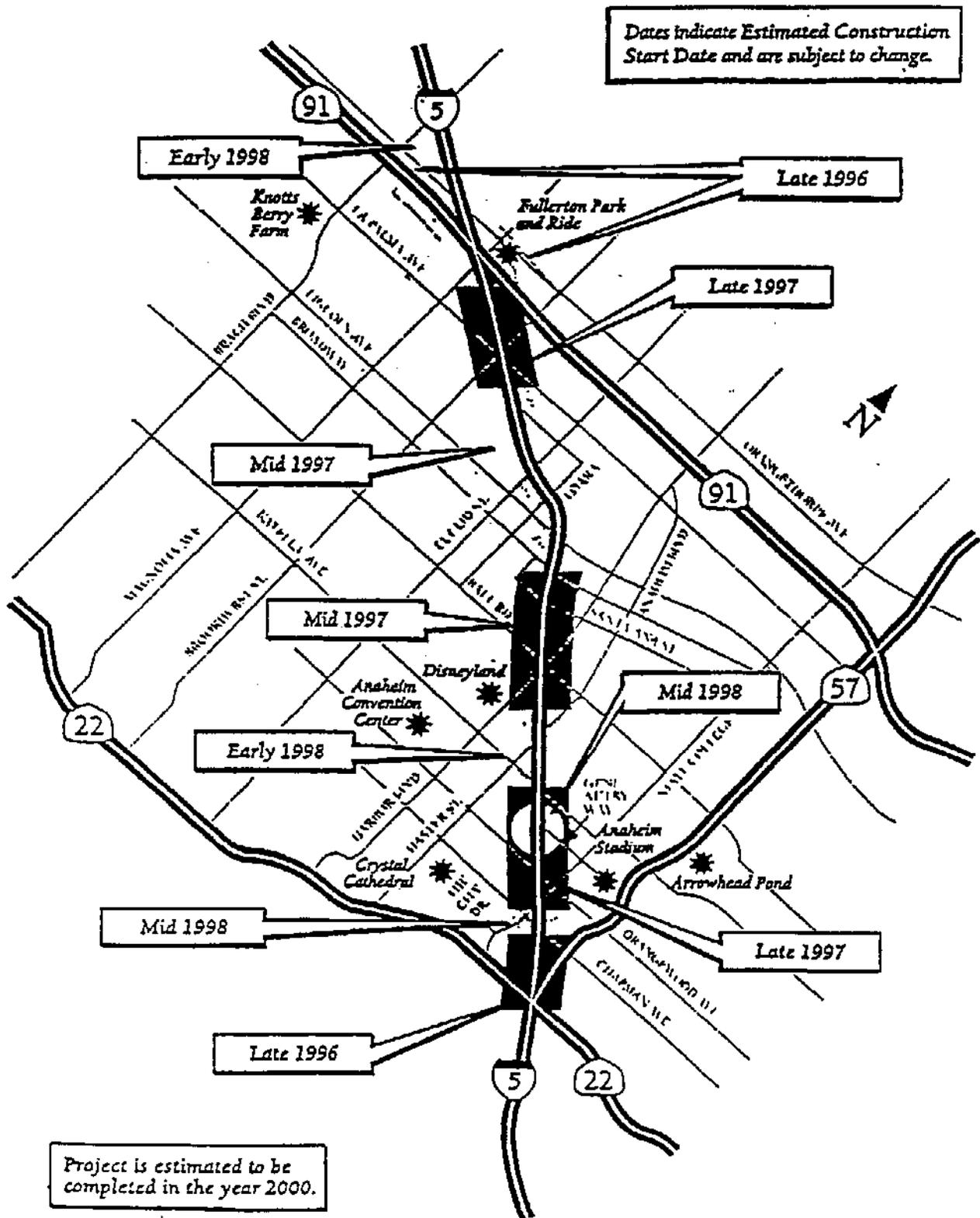
Figure L-11. I-5 Improvement Project (Orange County).

L.8   HOV Lane Cost Experience from Other U.S. Regions

Over the past 10 to 15 years, several urban regions in the United States have embarked on the addition of a HOV lane along their freeways. Table L-8 lists various examples of these types of projects, dating from 1986 to 1993. Costs range from $2.5 million per mile to $49.5 million per mile. These figures have not been escalated to today's dollars, and detailed descriptions were not available at the time of data collection. Additionally, cost elements vary from project to project. Thus, no comparative assessment or conclusion relating to the AHS costs could be drawn.

The addition of HOV lanes into an urban freeway may differ from inserting a dedicated AHS lane(s). This stems from different degrees of separation from manual lanes, treatment of the transition from manual to automated transition, entry/exit ramps, merging/diverging lane requirements, and treatment of freeway-to-freeway interchanges. One, therefore, might expect that some HOV lane costs would be less than dedicated-AHS lane cost. But such conclusions would have to be substantiated with comparable site-specific case studies.

L.9   Conclusions

This report only provided order-of-magnitude cost estimates for hypothetical cases for the urban, inter-city, and rural environments. It has been shown that the cost of adding dedicated-lane AHS operations to an existing freeway system can vary widely, especially in congested urban areas. In the urban environment, if ROW is not available, a dedicated AHS lane for both directions of a roadway may cost up to $50 million per mile. For the inter-city application, the cost is estimated at approximately $7 million per mile. In the rural environment, the cost is around $3.5 million per mile but the large majority of these costs are not unique to AHS; they would be incurred for non-AHS highways as well.

At this stage of the program, there are no design standards for a dedicated AHS civil infrastructure. Assumptions used as a basis for these cost estimates reflect existing highway design and construction standards and practices. Although highway configuration is independent of most concept attributes, it is mostly dependent on characteristics of a site-specific application as well as technologies. AHS configurations can be further refined once AHS technological characteristics are better understood and a real site can be modeled. It is important to keep in mind that site-specific AHS applications may result in substantial reductions or increases to the cost estimates presented in this report.

The most critical factor in calculating the cost of adding a dedicated AHS lane(s) to existing highways (especially in the urban environments) is the required AHS highway geometrics or configuration. A discussion of highway configuration issues can be found in Section 7.0 of this report. Some of the outstanding issues include the dimensions of lanes, ramps, shoulders, breakdown areas, etc.

The next phase of the AHS program will take these steps further. Case studies are being identified. Also, as the AHS concept and its systems characteristics are defined and developed during the next few years, a better understanding of highway geometric characteristics will be realized. This will then provide a better basis for creating cost estimates for the civil infrastructure needs of AHS.

Table L-8
Characteristics of Proposed Freeway HOV Priority Lanes

Project Description	Project Length	Date of Operation	Des & Const Cost ($million)*	$Million/ mile
Denver, I-25	10.0	1989	66	6.6
S 2 mi, 2 lane reversible				
N 8 mi, concurrent flow				
Houston, US 59 Southwest Fwy	8.5	1990	102	12
Physically sep in fwy median				
initial, 1 lane reversible				
ultimate, 7.5 mi of 2 lane 2 way				
+ 1 mi of 1 lane reversible (1995)				
Houston, US 290 Northwest Fwy	14	1988	105	7.5
Physically sep in fwy median				
2 lanes 2 direction	2			
1 lanes reversible	12			
Houston,I-10 Katy Freeway	5.3	1987	13	2.5
Extension of Operating Transitway				
Physically sep in fwy median				
1 lane reversible				
Houston, I-45, Gulf Fwy	15.5	1988-1990	90	5.8
Physically sep in fwy median				
1-lane reversible				
Houston, I-45 North Freeway	4.9	1988	22	4.5
Extension of Operating Transitway				
Physically sep in fwy median				
Miami/Fort Lauderdale, I-95	42.0	1991	456	10.9
Extension of I-95 concurrent flow				
1 lane each direction				
Seattle, I-5, S of CBD				
1 concurrent flow NB lane	7.3	1992	33	2.7
1 concurrent flow SB lane	4.8			
Seattle, I-90, E of CBD	9.5	1993	470	49.5
2 lanes-reversible				
Seattle, I-405, Tukwila-N.Renton	5.0	1991	75	15
1 concurrent flow lane each direction				
Washington, D.C. I-395 - Shirley Hwy				
Interim, concurrent flow	7.0	1986	4	0.6
Permanent, 2 lanes reversible	19.0	1990	95	5.0

Source: Institute of Transportation Engineers, 1985 Survey of Transitway Projects
* Costs must be viewed with caution since the different projects do not include the same cost elements

Appendix M.   Societal and Institutional Perspectives

M.1   Introduction

The AHS concepts and concept attributes evaluated during this phase were developed within the context of societal and institutional considerations. Societal and institutional perspectives are expected to play as significant a role in system development and deployment as the technological and engineering issues that must be addressed. A system that is not compatible with existing or expected societal and institutional priorities and requirements will face a more challenging deployment path than one which is compatible. In some cases, where the potential benefits warrant and are compelling, societal priorities may change and institutional requirements be adapted to accommodate an AHS.

It is important to note that the societal and institutional conditions that we see today are reflective of the trends and priorities of today's society, within the context of our historical experiences. As those experiences change, so may the priorities, and with them the institutional conditions and requirements for addressing those priorities. Anticipating the reaction of agencies and other institutions is a speculative exercise, and the analysis has been limited to existing policies (with an emphasis on innovations that have recently been implemented), and in some cases, policies that are already under discussion in order to adapt to priorities raised by technological innovations that are ready for deployment. Instances where changes to these policies would facilitate AHS deployment are identified.

There are precedents where procedural, regulatory, and institutional changes have occurred in order to facilitate the deployment of an improvement that was identified as a national priority, such as the Interstate Highway System. The interstate system was a case of a major investment that fundamentally altered transportation in the US. Technological innovations that bring new modes of travel (such as commercial aviation), also usually result in the development of new institutions and regulations (FAA).

It is hoped that this report will stimulate further discussion of the perspectives and issues to be considered as concepts move through the stages of development. It also may assist developers and policymakers in revising regulations and perhaps developing new institutions that are better able to deploy, operate, and regulate new systems. These institutions and regulations are social constructs; the ease or difficulty with which they can be modified will in most cases be driven by the relative importance of proposed improvements and the impact which regulations and institutions would have on their deployment. An AHS that offers the potential for a landmark improvement in transportation performance would justify such changes.

