

Automated Highway System (AHS)

WBS C1 Final Report

Develop Initial Suite of Concepts & Workshop #2

June 10, 1996

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ABSTRACT

Task C1 is the first in a series of activities to define and assess alternative concepts for the Automated Highway System. Specifically, the goal of this task was to develop a set of six high level concept families for more detailed analysis in subsequent tasks.

Six major characteristics distinguish AHS approaches at this level, with the most fundamental being the allocation of intelligence, since it drives the allocation of sensing, processing and decision making. The alternatives range from an autonomous vehicle to a system completely controlled by infrastructure electronics. Separation policy has moving slots, or free agents, or platoons of vehicles. Lane sharing between manual and AHS-equipped vehicles, the manner in which they are separated, the mixing of vehicle classes, the approach to entry and exit and the level of automation of obstacle detection and avoidance are also important characteristics.

Five teams evaluated these concepts relative to throughput, safety, cost, flexibility and acceptability.

In a parallel activity, seven contractors developed independent AHS concepts. The Battelle/OSU team developed the Integrated System Concept, which places much of the intelligence in the vehicle. Calspan developed an evolutionary set of three concepts: mixed flow, dedicated AHS lane with a mixed transition lane, and full automation with dedicated transition lanes. Haugen Associates developed PAC-ITS, which consists of mixed packet trains of 15 or 20 vehicles mechanically coupled together for intercity travel and uses a professional "pilot" to control each packet train from a special lead vehicle. Honeywell, BRW and the University of Minnesota developed a hybrid of infrastructure supported and managed, with lane changes managed by the roadside. The urban setting has platoons in dedicated, barriered lanes. Rural areas support free agents mixed with manual. SRI bases its concept on precise position determination, data integration and supervisory control in the vehicle. Toyota Motor Corp. developed the Light AHS

concept, which uses photonics where appropriate to sense, communicate and control. The Virginia Tech Center for Transportation Research developed a Cooperative Infrastructure Managed System (CIMS), that shares command decisions between the vehicle and infrastructure. The system fuses sensory data from both, using ultra-wideband communications.

Several conclusions came out of this analysis based on recurring themes and composite qualitative scores:

- A fully infrastructure controlled system or a slot approach lacks robustness and should not be considered further;
- Dedicated, barriered lanes and a level of global assistance to the vehicles, is required for maximum throughput performances.
- Multiple layers of capabilities are required to support regional differences, different steps in the deployment of AHS, and graceful degradation because of malfunctions;
- It would be desirable to include a capability to operate on non-dedicated lanes with manually driven vehicles.

In some cases, the conclusion was the identification of key issues to be addressed in the next phase. These issues drove the definition of the concept families. Also, many issue areas were determined to be local decisions; the AHS must support various options in entry/exit approach, vehicle class mixing and barriers.

The Workshop presented the Conclusions and Candidate concepts to the stockholders—transportation users, trucking, transit, local and state agencies and MPOs, vehicle, electronics and highway design industries, insurance, financial and environmental interests.

Their feedback resulted in five final concepts: Independent Vehicle, Cooperative Vehicle, Infrastructure Supported, Infrastructure Assisted, and Adaptable.

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0. EXECUTIVE SUMMARY

0.1 GOALS OF THE TASK

Task C1 is the first in a series of activities of the National Automated Highway System Consortium (NAHSC) to define and assess alternative concepts for the Automated Highway System. A spiral approach is used, in which the initial work is done at a high, but broad level, with later steps focusing on fewer options in greater detail. Thus, there are two major challenges in Task C1. One is to do meaningful comparisons at a high conceptual level without discussing implementations or other lower-level specifics. The other is to ensure that the virtually limitless alternatives for the Automated Highway are all given a fair hearing.

This is driven by the needs and desires of the various stakeholders:

- Transportation users
- Insurance and financial industries
- Transit operators
- Environmental interests
- Vehicle industry
- Electronics industry
- Highway design industry
- State agencies and metropolitan planning organizations
- Local agencies
- Trucking industry

Specifically the goal of this task was to:

- Identify a small set of high level characteristics, and a range of alternatives for each, of any AHS concept
- Define and elaborate a set of representative system concept designs across this set of characteristics
- Evaluate these characteristics and these representative system concepts against the objectives of an AHS
- Develop a new set of high level characteristics based on the conclusions drawn from this evaluation effort
- Develop a set of approximately six new concept families to form a basis for studying the new set of concept characteristics

0.2 APPROACH

Foremost is the identification of the dimensions or characteristics that distinguish AHS approaches at the conceptual level. Specifically, these are characterizations that are independent of implementation. These characteristics and the alternatives within each are first analyzed independently. This then suggests a refined list of characteristics and alternatives. Since these dimensions are closely interrelated, there is a limit to how much can be decided by considering them independently. Hence, the bulk of the activity is the development and analysis of a set of candidate concepts that reflects the range of dimensional alternatives. These candidate concepts are described in sufficient detail to support evaluation. Each candidate is then evaluated relative to the objectives and characteristics for the AHS. Individual results are merged for an overall assessment. These evaluations may suggest the elimination of unpromising alternatives, but more importantly, they suggest new concepts, promising combinations of concepts that perform better than either alone, and new issues to be considered.

In a parallel effort, a national solicitation has been made for concept proposals. This ensures a broad range of approaches not limited by the experience and background of the core teams. The most interesting and promising of these are funded for development. The contractors are to develop, evaluate, document and present their concepts. The results of both of these activities feed into the selection of the six concept families.

Thus, the approach is a process of "reconcepting" in which the concept families reflect the issues and insights, and are not merely a "down-selection" from the original concepts. The evaluation process and the six concept families are presented to the stakeholders in Workshop #2, and the stakeholders are asked for feedback in breakout sessions

0.3 CONCEPT CHARACTERISTICS

A concept is a framework in which an AHS system is defined. It is not a system design or an implementation, but a structure within which a design may be built. For the most part, a concept is defined in terms of the choices for the key decisions that drive the design. These choices are called dimensions or characteristics. There are several dimensions or characteristics that define any possible AHS solution at the concept level. These were identified based on core team inputs, the Precursor Studies and other studies. Following are the initial set of characteristics. Some were eliminated from this phase of concept development since they were determined to be implementations, local decisions or imposed from without, as indicated by "*".

- Distribution of Intelligence/Sensing/Processing
- Communications*
- Separation Policy (platoon, free agent, slot)
- Roadway Interface (normal, pallet, RPEV, other)*
- Obstacle Response Policy for Sensing and Avoidance
- Vehicle classes in a lane (one class only, mixed classes)
- Mixed Traffic Capability (dedicated and mixed, dedicated only)
- Lateral Control Approach*
- Longitudinal Control Approach*
- Entry/Exit (transition lane, dedicated station)
- Lane Width Capability (normal only, normal or narrow)*
- Design Speed (speed limit, higher than speed limit)*

This led the teams to the definitions of the major characteristics

0.4 MAJOR CHARACTERISTICS AND THEIR ALTERNATIVES

The evaluated concepts are built around the six key characteristics or dimensions that distinguish essentially different approaches to the Automated Highway System.

Characteristic 1: Allocation 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 requirements on sensing and communications, and on the nature of the AHS system as a whole. The locus of intelligence and control is largely the key description of the architecture. It will impact who pays the costs, how the automated highway evolves and whether a system optimum or individual optimum can be achieved. In this section the word "infrastructure" refers to infrastructure-based electronics, as opposed to vehicle-based electronics.

Eleven different alternatives were initially identified, but this number made the total number of concept alternatives unmanageable. The Concept Team realized that it was not feasible to do an exhaustive analysis of all alternatives, so the five most promising alternatives were selected, supplemented by enough others to form a broad and representative sample of approaches. This does not mean that those that were not selected were eliminated for all time. The "re-concepting" approach allows the reintroduction of alternatives if the analysis points that way.

Autonomous

Autonomous is equated to automated vehicle. The infrastructure provides at most the basic ITS services (in-vehicle information and routing, but not control) and something for the vehicle to sense to determine its position in the lane (such as magnetic nails or existing stripes). The vehicle does automatic lane, speed and headway keeping. The roadway contains no more AHS-specific intelligence than the immediate location of the road. The vehicle senses its surroundings, including adjacent vehicles and lane, but does not communicate with the infrastructure (except possibly for standard ITS features), nor does it communicate with other vehicles.

Cooperative -

The cooperative option also has minimal infrastructure intelligence, but includes the addition of short range vehicle-to-vehicle communications for vehicle coordination. This allows coordinated lane changes and platooning. There is no infrastructure support beyond that in the previous alternative. Since this is all done locally, there is no region-wide traffic optimization, other than through digital ITS advisories. There is no entry or exit flow control. There may be passing of information vehicle-to-vehicle or platoon-to-platoon, for example in an emergency, or for distribution of global intelligence throughout the vehicles on the roadway.

Infrastructure managed

In the Infrastructure Managed alternative, the infrastructure communicates with individual vehicles rather than groups of vehicles. Thus, the infrastructure manages anything other than steady state in the lane. Specifically, the vehicles maintain steady state including lane keeping, headway keeping, speed maintenance and platooning, but for any special request, such as lane change, entry or exit, the infrastructure takes command. These are high level commands; the vehicles will determine the steering, braking and throttle needed to execute them.

Infrastructure controlled

Here the vehicles are completely controlled by the infrastructure, which will continually track and send commands to individual vehicles. These commands may be in the

Infrastructure supported

Infrastructure supported is an enhancement of the cooperative alternative. Here the cooperating vehicles are given location-specific information from the infrastructure electronics that is monitoring the global situation (flows and trouble spots, not individual vehicles). The information sent will not be specific to any one vehicle or platoon, though it may be lane-specific. It will be in the form of general parameters, such as target speed or spacing, dependent on the current situation. The information could be static as well, such as: lane ends, merge left; speed limit 65; slow, curve ahead; exit 165. The vehicles are still maintaining their steady state and negotiating their lane changes, but now these are informed by the broader view maintained by the infrastructure. Communication is with groups of vehicles.

form of steering, braking and throttle commands, or they may be acceleration, deceleration and turning commands. The vehicles have no intelligence beyond the ability to translate these commands into corresponding commands for their own actuators, and to monitor and adjust their response. They may not have sensors for roadway geometry or surrounding vehicles; if they do it is only as a means of data collection for the infrastructure.

Characteristic 2: Separation Policy

The separation policy defines the relationship of each vehicle to the one in front of it. It defines the position that each vehicle will maintain. As such, it has major impacts on safety and throughput. Three possible alternatives are given below

Alternatives and their Descriptions

Free Agent	<ul style="list-style-type: none"> • Maintains safe distance from the vehicle it is following, and travels at safe speed. • Travels at speed limit (or lower but safe speed) if no vehicle is ahead within the safety distance. ▪ Grouped free agents are not considered platoons since they do not operate as units. • Free agents are not free of outside influence. They may receive commands from the infrastructure or from other vehicles.
Platooning	<ul style="list-style-type: none"> • Platoons are clusters of vehicles with short spacing between vehicles in the platoon and long spacing between platoons to ensure the relative speed is low if a malfunction causes a collision. The longer inter-platoon spacings ensure no inter-platoon collisions. • Tight coordination within the platoon is required to maintain the close spacing. • A platoon acts as a unit, synchronizing the actions of each of the vehicles.
Slot	<ul style="list-style-type: none"> • Roadside control system creates and maintains moving slots on an AHS lane that partition the AHS lane at each moment in time. • Slots then are moving roadway segments, each of which typically holds at most one vehicle at any time. • Vehicles are identified and managed by association with their slots. • Vehicles that need more space (e.g. heavy trucks) may be assigned multiple slots. • In a basic slotting concept, the slots are of fixed length. Slots can be visualized as a point-following technique. That is, vehicles are assigned to follow moving points rather than other vehicles.

Characteristic 3: Mixing of AHS and non-AHS Vehicles in the Same Lane

Mixed traffic operation refers to the degree to which vehicles under manual control and vehicles under automated control share the roadway (i.e., the main line of the roadway, which consists of the through lanes, rather than a ramp or transition lane). At one extreme is full mixing, in which automated and manual vehicles under normal operations share a mainline lane. At the other extreme is dedicated automated lanes, with a physical barrier that makes it virtually

impossible for a manually operated vehicle to enter. In between are configurations in which lanes are dedicated to automated use, but there is not complete physical separation. Thus, the distinction among the four alternatives below is the likelihood that a manually operated vehicle will find itself in a lane with automated vehicles. The alternatives below are presented in order of increasing danger of a manually operated vehicle incursion into automated (or transition) lanes, either through driver error or vehicle failure.

Alternatives and their Descriptions

<p>Dedicated Lanes - Continuous Physical Barriers</p>	<ul style="list-style-type: none"> • Automated lane(s) are physically separated from manual lanes. • Examples are an innermost lane on a freeway that may be converted to automated use, with a continuous solid barrier between this lane and adjacent manual lane, and a fully automated highway that is not adjacent to any manual roadway, either from new construction or by complete conversion to automation.
<p>Dedicated Lanes - Some Gaps in Physical Barriers</p>	<ul style="list-style-type: none"> • Occasional gaps in physical barrier allows transition from adjacent lane(s). • Can permit adjacent lane to be a transition lane.
<p>Dedicated Lanes - Virtual Barriers</p>	<ul style="list-style-type: none"> • Virtual barriers are any demarcation that separate the dedicated automated lanes from other traffic, but do not physically prevent movement between lanes. • A common example is yellow lines.
<p>Full Mixed Lanes</p>	<ul style="list-style-type: none"> • Automated and manually-driven vehicles co-exist in same through lane at all times. • This is the only alternative where manual vehicles are present in the lane on a normal, non-emergency basis.

Characteristic 4: Mixing of Vehicle Classes in a Lane

Vehicle classes refer to levels of performance characteristics, such as passenger cars, heavy trucks and transit. For equity and economic viability the automated

highway must accommodate all classes, but not necessarily in the same lane. Vehicles with very different performance must maintain different spacing than those with compatible performance. It may not be feasible to mix classes within a platoon.

Alternatives and their Descriptions

Mixed	<ul style="list-style-type: none"> • This alternative supports all classes in all lanes at the same time. • It may or may not mix classes within platoons. • It may or may not form vehicles into same-class blocks or otherwise manage the various classes on the lanes.
Not Mixed	<ul style="list-style-type: none"> • In this alternative only one class (or group of similar classes) is allowed in each lane. • For example, there may be a lane for heavy trucks and buses and another for cars and light trucks. This may change with time of day, for example allocating more lanes for cars during rush hour.

Characteristic 5: Entry/Exit

Entry and exit provides alternatives for automated vehicle transitions to and from

manual roadways, based on their impact on other traffic.

Alternatives and their Descriptions

Dedicated	<ul style="list-style-type: none"> • This alternative has on ramps and off ramps that are used solely by automated vehicles to place vehicles in the automated lane without passing through manual traffic. • Transitions between manual and automated operation occur somewhere on these automated ramps and may or may not require the vehicle to stop.
Transition	<ul style="list-style-type: none"> • A transition lane is the lane next to the first fully automated lane. • Automation occurs in this lane so that they merge into the fully automated lane under automated control. This merge action is similar to that used currently to enter an HOV lane. • Transfer of control occurs in this lane so that they merge into the fully automated lane under automated control. This merge action is similar to that used currently to enter an HOV lane.

Characteristic 6: Obstacle Detection and Avoidance

Obstacles are potentially hazardous objects and may include such things as stalled

vehicles, manual vehicles from adjacent lanes, dropped cargo, animals, and vehicle parts such as bumpers or hubcaps. There is no way to prevent obstacles on the roadway.

Alternatives and their Descriptions

Manual Sensing Manual Avoidance of Obstacles	<ul style="list-style-type: none"> As is currently done on conventional highways, the driver watches the road ahead and to the sides. If a hazard is seen, evasive action, such as braking, swerving, or changing lanes, is taken.
Automated Sensing Manual Avoidance of Obstacles	<ul style="list-style-type: none"> The vehicle has the capability to detect obstacles in the road ahead and to brake automatically. Once the vehicle stops, the driver takes control to steer around the obstacle if necessary.
Automated Sensing Automated Avoidance of Obstacles	<ul style="list-style-type: none"> If an obstacle is sensed, the vehicle determines and executes the appropriate response, including braking and/or lane changes. Possible variations are swerving, or use of a "panic button", for hazards missed by the sensor, but detected by the driver (e.g., deer about to enter roadway; ladder or nails in the road).

0.5 THE INITIAL SET OF CANDIDATE CONCEPTS

Since the initial set of candidate characteristics are highly interrelated, there is a limit to the insight that can be gained by evaluating them individually. Thus, several candidate concepts were formed from compatible combinations of characteristics. Strict combinatorics produces an unwieldy number of alternatives, so selection criteria were used to choose 22 candidate concepts

that are initially defined in terms of the alternatives for each of the characteristics. (See Table below.):

- All candidates must make sense,
- The candidates must span the range of possibilities, and
- Multiple variations on the most promising alternatives are to be included.

The initial analysis suggested a 23rd candidate, number 3a.

Twenty-Three Candidate Concepts

Candidate Concept Identifiers	1a	1b	2	3	3a	4	5	6	8a	8b	9	10	11	12a	12b	13	14	15	16	17	18	19	20	
Distribution of Intelligence																								
Autonomous	X	X																						
Cooperative						X	X													X	X			
Infrastructure Supported								X	X	X	X						X		X				X	
Infrastructure Managed					X							X	X	X	X	X	X	X					X	
Infrastructure Control			X	X																				
Separation Policy																								
Free Agent	X	X	X			X		X	X	X		X		X	X			X	X		X		X	
Platooning							X				X		X			X	X			X		X		
Slot				X	X																			
Mixing AHS & Non-AHS Vehicles in Same Lane																								
Dedicated lanes with continuous physical barriers			X	X	X				X	X	X			X	X	X						X	X	X
Dedicated lanes with some gaps in the physical barriers						X	X	X				X	X				X							
Dedicated lanes with virtual barriers																			X	X				
Full Mixing	X	X																X						
Mixing Vehicle Classes in Same Lane																								
Mixed	X	X	X			X	X	X	X		X	X	X	X			X	X	X	X	X	X	X	
Not Mixed				X	X					X					X	X							X	
Entry/Exit																								
Dedicated			X	X	X				X	X	X			X	X	X						X	X	X
Transition	X	X				X	X	X				X	X				X	X	X	X				
Obstacle																								
Manual sensing and avoidance of obstacles	X																							
Automatic sensing, stop or manually avoid																						X	X	X
Automatic sensing and automatic avoidance maneuver if possible		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X				

The next step was to describe each concept to a sufficient depth to allow evaluation. Specifically, each candidate concept was described with enough detail to represent a range of possibilities in order to provide a design that can be evaluated. That is not to say that the details are necessarily the only, or even the best, approach. The goal is representatives of the richness of the possibilities.

Each of the descriptions was then assigned to a particular organization. Similar concepts were intentionally assigned to different organizations to get a range of viewpoints and approaches. The descriptions presented physical, functional and operational viewpoints. These documents were not only descriptive, but also provided insights into the applicability and limitations of various combinations of concept dimensions. The more than 200 pages of concept description were summarized into an eight page matrix.

0.6 CONCEPT EVALUATIONS

With the concepts described, they could be evaluated against the AHS system objectives and characteristics.

Five overall evaluation teams were formed. Rather than assign each team to some group of concepts, each team was tasked to evaluate all of the concepts relative to a major issue area. This approach was chosen

to allow greater depth in the evaluations and uniformity across all concepts. The teams were Throughput, Safety, Cost, Flexibility and Deployability, and Acceptability. Each team consisted of members from multiple organizations. Each of the Objectives and Characteristics was assigned to one of these teams, as indicated in the table on the following page.

The goals of the evaluations were to:

- Eliminate unpromising candidate concepts
- Eliminate unpromising key characteristics solutions
- Identify additional key characteristics
- Identify trade studies
- Suggest improvements to the candidate concepts
- Suggest additional promising candidate concepts
- Identify six promising concept families.
- Justify selections of the six concept families

Each team developed a plan for evaluation of the concepts that included, but was not limited to, an assessment relative to the Objectives and Characteristics. The evaluations were performed according to the plans. In general, the evaluations were qualitative, but were reported as numerical ratings. The evaluation reports are included in this document.