Methodology. Issues were identified through the Precursor Systems Analyses phase of the federal AHS program and the earlier Task C1 analysis, and were defined and analyzed in major part through discussions with AHS stakeholders, including highway agencies, the vehicle industry, the electronics industry, the highway design industry, and user groups -- drivers, transit agencies and the trucking industry. These discussions have

provided input on large-scale issues including the mechanics for deployment, liability, environmental issues, and what has become known as the Five Who's (as suggested by J.R. Robinson of Virginia DOT):

1)   Who would own the system?
2)   Who would pay for the system?
3)   Who would operate the system?
4)   Who would maintain the system?
5)   Who would regulate and enforce the system?

Issues were also identified by reviewing the development and deployment of "precursor" innovations such as HOV lanes, ITS services such as electronic toll collection (ETC) and adaptive cruise control, and the use of quasi-public authorities and multi-agency coalitions to finance, build, and operate major transportation systems. The theory behind this exercise is that agencies and other institutions will react, at least initially, to new innovations by falling back on their existing procedures.

Issues have been analyzed within the context of the defined concept attributes. In many cases several viable procedural options have been identified, and it would be premature to recommend a single option. Nevertheless, strengths and weaknesses are noted. AHS improvements would largely be deployed at the state level, and each state has a different way of doing business. Therefore, in most cases it is not useful to suggest that there is only one procedural path to deployment.

M.2   Institutional Perspectives

Institutional perspectives cover the concerns of organizational stakeholders, including the federal, state, and local governments, quasi-governmental organizations, and private organizations such as manufacturers, insurers, and potential infrastructure providers. The concerns of each cover specific issues which must be addressed in order to facilitate the participation of each.

M.2.1 Institutional Responsibilities

This section provides a conceptual organization of responsibilities for the "Five Who" questions. In many cases, the actors will be the same as exist in the current highway system. In some, the roles will shift, and responsibilities will be increased. In others, new actors will be identified. In a few cases, new issues are identified that must be addressed by the existing actors.

M.2.1.1 Ownership

Ownership is an issue for each component of an AHS: highway civil and electronic infrastructure, vehicles and vehicle equipment, and also radio frequency spectrum. Ownership is important because it comes with bundles of rights and responsibilities. Owners can enjoy and profit from the use of their property. At the same time they are responsible for ensuring that the property does not harm or damage other persons or their property.

Infrastructure

Three types of organizations exist today that could be capable of owning an AHS infrastructure system. In most cases highway infrastructure is owned by the state, through a highway agency. In some cases, quasi-independent authorities own toll roads or bridges and tunnels. In a few emerging cases, private organizations and enterprises are buying an equity stake in new highway systems in a public-private partnership.

Most of the existing freeway infrastructure is owned by the states and is under the jurisdiction of state agencies that report directly to the state government. These systems were built using state and federal funds under the national and interstate highway programs. While the freeway system meets today's needs, these agencies continue to add projects that enhance connectivity and increase capacity for the future.

The toll road and bridge authorities (and many transit properties) are chartered by states or groups of states. Their leaderships are appointed by elected officials, but they are otherwise independent. Their ability to charge tolls (and fares) provides them with a dedicated funding source that facilitates this independence. They build, own, and operate their facilities, and in some cases acquire existing facilities from state agencies. They are authorized to issue bonds which are generally financed, at least in part, by toll (or farebox) revenue and guaranteed by the state. In most cases they handle their own right-of-way acquisition. However, in cases where condemnation through eminent domain is required, the state usually will condemn the property and then transfer it to the authority. The toll revenue also covers their operations and maintenance costs. They are also usually required to meet state design and environmental guidelines, and they are responsible for the safe operation of their facilities.

In recent years, some states, including California and Virginia, have entered into agreements with private companies to deploy new transportation facilities, such as toll roads. A recent highway example is the San Miguel Mountain Parkway (California SR 125), which is being planned for the San Diego area. This project makes use of several innovative procedural and deployment concepts that would be applicable to an AHS facility.

The San Miguel Mountain Parkway is being developed by a limited partnership, under an exclusive franchise issued by California Department of Transportation. Enabling legislation was required to allow Caltrans to make such an agreement. The project is

currently undergoing environmental clearance, which is a prerequisite for finalization of the financing plan. The arrangement is expected to include the following features:

- The San Diego Expressway Limited Partnership (SDELP) will design and build the new facility, transfer "operational control and title" to California Department of Transportation (CALTRANS), which will lease the facility back to SDELP for a period of 35 years. SDELP is a limited partnership, with California Transportation Ventures, Inc. as the managing partner. SDELP has the option to extend the lease for up to 99 years following transfer of ownership to CALTRANS.

- During the 35 year operational period, CALTRANS retains ownership of the facility, making it subject to the Tort Claims Act, that limits the claims that can be filed against the project, its sponsors, and the operators. It is important to note that other states have regulations that specifically prohibit state agencies from extending such immunity to contractors.

- CALTRANS is prohibited from building a competing facility within 3 miles of the facility.

- CALTRANS will exercise its rights of eminent domain, at SDELP's request to condemn right-of-way in order to expedite project development. SDELP will assume the purchase price for these properties. Three major developers in the corridor will donate almost 60 percent of the required right-of-way.

- SDELP is required to assemble financing, with the assistance of CALTRANS. The financing package was not originally intended to have state guarantees, although the new State Infrastructure Bank may be involved as plans evolve.

- SDELP will develop the facility in conformity with CALTRANS and FHWA standards.

- SDELP will establish and modify toll rates at its own discretion for up to 35 years. It also retains subleasing rights for concessions and advertising. SDELP is permitted to earn a rate of return of up to 18.5 percent of total project costs.

This arrangement limits SDELP's risks to development and construction costs, and traffic and revenue generation (SDELP receives an incentive return, which can be shared with local jurisdictions, if vehicle occupancy exceeds 1.1). CALTRANS assumes remaining liability risks and would be liable for damages should it default on the contract.

Since authority and private ownership usually require toll-based financing, it should be assumed that state ownership will be required for AHS facilities that do not charge tolls or other user fees. However, enabling legislation would be required to establish an independent authority or to authorize agreements with private companies. Many states already have passed such legislation, if not for transportation purposes, then for the

provision of public utilities or services. Nevertheless, this still represents an innovation for transportation that requires a certain level of consensus in order to pass.

Vehicles and Equipment

The ownership of AHS vehicles and equipment is most likely to follow existing conditions. Today, most drivers own or lease their vehicles. The simplest approach would be to consider AHS equipment to be yet another feature, like an airbag, or ABS, which may be optional, or may be required. However, several reasons may emerge, which would make it attractive to consider other options. AHS equipment may prove to be too expensive to be purchased by most auto owners. The alternative to individual ownership would be ownership of the equipment and/or the vehicles by either private companies or a government agency. A private company would then rent the equipment to individuals on a per-month or per-mile basis. This arrangement would only work if the agency involved were able to competitively price their product.

Vehicle fleet owners are potentially early owners of AHS equipment when economies – and benefits – of scale make AHS more affordable and desirable.

Radio Frequency

Ownership of radio frequency is a new issue that is only emerging today. The Federal Communications Commission has indicated that it is considering options to reduce the bandwidth of channels for private land mobile radio (PLMR). The demands for channels have increased due to emerging markets in cellular communications and also many ITS technologies like AVI, information systems, and security and emergency response systems (Maul & Greichen, 1996.). The goal is to reduce these channels from 25 KHz to 6.25 KHz by the year 2005. The FCC has also begun auctioning channels, which is likely to increase costs for all users, who would bid for the right to use a certain frequency.

Under AHS concepts that require radio communication, one or more channels would need to be acquired and made available to the system. The system operators would be the most logical party to purchase the channels. This issue is more complicated if a "cooperative" system is developed, that does not use infrastructure, but does rely on vehicles broadcasting information. Under these circumstances, bandwidth would still need to be reserved, at a national level.

The conversion to narrower bandwidths will also have an impact on AHS system design, since narrower bands may not be able to carry as much information as the wider bands. As competition for bandwidth increases, channel security may also be threatened and the potential for interference from other sources will increase.

M.2.1.2 Payment

The question of who pays for AHS reaches to the fundamental purpose of the system. Is it to be a program that will offer a premium service available to those who can afford it? Or will it be a system that serves a larger public purposes of making all vehicular traffic move more quickly and increasing capacity without increasing lane mileage? Or a combination (free use for carpools during rush hours)? If premium service is the limit of the objective, then a payment system that burdens users with equipment purchase costs and user fees (tolls) to retire infrastructure capital and system O & M costs will be adequate. Eventually, these costs can be expected to come down as acceptance increases and technology costs come down, making AHS more affordable and broadening its potential market.

This user-based payment approach may also work if the objective is to serve the larger public purposes. However, the federal and state agencies may also wish to subsidize AHS infrastructure deployment by making capital investments as part of their general capital program. This would burden all taxpayers with the costs for deploying a system. However, it would also reduce the individual user cost, making the decision to use AHS less expensive.

Capital Costs

Capital funding for transportation systems would largely depend on the ownership structure. Funding for state-owned facilities involves competition among highway, transit, bicycle/pedestrian, and intermodal projects for transportation trust fund and general fund dollars. These mostly federal dollars are allocated by metropolitan planning organizations and state DOT's in their Transportation Improvement Programs (TIP). Federal funds come from a variety of trust fund and general fund programs, including:

- National Highway Systems (NHS) for highways that fulfill crucial national mobility and economic goals

- Surface Transportation Program (STP) for highway maintenance and improvement, safety programs, and transportation enhancements

- Congestion Management and Air Quality (CMAQ) Program for projects that help meet Clean Air Act (CAA) mandates

- Interstate Maintenance Program to maintain key Interstate highways

- Bridge Program to maintain key bridges

- Section 3 for rail modernization, new transit systems, and bus systems

- Section 9 formula capital and operating assistance for transit

- Sections 16(b)2 and 18 to provide transit services for the elderly, people with disabilities, and people in rural areas

Some of these sources are dedicated to highway or transit only, while others, including CMAQ and STP are flexible and can be used for highway or transit. MPOs evaluate and rank projects that are competing for TIP funds based on their performance against a set of criteria based upon metropolitan planning factors from ISTEA. An AHS civil or electronic infrastructure project would compete with other transportation improvements for these TIP funds. AHS would likely be eligible for funding under most of the highway programs, STP, CMAQ (if it can be shown to reduce emissions) and from Sections 3 and 9 for AHS transit projects.