Evaluation Team Assignments

AHS Performance objectives and characteristics	Page*	Evaluation Team to which this item is assigned
Improve Safety	17	Safety
Increase Throughput	18	Throughput
Enhance Mobility	20	Acceptability
More Convenient and Comfortable Highway Traveling	21	Acceptability
Reduce Environmental Impact	22	Acceptability
Operate in Inclement Weather	23	Flexibility
Ensure Affordable Cost and Economic Feasibility	23	Cost
Beneficial Effect on Conventional Roadways	24	Throughput
Easy to Use	25	Acceptability
Infrastructure Compatibility	26	Flexibility
Facilitate Intermodal and Multimodal Transportation	26	Acceptability
Ensure Deployability	27	Flexibility
Provide High Availability	28	Flexibility
Apply to Rural Roadways	28	Flexibility
Disengage the Driver from Driving	29	Acceptability
Support Travel Demand Management Policies	29	Acceptability
Support Sustainable Transportation Policies	30	Acceptability (with input from the Cost Evaluation Team)
Provide Flexibility	30	Flexibility
Operate in a Mixed Mode with Non-AHS Vehicles	31	Flexibility
Support a Wide Range of Vehicle Types	31	Flexibility
Enhance Operations for Freight Carriers	32	Flexibility
Support Automated Transit Operations	32	Flexibility
Provide System Modularity	33	Flexibility

* Page on which description starts in the document, "Automated Highway System (AHS) System Objectives and Characteristics, 2nd Draft", May 22, 1995

0.6.1 Throughput Evaluation

The Throughput Team identified several issues that impact the throughput achievable by any one of the alternative concepts. These were divided into main line and interface issues.

Main line issues

Without any infrastructure assistance beyond the current definition of

infrastructure support in the individual lane-change maneuvers, it may be difficult for the lane-change vehicle to identify the neighboring vehicles that it needs to establish communication to, and to establish a dedicated communication channel. The same is true of merging. Unlike lane-changing, which can be aborted and retried downstream at a later time, merging in general must be performed successfully within a limited amount of space and time.

Failure to do so may result in safety hazards and disturbance to AHS traffic. This problem is particularly serious where the AHS has only one lane. This issue should be studied carefully in due course. Of special concern is merging due to blockage such as a stalled vehicle since, unlike the merging taking place at pre-determined merging locations, such merging at blockage may take place anywhere on the AHS.

Interface issues

Preliminary but quantitative study has shown that frequent entry/exit points and higher capacity on-ramps are needed to feed high flow rate on the mainline. A high AHS mainline capacity may not be fully used if the interface issues are not resolved. The access and egress of the AHS vehicles through the manual portion of the highway may cause significant disturbance to the traffic on the manual lanes. The speed differential between manual and automated lanes may lead to the necessity of a large reception gap for an entering vehicle, which in turn may lead to a lower entry rate into the AHS, or the actual speed differential may need to be kept below a certain threshold for safety and efficient entry.

Evaluation Approach

The alternative concepts were evaluated based on these and other issues. The focus was on normal operations. Each concept was given a qualitative Throughput Rating:

- 1 less than conventional
- 2 similar to conventional
- 3 1 - 2 times of conventional
- 4 2 - 3 times of conventional
- 5 3 times or more of conventional

The throughput team reached strong consensus in some areas regarding reconcepting and downselect suggestions.

On mixing of AHS and Non-AHS vehicles:

“Full Mixing” of AHS and non-AHS vehicles in a lane is not considered as AHS but something short of AHS. The Throughput Team felt that an option of mixed Traffic operation should be treated separately either as an earlier deployment stage or as a possible rural application.

On distribution of intelligence:

Create a new distribution called “Infrastructure Assisted”. The Infrastructure Assisted solution provides more functionality than the Supported in that communication from the infrastructure to INDIVIDUAL vehicle or platoon and vice versa is allowed at merging locations, e.g. on-ramps, highway-to-highway interchanges, blockages and other merging locations.

Autonomous Concepts that operate mixed with manual have inherent throughput limitations. (Although some variations of them could be good intermediate steps toward mature AHS.)

Eliminate Infrastructure Controlled concepts. (Although applications of infrastructure control that do not have the same limitations should be considered)

On obstacle detection and avoidance

Leave Obstacle Detection and Avoidance in for further analysis. There does not exist sufficient evidence regarding the viability of the automated solutions. Treat this concept characteristic as an attribute that needs to be explored for each selected concept, instead of as a concept discriminator.

0.6.2 Safety Evaluation

The Safety Team evaluated each of the concept characteristics relative to the following key safety issues.

- Emergency and failure handling capability
- Inclement weather
- Media event potential
- Complexity (testability and verifiability)
- Coordination required
- Data/Sensor fusion potential
- Maintenance deferral problem potential
- Average collision rate
- Average collision speed and severity
- Average number of vehicles per collision.
- Robustness

Entry/exit

All members of the team agreed that dedicated entry and exit ramps are preferred for their ability to control rogue vehicles, allow controlled and more thorough check-in of vehicles if needed, and prevent gore point problems, but entry/exit is an implementation issue, best solved by local roadway operators and should not be used as a concept discriminator. The AHS should be designed to support both approaches.

Mixing of AHS and non-AHS traffic in the same lane

Separate automated lanes with barriers between the automated lanes and the non-automated lanes were considered safest by the team. Mixing of AHS and non-AHS traffic may be possible without major safety impact in a few, limited cases, in single, barriered lanes. One of the major issues with barriers for single lane concepts that the team felt deserved mention was the potential for blockage of the lane, due to jamming between the barriers of a vehicle in a collision.

Mixing of vehicle classes

The safety team concluded that mixing of vehicle classes during active use of the roadway would compromise safety. Allowing different classes to use the automated roadway during different times would be acceptable if the roadway is checked for damage and debris after heavy vehicles have been allowed use of the roadway.

Obstacle avoidance

The safety team was unable to provide a definitive recommendation with respect to obstacle detection and avoidance approaches. Some members of the team believe that any manual involvement in obstacle avoidance is unsafe; other members strongly disagree, believing that driver takeover may be safer than automated avoidance in some, low traffic conditions. Neither side of the ensuing discussion was able to cite any significant studies to support their beliefs. Thus, work on both manual and automatic obstacle detection and avoidance approaches needs to be continued

in the next phase of concept development. The team recommended that manual detection and avoidance not be discarded from consideration until definitive study of the possible options and their impact can be performed. In some cases, manual intervention may have the potential to be safer than automatic avoidance. Combined manual and automatic detection and avoidance techniques may have potential and should also be explored.

Separation policy

Traditional slot concepts, being based on infrastructure control were considered unsafe by the safety team, and should be dropped from further consideration. This is primarily a robustness issue. The AHS will have to be designed to allow both free agent and platoon concepts to be implemented. Existing studies on this issue are based on some simplifying assumptions, and so no definitive conclusions can be drawn. Both platoon and free agent separation policies need to be studied further.

Distribution of intelligence

The safety team consensus was that all infrastructure control concepts were too prone to catastrophic failure due to common cause or common mode failures. Major multi-vehicle collisions were considered to be too likely when failure occurred for infrastructure controlled options to deserve further consideration. The safety team considered the other four possible distribution of intelligence options to be more correctly layers in a well developed AHS system instead of separate concepts. The AHS must support operation as an infrastructure managed system. It must also support operation, albeit possibly at a lower throughput, as an infrastructure supported, as a cooperative, and as a autonomous (driver alertness is an issue here) system. The concept which should be explored is how to provide the needed layering of functionality to allow the AHS to respond to differences in local installations and to failures with appropriate spacing and speeds to ensure safety is not compromised. An infrastructure managed design with its ability to maintain visibility over a significant roadway area, and to recommend

or command emergency response of vehicles when unexpected events occur, was considered to provide the maximum safety achievable without undue vulnerability to common mode or common cause failures.

0.6.3 Cost Evaluation Summary

The concepts were ranked with regard to cost, from a purely qualitative perspective. The process requires quantitative judgments for comparison purposes only, but no functional cost estimates have been performed in this evaluation. The 22 Concepts have been considered as "end-state," with an average degree of complexity. The concepts were evaluated relative to the four "key" cost elements and the results are given in the table on the following page.

Sensitivity analysis of the various weightings showed that seven Concepts consistently occur at the high end of the composite ranking, regardless of how the weights are modified. It also showed that six Concepts consistently appear at the low

end of the composite ranking. The remaining nine Concepts fluctuate in their relative positions, but are uniformly found in the middle portion of the ranking. The following list identifies the groupings, plus the common attributes shared in each group.

- *Group A: Toward the high end of the cost ranking scale*
Characterized by fully dedicated AHS facility with considerable infrastructure support (Concepts 2, 3a, 8b, 12a, 12b, 13, and 19)
- *Group B: Mid-range of the cost ranking scale*
Characterized by dedicated AHS lanes with moderate infrastructure support (Concepts 6, 8a, 9, 10, 11, 14, 15, 18, and 20)
- *Group C: Toward the low end of the cost ranking scale*
Characterized by slightly modified existing roadway and an emphasis on vehicle-based intelligence (Concepts 1a, 1b, 4, 5, 16, and 17)

Evaluation of the 22 Candidate Concepts Using Four Key Cost Elements

Key Cost Elements	Description	Concept Dimension That Most Impacted this Cost
1. Infrastructure and Support Capital Costs–Civil/Structural	Costs associated with building or modifying functional portion of the highway to meet AHS service requirements, estimated to constitute about 30% of all costs. Includes the paved surface, plus entry or exit ramps and any elevated portions of the freeway.	AHS and non-AHS mixing, estimated to drive 80% of the cost. The alternatives were: <u>Dedicated</u> - continuous barriers 10* - gaps in barriers 5 - virtual barriers 4 <u>Full mixing</u> 1
2. Infrastructure and Support Capital Costs–Systems and Instrumentation	Cost of building infrastructure network, estimated to contribute about 30% of all costs. This could involve the construction of a central control facility, as well as any remote communication stations.	The characteristic that drives about 70% of this cost is Allocation of Intelligence, rated as follows: Autonomous 1 Cooperative 1 Infrastructure supported 4 Infrastructure managed 7 Infrastructure controlled 10
3. Vehicle-Based Capital Costs–Instrumentation	Vehicle costs attributed to AHS functions only, about 20% of all costs. This cost element does not attempt to account for the total vehicle cost, but concentrates on those costs added purely to support AHS.	About 70% of this cost is driven by Obstacle Detection, rated as follows: Manual sense/manual avoid 5 Auto sense/manual avoid 6 Auto sense/auto avoid 5 (or 10 depending on infrastructure involvement)
4. Operations and Maintenance	Cost of operation and maintenance expenses for the infrastructure and the vehicles, about 20% of all costs.	About 60% of this is driven by Allocation of Intelligence, rated as follows: Autonomous 1 Cooperative 1 Infrastructure supported 4 Infrastructure managed 7 Infrastructure controlled 10

*: On a scale of 0 (no cost) to 10 (most expensive)

0.6.4 Flexibility Evaluation Summary

The Flexibility group applied a structured decision analysis method. The process assured the findings are defensible and supported by the whole team. The process steps are defined as follows:

- Review Objectives and Characteristics for Discriminating Criteria
- Develop Criteria Definitions and Scoring Symbols
- Score Each Concept Based on Criteria. This scoring was done independently

by Flexibility Team members across multiple organizations.

- Process and Analyze the Data
- Report Findings

Two statistical outliers were identified and indicate poor choices in terms of flexibility. The common trait of the two concepts was *infrastructure control* distribution of intelligence. The group sought out concept dimensions common to the best ranked concepts. The two best scored concepts were based on a *vehicle autonomous* distribution of intelligence. Other

dimensions common to the favorably scored concepts are: *free agent* separation policy, *full mixing*, *dedicated lanes with virtual barriers*, *mixed vehicle classes* within a lane, and *transition lanes* for entry exit. At the opposite end of the spectrum, in addition to *infrastructure control* distribution of intelligence, *dedicated lanes*, *dedicated entry/exit*, and *not mixed vehicle classes* were identified as poor architecture solutions for deployment and flexibility.

Two simple sensitivity analyses were performed. As mentioned earlier, the relative scoring was not affected by changing some of the individual scores. Also, weighting of the criteria (based on a survey of the PMC) did little more than change the relative position of some concepts by a couple of places.

This led to the following observations on the concept characteristics.

Flexibility Evaluation Results

Architecture	Favored Dimension	Indifferent to the Flexibility Evaluation	Discouraged Dimension
Distribution of Intelligence	Autonomous	Cooperative Infrastructure Supported Infrastructure Managed	Infrastructure Control
Separation Policy	Free Agent	Platooning Slot	
Mixing of AHS and Non-AHS Vehicles in Same Lane	Dedicated Lanes with Virtual Barriers Full Mixing		Dedicated Lanes with Continuous Physical Barriers Dedicated Lanes with some Gaps in the Physical Barriers
Mixing of Vehicle Classes In a Lane	Mixed		Not mixed
Entry / Exit	Transition		Dedicated

0.6.5 Acceptability Evaluation Summary

The Acceptability Team addressed issues related to the social, user, and political acceptability of AHS. The Acceptability Team was built from the Societal and Institutional (S&I) team that is and has been looking at numerous related issues. The people making up the S&I team are well distributed among the consortium organizations.

The process of evaluating the concepts was by nature a very qualitative endeavor, based on best professional judgment as well as any research results known to each team member in his or her knowledge base of information. An additional method sometimes used to assist in the evaluation was to concentrate on

the six concept characteristics and investigate the dimension(s) which was(were) the true determinant(s) of the impacts of each of the concepts relative to each of the evaluation criteria.

A numerical score was computed by giving equal weight to each team member who actually made a selection for each concept and evaluation criterion.

Extensive sensitivity analysis was done relative to weightings. The following three conclusions were the strongest to come out of this analysis:

- automated obstacle detection and avoidance is very important
- some form of infrastructure involvement is important (support or manage)

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- platoons generally looked on positively, though not exclusively

These three findings remained fairly consistent even allowing for the sensitivity analyses. The one notable consistency throughout the acceptability evaluation analysis is that automated obstacle detection and avoidance is very important and so the Acceptability Team recommended that the dimension of manual control of obstacle avoidance should be deleted from further

consideration. However, this was countered by recommendations by the Safety Team and the use of at least some manual control in some of the solicited concepts.

It was suggested by the Acceptability Team that any concept should support more than one alternative in each of the following dimensions: separation policy, mixing of AHS/non-AHS, mixing of vehicle classes, entry/exit.

Key Societal and Institutional Issues Addressed

<u>Mobility/Access</u>	<u>User Issues</u>	<u>Environment</u>	<u>Other</u>
<ul style="list-style-type: none"> • Trip Time Predictability • Trip Time • Accessibility • Intermodal Transportation Operations 	<ul style="list-style-type: none"> • Adaptability /Training • Driver Participation (level of engagement in non-driving activities) • Driver Participation (level of engagement, ability to monitor the goings-on of the system and ability to communicate with the system) 	<ul style="list-style-type: none"> • Vehicle Emissions • Fuel Consumption • Travel Demand Management /Transportation Systems Management Policies (TDM/TSM) 	<ul style="list-style-type: none"> • Ease of Construction and Maintenance • Ease of Traffic Operations

0.6.6 Summary of the Evaluation Studies

Infrastructure Control and Slots

The Throughput and Flexibility Teams recommended eliminating infrastructure control. The Safety Team also recommended eliminating these concepts since they are prone to catastrophic failure; and since traditional slotting approaches are based on infrastructure control, they too should be eliminated. No team advocated infrastructure control or slots.

Low infrastructure alternatives

Autonomous concepts were given a low rating for throughput, and for this reason the Throughput Team recommended eliminating them as end state candidates. On the other hand, the Cost Team found these to be the least expensive, and the Flexibility Team rated them the highest. This suggests that

they should be retained at least as intermediate and rural solutions.

High infrastructure alternatives

High throughput is aided by high infrastructure involvement, though complete infrastructure management is not necessary. Infrastructure Assisted, an intermediate approach in which the infrastructure communicates with selected individual vehicles as necessary, should be considered. The Safety Team found acceptable only those concepts that included layers of control, including autonomous, cooperative, infrastructure supported and infrastructure managed. The Acceptability Team said that some form of infrastructure involvement is important. But the Cost Team found these alternatives to be the most expensive, while the Flexibility Team was indifferent.

Obstacle detection and avoidance

The Throughput Team said that this requires further study. There was much difference of

opinion among the safety team; manual detection and avoidance should not yet be eliminated. But the Acceptability Team said that automated obstacle detection and avoidance is very important, and in fact that manual control of obstacle avoidance should be deleted from further consideration.

Mixing with manual

The Throughput Team considered concepts that allow mixing with manual vehicles not full AHS, just a stepping stone. Separate, barriered lanes are safest, according to the Safety Team, but mixing may be possible in limited cases. But the Flexibility Team rated the concepts that allow mixing highest.

Local options

The Acceptability Team recommended that any concept should support multiple options in separation policy, mixing with manual, mixing of classes and entry/exit. The other teams showed some preferences in these areas, but generally agreed that these should be local decisions. The Safety Team concluded that dedicated entry and exit ramps greatly improve safety, but this is a local decision. They also thought that mixing classes at the same time would compromise safety. On the other hand, the Flexibility Team favored mixed classes as well as transition lanes. Platoons were generally looked on favorably, but not exclusively. The Flexibility Team found platoons acceptable, but preferred free agents. This suggests class mixing and platooning as local options

0.7 OVERALL EVALUATION

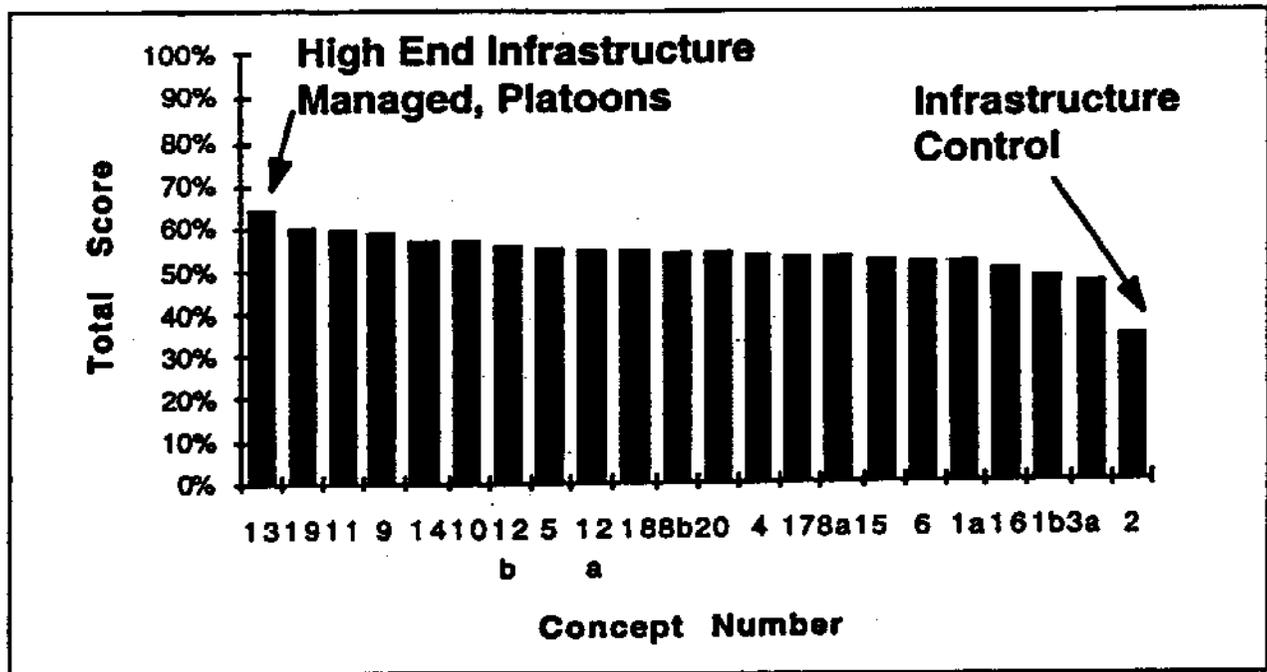
The above summary shows that the five teams often had conflicting rankings. For example, infrastructure based systems rank high in throughput but low in flexibility, while autonomous systems are given good cost are flexibility ratings, but poor throughput ratings. Hence, it is not obvious

which are the best alternatives. The evaluation results were fused to produce overall evaluations.

One approach involved weightings of the quantitative results. In addition to the insights and conclusions discussed above, the evaluation teams each defined a numerical rating scheme for the concept alternatives. The NAHSC's Program Manager's Council rated the relative importance of each of the evaluation criteria in two separate surveys. These surveys were used by the Expert Choice tool (a decision support tool used in this task) to generate weightings for the criteria. The weightings were then used to produce overall evaluation scores of the concepts, including cost as one of the factors, as shown in the next figure.

The Infrastructure Controlled alternative is rated very low, so much below the others that it should be eliminated in its present form. Looking at the high end shows the options with the most layers of control and the most sophisticated control. These rated high even when cost was taken into account. On the other hand, no concept was excellent across the board, as indicated by the top score being less than 70%. This indicates that there are tradeoffs, and that different weightings will change the results.

The weightings were also used to produce an overall merit score (excluding cost) and plot it against cost. (See Figure following) This was used to identify a range of good price-performance options. The best choices for a given cost are those toward the top edge of the collection of points. Infrastructure Controlled and Slots appear to be poor choices, since they are estimated to be similar in cost to other options with higher merit scores. This diagram indicates a range of reasonable price-performance options between the simple lane and headway keeping concept (autonomous) and the concept that pushes control and throughput to the maximum (full function).



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Overall Concept Comparison

The reader is cautioned, however, that this analysis does not provide a basis to make really strong statements about many of the dimensional choices, since the ratings are qualitative and non-linear. In fact, this first-cut analysis was based on best engineering judgment of domain experts rather than rigorous analysis. This is in the nature of the spiral approach being used. As more serious engineering analysis is performed on fewer concepts in succeeding Tasks C2 and C3, and as stakeholder preferences are better understood, these results will be modified and refined.

The other approach to overall assessment is the identification of cross-cutting conclusions and insights. The evaluation results generated conclusions and identified key issues, including the following.

- Infrastructure controlled concepts should not be continued in the present form.
- Global assistance is necessary in some form for maximum throughput.
- Infrastructure assisted, which allows local management of individual vehicles, is better than either infra-

structure managed or infrastructure supported.

- The best concepts are layered to include underlying capabilities for evolution, safe degradation and local options.
- Concept families should be defined as compatible sets of evolutionary options

The evaluation results identified the following major issues:

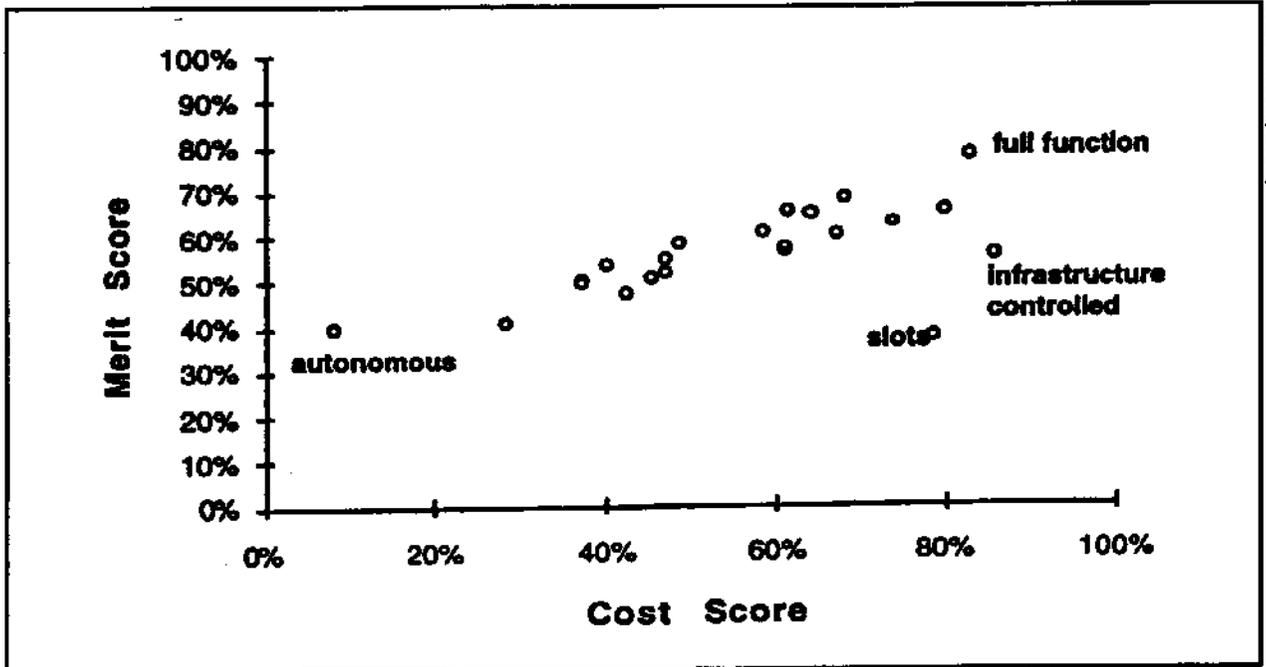
- Infrastructure involvement
- Role of the driver
- Amount of layering (options)
- Separation policy
- Manual and automatic vehicle mixing

0.8 THE SOLICITED CONCEPTS

NAHSC solicited outside concepts for AHS, to bring in a diversity of ideas. Of the submitted proposals, seven teams were given contracts to develop concepts.

0.8.1 An Integrated Automated Highway System (AHS) Concept With Special Features For Buses And Trucks

The Integrated System Concept (ISC), being developed and evaluated by the



Overall Concept Merit vs. Concept Cost

Battelle/OSU Team with its subcontractors TRC and BRW, is a concept which includes a multitude of operating procedures and infrastructures, and a special emphasis on trucks and buses. The different operating procedures and infrastructures issue is especially relevant to providing the level of flexibility needed to accommodate differing Urban, Rural, and Fringe situations even in a fully deployed AHS implementation. This flexibility also helps in both local and partial implementability of AHS technologies, and multi-stage deployment.

The ISC is based on a vehicle heavy distribution of intelligence. The ISC concept involves a "smart" vehicle and a minimally instrumented infrastructure in Rural areas, and increased levels of sensing and communication to provide additional functionality in the Fringe and Urban environments. The Concept is being developed assuming the availability of passive roadway-based markers and passive vehicle-based indicators. Currently, the concept features (1) OSU's radar reflective stripe as the roadway marker which facilitates lateral (and other) vehicle control functions, and (2) OSU's Radar Reflective Patch as the vehicle-based type of indicator which facilitates follow-the-leader or

convoy operation of heavy duty vehicles. One key aspect of these technologies is the ability to function well in a variety of situations - i.e., in inclement weather, in tunnels, on metal bridges, etc. Additionally, the Radar Reflective Stripe technology can provide a "look ahead capability" for roadway geometry changes (curves).

The ISC specifically considers truck convoys in Rural areas and bus convoys in Urban areas. These special applications are woven into the main Concept and evaluated as a whole. Special attention is being given to allowing the owners/operators of AHS capable vehicles to derive the maximum benefit of the vehicle heavy distribution of AHS intelligence in all driving scenarios - e.g., various evolutionary stages of AHS deployment, mixed traffic, and even on non-AHS roadways.

0.8.2 Mixed Flow Through Dedicated Flow

Calspan has grouped together three market-driven, evolutionary concepts to cover the range of applications. All three concepts move vehicles as individual free agents rather than groups. When a lane is dedicated to automated mode use only, the vehicle

class description would include a mass ratio specification (heaviest allowed to lightest allowed) and a maximum width specification. Vehicles outside the class would have the opportunity to use the automated mode in the other lanes mixed with vehicles operating in the manual or partially automated mode.

Concept 1 - Mixed Flow. In the mixed flow concept, the automated mode can be used in any lane. Modest driver comfort, convenience and safety benefits can be predicted for this concept, if the automated vehicles operate in the same lane, pairing up if the opportunity arises, but this phase does not significantly increase the throughput capability. It applies, even in the long term, to four-lane freeways because it allows manual vehicles the opportunity to pass. The infrastructure would monitor and advise. The driver would, in early deployment, be particularly alert for foreign objects and the behavior of manual vehicles.

Concept 2 - Mixed Transition Lane. The mixed transition lane concept evolves from the mixed flow concept on wider freeways when participation grows to the point where only a few vehicles are displaced by dedicating a cruise lane to automated use. The mixed lane adjacent to the cruise lane becomes a transition lane. To maximize the throughput of vehicles of all sizes, automated heavier vehicles would cruise in the rightmost lane mixed with manual traffic, using the transition lane to pass if necessary. As participation builds over time and the flow in the dedicated automated lane increases, a physical barrier would be used to protect the automated cruise lane from the other traffic and foreign objects. The vehicle itself would be responsible for lane and gap regulation, vehicle/driver malfunction management, access/egress execution, emergency braking, obstacle management, surface condition, and incident detection.

Infrastructure remote control stations through sector broadcasts would be responsible for speed gap commands and regularization by sector, traffic sensing, obstacle detection (shared with vehicle and driver), weather sensing (including surface

condition), and management of driver malfunction. The Freeway Traffic Operation Center would be responsible for flow management, incident management, and weather factor integration. It would operate the remote control stations and receive information from them using a two-way data link. The driver is "on-call" to manage malfunctions that require some driver role.

Concept 3 - Dedicated Flow. The dedicated flow concept removes manual vehicles from the transition lane. With a dedicated transition lane and sufficient participation to justify the cost of substantial roadway modification, large access and egress flows can be managed. This would include demerging and merging of high flows at the intersection of two AHS's. It also would include connecting the transition lane with a manual freeway entry/exit so that the entire process becomes automated. In this concept, a mature AHS might allow the driver even more freedom of activity.

0.8.3 PAC-ITS (Packet Autopiloted Cruiseway-Intelligent Transportation System)

Haugen Associates has developed this concept of mechanically linked packet trains for intercity travel.

The PAC-ITS Concept is designed around mechanical links and a trained human pilot, rather than relying on complex electronic sensors and logic. This allows complete driver disengagement with minimal personal car modifications and driver adaptation. This concept is designed to achieve the highest possible roadway capacity with greatly enhanced safety and major reductions in energy use and emissions. PAC-ITS trains are designed for faster travel between cities. The overall simplicity of PAC-ITS should allow its deployment in mixed traffic to begin within the next decade.

- A packet train is a mix of 15 or 20 vehicles - personal cars, low profile buses and freight units - mechanically coupled together for intercity travel
- A professional "pilot" controls each packet train from a special lead vehicle

- All vehicles in the packet train are guided by a high-tech lateral guidance system controlling them to keep precisely the same path
- The power trains and brakes of all vehicles are interconnected so they accelerate and brake as one unit
- PAC-ITS trains might initially operate on the Interstate; eventual operation is envisioned on new high-speed guideway using reserved time slots with high safety margins

0.8.4 The Honeywell-BRW-University of Minnesota Concept

This concept is a hybrid of infrastructure-supported and infrastructure managed intelligence. Whereas lane changes are requested from and managed by the roadside system, it has no authority to reroute vehicles--vehicle navigation is controlled by each individual vehicle, based in part on information supplied by the roadside system (e.g., about accidents). Vehicles travel as platoons in the urban setting and as free agents in the rural setting.

In the urban setting, there are dedicated lanes with continuous physical barriers to separate the automated lane from the manual lanes. In the rural setting, full mixing of automated and unautomated vehicles is allowed. In both settings, the various vehicle classes are mixed in all lanes. However, in the urban setting, special lanes and/or large-scale bypasses are provided for poor performance vehicles where there are (1) significant grades in the roadway, and (2) areas of consistently high density traffic. In the urban setting, dedicated on- and off-ramps are used, with an inspection site at each on-ramp. In the rural setting, there are nondedicated on-ramps with inspection sites; there are no dedicated off-ramps. Also, in both settings, automatic sensing and automatic avoidance maneuver (if possible) are used.

0.8.5 Evolutionary AHS Concept Based On Precise Positioning, Image Recognition, And Intelligent Autonomous Control

SRI has developed an evolutionary approach to AHS that, with minimal infrastructure requirements, provides selected interim capabilities and utility to ensure a viable and mature system upon completion of a phased development effort.

The absolute precise positioning supplied by this concept is a major step in the development of practical Roadway Powered Electric Vehicles (RPEV). Precise positioning allows the power to be transferred to the vehicles at very limited distribution points. The ultracapacitor, currently being developed, allows the vehicle to take on a large amount of electrical energy in a small fraction of a second.

There are four key aspects to the concept:

- Vehicle ability to measure its absolute position on the road to within a centimeter or two using carrier phase Global Positioning System (GPS);
- Integration of data from multiple active and passive sensors to ensure reliability and form a dynamic model of the environment around the vehicle for situation awareness;
- Supervisory control system for each vehicle that can recognize and efficiently react to critical events;
- Majority of sensors and system control reside in the vehicles so the infrastructure changes are minimal. The dominant technologies chosen to provide the required capabilities are: GPS for position location, and image recognition using multi-spectral sensors (optical, infrared, radar and LIDAR).

0.8.6 Light AHS Concept

Toyota Motor Corp. has developed the concept of a Light Car that, together with a

Light Infrastructure, forms a Light AHS. Through an evolutionary development approach, the Light AHS is intended to be light in terms of the cost of modifications to the existing infrastructure, light in the complexity of the vehicle, light on the wallet of the car-buying and road-building taxpayer, and light in the effect of implementation on society. It features the use of light (Photonics) technologies where appropriate to sense, communicate, and control. Deployment is done in phases to "think and learn while running" in an attempt to focus investment on high return areas of AHS' promise. Putting as much of the technology on the vehicle as possible will continually renew AHS with each succeeding car model. As technology progresses, the Light AHS will become lighter, particularly in the infrastructure. The Light AHS Concept maximizes the use of currently existing highway infrastructure over the course of the AHS evolution.

The Light Car uses precise measurements made by onboard optical sensors to guide the vehicle, includes a magnetic marker lane reference and a roadway-to-vehicle communications system, and extends the Light Car to include an onboard map database for coarse road geometry information and roadway features. The combination of these technologies makes possible a near-term, realizable, robust, redundant, full-featured vehicle that can be used on any AHS segment in the US.

0.8.7 Cooperative Infrastructure Managed System (CIMS)

The Virginia Tech Center for Transportation Research proposes to develop a concept for a cooperative infrastructure/vehicle based automated management approach referred to as a "Cooperative Infrastructure Managed System" (CIMS) that builds on the various strengths of several systems in a cooperative fashion. The CIMS system is neither a totally vehicle-based system nor a totally infrastructure-based system. It relies on cooperation between processors on the roadside and on the vehicle and shares command decisions between the vehicle and the infrastructure. The concept uses

communications to integrate the vehicle with the roadside. In addition, this system does not need complex roadside sensors to detect and manage the vehicles. Instead, it uses cooperation between the vehicle and roadside infrastructure to determine the best path for each vehicle on the road based on a global knowledge of location of all the vehicles in an area. Through this cooperation the tasks best suited for the vehicle are performed on the vehicle and the tasks best suited for the infrastructure are performed at the roadside.

The system fuses together the multiple sources of sensory data from both the vehicles and infrastructure into a layered management algorithm designed to optimize the safety of the system while maintaining designed throughput potential. The use of a new solid state ultra-wideband communications system is included for precise vehicle and roadside waypoint location and simultaneous information sharing. The location from this sensor can be fused with on-board sensors to provide an accurate picture of the surroundings in which to develop an integrated control strategy. This design approach attempts to fully exploit the opportunity of cooperation between the roadway and the vehicles to simplify the sensors and processing required for autonomous vehicle operation. By taking some of the bulk of the processing and sensing load off the vehicle and distributing it throughout the infrastructure, added vehicle costs are minimized with little added infrastructure. All sensory input the vehicle has to offer can be communicated to the infrastructure and integrated with the global information set.

0.8.8 Conclusions from the Solicited Concepts

The effort and thought that the contractors gave to this work, and the ideas, concepts, and recommendations they provided us have strongly influenced the concluding effort of this task, that is, selection of the issues on which the 6 concept families would be based. Further, they have given us their insight on various other technical approaches to AHS which have broadened

the range of enabling technologies we will consider. A few of the more important recommendations we got from these contractors are:

- We should consider using a suite of different types of sensors, both on the vehicle and along the infrastructure, along with sensor fusion algorithms to increase the probability of maintaining a true situational awareness.
- We should have a flexible design to address a wide variety of market opportunities in addition to the congested urban application. Indeed, there was a healthy difference of opinion as to which application would be the first the market would embrace.
- We should include introductory systems to stimulate the market for more advanced and higher performance fully Automated Highway Systems.
- We should design the system to operate with a minimum of infrastructure in areas where maximum throughput performance was not needed.
- We would need an infrastructure component to achieve maximum throughput performance.

In final conclusion, this effort achieved its goals. We solicited for strong, helpful concepts and we got them.

0.9 THE SIX CONCEPT FAMILIES

In the final act in this first phase of concept development, the Concept Team took the conclusions of the evaluation teams and the recommendations of the contractors and synthesized both into a new set of critical characteristics and a new set of six concept families with which to study them.

The results of the evaluation teams differed immensely on large issues, which means that the concept development will be a precarious balancing act between the various needs of agencies and consumers. These competing forces drove the need to develop concept "families" for C2, which narrow down evaluation choices, but also open up the concept to deployment and evolution factors.

The six concept families are based on two sets of conclusions:

1. The conclusions of the evaluation teams with respect to the 6 characteristics or dimensions used in the C1 task.
2. The recommendations of the evaluation teams and the Contractors for additional characteristics or dimensions which should now be explored.

In the first set, the evaluation teams recommended:

1. The Infrastructure Controlled system architecture option (where the infrastructure gives brake, throttle, and steering commands to the vehicles) be eliminated but that all other architectures deserve further study.
2. The slot approach to separation control be eliminated, but that both platooning and free agent are viable options requiring further study.
3. The types of physical barriers, the mixing of classes of vehicles, and the entry/exit configuration be local options and that any AHS must support all those options.

In the second set, the Evaluation Teams and the Contractors recommended:

1. Concept families have multiple layers of capabilities to support regional differences, different steps in the deployment of AHS, and graceful degradation because of malfunctions.
2. It would be desirable for a concept family to include a capability to operate on non-dedicated lanes with manually driven vehicles (along with, of course, the capability to operate in dedicated lanes).

Therefore, in Task C1, what remained were these useful conclusions and a set of 5 important unresolved issues and important new issues to guide us in the selection of the 6 concepts families and in the questions we should address in Task C2. Concisely, these issues are:

1. The throughput and safety issues of free agency vs. platooning.

2. The role of the driver, either because of technology limitations, safety concerns, or public acceptability.
3. The optimal amount of layering
4. The optimum level of infrastructure involvement.
5. How to mix automated and manually driven vehicles.

The level of infrastructure involvement, specifically the allocation of intelligence, came up repeatedly as the key concept discriminator. This was echoed very clearly by the Stakeholders in the Workshop. Hence, this was taken as the basis for the definition of the concept families. However, the analysis had shown that Autonomous and Cooperative as originally defined are not powerful enough to become the end state AHS, so the first two concepts were defined in terms of pushing these approaches to their

limits. The third and fourth concepts are both based on Infrastructure Supported. The third specifically addresses the issue of the role of the driver. The initial concept candidates had downplayed the driver, but the evaluation teams, especially Safety, questioned the assumption that the driver could be completely removed at all times and under all conditions. The fifth concept is based on Infrastructure Assisted, a new allocation that allows communication with and management of individual vehicles, as in Infrastructure Managed, but does not require continuous tracking of them, and so takes advantage of Infrastructure Supported approaches when and where individual management is not needed. The sixth approach cuts across all of these. It is a unified concept that allows any of the allocation approaches to be used based on situations, failures, or local options.

The Six Concept Families Selected and Their Architectural Focus

Concept Families	Architectural Focus
Vehicle Centered	Maximizes the performance that can be obtained from lone vehicles, while at the same time holds down cost by eliminating the cooperative layer. May be minimally supplemented with infrastructure assistance to improve throughput. Provides an early benefit for urban users in the form of driver disengagement, and for rural and intercity users in the form of driver-assisted truck and bus platoons.
Cooperative Plus	Obtains the maximum performance achievable without requiring infrastructure electronics through the use of extensive vehicle-to-vehicle communication to pass messages over extended ranges and by providing the vehicle with substantial on-board processing.
Driver Involvement	Makes use of man-in-the-loop operations. Exact areas of human involvement are design options, and may include obstacle detection, obstacle avoidance, and handling catastrophic hardware/software failures or other unexpected problems. Range of design options will be refined later, based on technology studies which reduce the uncertainty regarding man vs. machine performance.
Infrastructure Supported Platoons	Focuses on throughput and safety implications of driver disengaged platooning, in the framework of an infrastructure-supported system where the infrastructure does not communicate with individual vehicles. Similar to Infrastructure-Assisted architecture so this concept family pair will also provide an excellent comparison of the benefits and cost of infrastructure-supported vs. infrastructure-assisted.
Infrastructure Assisted Platoons	Focuses on throughput and safety implications of driver disengaged platooning, in the framework of an infrastructure-assisted system where the infrastructure communicates with individual vehicles when appropriate (for example, merge points). Similar to Infrastructure-supported architecture so this concept family pair also provides an excellent comparison of the benefits and cost of infrastructure-supported vs. infrastructure-assisted.
Maximally Layered	Provides a family of choices, with full layering for geographic, deployment, and failure options, and numerous alternatives in the other dimensions. Architecture has flexibility and can evolve as experience is gained from early deployments. Architecture has robustness in the case of failure, but may be costly to implement and maintain. Also, it defines the transfer of control from one layer to the next.