Many states also use their own trust funds that are financed by gasoline taxes and motor vehicle registration fees. States may issue bonds that are secured by the expected revenue that will come from these taxes. Usually a referendum is needed to authorize such taxes and bond programs. These funds are needed to meet the matching requirements to qualify for federal funds. In many cases they also fund projects outright. As federal contributions to transportation projects are reduced, due to budget constraints, transportation trust funds help states build and maintain their systems. MPOs may control at least part of these funds. The reliance on gasoline taxes and motor vehicle registration fees assigns the cost to highway users, at least partially in proportion to their reliance on those systems.

Toll road authorities also usually have the capacity to issue bonds to fund capital improvements, which they secure with toll revenues. States frequently exercise influence on these decisions by virtue of their power to appoint board members. They also may have a formal oversight capacity. This funding capability frees these authorities from the annual appropriations battles that state highway agencies face. Private toll road operators also issue toll-backed bonds, which may or may not have additional state guarantees.

An additional option, that can be used to meet at least part of the capital costs for a system with any ownership, is the use of special tax districts. (SAIC Legal Issues Report, 1994). Under this option, a corridor that would benefit from the implementation of a major transportation improvement is identified, and an assessment is made on the real property in that corridor, or a sales or other excise tax is levied on consumption. These districts are frequently used to fund sewage and water improvements and fixed guideway transit projects. They have also been employed to finance highways in Virginia, and are under consideration in other states. SR 125, the private toll road in California, includes a provision for funds to be provided by nearby developers if toll revenues do not meet forecasts for early years. The developers accept this burden, since they will benefit from the increased accessibility provided by the highway.

M.2.1.3 Operations and Maintenance

Operations costs for an AHS would include the costs to operate and maintain all equipped highways, including roadways and other civil infrastructure, signage, lighting, and possibly toll collection. AHS highways would also require operations and maintenance for sensors, communications, and operations coordination. In addition, the maintenance standards for roadways would probably need to be more exact, in order to reduce the risk of collisions or other mishaps. This would probably increase infrastructure maintenance costs.

State-owned highways depend on annual appropriations, and sometimes a trust fund to meet these costs. The taxpayer ultimately bears the costs. Toll roads, authority and private, depend on toll revenue to cover O & M costs, which are borne by facility users.

AHS systems are likely to require increased commitment of resources to operations and maintenance tasks. The civil infrastructure will still require maintenance, roadways will still need to have snow plowed, and highways will still need to be patrolled. In addition, all of the new systems will require resources for operation and maintenance.

Operations

The operation of an AHS highway, particularly a facility with significant electronic infrastructure, will be more complex from an agency standpoint than the operation of a conventional highway. The collection, processing, and distribution of information will be a substantial and continuous task. For the infrastructure-dependent systems, an operations center will be necessary to collect, manage and distribute information throughout the system. ITS systems often already require operation centers that serve many of these purposes. The sensors and communication systems would be operated and controlled by the op center. Other major activities, including check-in and check-out, and toll collection, would be coordinated with the operations center, but would possibly require an on-site operational presence.

The responsibility for infrastructure operations would logically sit with the owner of the roadway. However, the owner (state DOT, authority, private interest) may wish to contract or delegate responsibility for operations to another public or private organization. Many state laws limit the extent to which these functions can be contracted, due to liability concerns and labor restrictions.

Vehicle owners would also have responsibility for certain operational tasks. Under one of the infrastructure concepts, vehicles would receive instructions from infrastructure at critical segments, such as on/off ramps. In the case of cooperative and independent vehicle concepts, operational controls, sensors, and communications all reside in the vehicle and responsibility resides with the vehicle owner. However, the owner would also expect the vehicle to perform according to a defined set of criteria. The limits of the vehicle and equipment manufacturers' responsibility will need to be defined.

Maintenance

AHS maintenance concerns would extend to civil infrastructure, electronic infrastructure, and vehicles and equipment. Conventional highway systems also face these issues. However, an AHS will require closer tolerances in order to operate safely and satisfy insurance and liability concerns.

The requirements for civil infrastructure maintenance for an AHS system could be greater than for a conventional highway system. There will be less tolerance for damaged roadway surfaces, since such problems might not be detected by sensor systems. The implication for vehicle-based mixed traffic systems is that the maintenance standards must be improved for all expressways, so that automated vehicles can be operated safely. This would substantially increase general roadway maintenance costs for mixed traffic scenarios. Since not all highway agencies will necessarily be able to afford or wish to make these improvements, even vehicle-based, mixed-traffic AHS may only be functional on certain highways.

Vehicle maintenance is currently regulated at the state level, if at all. States may require vehicles to pass periodic inspections that evaluate whether they can be operated safely. These inspections cover the critical operations systems, including steering, brakes, suspension, tires, and lights. CAA air quality non-attainment areas frequently also require vehicles to pass emissions inspections. The vehicle owner is responsible for ensuring that their vehicles are inspected and meet the criteria. Law enforcement agencies will pull over vehicles without valid and current inspection stickers. Clearly, such an enforcement regime will not meet the requirements for AHS operations on dedicated facilities. However, check-in stations will electronically query vehicles to ensure that they have valid and current inspections. Vehicles would also be required to conduct a diagnostic check of their essential systems, and will not be cleared to enter the dedicated roadway unless they clear these checks.

Concepts that operate with mixed traffic, would not necessarily have these check-ins. The vehicle start-up, or transition to automated operation, could however include a diagnostic procedure to self-inspect all essential systems. If one of these systems failed, then the vehicle would not complete the transition to automated operation. Under this scenario, the diagnostic equipment itself would need to be frequently inspected and tested to ensure that it is functioning correctly.

Because of the increased number of essential systems, and the growing complexity of the vehicles, maintenance and repair costs for owners may increase for automated vehicles. All of the mechanical systems on today's vehicles would still need to be maintained, and the sensor, guidance, and communications packages would be added on. Of course, many parts of these packages are likely to be added on vehicles gradually over a number of years as consumers respond to the various ITS advancements that are precursors to and subsystems of AHS.

Electronic infrastructure, like the vehicle equipment, will be capable of performing diagnostic checks on its systems, but they will still require frequent inspections and maintenance. This maintenance could be performed by the staff of the highway agency, by the equipment manufacturer or vendor, or by a third party contractor.

M.2.1.4 Regulation and Enforcement

Responsibility for regulation and enforcement would probably devolve to roles that are played on the highway today. Law enforcement would be responsible for regulating driver behavior and procedures. State departments of motor vehicles, or contracted inspectors, would be responsible for maintaining vehicle maintenance standards. Law enforcement agencies would also monitor vehicle conditions (as they monitor and ticket vehicles for broken headlights today). The National Highway Traffic Safety Administration (NHTSA) would be responsible for overseeing equipment standards and the FCC would be responsible for regulating radio frequencies and use.

Rules of the Road

An AHS, particularly one that operates on dedicated lanes, will require at least some amendment to the existing traffic laws. These laws would regulate both AHS and non-AHS vehicles. The areas that they would need to cover would be driven by the type of system deployed, and could include:
- restrictions of AHS-dedicated lanes to AHS vehicles
- restrictions on where automated operations would be permitted
- operational rules on speed, passing, tailgating, stopping, and other behavior

It may be necessary to require AHS vehicles to identify themselves with indicator lights or other signals, particularly in mixed traffic, and to ensure that manual vehicles are prevented from entering dedicated automated lanes.

Vehicle Equipment Standards

The Federal Motor Vehicle Safety Standards (Title 49, Part 571 of the Code of Federal Regulations) regulate equipment standards for automobiles and other motor vehicles. The standards cover an array of vehicle components, including braking, tires, illumination, seating, and instrumentation. The standards are administered by NHTSA, but the vehicle manufacturers are required to self-certify their compliance with these standards. Failure to do so, when demonstrated by consumer complaints or other evidence of substandard equipment, can result in substantial fines and damage awards to consumers and others who may have been injured in a mishap.

The federal regulations for some components, including cruise control, are quite limited. In the case of cruise control, the control features on the dashboard must be illuminated, and there are regulations on the positioning of controls on the vehicle's steering wheel and spokes. There are no other federal standards to be met for performance or reliability.

This places the burden on the manufacturer to establish its own standards for quality and performance. However, it is likely that if a pattern of cruise control related accidents was established, additional product standards would be prepared. The implications for a system as complex as an AHS and with national interoperability is that these performance standards must be set nationally.

M.2.2 Investment Analysis

The decision to employ an AHS system will probably follow the same patterns that are used to decide on other transportation improvements. This involves an investment analysis that identifies the most effective strategy to address a problem from cost-benefit, environmental, and community perspectives.

M.2.2.1 Major Investment Studies

A Major Investment Study (MIS) is a planning activity that is intended to identify solutions to transportation problems in specific corridors. An MIS is required before a major transportation investment (generally a new highway or transit facility, or significant expansion to an existing facility) with a substantial federal contribution can be planned and programmed. It is a procedure that has come from ISTEA and is a departure from the previous approaches, which focused on specific modes. While an MIS is not a cookbook-type study with line by line requirements, most include the following components (Hoover, 1994):

- coordination among interested local, state, and federal agencies
- early and meaningful public involvement
- focus on solving identified transportation and mobility problems
- consideration of all reasonable alternatives (including do-nothing, transportation system management (TSM), highway, transit, land use and transportation demand management)
- demand forecasting that includes level of usage and considers person movement, freight movement, impact on other facilities (i.e., other highways or transit facilities) and input to other impact assessments, such as air quality
- assessment of alternatives to the extent that they address environmental and community concerns:
    - mobility, including needs of transit dependent groups
    - socio-economic, land use, and development concerns
    - air quality and other environmental and energy concerns
    - operating efficiency and safety
    - goods movement/safety
    - financial performance

One of the key differences between an MIS and previous procedures is the emphasis on problem solving. An MIS is identified for a transportation corridor, which may be associated with an existing highway or rail line, but is not defined by it. It is defined by the travel and mobility needs shared by its residents and economic interests. The initial

technical effort for a study focuses on defining mobility problems within the specified corridor. Potential problems may include the lack of transportation links to an important destination, or inadequate capacity on existing facilities. The sponsoring agency should ensure that the public is allowed to participate in this and subsequent steps. This work supports the development of project goals and objectives, and eventually, a statement of purpose and need.