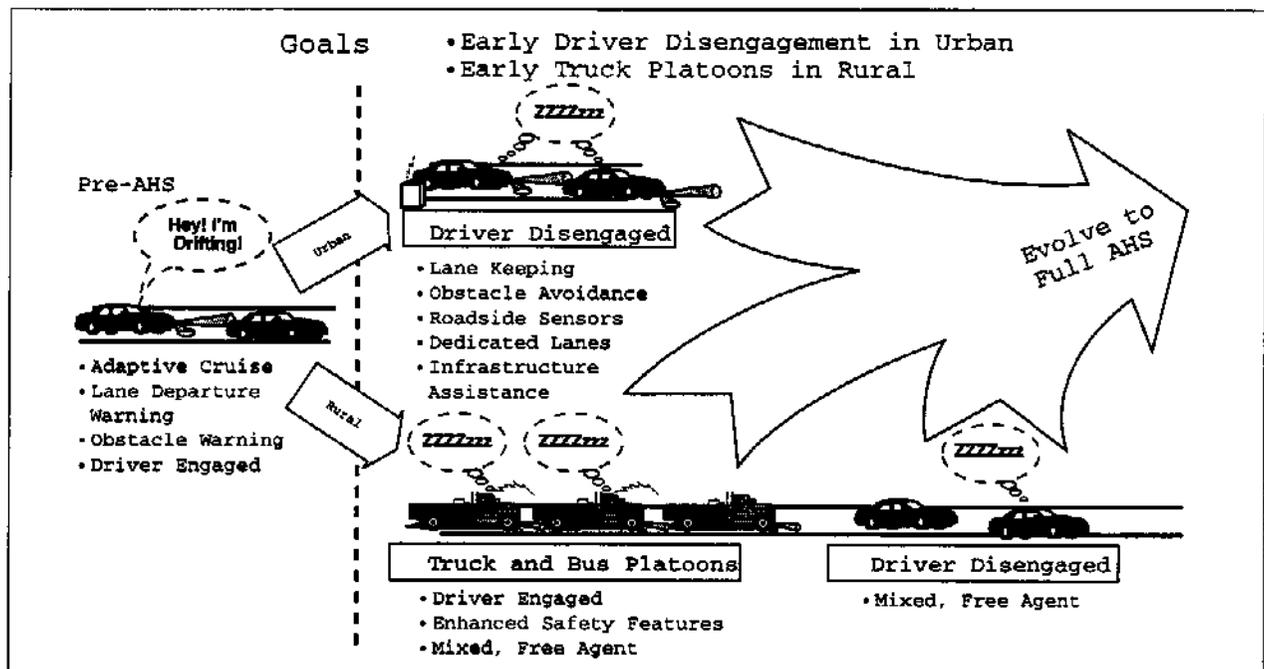
Diagrams of these families follow.

0.10 STAKEHOLDER FEEDBACK

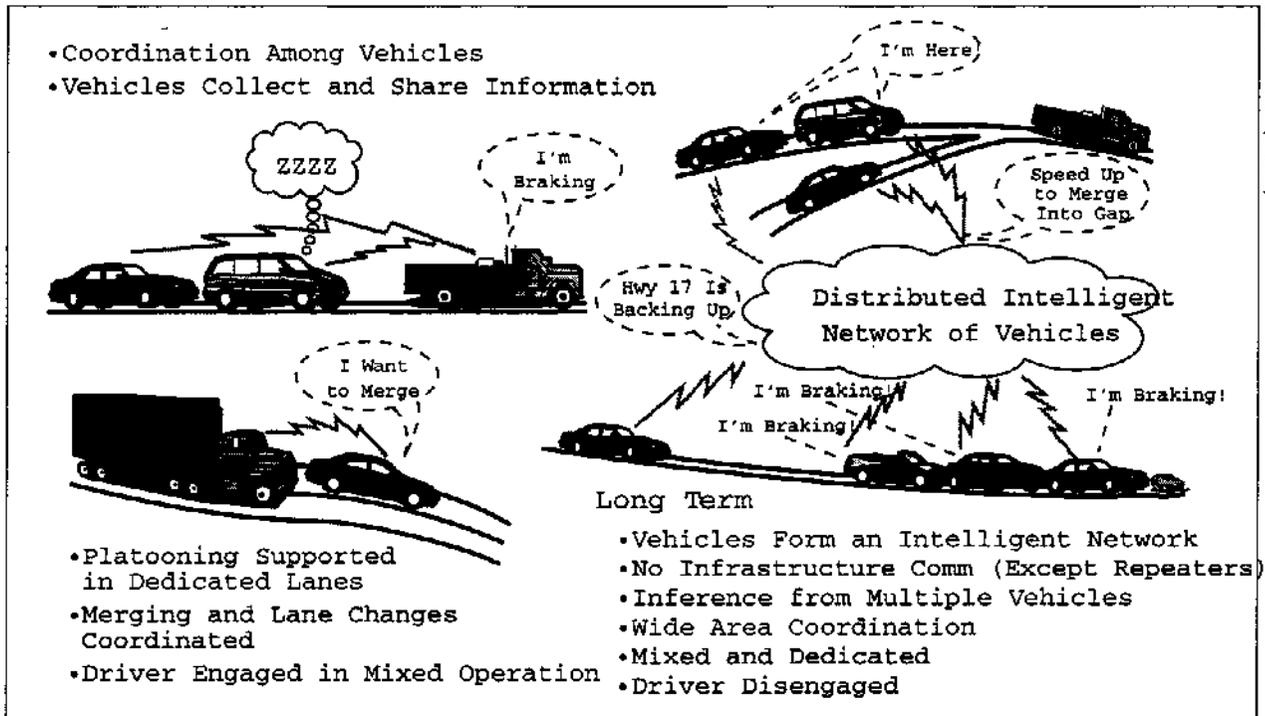
The six concept families were presented at the Automated Highway System Concepts Workshop October 18 - 20, 1995 in San Diego. Based on stakeholders feedback, the third concept family, Driver Involvement, was eliminated, and the role of the driver became a cross-cutting issue to be studied across all concepts. The same was done for platooning, and so fourth and fifth concepts were broadened to include free agency. The five remaining concepts now have new

names to incorporate these changes and to clarify the intent of each:

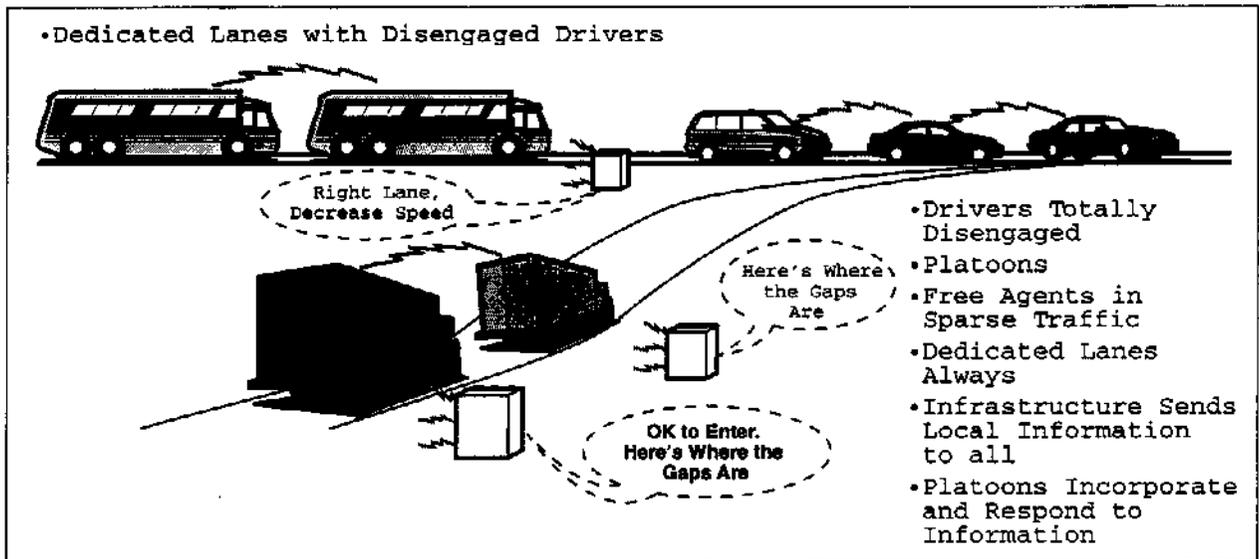
- Independent Vehicle (formerly Vehicle Centered)
- Cooperative Vehicle (formerly Cooperative Plus)
- Infrastructure Supported (formerly Infrastructure Supported Platoons)
- Infrastructure Assisted (formerly Infrastructure Assisted Platoons)
- Adaptable (formerly Maximally Layered)



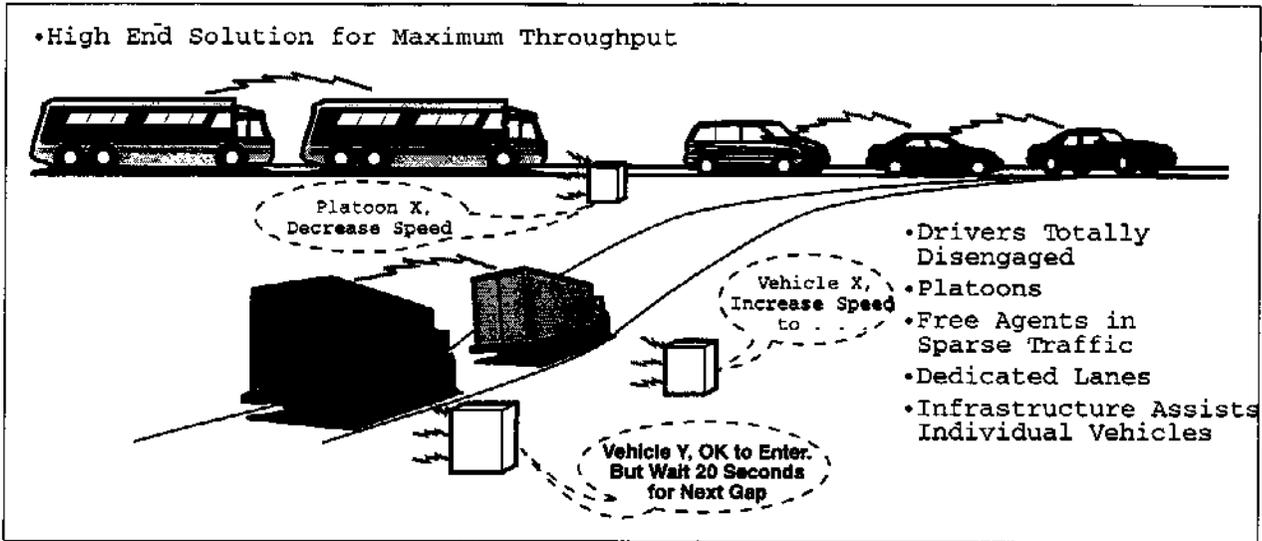
Independent Vehicle



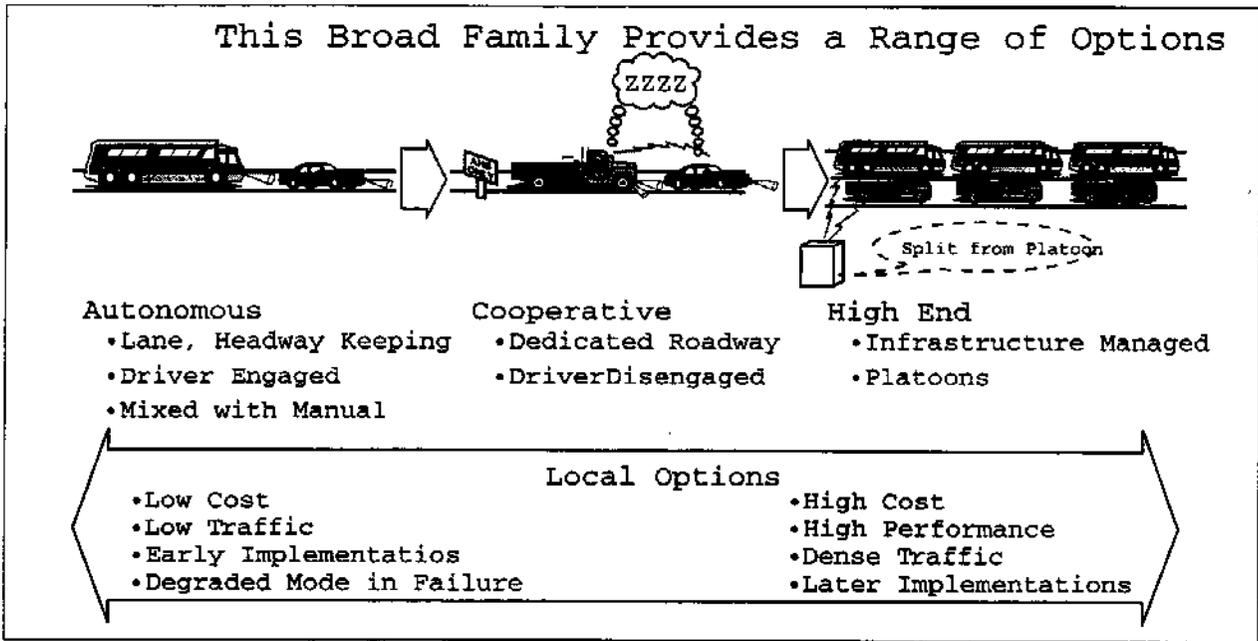
Cooperative Vehicle



Infrastructure Supported



Infrastructure Assisted



Adaptable

0.11 - THE NEXT STEPS

The AHS C1 effort will be followed by the AHS C2 effort, which will expand upon the five concept families and ultimately select three preferred concepts. The subtasks planned are as follows:

- Flesh out the five concept families with the “best” conceptual design.
- Define application scenarios based on real-world reference sites.
- Perform cross-cutting studies in the driver role, separation policy implications for throughput and safety, cost, market elasticity, and technology capabilities.

- Define the concept evaluation framework, requirements and measures of effectiveness.
- Canvass for stakeholder representatives.
- Evaluate the candidate concept families.
- Solicit stakeholder reviews and develop MOE weightings.
- Prepare and hold Workshop #3.
- Document the process and the selected three concepts.

1: INTRODUCTION AND METHODOLOGY

Task C1 is the first in a series of activities to define and assess alternative concepts for the Automated Highway System. A spiral approach is used, in which the initial work is done at a high, but broad level, with later steps focusing on fewer options in greater detail. Thus, there are two major challenges in Task C1. One is to do meaningful comparisons at a high conceptual level without getting into implementations or other lower-level specifics. The other is to ensure that the virtually limitless alternatives for the Automated Highway are all given a fair hearing. Specifically the goals of this task were to:

- Identify a small set of high level characteristics, and a range of alternatives for each, of any AHS concept
- Define and elaborate a set of representative system concept designs across this set of characteristics
- Evaluate these characteristics and these representative system concepts against the objectives of an AHS
- Develop a new set of high level characteristics based on the conclusions drawing from this evaluation effort
- Develop a set of approximately six new concept families to form a basis for studying the new set of concept characteristics

There are several aspects of the AHS problem that make its development quite different from the usual systems engineering approach used on DoD and other programs. First of all, this is an entirely new approach to transportation. There are no similar systems existing. Hence, performance and public acceptance cannot be extrapolated from analogous systems. Further, there is not a single customer, rather diverse groups of stakeholders with differing, and often conflicting demands. So a major challenge is a balancing of these requirements to produce the top level system requirements that would normally come from a single customer. This balancing comes from

examining the trade-offs within the context of a particular AHS concept. Thus, the task revolves around the identification and analysis of the full range of AHS concepts.

The first step is the identification of the dimensions or characteristics that distinguish AHS approaches at the conceptual level. Specifically, these are characterizations that are independent of implementation. These characteristics and the alternatives within each are first analyzed independently. This then suggests a refined list of characteristics and alternatives. Since these dimensions are closely interrelated, there is a limit to how much can be decided by looking at them independently. Hence, the bulk of the activity is the development and analysis of a set of candidate concepts that reflects the range of dimensional alternatives. These candidate concepts are fleshed out and described in sufficient detail to support evaluation. Each of these candidates is then evaluated relative to the objectives and characteristics for the AHS. The individual results are merged for an overall assessment. These evaluations may suggest the elimination of unpromising alternatives, but more importantly, they suggest new concepts, promising combination of concepts that perform better than either alone, and new issues to be considered.

In a parallel effort, a national solicitation has been made for concept proposals. This ensures a broad range of approaches not limited by the experience and background of the core teams. The most interesting and promising of these have been funded for development. The contractors are to develop, evaluate, document and present their concepts. The results of both of these activities feed into the selection of the six concept families.

The overall process is one of "reconcepting" in which the families reflect the issues and insights, and are not merely a "down-selection" from the original concepts. The evaluation process and the six concept families have been presented to the stakeholders in Workshop #2, and the

stakeholders were asked for feedback in breakout sessions. This led to revisions in the set of concept families.

The concept development was supported by two parallel activities. The first was a Quality Function Deployment (QFD) process to break the 24 Goals and Objectives into specific measures of effectiveness in a structured way. While these measures will not be quantifiable until much more extensive concept design, they provided guidance for the Concept team in the measures of goodness that will be applied. The other parallel activity was Functional Decomposition. This was a structured approach to defining complete functional requirements. These provide a framework for the developing concepts, while at the same time, the concepts provide a check on the functional requirements. These activities were not a direct piece of the concept

development, and so will not be described further here.

1.1 GENERAL FOUR STEP APPROACH

Figure 1.1-1 diagrams the classical four step process used by the team. This iterative process has been used successfully for many years in the development of military and other systems. It has been adopted by the System Architecture Committee of ITS America as the recommended approach for the development of ITS architectures. Many of the steps take advantage of other AHS task activities. The following description of the process is based on the document presented to the Architecture Committee, "A Candidate IVHS Systems Architecture Process" by Nancy Rantowich, Hughes Aircraft Company.

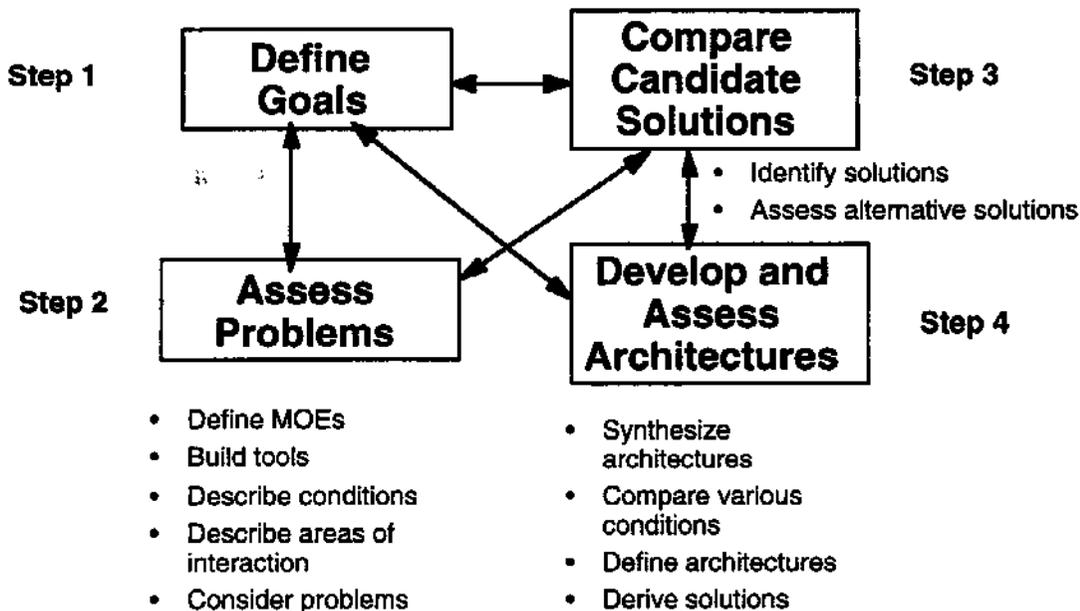


Figure 1.1-1. The classical four step process for concept development iteratively builds concepts that meet customer needs.

The classical methodology for synthesizing architectures traditionally uses the four basic steps shown: (1) defining the goals, (2) assessing the largest problems in reaching those goals, (3) identifying and assessing the entire range of solutions, and (4) synthesizing/assessing/refining architectures encompassing these solutions. The

Concepts Team applied these same steps in constructing the architectural concepts.