Alternatives are then developed to address these goals and objectives. Alternatives using a variety of modes (highway, transit, other) should be considered. Multi-modal options are encouraged. The recommendation that emerges from an MIS need not maintain complete fidelity with the alternatives that were evaluated. In fact, the sponsoring agency is encouraged to appropriate effective and compatible features from many alternatives in order to develop the most effective strategy possible.

A technologically feasible and accepted AHS concept could be presented as one or more alternatives to be considered in an MIS. One option might be a package of policies to encourage the employment of vehicle-based technologies in mixed traffic. A second could include civil infrastructure to support a dedicated lane, which might or might not be barrier-separated, but would still rely on vehicle-based AHS electronics. A third approach might use dedicated lane with electronic infrastructure.

M.2.2.2 Investment Criteria

The MIS alternatives are evaluated against criteria developed from the concerns listed above in order to identify the most effective investment strategy. These criteria are also related to the goals and objectives.

Mobility

Mobility criteria may include travel time, throughput, changes in vehicle miles traveled (VMT) or person miles traveled (PMT), changes in in-vehicle time (VHT) and increases in transit ridership and vehicle occupancy. Depending on the goals and objectives, some of these criteria may be more important than others. It should be noted that successful highway projects could actually reduce VMT and/or VHT, by adding a transportation link that allows drivers to take a significantly shorter route to reach a destination.

Cost Effectiveness

These projects must compete with other projects in the same region, and often with projects from other regions, and cost effectiveness is a key issue. Capital and operating costs are estimated for each alternative. Capital costs are calculated on an annual basis for the number of years that an improvement will last. In the appropriate cases, operating costs are balanced against potential toll and/or farebox revenue to determine an operating balance. The annualized costs are then balanced against the mobility benefits that are gained, yielding measurements like cost per hour of travel time saved or cost per new

transit trip. It is important to ensure that the measurements be developed so that different modes can be evaluated on a fair and equal footing.

Environmental Issues

An MIS has two options to address environmental issues. Option One defers detailed environmental review until a Draft Environmental Impact Statement (DEIS) study is conducted on the preferred investment strategy. Option Two runs the DEIS concurrently with the MIS. All of the alternatives would be analyzed in the DEIS, which would support the MIS recommendation. If the alternatives are expected to face the same environmental issues, then Option Two would probably be preferable. If the alternatives have environmental characteristics that are disparate, then Option One would probably be preferable. However, even under Option One, a screening level analysis of environmental issues should be completed.

Evaluation

An AHS' competitiveness in an MIS evaluation will be based on the extent to which the benefits of the new technology offset higher costs. An alternative with dedicated lanes and electronic infrastructure would need to be at least as cost effective as a conventional highway alternative. This is not an unreasonable expectation, particularly if a conventional highway would require a greater number of lanes, within an area where right-of-way costs would be high. However, an AHS alternative that could offer significant benefits in mixed traffic, at a relatively low cost, might be even more competitive.

An AHS also should not have unacceptable environmental impacts. Any transportation improvement that would have an unacceptable environmental impact, would have to be considered to be fatally flawed. Areas of concern might be wetlands of exceptional resource value, critical habitat for threatened or endangered species, significant historic sites or archeological ruins, or sensitive community sites, such as hospitals. Alternative performance would also be evaluated for traffic, air quality, and noise impacts. For these criteria, there might not be a fatal flaw, but some alternatives may perform significantly better than others. (Depending on the geographic area and specific location, exceeding traffic, air quality or noise standards could be a fatal flaw, if not mitigatable -- *see Section M.2.3 Environmental Review*.)

M.2.2.3 Community Opinion

The opinions of members of the communities to be affected by a proposed project receive much more attention in the MIS and environmental procedures than they did in the past. Sponsoring agencies <u>must</u> involve members of the community in the planning process at the earliest stages. Effective public involvement can enhance the planning process in a number of ways:

- by ensuring that the problem statement, goals and objectives, and purpose and need reflect the concerns of the community

- by allowing members of the community to suggest alternatives for consideration that might be overlooked by the agency (many of the suggestions are "unusual," but every once in a while an innovative and effective solution is born this way)

- by allowing community members to have a voice in the evaluation process

If consensus can be reached on the purpose and need for a project, on the alternatives to be considered, and on the evaluation, then the recommendation will have legitimacy and a much greater likelihood of being accepted. This will make funding more easily attainable, and will reduce the likelihood of legal challenges, which have delayed and killed many projects.

However, even with a proactive public involvement program, a project may still face stiff opposition. In some cases a community will have several factions with competing or otherwise incompatible interests. Sometimes these interests cover the functionality of a project. More often they are fisticuffs over Not In My Backyard (NIMBY) issues. In these scenarios a community will accept the need for an improvement, but object to having it run through their vicinity. Noise, vibration, air quality, traffic, and visual impacts are the most frequently identified concerns.

M.2.2.4 Financing Plan

Successful AHS deployment will only be possible if a financial plan can be developed to cover both capital and O & M costs. Financial plans must be developed at a fairly early stage, since funding sources are a key factor in determining what environmental documentation will be required to advance the project. A financial plan will largely be based on the determination of ownership and payment (discussed in Sections M.2.1.1 and M.2.1.2). Each of the scenarios has potential advantages and disadvantages.

Systems that are built using federal or state transportation funds must compete with other transportation projects in the TIP process, unless they are identified for specific earmarks in appropriations legislation. While ISTEA has reduced the use of earmarks, they have not been eliminated, and probably won't be when the law is renewed in 1997. While ISTEA is a long way from being renewed, and the final shape of the bill can't really be predicted, it does seem that most interested parties favor increased flexibility in the funds that are disbursed by states and/or states and MPO's. The American Public Transit Association (APTA) has recommended that CMAQ and STP, which can be applied with greater flexibility than highway or mass transit general funds, be increased by 58 percent, while the highway and transit general funds would grow by only 12 percent. The American Association of State Highway and Transportation Officials (AASHTO) favors the use of block grants that would have no restrictions on their use; if this approach were

adopted, states would be free to assign those funds to whatever projects they choose to prioritize.

The emergence of ETC as a viable technology appears to have stimulated the development of a new generation of toll roads, particularly in the country's fastest growing areas. Toll roads also offer the opportunity to deploy new infrastructure without burdening the general taxpayer. In an age in which discretionary spending at the federal and state levels has been and is likely to continue to be constrained, this is a way to finance new infrastructure projects.

M.2.3 Environmental Review

Major infrastructure projects involving federal funds must undergo an environmental review prior to proceeding into final design. An AHS infrastructure project would be subject to these requirements. NEPA (CFR Title 23, Chapter 1, Part 771) requires an Environmental Impact Statement (EIS) for any Class I action (project) that will use federally administered funds for construction, or affect a resource under federal jurisdiction. A Class I Action would be a new expressway, busway/HOV facility, or fixed guideway transit system. Class II Actions that are not expected to have significant environmental impacts may qualify as categorical exclusions (CE). Class III Actions are projects for which the sponsors are unsure whether the facility will qualify as a CE or require an EIS. In this case they would initiate an Environmental Assessment (EA), which would determine what type of document needs to be prepared and which does not require as great a level of effort as an EIS. Should an agency identify a potential impact during the preparation of an EA, then an EIS would be initiated.

Many states have similar environmental review requirements for projects that use state funds (and some cities have their own environmental review requirements). Projects that are being built by private interests will usually require a state-level review, because the state will participate by condemning property or by securing the financing.

Categorical Exclusions

An AHS that includes electronic infrastructure, but does not involve major new construction, could probably qualify as a CE. Statewide programs to encourage use of vehicle-based systems in mixed traffic might also qualify. Examples of actions that currently qualify as CE's include actions under a state's highway safety plan and installation of fencing, signage, pavement markers, and traffic signals. Actions that may qualify as CE's (provided that they receive federal approval) include:

- modernization of highway infrastructure by resurfacing, restoration, rehabilitation, reconstruction, adding shoulders, or adding auxiliary lanes

- highway safety or traffic operations improvement projects including ramp metering

- approvals for changes in access control

If any of these actions is expected to result in a significant environmental impact, then they would not qualify for a CE. Potential disqualifying impacts might include traffic impacts, impacts to water or wetlands, or impacts related to the construction phase. To the extent it is clear that electronic infrastructure improvements represent an action that could qualify as a CE, the appropriate action would be to submit to FHWA a letter describing the proposed actions and requesting concurrence with the assessment that these actions represent CEs.

Environmental Assessments

An AHS that dedicates a lane to automated use, increasing the number of lanes, but not taking new right-of-way, will qualify as either a Class I or Class III Action. In most cases this type of action will be identified following a Major Investment Study or an Interim Congestion Management Study (ICMS) which is used to evaluate options for highways that are congested and which generally follows MIS procedures. An Environmental Assessment (Class III) would:

- determine which aspects of the proposed action have potential for social, economic, or environmental impact

- identify alternatives and measures which might mitigate adverse environmental impacts

- identify other environmental review and consultation requirements which should be performed concurrently with the EA.

Following public involvement (which should take place at an early stage) and formal hearings, a recommendation will be made for a Finding of No Significant Impact (FONSI) if no significant environmental impacts are identified. The FONSI will require approval from the appropriate federal agency. If significant impacts are identified at any point during the process, then an EIS will be required.

Environmental Impact Statements

An AHS that will require construction of major new infrastructure including separate lanes and/or separate entry/exit ramps will automatically be a Class I Action requiring an EIS. A NEPA EIS involves a rigorous procedure which includes:

- issuance of a Notice of Intent by the appropriate federal agency to conduct an EIS on the proposed action. This is published in the Federal Register and sponsors are encouraged to publish it locally as well.

- a scoping process that identifies the range of alternatives and impacts and the significant issues to be addressed in the EIS. The scoping process must include the opportunity for interested agencies and members of the public to make comments.

- a statement of purpose and need that identifies the specific transportation problems to be addressed by the proposed action.

- evaluation of all reasonable alternatives to the action and discussion of the reasoning for why alternatives which may have been considered were eliminated from detailed study (an MIS would provide the substantiation for the elimination of most alternatives).

- summarize the studies, reviews, consultations, and coordination required by environmental laws or Executive Orders to the extent appropriate at this stage of the process.