When complete, the documentation of this methodology provides a quantitative substantiation that the chosen solutions are effective, more flexible and more cost-effective than competing solutions. It also indicates that they will well stand the test of

1. Introduction and Methodology

time as traffic conditions, consumers preference patterns, vehicles, local solutions and political and social environments continue to change. This entire process can be repeated a number of times. Each pass is called a phase.

Phase I, representing the first pass through the process is typically the most controversial. As such, it inevitably draws the most feedback and critical review. The second, third, and fourth phases are generally performed at higher and higher levers of fidelity. Other phases that follow can usually be accomplished more quickly, and are essentially reviews of the earlier processes (and their assumptions), done in light of more recent social, political, legal and technological developments.

Task C1 consisted of the first phase. The four basis steps within any phase, when applied to AHS concepts, can be expanded as follows.

1.2 DEFINE GOALS

The process starts with the goals, which in this case are based on stakeholder inputs and the nature of the automated highway. This part of the process is carried on outside of the C1 task, but is the driving force for C1, and also influenced by the findings of C1. The initial goals were already captured in the Goals and Objectives document. The parallel requirements activity use these goals to define quantified initial requirements, which are shaped by any tradeoffs of the MOEs for the candidate concepts. The functional requirements are developed using the functional decomposition process, with the candidate concepts serving as a check to

ensure that these functional requirements are in fact generic across the full range of feasible AHS solutions. Figure 1.2-1.

1.3 ASSESS PROBLEMS

Figure 1.3 shows the definition of problems and the measures of effectiveness. The feedback from the customer defines conditions and constraints that suggest a range of scenarios, which will be developed under C2. The goals and conditions and constraints have been translated into specific measures of effectiveness in a QFD session early in the C1 task. Cross-cutting trade studies will be a major activity of C2. The measures of effectiveness shape the activities of the Tools Team, by focusing on the aspects that need to be evaluated.

1.4 COMPARE CANDIDATE SOLUTIONS

The other two steps are the heart of the C1 Task, in that they develop and evaluate alternative solutions concepts. This starts by comparing candidate solutions, as diagrammed in Figure 1.4-1. The AHS problem is based on issues in various dimensions. These issues each address a single aspect of the AHS, such as whether or not platooning is used, or whether the intelligence lies mainly in the vehicle or in the infrastructure. These issues are evaluated separately before they are combined into unified candidate concepts. These dimensions or characteristics are described and discussed in Section 2. Figure 1.4-1.

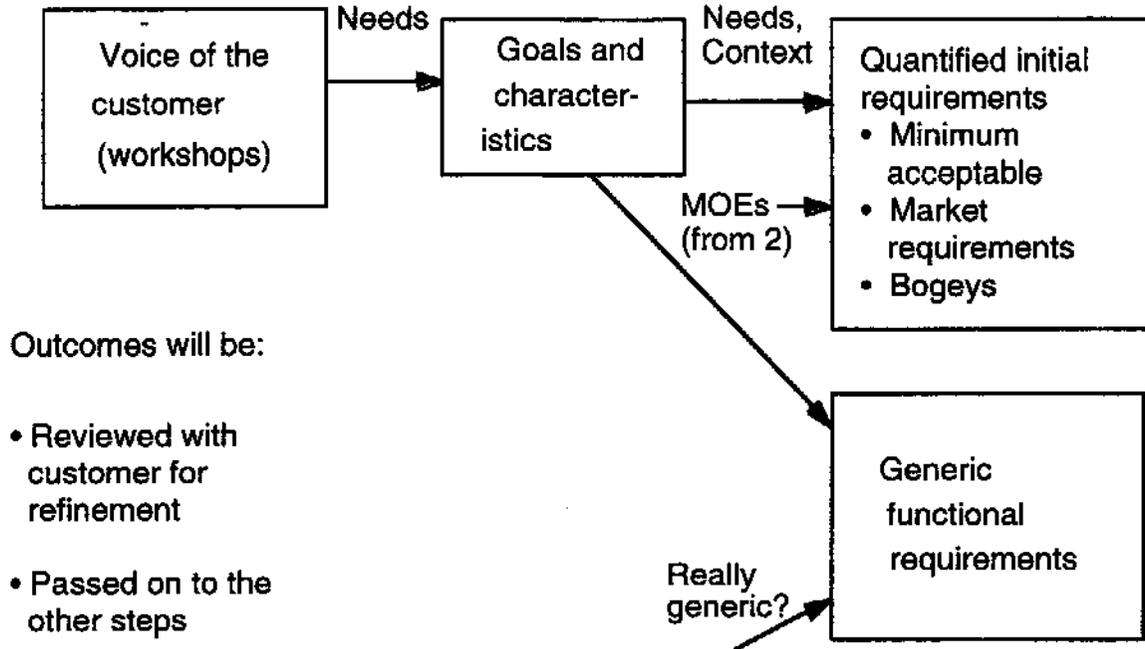


Figure 1.2-1. Define Goals. The goals that drive the concept development flow out of stakeholder inputs.

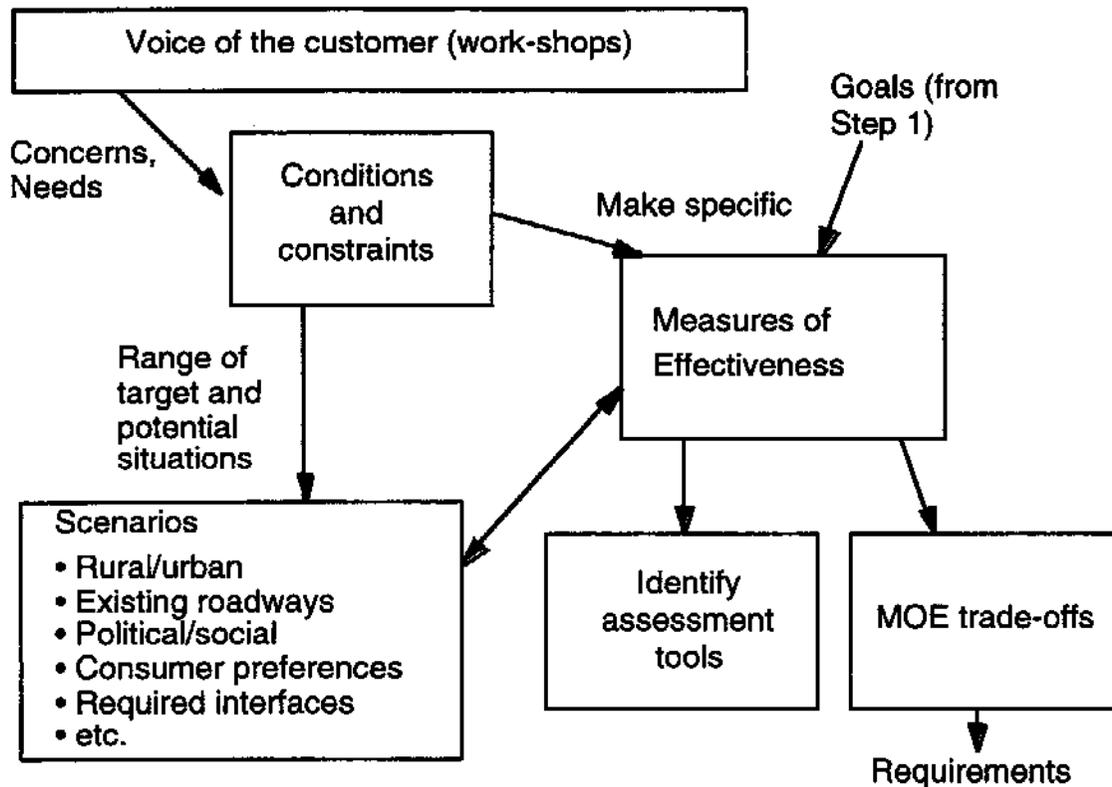


Figure 1.3-1. Assess Problems. The voice of the customer is translated into conditions, constraints, and specific measures of effectiveness. These then drive the application scenarios and the tool development.

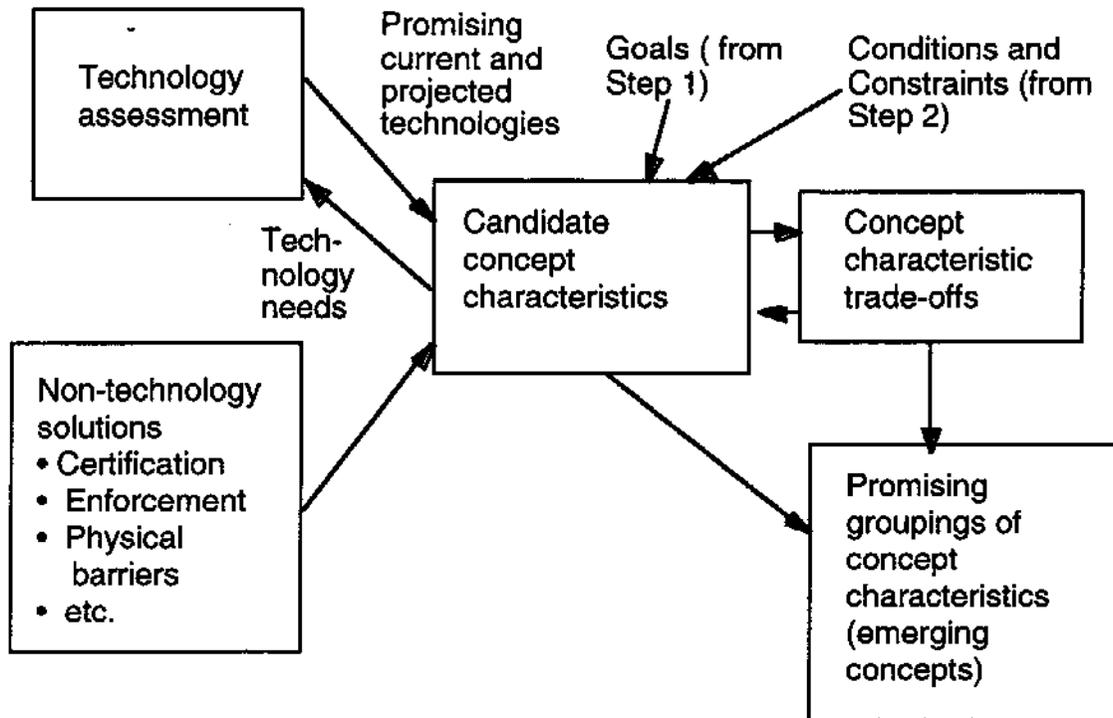


Figure 1.4-1. Compare Candidate Solutions. The alternatives for each of the concept characteristics are compared, suggesting promising characteristics and compatible groupings, leading to the development of full candidate concepts.

1.5. DEVELOP AND ASSESS ARCHITECTURES

The concept characteristics are highly interrelated, so there is a limit to how much can be learned by evaluating the alternatives alone. Figure 1.5 diagrams the final process that leads to the six candidate concept families that were presented to the stakeholders in the Workshop. A broad range of promising candidate concepts is built up from combinations of concept characteristics. Section 2.13 discusses the key characteristics selected, and Section 3 describes the candidate concepts. These are then evaluated against the key objectives, characteristics and measures of effectiveness. This evaluation process is described in Section 4. The six concept families are by no means the only outcome of this process. The evaluations suggest additional characteristics, alternatives and concepts. They also provide a check on the reasonableness of any requirements defined

at this point. Furthermore, the insights gained feed back into the other three steps of this process, so that the next phase in Task C2 may repeat a similar process in more depth with a more highly focused set of alternatives.

1.6. SYNTHESIS OF THE EVALUATION RESULTS

The evaluation approach that the team used when applying this process is centered on the Objectives and Characteristics. These were grouped into five evaluation areas -- throughput, safety, cost, flexibility and acceptability. Not surprisingly, the rankings of the candidate concepts were often in conflict when seen from these various viewpoints. Thus, the team chose an approach for weighting the factors. The process used was the Analytical Hierarchy Process (AHP), one of the most widely used decision support systems in the world. The tool used to implement this process was

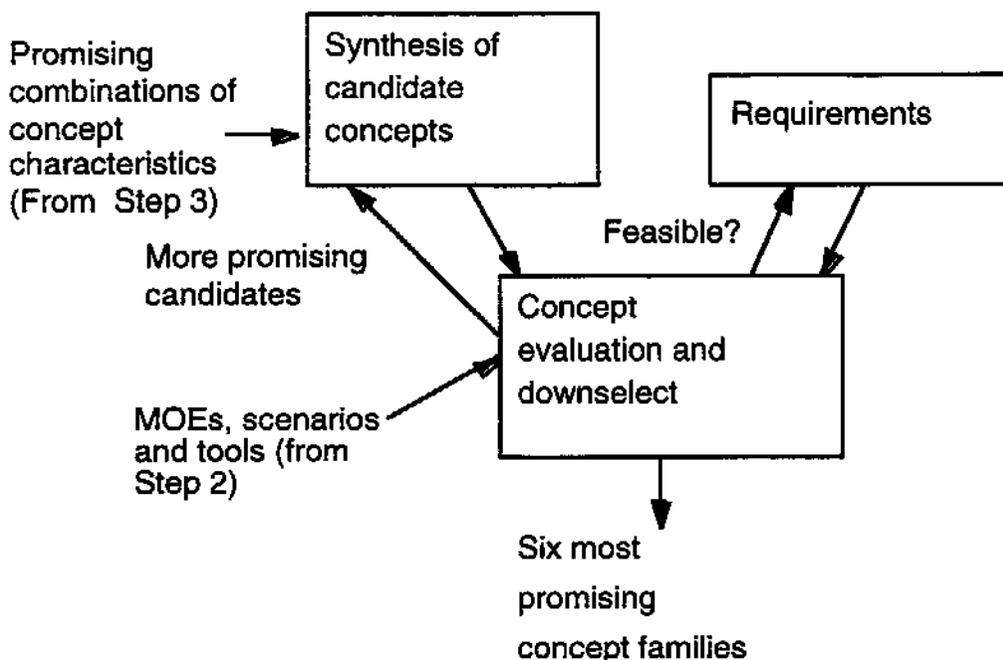


Figure 1.5-1 Develop and Assess Architecture. The concept characteristics are synthesized into candidate concepts. These are then evaluated against the key measures of effectiveness and requirements identified so far.

Expert Choice. This allowed the Program Manager’s Council to rate the relative importance of the factors, and the tool then merged these inputs into weightings. This is described further in Section 5. The ratings were based on the feedback that had been received from the stakeholders.

The team did not rely exclusively on quantifiable results. Many of the key results were insights into what made sense and what did not, and ideas for improvement that went outside the initial boundaries. Section 7 describes the resulting six concept families. It may be noted that these concept families are not selected from the original 22, but are based on the combination and development of them. As noted above, the process is not so much one of down-selection, but of “re-concepting” to form new concepts that perform better than the original choices.

Section 8 presents the stakeholder feedback to the six concept families. Section 9 discusses the revisions to the set of concept families, based on that feedback, and the plans for future work.

The appendices document various supporting material which does not easily fit into the flow of the main text.

1.7 ORGANIZATION OF THIS DOCUMENT

The sections of this document are arranged to follow as much as possible the sequence of this process. Section 2 defines and examines each of the concept dimensions or characteristics. Section 3 then discusses the 23 candidate concepts that were developed around combinations of these characteristics. Section 4 presents the results of the evaluations of the candidate concepts. The observations, conclusions and issues that came out of these evaluations of the candidate concepts are in Section 5. Section 6 summarizes the solicited concepts, which are described in detail in separate documents. Section 7 describes the six concept families that grew out of the insights from the solicited concepts and the development and evaluation of the Consortium’s 23 candidate concepts.

2. CONCEPT CHARACTERISTICS

A concept is a framework in which an AHS system is defined. It is not a system design or an implementation, but a structure within which a design may be built. For the most part, a concept is defined in terms of the choices for the key decisions that drive the design. These choices are called dimensions or characteristics. There are several dimensions or characteristics that define any possible AHS solution at the concept level. These were identified based on core team inputs, the Precursor Studies and other studies.

The concept characteristic may be divided into two types: design level characteristics and operational or requirements level characteristics. The design level characteristics may be further divided into two types: architecture and technology. The following descriptions may help:

A technology characteristic addresses the use of a specific technology, such as a technology for sensing lateral position in order to control steering.

An architecture characteristic addresses the allocation of a requirement to an architecture element, such as allocating hazardous object detection to the vehicle or to the infrastructure.

An operating requirement characteristic addresses the need for, or the performance level of, a requirement. Examples are a maximum operating speed, the ability to platoon, or the requirement to allow either mixed classes of vehicles or only a single class of vehicles in a single lane. Selecting operating requirement characteristics permits designs to be synthesized.

A solution to a concept characteristic, is just that, an operational or design alternative for that characteristic. One of the major engineering efforts of this task was to identify the feasible set of solutions for each concept characteristic.

The formation of a concept involved selecting one, or a set of, solutions from each identified concept characteristic and

combining them into a single concept, called a concept family since so many aspects of a complete concept are still undefined.

To begin the effort to define a suitable set of initial concept characteristics at the onset of this C1 task, a review was made of all the characteristics used to define Representative System Configurations in the PSA studies. Some of these characteristics, however, had to be excluded based on the ground rules set by the FHWA in their Request for Applications. For instance, an option for using narrow vehicles could not be included. As a second step, various published proposals for an AHS concept development procedure were reviewed, especially certain papers prepared by Bill Stevens of MITRE. Again, a few characteristics were now precluded but most could be still considered. Finally, the consortium's efforts to define system objectives and characteristics, as part of the B1 task, and to identify useful options on system characteristics from that effort were reviewed. From all of these collected characteristics, a set was selected that had the most potential impact on a design at this time in the process. Concept characteristics considered for initial evaluation were:

- 1) Distribution of Intelligence/Sensing/Processing (architecture): vehicle only, vehicle predominant with some infrastructure, infrastructure predominant
- 2) Communications (architecture): no communications, vehicle-to-vehicle only, vehicle-to-vehicle and vehicle-to-infrastructure
- 3) Separation Policy (operating requirement): free agent, platoon, slot
- 4) Roadway Interface (operating requirement): normal, pallet, RPEV, other
- 5) Obstacle Response Policy for Sensing and Avoidance (operating requirement): sensing, prevention, avoidance response
- 6) Vehicle classes in a lane (operating requirement): one class only, mixed classes

- 7) Mixed-Traffic Capability (operating requirement): dedicated and mixed, dedicated only
- 8) Lateral Control Approach (technology)
- 9) Longitudinal Control Approach (technology)
- 10) Entry/Exit (operating requirement): transition lane, dedicated station
- 11) Lane Width Capability (operating requirement): normal only, normal or narrow
- 12) Design Speed (operating requirement): speed limit, higher than speed limit

Many of the issues discussed below continued to be studied well beyond this initial assessment. Consequently, the later and current thinking of the Consortium may be different from views expressed here.

2.1 DISTRIBUTION OF INTELLIGENCE

2.1.1 Introduction

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 requirements on sensing and communications, and on the nature of the AHS system as a whole. The locus of intelligence and control is largely the key description of the architecture. It impacts who pays the costs, how the automated highway evolves and whether a system optimum or individual optimum can be achieved.

It is assumed that for every architecture being considered, each vehicle operates under its own power, and its own physical control, on freeway-like roadways (limited access and no physical contact with the vehicles except as a wheel surface). On the other hand, there is no presupposing the conclusions of any of the other concept teams. For example, an alternative will not be eliminated simply because it is mixed traffic or communications-heavy.

2.1.2 Intelligence Functions

Intelligence functions consist of sensing, assessing the situation, determining a response and executing the response. These occur at local or global levels. For example, a vehicle may sense the edges of the lane and adjust its position, or a traffic management center may sense the regional traffic conditions and weather and adjust platooning parameters.

2.1.2.1. AHS intelligence functions

A list of intelligence functions that may be performed for the AHS system follows. They are grouped according to what is being sensed, the size of the area being sensed, and what is being affected in the response.

Few vehicles/area surrounding a single vehicle/individual vehicle

- sense relative longitudinal position
- adjust relative longitudinal position
- determine lateral position/velocity relative to other vehicles
- determine safety of lane change
- adjust longitudinal position/speed for lane change
- execute lane change

Lane/around and just ahead of a single vehicle/single vehicle

- sense lateral position relative to lane
- adjust lateral position relative to lane

Multiple vehicles/lane segment/vehicles in close proximity

- direct other vehicles to accommodate lane change

Single vehicle/single vehicle/involved vehicle and possibly large number of upstream vehicles

- sense potential hazard due to other vehicle

Object on roadway/small roadway segment/possibly large number of upstream vehicles

- sense obstacle hazard
- react to hazard

System failure/roadway segment/involved vehicles or equipment, possibly large number of upstream vehicles

- sense incident/ malfunction

- react to incident/ malfunction

Vehicles/part of all of the automated highway system/many or all vehicles on the automated highway

- adjust traffic to optimize flow
- determine traffic management strategy
- determine optimal traffic flow parameters
- monitor traffic

Vehicles/part or all of the automated and/or manual highway system/single vehicle

- determine route
- modify route
- determine lane
- test for entry
- manage entry
- test for exit
- manage exit

2.1.2.2. Possible allocation of functions

Each of these functions may be allocated to one of the following:

- **Vehicle** — The vehicle contains a processor that receives inputs from its own sensors, from nearby vehicles and/or from the infrastructure. It assesses the situation and adjusts itself accordingly (e.g., through throttle, braking or steering commands). It may also formulate messages for the infrastructure or other nearby vehicles. This is a natural allocation for functions that involves a single vehicle based on data about its immediate surroundings. The moving vehicles are also a potential means to move data around a large area. For example, incident information can be transmitted to vehicles upstream by vehicles traveling in the opposite direction.
- **Cooperative vehicles** — The vehicles are equipped as above, but share data and negotiate decisions. This is a natural allocation for functions involving multiple vehicles in a small area, such as a lane change.
- **Roadside (infrastructure)** — There is processing power (or at least data storage) in the roadway, above the roadway, or on the roadside, and some means of communicating with the processors in the vehicles in the area,

either individually or through a broadcast. The information that the vehicles receive is specific to the location. This may be a simple "smart sign" (exit number, maximum speed, etc.) or it may be dynamic (change speed or spacing due to weather) Examples of implementations are tag-beacon and road-embedded magnetic information. There may be a connection to a central location for more regional information. It also may fuse information received from multiple vehicles in the area. Processing may be limited by the short time that the moving vehicles are within communications.

- **Central (infrastructure)** — There is processing power at some location not necessarily at the roadside, but in communication with the vehicles and/or roadside processing or data collection. This is a good allocation for functions that require oversight of a region. This may build on an existing TMC, which will have increased information and decision capability as ITS gets implemented.
- **Human** — It may be that some exceptional functions require image processing and judgment that are beyond the state-of-the-art for automated processing, and are best left to the driver.
- **Not done** — The listed functions are not all required for AHS. The alternatives should include some lower cost options that focus on the essential functions only.

2.1.2.3. The need for global functions

One major issue is whether there need to be functions that adopt a more global or external viewpoint, rather than the viewpoint of a single vehicle. This would indicate the need for at least some of the intelligence to be maintained outside of the individual vehicle, for example in a central TMC or in a virtual TMC distributed throughout the vehicles. There are clearly such functions performed now for conventional roadways. We will assume that these will continue to evolve as ITS gets implemented. The

question is whether there are such functions that are specific to AHS. The following is a list of such functions.

- Speed determination based on global conditions
- Platoon management (e.g., speed, split, join, lane changes, inter-platoon spacing, inter-vehicle spacing)
- Incident detection, immediate response (safety), longer term response (traffic management)
- Response to excess demand (e.g., stadium traffic)
- Response to weather/temperature changes
- Response to other ITS information (Note: ITS collects much information, but merely sends it to the driver for him to respond. AHS must formulate its own response)
- Lane selection for trips
- Check-out, including waking the driver enough to drive manually
- AHS entry checking (equipped, safe, etc.)
- Rogue vehicle handling

2.1.3 Candidate Alternatives

Ten alternative allocations were developed, spanning the range from all in the vehicle to almost all in the infrastructure.

All in vehicle:

- Adaptive cruise control and lane-keeping
- Autonomous
- Locally cooperative
- Distributed across region (small region, medium region and large region variants)

Almost all in vehicle:

- Infrastructure supported
- Directed platoons
- GPS-based

Mix of road and vehicle:

- Medium-term goal control
- Short-term goal control

Nearly all in the road:

- Throttle, steering control

These have been selected to span the reasonable possibilities. We noted that in

most cases the solution was defined by where the line was drawn separating vehicle functions from infrastructure functions on either a continuum from local knowledge to global knowledge or from millisecond response times to long-term response times. The more local functions were always done by the vehicle and the more global by the infrastructure, and similarly the short response functions were done by the vehicle and the long response by the infrastructure. We were concerned that this pattern may indicate some underlying assumptions on our part. To counter this bias we added a GPS-based concept from one of the proposals received in response to the NAHSC solicitation; in that concept GPS (an infrastructure feature) is used to calculate headways, a local and fast response function. The team was asked to try to think of additional solutions that break the pattern.

Following is a description and discussion of the ten candidates and the comparison baseline.

2.1.3.1. Baseline

The current traffic system, with ITS deployed, but no Automated Highway System. Vehicles are driven manually by drivers, but ITS services (e.g., navigation) provide support. All other concepts are in addition to the baseline. This is included for reference and is not a candidate concept.

2.1.3.1.1. Design implications

None. It is expected that the basic ITS services (those involving collecting, fusing and disseminating information) will occur before AHS or any vehicle control features such as collision avoidance. This will occur independent of AHS. Table 2.1.3-I indicates the implications of this alternative on the other characteristics.

2.1.3.1.2. Pros

People understand it and trust it. Navigation support will provide limited safety measures (due to people driving vs. having their head buried in a map.) and will provide some environmental benefit as a result of less "getting lost" time. There will be few or no

privacy issues associated with navigation support. Few infrastructure improvements are required to implement this technology, and they will happen before AHS is implemented.

2.1.3.1.3. Cons

It is not an automated highway system. Human errors cause the great majority of accidents, injuries and loss of life. Road capacity is limited by human reaction times, which are very slow compared to automated reaction times. This is not an adequate solution for the long-term problem of roadway overuse and inadequate infrastructure. It provides very limited safety/environmental benefits. It provides no increase in throughput. It provides no improvements to travel time and travel time predictability. It does not enhance mobility for those who are overwhelmed by driving on our freeways. There are no benefits for inclement weather operation. It does not disengage the driver from driving or reduce the stress of the driver.

2.1.3.1.4. Baseline functions

Check-in is done by the human, who has complete responsibility for ensuring that he and his vehicle are in a condition for safe operation. There may be general information provided to the driver at check-in and/or ramp metering. Sensing of roadway, vehicles and obstructions is done visually (by humans), supplemented by road feel and hearing. Hazards are detected by human inferencing based on visual (or other) detection. This may be very sophisticated, including a prediction of threats, e.g., that a deer is about to run onto the road, that the driver is not paying attention, that the car's bumper is loose, that an object is just a paper bag and not a threat.

Maneuver planning is done manually. The driver watches surrounding traffic, estimates the size of the space between vehicles, and predicts movements of other vehicles. He may attempt to communicate his intentions to other vehicles using turn signal and facial expressions. Maneuver execution is manual. The driver steers into position. For check-out, the driver maneuvers the vehicle off the

roadway, possibly selecting an alternative exit due to congestion.

The Traffic Management Center collects, fuses and analyzes data collected by roadway sensors, infers traffic conditions and disseminates human-readable messages to drivers (e.g., take alternate route). Link impedances are also sent to route guidance and trip planning processors. The Traffic Management Center remotely monitors equipment status and sends out crew to fix problems. The TMC is alerted to emergencies by motorist cell phone calls. Tow truck, ambulance and/or fire truck are dispatched as needed. Human-readable warnings are sent to vehicles upstream.

2.1.3.2. Adaptive cruise-control (ACC) and automated lane keeping

Some vehicles have adaptive cruise control (maintains constant headway, rather than constant speed) and lateral cruise control (keeps vehicle in its lane) when driving in mixed mode on ordinary highways. These aids automate nearly all of the driving, but drivers remain fully responsible, especially for lane changes, entry and exits, and unusual events.

2.1.3.2.1. Design implications

Each equipped vehicle has some capability for sensing the distance to the vehicle ahead. It also has some means for sensing the edges or center of the lane. The sensed data is evaluated by the in-vehicle processor, which formulates commands to the brake, throttle and steering mechanisms. Depending on the lane sensing approach, there may need to be roadway modifications, such as magnetic nails, to allow the road to be sensed. Even if the roadway stripes are sensed, there is an implied requirement for regular and thorough maintenance. Table 2.1.3-I indicates the implications of this alternative on the other characteristics.

2.1.3.2.2. Pros

This is a good starting system, that allows some rudimentary automation without great infrastructure expense. It can be implemented one car at a time, with the cost borne

by the motorist, who gets personal benefit from it. The public gradually gets comfortable with automated driving and may be more accepting of a full automated system. As with the current speed-keeping cruise control, the liability rests with the driver and not the system. Both of these features improve safety by reducing the likelihood of accidents occurring for long-distance trips on sparsely populated roadways. ACC may provide limited environmental benefits due to smoother accelerations/decelerations. These technologies may reduce the stress of the driver, although they will not eliminate it. There will be no privacy issues for these technologies. No or minimal infrastructure upgrades are required.

2.1.3.2.3. Cons

It is not an automated highway system as defined by Congress. The driver must stay alert, and so does not get the benefits of "brain-off" driving. Road capacity is not significantly better than that of the current manual system, since the mixed traffic must maintain close to current spacings. There is a safety concern that once the driver is in his lane and no longer has to perform routine activities, he will fall asleep or otherwise lose attention, so that he is not able to respond to emergencies. This is not an adequate solution for the long-term problem of roadway overuse. These technologies may only have meaningful application in intra-city/rural travel and provide no relief to urban traffic problems because of potential problems in using these technologies in high-volume traffic situations. This includes the problems of high-speed travel coupled with socially accepted vehicle spacing that is in fact dangerous. ACC users that are frequently cut off will discontinue use of this feature in these urban settings. It provides no increase in throughput. It provides no improvements to travel time and travel time predictability. It does not enhance mobility for those who are overwhelmed by driving on our freeways. There are no benefits for inclement weather operation. It does not disengage the driver from driving or greatly reduce the stress of the driver. It provides very limited environmental benefits. Safety may be compromised due to the driver

trusting these technologies "too much", and not relying on his/her own judgment.

2.1.3.2.4. Baseline functions

Check-in is done by the human, who has complete responsibility for ensuring that he and his vehicle are in a condition for safe operation. There may be general information provided to the driver at check-in and/or ramp metering. The vehicle is driven manually until underway on the chosen lane. The driver then selects maximum speed and minimum spacing, and puts the vehicle into cruise control. The vehicle senses the lane edges and any vehicle immediately ahead of it. The driver senses vehicles in other lanes and spots obstructions. Hazards are detected by human inferencing based on visual (or other) detection.

The driver plans all maneuvers. To execute the maneuver, the driver puts the vehicle into manual mode and performs the execution, whether an emergency maneuver or a lane change. The vehicle goes immediately into manual mode whenever the driver takes any action, such as steering or braking. Alternatively, the driver may use the mode switch. To check out, the driver puts the vehicle in manual mode and drives off the highway.

The Traffic Management Center collects, fuses and analyzes data collected by roadway sensors, infers traffic conditions and disseminates human-readable messages to drivers (e.g., take alternate route). Link impedances are also sent to route guidance and trip planning processors. The Traffic Management Center remotely monitors equipment status and sends out crew to fix problems. The TMC is alerted to emergencies by motorist cell phone calls. Tow truck, ambulance and/or fire truck are dispatched when appropriate. Human-readable warnings are sent to vehicles upstream.

2.1.3.3. Autonomous

The vehicles are driven entirely by on-board automatic control, but vehicles do not coordinate with each other. Special infrastructure support for AHS is minimal (e.g.,

clearly painted lines, perhaps magnetic nails).

2.1.3.3.1. Design implications

Each equipped vehicle has some capability for sensing the distance to the vehicle ahead and the location and speed of the vehicles in the adjacent lanes. It also has some means for sensing the edges or center of the lane. The sensed data is evaluated by the in-vehicle processor, which formulates commands to the brake, throttle and steering mechanisms. Depending on the lane sensing approach, there may need to be roadway modifications, such as magnetic nails, to allow the road to be sensed. Even if the roadway stripes are sensed, there is an implied requirement for regular and thorough maintenance. The vehicle must not be allowed to exit under automated mode, since the driver may not be awake, though it should be able to perform other standard maneuvers. Table 2.1.3-I indicates the implications of this alternative on the other characteristics.

2.1.3.3.2. Pros

This is a good starting system that allows some rudimentary automation without great infrastructure expense. It can be implemented one car at a time. The cost is borne by the motorist, who gets personal benefit from it, even on standard roads (headway keeping and lane change warning). The public gradually gets comfortable with automated driving and may be more accepting of a full automated system. As with the current speed-keeping cruise control, the liability rests with the driver and not the system. When linked to a standard ITS in-vehicle navigation system, it is capable of automating a complete trip, including lane changes and interchanges. There will be no privacy issues associated with independent, autonomous vehicles. There may be environmental benefits associated with this concept (due to smoother accelerations/decelerations). Few modifications are required of the infrastructure.

2.1.3.3.3. Cons

It is not an automated highway system as defined by Congress. The driver must stay alert, and so does not get the benefits of "brain-off" driving. Road capacity is not significantly better than that of the current manual system, since the mixed traffic must maintain close to current spacings. There is a safety concern that the driver will fall asleep or otherwise lose attention, so that he is not able to respond to emergencies. The vehicle may not have the capability to respond to emergencies. There is no coordination between vehicles, so there may not always be opportunities for lane changes. This will be especially true when a large number of vehicles are equipped and are maintaining fixed spacing. A "bail out" capability must be provided whenever there is a forced lane change or merge (e.g., on-ramp). The drivers are unpredictable, so there are safety threats. Safety may be compromised by a lack of "forewarning" for accidents, obstacles, and roadway conditions that lie ahead. Traffic flow will not be coordinated and optimized for throughput and safety. Rather, it will be automated "chaos" as determined by the limited capability and knowledge of the on-board computer. Unless traffic flow is optimized, the goals of reliable and reduced trip times may not be realized. Platooning, and the associated environmental benefits, will be problematic without intra-vehicular communications (e.g., even if platoons form, there needs to be a limit to the number of vehicles within the platoon and vehicles need to be able to "break out" of the platoon gracefully.) This concept does not provide the level of assurance required by the elderly and other users who are currently afraid to drive on the highways. This limited technology will probably not support a wide range of vehicle classes on the same roadway, requiring separate AHS lanes for heavy and light vehicles. This concept does not support local travel demand management policies. Inclement weather operations may be minimized unless the on-board sensors can detect weather conditions and the vehicle can adjust speed and vehicle spacing accordingly.

2.1.3.3.4. Baseline functions

Check-in is done by the human, who has complete responsibility for ensuring that he and his vehicle are in a condition for safe operation. There may be general information to the driver and/or ramp metering. The vehicle is driven manually until the driver puts it into the automated mode. He selects maximum speed and minimum spacing and puts the vehicle into cruise control.

Sensing of roadway, vehicles and obstructions is done by the vehicle. The vehicle senses the lane edges, any other vehicle immediately ahead and vehicles in adjacent lanes. Obstructions are identified by human inferencing based on visual (or other) detection. This may be very sophisticated including a prediction of threats, e.g., that a deer is about to run onto the road, that the driver is not paying attention, that a car's bumper is loose, that an object is just a paper bag and not a threat. The vehicle senses vehicles and other large objects directly in front or to the side (but needs the driver to react).

The vehicle plans maneuvers based on the route guidance from the ITS navigation system in the vehicle. Maneuver execution is done by the vehicle, which checks for a space in the next lane, and moves into it when it is safe to do so. It may predict spaces based on velocity and acceleration of adjacent vehicles and modify its own speed or position to fit into a space. The vehicle goes immediately into manual mode whenever the driver takes any action, such as steering or braking. Alternatively, the driver may use the mode switch.

For check-out, the driver puts the vehicle in manual mode and drives off the highway. The automated system will not perform an exit.

The Traffic Management Center collects, fuses and analyzes data collected by roadway sensors, infers traffic conditions and disseminates human-readable messages to drivers (e.g., take alternate route). Link impedances are also sent to route guidance and trip planning processors. The Traffic

Management Center remotely monitors equipment status and sends out crew to fix problems. The TMC is alerted to emergencies by motorist cell phone calls. Tow truck, ambulance and/or fire truck are dispatched when appropriate. Human-readable warnings are sent to vehicles upstream.

2.1.3.4. Locally cooperative

The vehicles are driven entirely by on-board automatic control, and vehicles communicate with neighbors to adjust immediate traffic, and pass sensor information. This simplifies joint maneuvers (e.g., merging), and might support small, autonomous platoons. Infrastructure support specifically for AHS is small, and only passive.

2.1.3.4.1. Design implications

Each equipped vehicle has some capability for sensing the distance to the vehicle ahead and the location and speed of the vehicles in the adjacent lanes. It also has some means for sensing the edges or center of the lane. The sensed data is evaluated by the in-vehicle processor, which formulates commands to the brake, throttle and steering mechanisms. Depending on the lane sensing approach, there may need to be roadway modifications, such as magnetic nails, to allow the road to be sensed. Even if the roadway stripes are sensed, there is an implied requirement for regular and thorough maintenance. There is also vehicle-to-vehicle communications at least among adjacent vehicles. Each vehicle has the capability to formulate instructions or parameters for its neighbors, and the capability to respond to similar inputs. Whereas all of the preceding alternatives allowed different equipment (or no equipment) in each vehicle, this concept requires commonalty at least in the formulation and use of inter-vehicle information. This means that message and processing standards must be set, and that vehicles that are not properly equipped are prevented from entering the roadway. Table 2.1.3-I indicates the implications of this alternative on the other characteristics.

2.1.3.4.2. Pros

This is a dedicated automated system, but with minimal infrastructure expense. The unpredictability of humans has been eliminated. All of the vehicles are operating under the same rules, and so smooth and safe system operation is possible. Capacity is much better than in mixed traffic, as the vehicles will form spontaneous platoons. The problem of lane changes seen in the previous alternative is eliminated, as lane changes are now coordinated. There will be few or no privacy issues associated with locally cooperative vehicles. The environmental benefits are somewhat enhanced because of the potential for platooning. Minimal infrastructure upgrades are required. This concept will alleviate driver stress and meet the objective of removing the driver from the loop.

2.1.3.4.3. Cons

There is a "chicken-and-egg" problem in getting this started, since dedicating roadways to such a system will take away from existing or potential manual roadways, and yet will initially benefit only a few motorists. The motorists will not be motivated to buy equipped vehicles until there are convenient dedicated roadways. Subsidies may be necessary for motorists, certainly for roadways. The dedicated roads will bring charges of elitism. Vehicles that are not adequately equipped must be prevented from entering, or handled safely if they do enter. Since there is no global control, traffic flow on this system is not optimized. Surface street congestion may back up onto the automated highway. The vehicles are not given warning about conditions ahead for which they should adjust spacing or speed. To upgrade the system technology, all vehicles would have to be upgraded. Consumers may balk at having to install a new software load or implement new hardware in order to continue use of the AHS. Safety may be compromised by a lack of "forewarning" for accidents, obstacles, and roadway conditions that lay ahead. Traffic flow will not be coordinated and optimized for throughput and safety. Unless traffic flow is optimized,

the goals of reliable and reduced trip times may not be realized. This limited technology will probably not support a wide range of vehicle classes on the same roadway, requiring separate AHS lanes for heavy and light vehicles. Inclement weather operations may be minimized unless the on-board sensors can detect weather conditions and the vehicle can adjust speed and vehicle spacing accordingly. This concept does not support local travel demand management policies. This option will probably not support a wide range of vehicle classes. Passive infrastructure requires that the vehicle be able to determine when its exit is approaching and respond accordingly. This could complicate the platoon concept and the checkout process. The development of sign recognition technology and/or an extensive on-board, region-specific database may be required.

2.1.3.4.4. Baseline functions

Vehicles that do not meet the check-in standards must be kept off the roadway. This is one area in which some sort of infrastructure intervention may be necessary. This could be very expensive, especially if there are a lot of entrances and if physical barriers and reject routes are used. An alternative is to post warnings but not have a check-in. Vehicles test each other through their communications, and back off and send an alarm if necessary. Vehicles not properly equipped would be given heavy fines.

The vehicle senses the lane edges, the vehicle immediately ahead, vehicles in adjacent lanes and obstructions. Warnings are passed to other vehicles in the area. The vehicles detect hazards and warn each other. The vehicle plans normal maneuvers based on the route guidance from the ITS navigation system in the vehicle. Evasive maneuvers are planned by the vehicle and disseminated to surrounding vehicles. The vehicle communicates its intention to maneuver to the surrounding vehicles, who then open up the necessary space in a predictable manner. It vehicle may predict spaces based on velocity and acceleration of adjacent vehicles and modify its own speed or position to fit into a space.