The DEIS is circulated (following FHWA/FTA approval) and the public is given the opportunity to provide comments in writing or at hearings. Following circulation and review, a Final Environmental Impact Statement (FEIS) will be prepared. The FEIS will identify the preferred alternative, and evaluate all reasonable alternatives that were considered. It will also discuss all reasonable comments that have been received, as well as agency responses. Mitigation strategies for environmental impacts will be identified and costed. Once the FEIS has been accepted (following a 30-day review period) the appropriate federal agency will issue a Record of Decision (ROD) which is needed to proceed with final design and construction (Preliminary engineering may occur concurrently with the DEIS).

An EIS for any project, including an AHS highway, addresses a whole range of socio-economic, cost, environmental and community issues. The proposed action, No-Build, TSM, and possibly other alternatives are compared and evaluated against these criteria. An AHS may have special implications for a number of these issues, including:

- Air Quality: This issue is particularly important in CAA non-attainment areas. A proposed action in a non-attainment area usually cannot result in increased emissions, and all actions taken together must be consistent with the required State Implementation Plan (SIP) to decrease emissions. The factors that are considered include the emissions that can be expected from the proposed technology [gasoline internal combustion (auto) vs. diesel (bus/commuter rail) vs. CNG (bus) vs. electric (light/heavy/commuter rail)], the effects on VMT and VHT, and ambient climate. Analysis is done at the mesoscale, covering regionwide air quality and focusing on volatile organic compounds, and nitrogen oxides, and at the micro-scale, which focuses on local effects and is particularly concerned with CO emissions.

  One of the intended benefits of AHS, which has been at least partially validated in preliminary model results, is to achieve a reduction in emissions as a function of

VMT while under automated control. This will come as a by-product of the increases in efficiencies that will result from reductions in acceleration and deceleration that occur under automatic operation, and particularly with reduced aerodynamic drag during platoon operations.

However, several factors that are at least partially dependent on local conditions prevent a definitive assumption that AHS will reduce emissions in all cases. Total trips may increase and trip length may increase, due to the increasing attractiveness of highway travel. Queues at AHS entry and exit points may result in additional engine idling that would increase local CO emissions.

It is also important to note that highway travel represents only a part of the total emissions budget for any airshed. Other contributors will include conventional highway trips, local auto trips, and fixed source emissions. Reductions due to AHS would be beneficial, but they would still only represent part of the total problem addressed by an SIP.

Another issue to consider is the improvements that are being made and can be expected to continue in reducing tailpipe emissions technologically. As internal combustion (gasoline-powered), compressed natural gas (CNG), fuel cell, and battery technologies are developed and improved, much of the urgency to reduce VMT and VHT to improve air quality will be reduced.

- Electro-Magnetic Radiation (EMR) and Electro-Magnetic Interference (EMI): An AHS will likely require the use of a number of electronic systems, including GPS, radar and other sensors, radio, microwave, and other ITS technologies. These are all electronic systems, and they emit EMR. The effects of EMR on the environment and on human health continue to be studied, with the most recently announced findings of a national review comparing all studies as of a certain date concluding that there was no cause for alarm (nevertheless, there are those who remain concerned about possible carcinogenic and teratogenic effects). Along with the uncertainty about the actual systems that will be employed, the level of power they will require, and the extent to which they will emit EMR, leaves the potential implications for an environmental review up in the air. It is likely, as more about the phenomenon is known, and the systems are more definitively identified, that standards will be needed and established that will safeguard the environment and the population.

- Another EMR issue is the potential for interference. This has implications for both AHS and for surrounding activities. The integrity of AHS communications and sensor systems will be absolutely crucial to safe operation. Interference, from conflicting systems or from outside sources could compromise system integrity. Potential outside sources could include a range of consumer electronic systems. At the same time, there are likely to be off-highway land uses that will need protection against EMR, such as hospitals. Regulations exist to minimize interference, such as

restrictions on electronic devices around airports. However, an AHS may require more far-reaching restrictions, and have complex enforcement implications.

- Traffic: The potential increased capacity that would come from an AHS could have potential impacts on traffic at on- and off-ramps that will vary according to local conditions. Potential effects include:

    – queues at entry ramps that exceed reservoir capacity: if vehicle check-in is controlled and regulated to ensure that volume does not exceed capacity, and then total demand exceeds that capacity, vehicles may queue up at entry ramps, overflow reservoirs, and contribute to congestion on local streets.
    – increased traffic volumes in exit areas: higher exit ramp volumes can be expected to increase local street volumes, which may negatively impact level of service.
    – vehicle trip demand: the relative attractiveness of AHS travel may influence mode choice by making auto travel more attractive, and thus increasing total vehicle trips. This would potentially impact street networks at a regional level.

    All proposed transportation facilities must be examined to determine their potential for these effects. If impacts are identified, then they must be mitigated. Potential mitigation techniques may range from operational improvements to local streets to expansion of local street capacity.

- Property takings: Most projects also potentially require taking of private property for right-of-way or facility-supporting uses. The owners who are affected must be compensated at fair market value. An AHS, because it would presumably have higher capacity per lane mile, may require less right-of-way than a conventional facility with a similar capacity. However, a facility that adds lanes to an existing highway, but which requires separate entry/exits and interchanges, would potentially have greater ROW requirements. The potential need for larger turning radii (to accommodate greater speeds) would also increase ROW requirements.

- Socio-economic and land use issues: Each proposed action must be examined to determine its effects on demographics, travel demand, and land use patterns. This analysis uses a group of quantitative and qualitative measurements to see how well a project would complement planned and desired community development. Since those effects vary quite widely from location to location, it is difficult to characterize the ways that AHS might affect these patterns. In addition, policy decisions regarding the proposed system and made at the local level may negate or mitigate potentially negative impacts and may also enhance positive impacts.

Additional issues must be addressed, but the potential for differentiation from conventional highway projects is lower.

M.2.4 Liability / Insurance / Risk

Liability issues are among the societal/institutional issues of greatest concern by some stakeholders. If any of the potential stakeholders face increased risks that outweigh potential benefits, they will resist system development and implementation, and the viability of AHS will be threatened. Like many of the issues to be addressed, specific rules vary from state to state, however, some general issues are universal. Chief among these is each party's reasonable "expectation" of system/vehicle/equipment/component performance. In 1997, the NAHSC will co-sponsor a workshop that includes legal expertise from each of the key stakeholder groups to examine liability issues with automated vehicle safety and control systems and AHS. The remainder of this section summarizes research findings to date.

Under current conditions, the vehicle operator bears primary responsibility for safe operation of his/her vehicle. In most states the owner is required to be insured against liability in order to register a vehicle. Manufacturers are required to meet standards set by NHTSA that ensure that vehicles can safely operate as designed. Should their product fail to meet those standards, they can be found liable for damages. Most states enjoy some level of sovereign immunity, which protects them from many lawsuits. However, they are usually responsible for ensuring that roads are maintained in a safe condition. Certain states, particularly California, use comparative negligence doctrine, which may assign some liability to the state if highway conditions contribute to an accident.

The key change that would come with AHS is that drivers would be relinquishing control of their vehicles, and this will probably modify the assignment of liability. The reassignment of this liability would vary according to what scenario is employed. However, under all of these scenarios, the driver would be responsible for ensuring that the vehicle is in safe operating condition. Operators of check-in facilities would also share some of this responsibility, since they would effectively be certifying the safe operating condition of the vehicles.

AHS systems that would rely on independent vehicles with their own sensors, would transfer at least partial responsibility from the driver to whomever is responsible for vehicle performance, which could fall upon the vehicle owner, manufacturer, vendor, or inspection facility. The vehicle owner will continue to insure the vehicle, and manufacturers, vendors, and inspectors will continue to require product liability insurance. However, whereas the owner currently bears most of the liability, under this scenario, the exposure will be shared among all parties. The parties with the deeper pockets will be more vulnerable to large payouts unless punitive damage award limits were set.

If automated vehicles are operated in mixed traffic, their insurance would also need to account for the risks inherent in sharing the road with manually operated vehicles, which would be less predictable in their behavior. A collision involving both AHS and manually operated vehicles would raise two questions. The first would be: who is at fault? The answer would probably not be much different from what it would be if the collision were among manual vehicles. If one vehicle violated the rules of the road, then

it would be at fault, and its driver would be liable for damages. If the at-fault vehicle were automated, then the liability would fall upon the driver, manufacturer/vendor, and/or maintainer. This raises the second question: under what circumstances would an AHS manufacturer would be willing to expose itself to the risks that would come from mixed traffic operations.

AHS systems that employ cooperative technology will carry the same liability issues as the independent vehicle systems. However, the communications affecting vehicle control will make the assignment of blame and liability more ambiguous in the case of vehicular collisions. Since the system will rely on accurate and timely communication among vehicles, communications that are inaccurate could result in accidents. A miscommunicating vehicle might even cause an accident that includes other vehicles but not itself. Presumably the system would be designed to be self-checking and redundant to greatly reduce this likelihood. When an accident among manual vehicles is caused by a third party today, the reckless or unsafe driver must be identified or he/she can't be held liable. The same issue would apply to AHS vehicles. The concepts may call for "black boxes" that record all electronic and mechanical activity that takes place on the vehicles. However, unless vehicles identify themselves (and indications on the privacy issues front are that they probably won't) they will need to be identified by human witnesses. Under these circumstances, liability would be assigned to the drivers and vehicles who could be identified. Vehicle manufacturers in particular, are likely to resist liability exposure on this issue.

The infrastructure based concepts, which may or may not include communications, will have at least part of the potential liability assigned to infrastructure owners/operators. The infrastructure-based AHS electronics will be relied upon to provide information to vehicles which will affect the safety of vehicle operations (for the same reasons and with many of the same implications as explained above). The infrastructure owner/operator would be liable for collisions related to its operational controls where dedicated, barrier-separated lanes are used to prevent outside elements from causing collisions, the burden of ensuring effective obstacle exclusion is assigned to the roadway owner/operator.

While these concepts clearly alter the distribution of liability exposure, increasing the exposure of some stakeholders, this change should be balanced against what will be an overall decrease in risk. The primary performance objective of AHS is to improve safety. If one assumes that this objective will be met, a reduction in collisions and in collision severity will be a primary effect. This will reduce the number of claims and awards for damages. Overall risk and payouts for claims may be reduced. A balance of exposure and risk reduction will be the key to making AHS acceptable to each stakeholder.