Table 2.1.3-I. Correlation with other characteristics (Part 1 of 3)

	Comm	Separation Policy	Roadway Interface	Obstacle Response
Baseline	None	Free Agent only	World Standard	Human driver. Incompat. w/ all options
Auto Cruise Control/Auto Lane-Keeping	None needed	Free Agent only	World Standard	None that are platoon-based or use infrastructure
Autonomous	None needed	Free Agent only	World Standard	None that are platoon-based or use infrastruct.
Locally Cooperative	Vehicle-to-vehicle	Free agent or platooning	Any	Any

Correlation with other characteristics (Part 2 of 3)

	Veh Classes in Lane	Mixed Traffic Capability	Lateral Cntrl Approach	Long Cntrl Approach
Baseline	Mixed	Manual only	Direct imaging by human	Human driver in all vehicles
Auto Cruise Control/Auto Lane-Keeping	Mixed	Full mixing	Infrastr. support limited to ITS and electronic lane-marking	No infrastr. support beyond ITS; no cooper. from other veh.
Autonomous	Mixed	Full mixing	Infrastr. support limited to ITS and electronic lane-marking	No infrastr. support beyond ITS; no cooper. from other veh.
Locally Cooperative	Mixed	No mixing	Infrastr. support limited to ITS and electronic lane-marking	No infrastr. support beyond ITS; may use cooper. from other veh.

Correlation with other characteristics (Part 3 of 3)

	Entry/Exit	Lane Width	Design Speed
Baseline	All manual	Normal	105 kph
Auto Cruise Control/Auto Lane-Keeping	All manual	Normal	105 kph
Autonomous	Manual, switching to automated	Normal	105 kph
Locally Cooperative	Any	Any	Any

The Traffic Management Center collects, fuses and analyzes data collected by roadway sensors, infers traffic conditions and disseminates human-readable messages to drivers (e.g., take alternate route). Link impedances and alerts are also sent to route guidance and trip planning processors. The automated systems may access this information and use it to adjust spacing, speed or other characteristics. The Traffic Management Center remotely monitors equipment status, sends out crew to fix. TMC is alerted to emergency by motorist cell phone calls. Tow truck, ambulance and/or fire truck are dispatched. Human-readable warning is sent to vehicles upstream. Vehicles that sense a hazard or brake suddenly send disseminate specifics to surrounding vehicles, who take action.

2.1.3.5. Distributed across region

Similar to locally cooperative, but with much longer-range information passing. Upstream traffic information is supplied by vehicles. Large platoons, and platoon-to-platoon cooperation, are possible. Infrastructure support specifically for AHS is small, and only passive. Information dissemination is facilitated by communication from one direction of travel to the other. There are multiple variations on this concept depending on the extensiveness and complexity of the information passing and aggregation. For examples, in a very small region concept vehicles may only pay attention to what is within their graceful braking distance, while a large region concept would have at least the intelligence of a sophisticated Traffic Management Center (TMC) distributed throughout the vehicles on the roadway.

2.1.3.5.1. Design implications

Each equipped vehicle has some capability for sensing the distance to the vehicle ahead and the location and speed of the vehicles in the adjacent lanes. It also has some means for sensing the edges or center of the lane. The sensed data is evaluated by the in-vehicle processor, which formulates commands to the brake, throttle and steering mechanisms. Depending on the lane sensing

approach, there may need to be roadway modifications, such as magnetic nails, to allow the road to be sensed. Even if the roadway stripes are sensed, there is an implied requirement for regular and thorough maintenance. There is extensive vehicle-to-vehicle communications that allows message passing over a wide region. This includes message passing by vehicles traveling in the opposite direction, in order to cover gaps in the traffic. Each vehicle has the capability to formulate instructions or parameters for its neighbors, and the capability to respond to similar inputs. It also can fuse information passed it from other vehicles to help the network of vehicles formulate an assessment of the overall traffic situation. This type of distributed system management may be beyond the current state-of-the-art. This concept requires commonality at least in the formulation and use of inter-vehicle information. This means that message and processing standards must be set, and that vehicles that are not properly equipped are prevented from entering the roadway. Table 2.1.3-II indicates the implications of this alternative on the other characteristics.

2.1.3.5.2. Pros

This is a dedicated automated system, but with minimal infrastructure expense. The unpredictability of humans has been eliminated. All of the vehicles are operating under the same rules, and so smooth and safe system operation is possible. Capacity is much better than in mixed traffic, as the vehicles will form spontaneous platoons. Coordination occurs both at the local (immediate vehicle neighbor) level and the regional level. Flow optimization is done by the "virtual TMC" without additional infrastructure expense. Since the flow control is distributed, it is robust. There will be few or no privacy issues associated with vehicle-based intelligence. Throughput would be increased because of greater platooning capability. There will be less environmental impact because of smoother traffic flow. Travel times should be somewhat reduced and more reliable. Minimal infrastructure upgrades are required. This concept will alleviate driver

stress and meet the objective of removing the driver from the loop. The environment will have less impact on throughput and travel times.

2.1.3.5.3. Cons

There is a "chicken-and-egg" problem in getting this started, as above. Vehicles that are not adequately equipped must be prevented from entering, or handled safely if they do enter.

Distributing the system management to the vehicles runs counter to the current trends in ITS, which favor some centralized monitoring and control. This is an unproven technique. Roadway condition information is highly dependent on other vehicles being in the area in which you are traveling. Early commuters may get little or no information prior to traveling into an area that is hazardous. This concept requires vehicle sensors which can detect, interpret, and communicate hazardous conditions. This concept may over-reach current communications technology. Requiring the communications receiver to accept hundreds/thousands of simultaneous and probably redundant messages could be technically demanding and undesirable. Receiving one appropriate message from the infrastructure is more practical and technically clean. A heavy computational burden may be placed on on-board processors, especially if they are required to deconvolve thousands of messages coming from other vehicles. This would drive up the requirements/cost for these processors. Any computational overload could potentially create a safety hazard.

Traffic flow will still not be optimized without infrastructure support, thus, limiting the throughput advantages of a full-AHS. This option will probably not support a wide range of vehicle classes. Passive infrastructure requires that the vehicle be able to determine when its exit is approaching and respond accordingly. This could complicate the platoon concept and the checkout process. The development of sign recognition technology and/or an extensive on-board, region-specific database may be required. To upgrade the system

technology, all vehicles would have to be upgraded. Consumers may balk at having to install a new software load or implement new hardware in order to continue use of the AHS.

2.1.3.5.4. Baseline functions

Vehicles that do not meet check-in standards must be kept off the roadway. Vehicles test each other through their communications, and back off and send an alarm if necessary. Vehicles not properly equipped are given heavy fines.

The vehicle senses the lane edges, the vehicle immediately ahead, vehicles in adjacent lanes, and obstructions. Warnings are passed to other vehicles throughout the region. The vehicles detect hazards and warn each other, possibly over a large area. The vehicle plans normal maneuvers based on the route guidance from the ITS navigation system in the vehicle. Evasive maneuvers are planned by the vehicle and disseminated to nearby vehicles. The vehicle communicates its intentions to the surrounding vehicles, who then open up the necessary space in a predictable manner. The vehicle may predict spaces based on velocity and acceleration of adjacent vehicles and modify its own speed or position to fit into a space.

Each vehicle collects information about its immediate area (its speed, spacing, road conditions, hazards, etc.) and disseminates it to surrounding vehicles. Each vehicle fuses information it receives from nearby vehicles into a local assessment. These are then passed on and fused into more global assessments from which adjustments in flow are derived.

The Traffic Management Center remotely monitors equipment status and sends out a crew to fix problems. Vehicles detect or infer problems and alert the TMC. The TMC is also alerted to emergencies by motorist cell phone calls. Tow truck, ambulance and/or fire truck are dispatched when appropriate. Human-readable warnings are sent to vehicles upstream. Vehicles that sense or infer a hazard disseminate specifics to surrounding vehicles, who take

action, including commands to other vehicles and/or update of situation assessment.

2.1.3.6. Infrastructure supported

Similar to locally cooperative, but infrastructure provides general or location specific, non-vehicle specific, dynamic information (e.g., lane speeds, merging from lane A to B is currently allowed, all traffic leave lane C, etc.) and static information (e.g., this is exit 27, curve ahead, etc.). In a platoon implementation, these messages would be given to the lead vehicle in each platoon to disseminate to the rest of the platoon.

2.1.3.6.1. Design implications

Each equipped vehicle has some capability for sensing the distance to the vehicle ahead and the location and speed of the vehicles in the adjacent lanes. It also has some means for sensing the edges or center of the lane. The sensed data is evaluated by the in-vehicle processor, which formulates commands to the brake, throttle and steering mechanisms. There is vehicle-to-vehicle communications that allows message passing among nearby vehicles. Each vehicle has the capability to formulate instructions or parameters for its neighbors, and the capability to respond to similar inputs. It also accept inputs from the infrastructure modifying some of its parameters. This concept requires commonalty at least in the formulation and use of inter-vehicle information. This means that message and processing standards must be set, and that vehicles that are not properly equipped are prevented from entering the roadway. The infrastructure needs sophisticated sensing equipment or probe data collection, and a means for merging it and developing commands for the vehicles. There must be a means of communicating from the infrastructure to the vehicles at a certain location. Table 2.1.3-II indicates the implications of this alternative on the other characteristics.

2.1.3.6.2. Pros

This is a dedicated automated system. The unpredictability of humans has been

eliminated. All of the vehicles are operating under the same rules, and so smooth and safe system operation is possible. Capacity is much better than in mixed traffic, as the vehicles may be formed into platoons. Coordination occurs both at the local (immediate vehicle neighbor) level and the regional level. Flow optimization is done by the TMC, building on existing capabilities. Overall system monitoring enhances safety. There will be few or no privacy issues associated with this option. The environmental benefits are slightly enhanced because of the potential for platooning. Non-extensive infrastructure upgrades are required. This concept will alleviate driver stress and meet the objective of removing the driver from the loop. The environment will have less impact on throughput and travel times. Roadway condition information could be provided to the vehicles, enhancing safety.

2.1.3.6.3. Cons

There is a "chicken-and-egg" problem in getting this started, as above. Vehicles that are not adequately equipped must be prevented from entering, or handled safely if they do enter. Significant infrastructure expense may make this not cost-effective in rural areas. System optimum capacity will not be achieved since individual vehicles are not centrally managed. By not providing vehicle-specific information, a wide range of vehicle classes would be prohibited (e.g., commands would apply to vehicles with very specific performance characteristics, excluding classes of trucks, buses, etc.) This option does not seem to allow for real-time, dynamic traffic flow optimization. This will reduce the throughput maximization that could otherwise be achieved. This option does not allow for extensive platooning, which will reduce throughput. The semi-passive infrastructure may greatly complicate the check-in and check-out processes by not coordinating these activities. To upgrade the system technology or to fix a software bug, all vehicles would have to be upgraded. Consumers may balk at having to install a new software load or implement new hardware in order to continue use of the AHS.

2.1.3.6.4. Baseline functions

Vehicles that do not meet check-in standards must be kept off the roadway. The infrastructure tests them before they are allowed to enter. The vehicle senses the lane edges, the vehicle immediately ahead, vehicles in adjacent lanes and obstructions. Warnings are passed to other vehicles nearby. Infrastructure sensors also detect obstructions and other hazards.

The vehicle plans normal maneuvers based on the route guidance from the ITS navigation system in the vehicle. Evasive maneuvers to avoid immediate hazards are planned by the vehicle and disseminated to surrounding vehicles. The infrastructure may order other maneuvers for hazard avoidance or flow management. The vehicle communicates its intentions to execute a maneuver to the surrounding vehicles, who then open up the necessary space in a predictable manner. The vehicle may predict spaces based on velocity and acceleration of adjacent vehicles and modify its own speed or position to fit into a space.

The infrastructure uses sensors and/or vehicle-to-infrastructure messages to determine the traffic conditions. The TMC then fuses this to develop a situation assessment and formulate commands (e.g., increase inter-vehicle spacing, merge left) to vehicles at specific locations. The Traffic Management Center remotely monitors equipment status and sends out crew to fix problems. Vehicles detect or infer problems and alert the TMC. The TMC is also alerted to emergencies by motorist cell phone calls or by sensors and inference. Tow truck, ambulance and/or fire truck are dispatched when appropriate. Human-readable and electronic warnings are sent to vehicles upstream. Vehicles that sense or infer a hazard disseminate specifics to surrounding vehicles and to the TMC, which takes action.

2.1.3.7. Directed platoons

Similar to locally cooperative. Vehicles drive themselves automatically, and through cooperation form themselves into platoons, allowing individual vehicles to merge in and

out as necessary. The infrastructure provides specific instruction (e.g., maintain 55 mph, join with platoon ahead, split into two platoons, etc.) to each of the platoons, along with road geometry information.

2.1.3.7.1. Design implications

Each equipped vehicle has some capability for sensing the distance to the vehicle ahead and the location and speed of the vehicles in the adjacent lanes. It also has some means for sensing the edges or center of the lane. The sensed data is evaluated by the in-vehicle processor, which formulates commands to the brake, throttle and steering mechanisms. There is vehicle-to-vehicle communications that allows message passing among nearby vehicles. Each vehicle has the capability to act as a platoon leader or platoon follower. It also accepts commands from the infrastructure relative to its platoon. This concept requires commonality at least in the formulation and use of inter-vehicle information. This means that message and processing standards must be set, and that vehicles that are not properly equipped are prevented from entering the roadway. The infrastructure needs sophisticated sensing equipment or probe data collection, and a means for merging it and developing commands for the vehicles. It must also have a means of monitoring the position and status of each platoon. There must be a means of communicating from the infrastructure to the individual lead vehicles. Table 2.1.3-II indicates the implications of this alternative on the other characteristics.

2.1.3.7.2. Pros

This is a dedicated automated system. The unpredictability of humans has been eliminated. All of the vehicles are operating under the same rules, and so smooth and safe system operation is possible. Capacity is much better than in other alternatives since each platoon is individually managed. Overall system monitoring enhances safety. This option is the first to provide flow optimization commands from the infrastructure to the vehicles. This will help maximize throughput. The environmental benefits are more enhanced because of

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greater platooning potential. This concept will alleviate driver stress and meet the objective of removing the driver from the loop. The environment will have less impact on throughput and travel times. Safety is enhanced by infrastructure-supplied information on accidents, obstructions, and roadway conditions.

2.1.3.7.3. Cons

There is a "chicken-and-egg" problem in getting this started, as above. Vehicles that are not adequately equipped must be prevented from entering, or handled safely if they do enter. Significant infrastructure expense may make this not cost-effective in rural areas. Individual platoon management requires extensive two-way vehicle-infrastructure communication and sophisticated processing. By not providing vehicle-specific information, a wide range of vehicle classes would be prohibited (e.g., commands would apply to vehicles with very specific performance characteristics, excluding classes of trucks, busses, etc.)

2.1.3.7.4. Baseline functions

Vehicles that do not meet the check-in standards must be kept off the roadway. The infrastructure tests them before they are allowed to enter. Entering vehicles give their destination so that they may be placed in proper platoons. The vehicle senses the lane edges, the vehicle immediately ahead, vehicles in adjacent lanes and obstructions. Warnings are passed to other vehicles nearby. Both vehicles and infrastructure detect obstructions and other hazards.

The infrastructure plans normal maneuvers based on the origins and destinations of the individual vehicles. The infrastructure places vehicles in platoons. Evasive maneuvers to avoid immediate hazards are planned by the vehicle and disseminated to surrounding vehicles. The infrastructure may order other maneuvers by individual platoons for hazard avoidance or flow management. This includes splitting or joining platoons.

The infrastructure formulates and sends a series of commands to the platoons (an

unattached vehicle is a single-car platoon). For example, to allow a vehicle in the middle of a platoon to change lanes, it will do two splits on the platoon with the vehicle to free it, a split on the platoon in the adjacent lane, a lane change, and a join in each lane. The lead vehicle accepts each of these commands and communicates with the rest of the platoon to carry it out.

The infrastructure uses sensors and/or vehicle-to-infrastructure messages to determine the traffic conditions. The TMC then fuses this to develop a situation assessment. It constantly monitors the platoons and formulates commands to control them for optimal flow. The Traffic Management Center remotely monitors equipment status, sends out crew to fix. Vehicles detect or infer problems and alert the TMC. TMC is also alerted to emergency by motorist cell phone calls or from monitoring the platoons. Tow truck, ambulance and/or fire truck are dispatched as appropriate. Commands are sent to platoons in the area to avoid danger. Electronic warning is sent to vehicles upstream.

2.1.3.8. Medium-term goal control

This is a level in which the vehicle and the infrastructure share the intelligence, with the more complicated decision making (the car in front is stalled, change lanes to get around it) directed to specific vehicles by commands from the infrastructure. Such infrastructure decisions may also be initiated by the vehicle, for example by requesting a lane change. Table 2.1.3-II indicates the implications of this alternative on the other characteristics.

2.1.3.8.1. Design implications

Each equipped vehicle has some capability for sensing the distance to the vehicle ahead and the location and speed of the vehicles in the adjacent lanes. It also has some means for sensing the edges or center of the lane. The sensed data is evaluated by the in-vehicle processor, which formulates commands to the brake, throttle and steering mechanisms. There is vehicle-to-vehicle communications that allows message passing among nearby vehicles. Thus, each

vehicle is able to maintain steady state. Each vehicle also accepts commands from the infrastructure. This concept requires commonality at least in the formulation and use of vehicle-infrastructure information. This means that message and processing standards must be set, and that vehicles that are not properly equipped are prevented from entering the roadway. The infrastructure needs sophisticated sensing equipment or probe data collection, and a means for merging it and developing commands for the vehicles. It must also have a means of monitoring the position and status of each vehicle. There must be a means of communicating from the infrastructure to the individual vehicles.

2.1.3.8.2. Pros

This is a dedicated automated system. The unpredictability of humans has been eliminated. All of the vehicles are operating under the same rules, and so smooth and safe system operation is possible. Capacity is much better than in other alternatives since each vehicle is individually managed. Overall system monitoring enhances safety. No vehicle-to-vehicle communications are required. This concept will alleviate driver stress and meet the objective of removing the driver from the loop

2.1.3.8.3. Cons

There is a "chicken-and-egg" problem in getting this started, as above. Vehicles that are not adequately equipped must be prevented from entering, or handled safely if they do enter. Significant infrastructure expense may make this not cost-effective in rural areas. Individual vehicle management requires extensive two-way vehicle-infrastructure communication and sophisticated processing. Requires infrastructure modifications. A failure in this system (either communications regarding an obstacle, failure of the infrastructure to sense an obstacle) could be catastrophic.

2.1.3.8.4. Baseline functions

Vehicles that do not meet the check-in standards must be kept off the roadway. The

infrastructure tests them before they are allowed to enter. Entering vehicles give their destination so that they may be guided. The vehicle senses the lane edges, the vehicle immediately ahead, vehicles in adjacent lanes and obstructions. Warnings are passed to other vehicles nearby. Both vehicles and infrastructure detect obstructions and hazards.

The infrastructure plans normal maneuvers based on the origins and destinations of the individual vehicles. Evasive maneuvers to avoid immediate hazards are planned by the vehicle and disseminated to surrounding vehicles. The infrastructure may order other maneuvers by individual vehicles for hazard avoidance or flow management. This includes splitting or joining platoons. The infrastructure, not the vehicles, negotiates a space for a lane change. The infrastructure formulates and sends a series of commands to the vehicles. For example, change speed, change spacing, merge left. The vehicle carries out the command using its own lane and vehicle sensing. The infrastructure uses sensors and/or vehicle-to-infrastructure messages to determine the traffic conditions. The TMC then fuses this to develop a situation assessment. It constantly monitors the vehicles and formulates commands to control them for optimal flow.

The Traffic Management Center remotely monitors equipment status and sends out crew to fix problems. Vehicles detect or infer problems and alert the TMC. The TMC is also alerted to emergency by motorist cell phone calls or from monitoring the vehicles. Tow truck, emergency vehicles are dispatched. Commands are sent to vehicles in the area to avoid danger. Electronic warning is sent to vehicles upstream.

2.1.3.9. Short-term goal control

The vehicles control their actuators, but are given very short-term driving commands by the infrastructure (e.g., "keep straight," "drift 1 in/sec left," "accelerate," "start turning right on a 60 ft radius circle"). The vehicles send sensor data collected on-board and/or the infrastructure collects moment-by-moment vehicle information.