This question most clearly affects the roadway owner/operator. A system that completely isolates the automated vehicles from random, outside elements through barrier separation from traffic and non-highway objects, will have the highest level of safety and will be least likely to result in collisions. However, it will also place the greatest liability exposure on the roadway owner/operator.

However, since most states enjoy sovereign immunity and the states are the principal highway owner/operators, this would leave the manufacturers and drivers in the position of potentially being liable for collisions or other accidents over which they have little control.

This raises an interesting issue about the implications for private roadway operators. Most, but not all, states currently extend their sovereign immunity to concerns that operate and maintain highways under contract. If operators were to waive such protections for AHS operations, under conditions that would limit liability, two issues would be addressed. (1) States could delegate AHS infrastructure deployment to these contractors and avoid assumptions of increased liability. (2) Vehicle manufacturers would have greater confidence that they would not stand alone in the rare event of a collision. The contractors would include a risk factor and insurance cost in the tolls or user fees they would charge drivers.

The state can assist in managing liability and risk by adapting rules to the new situations presented by AHS systems. These adaptations can take the form of limits to punitive damage awards, and adoption of specific standards for vehicle and infrastructure performance. For infrastructure-based systems, states will probably need to relinquish at least part of their sovereign immunity. Failure to do so would unacceptably burden the manufacturers and vehicle owners.

The pricing of insurance will also be based on the relative risk and exposure for each stakeholder. Insurers offer discounts for some vehicle components which reduce payouts (according to actuarial data), such as airbags. In the case of AHS, it is important to note that the system will only cover freeway mileage, not local traffic, and therefore the potential for deep insurance discounts is low, except for those vehicles, such as interstate freight haulers, that have a very high proportion of freeway mileage. However, a key performance measure for an AHS system should be that it not raise risk for the vehicle owner/operator, and therefore, not require higher insurance premiums.

M.2.5 Deployment Issues

If one assumes that an AHS will be technologically possible and available as an option for deployment, the actual deployment path must still be considered. Several forces will interact to determine this path, including federal, local, and state agencies; vehicle and equipment manufacturers and vendors; and of course, transportation consumers. Since the needs and concerns to be addressed by an AHS will vary among regions, the decision-making process should be as flexible as possible. However, the need for interoperability demands that certain core standards be established.

M.2.5.1 Decision Process

Each location will address several questions before it decides to deploy an AHS. The question of whether a system is an appropriate investment would be addressed in an MIS or other investment analysis (already discussed). However, some other policy-level issues will need to be addressed before an MIS even becomes an issue for local deployment. A decisionmaking process that would offer flexibility to the states was suggested at the NAHSC Workshop #3 in Minneapolis in September, 1996. The suggested process was termed the Reactive Adaptive Management Portfolio (RAMP; suggested by John Lathrop and Kan Chen). RAMP would essentially organize the process as a decision tree, where core standards would be part of the trunk, and acceptable variations would be branches. Some of the decision points are described below.

Each jurisdiction must decide whether it wishes to accept the technology, along with all of the policy requirements and institutional issues that accompany it. They must be satisfied that the technology is safe. They will need to accept the standards that are established at the national level. They might wish to establish their own standards, provided that they do not conflict with the core system architecture. If an independent vehicle system that operates in mixed traffic is deployed, they will have no choice but to address these issues. It is possible that states could prohibit automated independent operations (as many states prohibit or restrict use of radar detectors). However, enforcement of that policy would probably prove difficult. It might be necessary to at least code roadways so that independent vehicles would only be able to automate in authorized areas. Acceptance of the technology might also come incrementally, although this would only be possible if the evolution could take place under mixed traffic operations.

The decision of when to make an infrastructure investment in AHS can be approached by states in two ways: they can be market leaders or market followers. Some states may wish to encourage AHS use and therefore make investments ahead of market penetration. This would have the effect of priming the pump and encouraging consumers to purchase cars with AHS equipment. Other states, because they may be skeptical or resistant to the technology, or because they don't want to make an investment in a system that nobody is using, will wait until a critical mass of AHS-capable vehicles are sold. At that point, they will make an investment and get in on a winning game.

The vehicle and equipment manufacturers will face a similar choice. Some will choose to accept the risks of being market leaders with the hope that they will stake out market share. Others will decide to wait until a proven technology is shaken out from the contenders, and then weigh in. On this side, there will also be a need to balance the proprietary nature of some technology components against the need to maintain a competitive marketplace.

The RAMP process at the state level would begin with the decision to accept the idea of an AHS. From that point, a decision might be made on whether to commit the state to an infrastructure-based system, to allow mixed traffic, or to maintain flexibility.

The selection of a system architecture will depend on a state's needs and expectations. Some states, particularly those with large rural areas, will seek to improve safety on long, lightly traveled highways where driver inattention is a significant problem. A separate AHS infrastructure may not be a justifiable investment in these areas. An independent vehicle concept, that operates on existing highways with mixed traffic, may be all that is needed to prevent people from falling asleep while behind the wheel.

In rapidly growing states, where land for right-of-way is still available, but where travel demand is growing, increased capacity and travel time reduction will be as important as safety improvements. In these areas, it should be possible to build dedicated lanes and entry/exit points, or even dedicated AHS highways.

In urban areas, where there is already congestion, but where right-of-way is constrained due to nearby development, the decision on the type of system to be deployed will be most difficult. The potential demand for AHS is likely to warrant dedicated lanes, but it will be difficult to implement them as additional lanes. The experience with HOV lanes indicates that adding lanes for special use is more palatable politically than taking them from the lanes that are currently available to normal traffic. However, this option can only be exercised by taking new right-of-way from properties that in urban areas have most likely been developed. This would increase costs, and also generate adverse community opinion. Taking an existing lane, assuming that it will provide sufficient right-of-way and that vehicle penetration justifies it, will increase overall highway capacity and reduce congestion for even the manual drivers.

Once a concept is accepted, the policy choices must be made on standards, principles for tolls or user fees, if applicable, potential for authority or private participation, and other regulations that establish the ground rules for system deployment. Once this framework is established, AHS systems can be considered as potential alternatives to address transportation problems within specific corridors.

Involvement of Fleet Carriers

The early involvement of transit providers in a potential AHS project will be crucial to successful implementation, particularly in cases where states wish to develop ahead of the market. Bus systems in major metropolitan areas like New York, Chicago, San Francisco. Seattle and Houston are substantial users of key highway segments and bridges. Increasing congestion on these highways threatens the reliability and travel time performance of these systems. Therefore, they are very interested in finding ways to avoid the impacts of this congestion and improve the reliability of their services. Transit providers have been important proponents of HOV lanes and ETC in these cities, in many cases forging cooperative arrangements with the highway agencies. Certain facilities including the Exclusive Bus Lane leading to the Lincoln Tunnel into New York and busway/HOV facilities in Houston, are currently operating at or near capacity. These

facilities would be clear beneficiaries of technology improvements that would increase throughput per lane and offer potential areas for early AHS deployment.

Perhaps more importantly, an early transit buy-in would put a high number of AHS vehicles, and an even higher number of AHS passengers, on the road at the outset of any deployment. This would result in a large initial market penetration (from a persons benefiting perspective) which could be used to justify subsequent deployments.

The trucking industry may offer a similar opportunity to develop an initial market very quickly. An AHS would be attractive to truckers because of the potential savings in safety, fuel and travel time. Consistent travel times would also be a big benefit for truckers. Even more important would be the potential gains in vehicle roadway hours, since driver fatigue would be reduced as a potential hazard, and maximum daily hour restrictions could possibly be adjusted.

M.2.5.2 Institutional Requirements

Policy changes will be needed in three key areas:

- national core standards for infrastructure and equipment and mechanisms to regulate and enforce those standards

- new traffic laws and enforcement

- tort and liability issues (as previously discussed).

New traffic laws and innovative enforcement techniques are usually developed on a state-by-state basis, with early deployers (and more activist legislatures) taking the lead, frequently emulated by other states.

The core standards for infrastructure and equipment will be required to ensure some level of interoperability. For infrastructure, universal object detection and sensor standards, communications standards, and civil infrastructure standards would be needed. Vehicles would require some universal standards for automated vehicle control and especially, communications protocols and technology.

M.3   Societal Issues

Societal issues cover the concerns that affect the population and groups with less formal identities than those that have been named as institutions.

M.3.1 Assessing User Need / Market Issues

A critical finding of a recent methodological consumer research study was that "consumers do not respond reliably to product concepts with which they have had little or no previous experience; they find it hard to envision where such a product would fit into their lives" (Horowitz, 1996, citing Lappin). Therefore, to measure consumer need for and acceptance of AHS, it is important to introduce it from the perspective of familiar highway driving.

To begin to identify the public's preferences among AHS and AHS-related technologies, a self-administered survey was conducted on the Internet during May and June 1996 via a website administered by Motoresearch, Inc. of Troy, Michigan, accessible via links from the "ITS America" and "National AHS Consortium" web pages. Beyond measuring attitudes toward AHS, the survey attempted to measure the need for AHS, and to better understand consumer attitudes and perceptions of some of the technologies upon which AHS may be based.

Just under five hundred self-selected individuals participated in this survey. The survey measured attitudes towards present highway driving, current use of cruise control, and interest in future technologies, specifically Adaptive Cruise Control, Collision Warning Systems, Automatic Steering, and AHS. The Internet was selected because its users represent, in general, a cross-section of technology "Innovators" and "Early Adopters." Consumer research suggests that Internet surveys attract high quality responses, compared with what might be expected from telephone or mail surveys.

Among the key findings of this survey were the following:

Present Highway Driving. On average, what respondents disliked about current highway driving, from most to least severe, were: *stress on the driver, the perceived impact on the environment,* and *congestion.* What they liked about highway driving at present, from most to least positive, were *the overall experience, perceived convenience, economy* and *safety*.

Future Highway Technologies. A majority of respondents liked each of the future technologies described in the survey and had favorable experiences with the current version of cruise control. Seventy percent of respondents liked the concept of *AHS* as presented in the survey. The average like-dislike rating of *collision warning systems* was significantly more positive than that of AHS, as described in the survey. The ratings of *AHS* and *adaptive cruise control* were not significantly different.

Open Ended Comments. A classification of positive open-ended comments, separately for each technology, indicates that the most frequent comments were of the *Potential Merit* and *Safety* types. The most common types of negative comments/concerns with AHS were related to the system's *Safety, Reliability,* and *Expected Cost.* Human factors issues were raised by some respondents, especially for *Collision Warning Systems, Automatic Steering,* and *Adaptive Cruise Control.*

Respondents indicated they would be willing to pay an average of $1.50 for an automated highway trip of 20 miles, and were willing to pay, on average, an extra 20 cents if tolls were charged electronically. In general, tolls were preferred (68%) over taxes as a means of collecting revenue.

Conclusions. A large proportion of respondents would like to see improvements in driving stress, environmental impact of driving, congestion, and safety, and believe that technology, including AHS, can meet their needs. Conditions necessary for public acceptance of AHS include high levels of (perceived) system safety, reliability, and benefit/cost ratio, and minimum driving-induced stress. Collision Warning Systems may satisfy drivers' needs for safety if human factors issues can be adequately addressed. This survey implies that when developing different potential AHS concepts, major consideration should be assigned, in this order, to: *driving-induced stress, system safety, system cost, effect on environment,* and *effect on congestion.*

A series of six consumer focus groups was held in May 1996 in the San Francisco Bay Area to gauge consumer reactions to AHS and AVCSS user services in the context of the daily driving experience. These groups elicited concerns about current driving conditions, as well as indications of what consumers would like or dislike about the AHS and AVCSS services and what they might be willing to pay for these services.

The primary concerns about present-day freeway driving involved traffic congestion, stress and the compromise of safety because of rudeness and inattentiveness of other drivers.

When Adaptive Cruise Control (ACC) was described for these consumers, about half said that they would use it, especially for longer drives on freeways that do not have extreme congestion. There was more interest among older drivers than younger (age 18-25) drivers, who were less willing to give up control of the car to a computer. The older drivers saw safety advantages in a system that could compensate for some of their difficulties in handling cars in difficult driving conditions such as nighttime and limited visibility. People stated a willingness to pay between $250 and $500 beyond the cost of normal cruise control, and a few were willing to pay up to $1000.

Collision avoidance systems (CAS) that included the computer taking over control of brakes and steering were less favorably received because of doubts about whether the systems could be made safe enough. People feared encountering complex situations that the systems could not handle, and were worried about the CAS itself breaking down. Collision warning was more favorably received by these groups of consumers, who indicated this by comments like, "The second set of eyes I like, but I don't like the extra hands and feet."

AHS was viewed more favorably than the CAS, because of the separation of the AHS lane from other traffic and its protection from the bad actions of other drivers. People liked the safety, convenience, stress reduction and opportunity to do other things while

traveling (such as reading or grooming themselves). They had concerns about the reliability of the system and felt the need for an opportunity to take back control in an emergency. They were interested in AHS for both commuter driving and long-distance driving, and were willing to pay prices in the range of $2000 to $5000 for this capability (with one frequent commuter going as high as $20,000).

One of the more surprising findings across the board was the greater receptivity to all of these technologies by the older drivers than by the younger drivers, who tended to be more skeptical of technology. They wanted proof by "independent" sources such as Consumer Reports that the systems would really work as promised before committing their support. There was general support for the technical feasibility, but concerns about the political and institutional barriers to deployment. There was strong support for the segregation of AHS vehicles from the rest of the traffic, and an expressed willingness to pay substantially more for AHS than normal automotive industry rules of thumb would tend to indicate.

M.3.2 Costs, Benefits and Tradeoff Issues

M.3.2.1 Introduction

The question "who is our customer?" arises in discussions for the final AHS prototype, the '97 demo, the system requirements, system characteristics and measures of effectiveness and the definition of concepts. The question begs us to differentiate between customers and stakeholders (McNeil et al., 1996).

The issue of differentiating between different types of customers and stakeholders is important as it influences the point of view from which the analysis of alternatives is carried out and how many of which type of customers will experience particular benefits and costs, as different customers will value costs and benefits differently.

The Automated Highway System ultimately has to meet the needs of travelers. These come in a variety of forms each with its own needs, concerns and requirements. Stakeholders include these customers but also include vendors and regulators. We must be careful not to design a system that does not meet real needs. While stakeholders have a vested interest in AHS, customers are purchasing a product, in this case an automated highway system. Stakeholders who influence financing and implementation are also the customers of the AHS program, and, in turn, their customers will buy AHS from them.

The concept of identifying the customer is important for determining from which point of view we are analyzing costs, benefits and tradeoffs. In the case of users versus non-users, a benefit to a user may be a cost to a non user, or vice versa. For example, a more convenient, faster route to work for a commuter may disrupt a residential neighborhood. Similarly, inter-generational issues are important when looking at different stakeholders. For example, large benefits may be derived by creating an AHS for the current generation, but we may impose environmental costs on subsequent generations.

Stakeholder groups are not unique. An organization or an individual could be a member of one or more stakeholder groups. For the purposes of this stakeholder/benefit and cost analysis, we have grouped stakeholders into categories, as follows:

"Society" represents society as a whole. As the costs and benefits to society as a whole should dictate the value of building an AHS, this is an important category. This category also provides an opportunity to include non-users that may not fit into any of the existing stakeholder or user groups.

"Users" represents a large non-homogenous group. The ability to differentiate between different types of users (peak vs. off-peak, work related and commuting trips vs. recreational, single and multiple occupant vehicles) is critical for the cost/benefit analysis. The drivers of CVO and transit vehicles are a category of users that are of particular interest.

Facility owners includes two stakeholder groups: government organizations and transit and commercial vehicle owners.

"Government organizations and other agencies" represents a broad category of stakeholders with very different needs and concerns. These include state DOTs, local government, metropolitan planning agencies, and turnpike and toll authorities.

"Transit" and "commercial vehicle" stakeholders are the operators, owners and providers of the services.

Private sector interests. These include the four stakeholder groups of "vehicle manufacturers," "vehicle electronics industry," "highway construction industry" and the "insurance industry." Their interests in AHS relate to opportunities for making profit. These industries may be involved in and impacted by the terms of their role as responsible corporate citizens.

Non-users include "environmental" stakeholders. This is broadly defined to embrace interests and concerns related to sustainability, neighborhoods, emissions, noise and energy use.

M.3.2.2 Benefit and Cost Categories

In representing benefits and costs there is considerable confusion between benefits and measures of effectiveness and attributes of the system. For example, "user friendly displays, controls, and operations" are not benefits but attributes of the system. Similarly, improved throughput is not a benefit but an MOE or attribute. Therefore we have developed some general classes of benefits and costs represented by the attributes:

performance (throughput or capacity), safety, reliability, economic, environmental and technical. Within these general groupings of attributes are sub-categories of benefits that can be estimated or measured. Some of these measures are part of a cost benefit tool under development.

Table M-1 identifies the relationship between the sub-categories of benefits and each of the stakeholder groups. The table reinforces the notion that different stakeholders will have different interests and this must be considered in the evaluation of concepts and potential applications, and in communications with stakeholders.

Table M-2 summarizes similar relationships between stakeholders and costs. Costs have been categorized by frequency. One-time costs are associated with the initial construction of the facility, infrequent costs refer to activities that occur more than once in the planning horizon, and recurring costs represent activities that occur either regularly or continuously. This table demonstrates the opportunities for double counting unless the point of view of the analysis is explicitly considered, transfer payments are recognized as such, and cost reductions that have already been included as benefits are not included again. The final column in both the cost and benefit tables indicates costs and benefits that are being included in the cost/benefit tool by the NAHSC.

The tables facilitate the process of being able to identify which costs and benefits accrue to which stakeholders and ensuring that benefits and costs are correctly and consistently included in the analysis. For each specific stakeholder group, its point of view is reflected in the costs and benefits identified by the check marks in the columns. Some care needs to be applied. For example, the vehicle purchase cost is a cost for a user but a benefit for the vehicle manufacturer. As another example, consider a toll. From the point of view of the automobile user, a toll is a real cost, but to society as a whole it is a transfer payment as it is cost to the motorist and income to the agency or institution running the AHS. Similarly, reductions in accidents have already been included as a benefit. If they again are accounted for as a cost (with a negative sign to indicate a reduction), they will be double counted. The tables also show that costs and benefits to society are represented by the union of the other stakeholders' costs and benefits. That is, costs and benefits accrued to society are the sum of all the costs and benefits for the other stakeholder groups assuming that non-user interests are adequately represented by the environmental stakeholders.

Table M-1. Stakeholder/Benefit Matrix

Stakeholder / Benefit	Society	Users	Govt Orgs	Transit	Trucks	Vehicle Manuf	Vehicle Elect Indust	Hwy Constr Indust	Enviro'l Interest	Insur'ce Indust	Included in Cost - Benefit Tool
Performance improvement											
Time savings	▤	▤		▤	▤						▤
Reduced vehicle operating and maintenance costs	▤	▤		▤	▤						▤
Safety											
Reduced accident costs	▤	▤	▤	▤	▤					▤	▤
Improved safety for highway workers	▤	▤	▤	▤	▤			▤		▤	▤
Improved response to incidents and emergencies	▤	▤	▤	▤	▤					▤	▤
Reliability, comfort and convenience											
Improved trip time reliability	▤	▤		▤	▤						
Reduced driver stress	▤			▤	▤						
Higher quality of service	▤	▤	▤								
Greater comfort/ convenience	▤	▤		▤	▤						
Improved mobility	▤	▤									
Environmental											
Reduced noise pollution	▤	▤	▤						▤		
Reduced air pollution	▤	▤	▤						▤		▤
Fuel savings	▤	▤		▤	▤						▤
Economic and technology											
Job creation	▤					▤	▤	▤			
Spin off technology	▤		▤			▤	▤	▤			
Economic stimulus	▤		▤								

Table M-2. Stakeholder/Cost Matrix

Stakeholder / Cost	Society	Users	Govt Orgs	Transit	CVO	Vehicle Manuf	Vehicle Elect Indust	Hwy Constr Indust	Enviro'l Interest	Insur'ce Indust	Included in Cost - Benefit Tool
One-time costs											
Infrastructure design and construction	▤		▤	▤	▤			▤			▤
Construction related disruption	▤		▤					▤	▤		
Maintenance of traffic during construction	▤		▤					▤			
Land and ROW acquisition	▤		▤					▤			▤
Vehicle design and production	▤					▤	▤				
Environmental damage mitigation	▤		▤					▤	▤		
Infrequent costs											
Infrastructure rehabilitation	▤		▤					▤			
Vehicle purchase	▤	▤		▤	▤	▤				▤	▤
Recurring costs											
Infrastructure O&M	▤		▤	▤	▤			▤			▤
Licensing		▤	▤			▤				▤	
Inspection	▤	▤	▤			▤				▤	
Noise	▤								▤		
Tax		▤	▤								
Education	▤	▤									
Vehicle O&M	▤	▤		▤	▤	▤				▤	▤
Tolls		▤	▤	▤	▤						

M.3.3 Privacy Issues

Americans are very concerned about their privacy rights and the effects that advances in technology may have on them. In many cases we must choose between convenience and personal security. We use credit cards, even though we know that our identities and purchasing behavior can be sold to others. We put our social security number on various forms, usually without a second thought. We walk into banks, schools, and stores with surveillance cameras that record our presence. We have accepted these intrusions because we benefit from the convenience or physical security that come with them. Nevertheless, many people are concerned that this information can be used in harmful ways, which can range from unwanted junk mail to intrusive surveillance by public or private organizations. The Fourth Amendment provides some protection against these intrusions, but not as much as many would like.

Some of the components of an AHS have the potential to compromise personal privacy, unless safeguards are established. ITS America is already addressing some of these issues, as the personal privacy issues of AHS also apply to AVI, traffic surveillance, and ETC. The privacy principles that they have developed will be used as the basis for the policies for AHS. Ideal system attributes would be:

- check in and check-out systems that inspect vehicles for systems integrity and valid registration/insurance, but do not record vehicle identities

- vehicle-vehicle and vehicle-infrastructure communications and sensor systems that coordinate operations, but do not permanently record vehicle identity

- systemic security that prevents eavesdropping

If these attributes cannot be met, then policy guidelines would be needed to ensure that the information collected by the system is kept secure and that it is not misused.

M.3.4 Land Use Issues and Sprawl

The link between land use and transportation is one that is both commonly recognized and frequently misunderstood. Access is one of the key factors in determining property value. A parcel that has good access to the region around it will be more valuable than a parcel with poor access. However, there are a number of other factors that contribute to the shape and type of development that will take place in a given area, including zoning, geology and topography, environmental issues, proximity to metropolitan areas, economic conditions and other socio-economic and demographic factors.

AHS, like any major transportation improvement, raises some concerns about land use on a number of levels. There are concerns about the effects of taking land for right-of-way purposes. There are concerns about developmental impacts at a local level. Finally, there

are concerns about "sprawl," the decentralization of urban form. In each case, the influence of a major transportation investment is manifest. However, the other factors discussed above, particularly zoning and land use policies, are often just as, if not more, influential.

Property Takings

Any major transportation investment, highway or fixed guideway transit, will require right-of-way. Unless it is re-using an obsolete facility, such as an abandoned rail line, the property will need to be acquired. In most developed areas, the property owners will sell their property or be compensated when it is condemned by the state. This also may impact the community by removing ratable properties from the tax rolls.

Local Land Use Impacts

Anyone who has seen an office park or mall spring up adjacent to a new arterial highway or expressway interchange will understand that highway access opens up a range of land use opportunities in previously undeveloped areas. A land use that has highway or transit access can be used by people from a larger service area. The land is more valuable, and therefore there is greater economic pressure to develop it to its "highest and best use." This development brings economic activity and improves a community's ratable base. However, it also brings costs; environmental impacts, infrastructure needs, policing, etc. Residential developments usually increase the number of school age children, and thus the need for additional classrooms. In a growing area without land use or zoning regulations, such developments near highways are as predictable as dandelions in spring. However, much of the developed areas, and even undeveloped areas, do regulate land use, and therefore can shape induced development so that it does not disrupt tax base or infrastructure needs.

Regional Land Use

The sprawl question is one that is driven by a number of factors, transportation-related and otherwise. Sprawl is a pejorative term that refers to the decentralization of traditionally urban land uses, including office commercial/retail, industrial, and residential. In the nineteenth and early twentieth centuries, these uses were largely concentrated in cities. The advent of the freeway made it possible to relocate these uses to the suburbs during the 1950's, 60's, 70's and 80's. However, improvements in building technology, changes in land use planning and policy, real estate pricing, and the current problems of congestion tend to slow down the sprawl that these highways encouraged. Many of our large metropolitan areas have now developed as far out as one can expect to drive in an hour. In many areas, transportation planning and investment is shifting from radial access to/from the center city toward connecting already dispersed activity centers within a metropolitan area.

On the other hand, some areas, particularly in the south and west, are still booming, and continue to see untrammeled growth. Most land use experts generally agree that a transportation improvement, such as AHS, that reduces travel time, will give people the opportunity to seek lower cost (outlying) real estate, that is still within an hour's (or whatever their tolerable travel time is) travel from wherever else they want to go. Travel time reduction at a reasonable cost is essentially the transportation force that encourages sprawl. It will continue to do so if an AHS is implemented, although the other forces that discourage sprawl will have greater influence than they had during the Interstate Highway building years.

Communities hold the power to establish comprehensive plans and zoning. If they choose to, they can develop plans that encourage "liveable communities" with good pedestrian links and access to community services. On the other hand they can chase rateables and permit sprawling subdivisions that generate high numbers of auto trips. Any major new transportation investment in a corridor, including AHS, makes sprawling development possible. A community must take positive action, by allowing sewer and utility improvements, and through their comprehensive plan and zoning, in order for it to happen.

Communities that are concerned about sprawl will need to deal with AHS in the same ways that they deal with other highway or transportation improvements. Land use is something that is controlled at the local level and to some extent at the state level as well. Areas that want to grow and develop will enact policies to support this goal and they will seize AHS as a tool to help. They will be some of the pioneers who are the first to use AHS. As with other transportation improvements, investment in AHS can be made to encourage growth where desired and discourage growth elsewhere. Investment in a network of AHS facilities could help to distribute growth where desired. Areas that do not wish to grow and develop will enact zoning and other land use restrictions that discourage it.

M.4   Conclusions

Development and deployment of an automated highway system will test the capacity of our society and institutions to adapt to progress and change. There is no evidence to indicate that any of the challenges presented by AHS will be insurmountable. If a system will offer substantial improvements in mobility, safety and convenience and comfort at a reasonable cost; and can do so without additional harm to the environment, then there will be support for policy changes. By the same token, a system that fails to deliver on any of those attributes will likely encounter opposition. In fact, the system and the policy framework that is developed to support it, should be crafted in a way to ensure that all interested parties; drivers and passengers, manufacturers and vendors, insurance, and roadway providers; benefit from each major increment of the system. Otherwise, the disappointed stakeholder group is likely to block implementation, by refusing to build, insure, or drive key system components.

Some of the key issues, as described in this section, include:

- assignment of responsibilities for ownership and operation of system components, including infrastructure, vehicles, and radio frequencies. In some cases, liability and other issues may actually make it more attractive to arrange for private ownership of components that have traditionally rested with the state or with semi-autonomous authorities. User-based payment systems are probably necessary to foster private participation in the deployment of infrastructure.

- development of new standards and regulations to deal with the new technology and changes in operational responsibilities.

- development of a system that can compete, on the basis of cost and performance, with conventional highway systems. Major Investment Studies, which evaluate a variety of modal and technological alternatives, are likely to be part of the predominant deployment path.

- environmental review of proposed facilities. Air quality, EMR, traffic, and socioeconomic issues will need special attention.

- fair and equitable assignment of liability and risk. An overall risk reduction will be essential to getting buy-in from most stakeholders.

- interoperability of a variety of system architectures, ranging from those with independent vehicles operating in mixed traffic to those with infrastructure support on dedicated lanes.

- satisfaction of privacy concerns so that individual rights are respected within the context of a safe and accountable system.

- coordination with local land use planning to prevent adverse impacts.

The list of issues to be addressed may appear daunting, but only to someone who has never tried to deploy a major transportation improvement. In the cases of infrastructure operations, insurance policy, and the development of new traffic regulations, a new paradigm will be needed. Most of the other issues are already faced by state DOTs on their major highway and transit projects. It would be unrealistic to expect AHS to avoid them. Many projects get stopped, because they are weak in one or more areas. The strong projects survive and are implemented. An AHS with proven technology, that is cost-effective, and that offers real benefits, will survive and reach implementation.

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In addition, the results of NAHSC Workshops, Stakeholder Forums, and Conferences have been considered in the preparation of this report.

Acronyms

AASHTO	American Association of State Highway Transportation Officials
AVI	Automatic Vehicle Identification
BTO	Build, Transfer, Operate
CAA	Clean Air Act (CAAA: Clean Air Act Amendments)
CE	Categorical Exclusion
CFR	Code of Federal Regulations
CMAQ	Congestion Management & Air Quality
CMS	Congestion Management System
DEIS	Draft Environmental Impact Statement
D-BOM	Design, Build, Operate, & Maintain
EA	Environmental Assessment
EIS	Environmental Impact Statement
EMI	Electro-Magnetic Interference
EMR	Electro-Magnetic Radiation
ETC	Electronic Toll Collection
FHWA	Federal Highway Administration
FONSI	Finding of No Significant Impact
FTA	Federal Transit Administration
HOV	High Occupancy Vehicle (HOV-3: HOV with 3 or more passengers)
ICMS	Interim Congestion Management Study
ISTEA	Intermodal Surface Transportation Efficiency Act
ITS	Intelligent Transportation Systems
MIS	Major Investment Study
MPO	Metropolitan Planning Organization
NEPA	National Environmental Policy Act
NHS	National Highway System
NHTSA	National Highway Traffic Safety Administration
NIMBY	Not In My Backyard
O & M	Operations & Maintenance
PMT	Person Miles Traveled
RAMP	Reactive Adaptive Management Portfolio
ROD	Record of Decision
ROW	Right-of-Way
SDELP	San Diego Expressway Limited Partnership
SIP	State Implementation Plan
STP	Surface Transportation Program
TDM	Transportation Demand Management
TIP	Transportation Improvement Program
TSM	Transportation Systems Management
VHT	Vehicle Hours Traveled
VMT	Vehicle Miles Traveled