Table 2.1.3-II. Correlation with Other Characteristics (Part 1 of 3)

	Comm	Separation Policy	Roadway Interface	Obstacle Response
Distributed across region	Needs powerful vehicle-to-veh. comm. Std. veh-to-infrastr. & infrastr-to-infrastr	Any	Any	Any
Infra-structure supported	Veh-to-veh comm needed for coord. Infrastr. must comm loc.-specific info. to groups of veh.	Any	Any	Any
Directed platoons	Veh-to-veh comm needed for coord. Infrastr.-to-veh 2-way comm must be cont.	Either platooning option	Any	Any
Medium-term goal control	Infrastr.-to-veh 2-way comm must be cont.	Any	Any	Any

Correlation with Other Characteristics (Part 2 of 3)

	Veh Classes in Lane	Mixed Traffic Capability	Lateral Cntrl Approach	Long Cntrl Approach
Distributed across region	Mixed	No mixing	Infrastr. support limited to ITS and electronic lane-marking	No infrastr. support beyond ITS; may use cooper. from other veh.
Infra-structure supported	Mixed	No mixing	Any	Any
Directed platoons	Mixed	No mixing	Any	Any
Medium-term goal control	Mixed	No mixing	Any	Any

Correlation with Other Characteristics (Part 3 of 3)

	Entry/Exit	Lane Width	Design Speed	
Distributed across region	Any	Any	Any	
Infra-structure supported	Any	Any	Any	
Directed platoons	Any	Any	Any	
Medium-term goal control	Any	Any	Any	

2.1.3.9.1. Design implications

Each equipped vehicle has some capability for sensing and correcting its relative movement. Each vehicle accepts commands from the infrastructure. This concept requires commonality at least in the formulation and use of vehicle-infrastructure information. This means that message and processing standards must be set, and that vehicles that are not properly equipped are prevented from entering the roadway. The infrastructure needs sophisticated sensing equipment or probe data collection, and a means for merging it and developing commands for the vehicles. It must also have a means of monitoring the position and status of each vehicle and its position and orientation relative to the roadway. There must be a means of communicating from the infrastructure to the individual vehicles. Table 2.1.3-III indicates the implications of this alternative on the other characteristics.

2.1.3.9.2. Pros

This is a dedicated automated system. The unpredictability of humans has been eliminated. All of the vehicles are centrally controlled, and so smooth and safe system operation is possible. Flow control is better than in other alternatives since each vehicle is individually and minutely managed. Overall system monitoring enhances safety. In-vehicle equipment is inexpensive, making the AHS more readily available to a range of drivers.

2.1.3.9.3. Cons

There is a "chicken-and-egg" problem in getting this started, as above. Vehicles that are not adequately equipped must be prevented from entering, or handled safely if they do enter. Significant infrastructure expense may make this not cost-effective in rural areas. Individual vehicle management requires extensive vehicle-infrastructure communication, sophisticated processing and huge amounts of real-time data. The system's knowledge of the roadway must be complete and accurate, but even so is not sufficient to support platooning. This concept requires a tremendous amount of infrastructure in order to support large

numbers/classes of vehicles. It must sense vehicle location, motion, and know its intention in order to properly command each vehicle. This would be computationally intensive, require an extremely robust communication architecture, and would lead to catastrophic failure conditions if any component had a glitch or a failure.

2.1.3.9.4. Baseline functions

Vehicles that do not meet the check-in standards must be kept off the roadway. The infrastructure tests them before they are allowed to enter. Entering vehicles give their destination so that they may be guided. The infrastructure senses the vehicles and obstructions relative to the roadway.

The infrastructure also detects hazards.

The infrastructure plans normal maneuvers based on the origins and destinations of the individual vehicles. Evasive maneuvers to avoid immediate hazards are planned by the infrastructure and disseminated to all affected vehicles. The infrastructure may order other maneuvers by individual vehicles for hazard avoidance or flow management. The infrastructure, not the vehicles, negotiates a space for a lane change. Maneuver execution is performed by the infrastructure, which formulates and sends a series of precise commands to the vehicles, such as "move left 2 degrees". The vehicle carries out the command using its position and orientation sensing.

The infrastructure uses sensors and/or vehicle-to-infrastructure messages to determine the traffic conditions. The TMC then fuses this to develop a situation assessment. It constantly monitors the vehicles and formulates commands to control them for optimal flow. The Traffic Management Center also remotely monitors equipment status and sends out crew to fix the problem. Vehicles are controlled by the infrastructure to avoid the problem. The TMC is alerted to emergencies by motorist cell phone calls or from monitoring the vehicles. Tow truck, ambulance and/or fire truck are dispatched when appropriate. Commands are sent to vehicles in the area and upstream to avoid danger.

2.1.3.10. Throttle, steering control

Direct signals from the infrastructure command throttle positions, steering angles, etc. The vehicles are driven under remote control from the roadway.

2.1.3.10.1. Design implications

Each vehicle accepts braking, steering and throttle commands from the infrastructure. This concept requires that vehicles that are not properly equipped are prevented from entering the roadway. The infrastructure needs sophisticated sensing equipment or probe data collection, and a means for merging it and developing commands for the vehicles. It must be able to formulate commands specific to the individual vehicle and roadway segment. It must also have a means of monitoring the position and status of each vehicle and its position and orientation relative to the roadway. There must be a means of communicating from the infrastructure to the individual vehicles. Table 2.1.3-III indicates the implications of this alternative on the other characteristics.

2.1.3.10.2. Pros

This is a dedicated automated system. The unpredictability of humans has been eliminated. All of the vehicles are centrally controlled, and so smooth and safe system operation is possible. Flow control is better than in other alternatives since each vehicle is individually and minutely managed. Overall system monitoring enhances safety. In-vehicle equipment is inexpensive, making the AHS more readily available to a range of drivers.

2.1.3.10.3. Cons

There is a "chicken-and-egg" problem in getting this started, as above. Vehicles that are not adequately equipped must be prevented from entering, or handled safely if they do enter. Significant infrastructure expense may make this not cost-effective in rural areas. Individual vehicle management requires extensive vehicle-infrastructure communication, sophisticated processing and huge amounts of real-time data. The system's knowledge of the roadway and of

the characteristics of each vehicle must be complete and accurate, but even so is not sufficient to support platooning. This concept requires a tremendous amount of infrastructure in order to support large numbers/classes of vehicles. It must sense vehicle location, motion, and know its intention in order to properly command each vehicle. This would be computationally intensive, require an extremely robust communication architecture, and would lead to catastrophic failure conditions if any component had a glitch or a failure. This situation is even more critical with both throttle and steering responsibility solely in the hands of the infrastructure.

2.1.3.10.4. Baseline functions

Vehicles that do not meet the check-in standards must be kept off the roadway. The infrastructure tests them before they are allowed to enter. Entering vehicles give their destination so that they may be guided. The infrastructure senses the vehicles and hazards and obstructions relative to the roadway.

The infrastructure plans normal maneuvers based on the origins and destinations of the individual vehicles. Evasive maneuvers to avoid immediate hazards are planned by the infrastructure and disseminated to all affected vehicles. The infrastructure may order other maneuvers by individual vehicles for hazard avoidance or flow management. The infrastructure, not the vehicles, negotiates a space for a lane change. To execute maneuvers, the infrastructure formulates and sends a series of precise braking, throttle and steering commands to the vehicles. The vehicle sends the commands directly to its actuators.

The infrastructure uses sensors and/or vehicle-to-infrastructure messages to determine the traffic conditions. The TMC then fuses this to develop a situation assessment. It constantly monitors the vehicles and formulates commands to control them for optimal flow. The Traffic Management Center remotely monitors equipment status and sends out a crew to fix problems. Vehicles are controlled by the infrastructure to avoid the problem. The TMC is alerted to

emergencies by motorist cell phone calls or from monitoring the vehicles. Tow truck, ambulance and/or fire truck are dispatched when appropriate. Commands are sent to vehicles in the area and upstream to avoid danger.

2.1.3.11. GPS-based

Very similar to locally cooperative, or distributed across region, but the vehicles depend upon GPS to precisely locate their relative positions. In its most extreme form, all short-range sensors on the vehicle are abandoned, and they maintain lane position by reference between their calculated absolute position, and map data.

2.1.3.11.1. Design implications

Each equipped vehicle has GPS and image recognition. The sensed data is evaluated by the in-vehicle fuzzy logic processor, which controls the brake, throttle and steering mechanisms. GPS may need to be augmented in places. There is a very reliable and accurate AHS roadway map database, updated in real time. There is vehicle-vehicle comm for headway keeping, collision avoidance and maneuver negotiations. Table 2.1.3-III indicates the implications of this alternative on the other characteristics.

2.1.3.11.2. Pros

This alternative has a described and viable evolutionary path. This is a dedicated automated system, but with minimal infrastructure expense. It takes advantage of existing and future GPS capabilities that will occur apart from AHS. The unpredictability of humans has been eliminated. All of the vehicles are operating under the same rules, and so smooth and safe system operation is possible. Capacity is much better than in mixed traffic, as the vehicles will form spontaneous platoons. GPS could provide extremely accurate range/motion information.

2.1.3.11.3. Cons

There is a "chicken-and-egg" problem in getting this started, since dedicating

roadways to such a system will take away from existing or potential manual roadways, and yet will initially benefit only a few motorists. The motorists will not be motivated to buy equipped vehicles until there are convenient dedicated roadways. Subsidies may be necessary for motorists, certainly for roadways. The dedicated roads will bring charges of elitism. Vehicles that are not adequately equipped must be prevented from entering, or handled safely if they do enter.

Since there is no global control, traffic flow on this system is not optimized. Surface street congestion may back up onto the automated highway. The vehicles are not given warning about conditions ahead for which they should adjust spacing or speed.

Roadway condition information is highly dependent on other vehicles being in the area in which you are traveling. Early commuters may get little or no information prior to traveling into an area that is hazardous. This concept requires vehicle sensors which can detect, interpret, and communicate hazardous conditions. This concept may over-reach current communications technology. Requiring the communications receiver to accept hundreds/thousands of simultaneous and probably redundant messages could be technically demanding and undesirable. Receiving one appropriate message from the infrastructure is more practical and technically clean. A heavy computational burden may be placed on on-board processors, especially if they are required to deconvolve thousands of messages coming from other vehicles. This would drive up the requirements/cost for these processors. Any computational overload could potentially create a safety hazard. Traffic flow will still not be optimized without infrastructure support, thus, limiting the throughput advantages of a full-AHS. This option will probably not support a wide range of vehicle classes. Passive infrastructure requires that the vehicle be able to determine when its exit is approaching and respond accordingly. This could complicate the platoon concept and the checkout process. The development of sign recognition technology and/or an extensive on-

Table 2.1.3-III. Correlation with other characteristics (Part 1 of 3)

	Comm	Separation Policy	Roadway Interface	Obstacle Response
Short-Term Goal Control	Infrastr.-to-veh 2-way comm must be cont.	True platooning probably not possible	Any, but most adaptable to RPEV comb. w/ veh. control	Infrastructure based
Throttle, Steering Control	Infrastr.-to-veh 2-way comm must be cont.	True platooning probably not possible	Any, but most adaptable to RPEV comb. w/ veh. control	Infrastructure based
GPS-Based	Veh-to-veh comm and GPS rcvr in veh needed. Std ITS infrastr.-to-veh and infrastr.-to-infrastr.	Free agent or platooning	Any	Vehicle-based

Correlation with Other Characteristics (Part 2 of 3)

	Veh Classes in Lane	Mixed Traffic Capability	Lateral Cntrl Approach	Long Cntrl Approach
Short-Term Goal Control	Mixed	No mixing	Mech. guided and dead reckoning most applicable. Others req. veh. to send pos. to infrastructure	Infrastructure based
Throttle, Steering Control	Mixed	No mixing	Mech. guided and dead reckoning most applicable. Others req. veh. to send pos. to infrastructure	Infrastructure based
GPS-Based	Mixed	No mixing	Veh GPS is compared w/ roadway DB	GPS and radar

Correlation with Other Characteristics (Part 3 of 3)

	Entry/exit	Lane width	Design speed	
Short-Term Goal Control	Any	Any	Any	
Throttle, Steering Control	Any	Any	Any	
GPS-Based	Any	Any	Any	

board, region-specific database may be required. To upgrade the system technology, all vehicles would have to be upgraded. Consumers may balk at having to install a new software load or implement new hardware in order to continue use of the AHS.

2.1.3.11.4. Baseline functions

The vehicle compares its own GPS position with those of nearby vehicles and the road database. Each vehicle will have a sensing or imaging system.

The vehicle plans normal maneuvers based on the route guidance from the ITS navigation system in the vehicle. Evasive maneuvers are planned by the vehicle and disseminated to surrounding vehicles. The vehicle communicates its intentions to the surrounding vehicles, who then open up the necessary space in a predictable manner. Emergency situations includes the distribution to other vehicles of GPS data.

The Traffic Management Center collects and monitors GPS positions of the individual vehicles. The Traffic Management Center also remotely monitors equipment status and sends out crew to fix problems. The TMC is alerted to emergencies by motorist cell phone calls. Tow truck, ambulance and/or fire truck are dispatched as appropriate. Human-readable warnings are sent to vehicles upstream. Vehicles that sense a hazard or brake suddenly send specifics, including GPS coordinates, to surrounding vehicles, who take action.

2.1.4 Evaluatory Alternatives

The initial selection of 11 alternatives was clearly too much for a comparative analysis. The team hoped that the above analysis would eliminate some clear poor choices, but this did not occur. On the contrary, it was found that there are a great number of alternatives within these alternatives, and that evaluation of the 11 choices required specification of more detail than was provided in the original fairly generic descriptions. In fact, each such description spawned further decisions, resulting in even more options. It soon became clear that it

was not possible to catalog the range of alternative options for allocation of intelligence. The team decided that the best and most realistic approach is to identify and describe a representative sample of evaluatory alternatives to be used in concept synthesis. While this is not an exhaustive selection, the subsequent analysis will allow a focus on the key discriminators, and possibly the development of new alternatives. The preceding analysis allowed the team to focus in on this more manageable number of alternatives by identifying these key discriminators.

Of all the functions that need to be performed by an AHS system, there are four key ones whose allocation drives the nature of the architecture. They are

- (1) local position keeping, which is the steady state maintenance of lane and headway position of each vehicle,
- (2) lane changing under normal circumstances such as entry, exit or interchange,
- (3) obstruction on roadway, including the detection of the vehicle or other obstruction, and the planning and execution of a response,
- (4) flow control, including any means to maintain an optimal system traffic flow, such as lane assignments, platoon assignments, speed and spacing adjustments, and entry and exit restrictions.

Table 2.1.4-I identifies the five evaluatory alternatives, and the ways in which they perform each of these basic intelligence functions. Each of the five alternatives is an elaboration of one of the options discussed in the previous section, as indicated. The last one is based on both short-term goal control and infrastructure control, since it was found that they are just different implementations of the same alternative.

2.1.4.1. Adaptive cruise control

This alternative is the minimal automated highway system, and in fact is merely an automated vehicle. The infrastructure provides the basic ITS services (in-vehicle information and routing, but not control) and some means for the vehicle to sense the lane.

This vehicle can maintain steady state once in its lane, but anything else, including obstacle detection and response, must be done by the driver. The benefit of this approach is as an entry level system that can evolve through vehicle purchases. It will allow drivers to get used to automated driving. It can operate with mixed traffic, and so is applicable anywhere and does not take away roadway. The major drawbacks are two-fold. First of all, it does not allow platooning or even efficient spacing, so there are no capacity benefits. Secondly, there are serious safety issues. The driver has no tasks to perform and yet must stay alert for hazards. The system provides no protection against these hazards through segregation of non-automated vehicles, warning or collision avoidance.

2.1.4.2. Locally cooperative

Here the vehicles coordinate through extensive vehicle-to-vehicle communications. This allows coordinated lane changes and platooning. There is no infrastructure support beyond that in the previous alternative. Since this is all done locally, there is not region-wide traffic optimization, other than through ITS advisories. The one enhancement to ITS for this option is the translation of human-readable messages to those that can be read and responded to by the automated vehicle. The platooning options will need to be very simple, such as with fixed lengths and spacings. Mixed traffic platooning is probably not feasible since getting like vehicles into platoons together requires a more global view. The positive aspects of this alternative are based on the greatly increased capacity possible with the minimal infrastructure modifications. The drawback, and possibly even danger, is the lack of global support. This limits capacity in that it cannot be optimized, and emergency response is hampered by a local view.

2.1.4.3. Infrastructure supported

This is an enhancement on the previous alternative. Here the cooperating vehicles are given location-specific information from the infrastructure that is monitoring the global situation. In particular, in a platoon-

ing situation, the infrastructure will give commands and information to the lead vehicles. In a non-platooning implementation, all of the vehicles in a region will be given parameters, such as target speed or spacing, dependent on the current situation. The vehicles are still maintaining their steady state and negotiating their lane changes, but now these are informed by the broader view maintained by the infrastructure. This alternative benefits from the dual view and control, but at a cost of extensive vehicle-to-vehicle and vehicle-to-infra-structure communications.

2.1.4.4. Infrastructure managed

This alternative allows the vehicles to maintain steady state including platooning, but for any special request, such as lane change, entry or exit, the infrastructure takes command. Thus, this is a "request-response" approach, in which the individual vehicles ask permission of the infrastructure to perform certain activities, and the infrastructure responds by sending commands to other vehicles (e.g., open up to allow a lane change). The infrastructure also takes the initiative in emergency situations. This allows much tighter overall system control than the previous alternative, but it requires tracking individual vehicles and extensive communications.

2.1.4.5. Infrastructure controlled

Here the vehicles are completely controlled by the infrastructure, which will continually track and send commands to individual vehicles. These commands may be in the form of steering, braking and throttle commands, or they may be acceleration, deceleration and turning commands. The vehicles have no intelligence beyond the ability to translate these commands for their own actuators and to monitor and adjust their response. This puts a heavy burden on the infrastructure in terms of real-time knowledge of the roadway and the vehicles, the computing power to manage the vehicles, and the communications power to be in continual control of all the vehicles. It is probably beyond the state-of-the-art to maintain tight platooning under this option.

Table 2.1.4-I. Functional Comparison of Major Alternatives

Alternative	Local position keeping	Lane changing	Obstruction on roadway	Flow control
Adaptive cruise control (based on 3.2)	Vehicle automatically senses vehicle ahead and roadway	Manual	Manual	ITS
Locally cooperative (based on 3.4)	Vehicle sensors, comm from other vehicles for exceptions or platoons	Cooperative negotiation among vehicles	Vehicle senses, communicates & coordinates maneuvers	ITS, some local self control
Infrastructure supported (based on 3.6)	Same as cooperative	Same as cooperative	Infrastructure senses, communicates to vehicles; they coordinate	Infrastructure monitors traffic, formulates responses, sends parameters to groups of vehicles
Infrastructure managed (based on 3.8)	Same as cooperative	Vehicle requests lane change; infrastructure responds with commands for surrounding vehicles	Infrastructure senses, sends commands to vehicles	Infrastructure monitors traffic, commands vehicles on exception basis, including entry and exit
Infrastructure control (based on 3.9 and 3.10)	Infrastructure senses vehicle positions and sends commands to control throttle, braking and steering	Infrastructure determines need for lane change from O/D, controls all necessary vehicles	Infrastructure senses, controls affected vehicles	Infrastructure monitors individual vehicles, carries out strategy through control of individual vehicles

2.1.5 Comparison of Evaluatory Alternatives

The following Table 2.1.5-I evaluates the five alternatives and the baseline relative to the Objectives and Characteristics. The concept designators relate back to the initial 11 concepts in Section 2.1.3. For example, C4 is discussed in Section 2.1.3.4. Ratings given to each concept are an order relative to other concepts (more than, less than), not a point score (33% greater than). The table is followed by a brief explanation of each of the Objectives/Characteristics listed in the leftmost column, and a discussion of the scores.

The ratings are intended to provide relative ordering, not measure. 6 is high, 0 is low. 2 is higher than 1, but not necessarily twice as much. The Baseline, or current system, is given a rating of 1 or 5 for all System Objectives and Characteristics as a reference.

2.1.5.1. Improve safety

This rating is based on the ability of the concept to reduce number of collisions, the severity of collisions, and the severity of injuries and value of property damage resulting. In general, safety is expected to increase with the increasing sophistication of the system. C2 has a range that goes below the baseline because of the possibility that this concept, which requires driver intervention, will cause drivers to be inattentive so that they do not intervene correctly or in time. C10 has a range which drops below C6 and C8 because the system is seen as being less "robust" - since the vehicles have little autonomous capability, a communications failure could have very serious consequences.

2.1.5.2. Increase throughput

In general, throughput is expected to improve with the increasing technological sophistication of the system. The addition of platooning to concepts which can support it is expected to further increase throughput, moving C6, C8, and C10 toward the upper

end of their ranges. C8 and C10 span greater ranges than C6 because it is thought that their centralized control could give them a slight edge over the inter-vehicle coordination required by C6.

2.1.5.3. Enhance mobility

This rating focuses on faster and more predictable trip times, and on the ability of people with reduced capability to use the AHS. All of these concepts will have more predictable trip times than the baseline due to the addition of ITS, with C6, C8 and C10 receiving further benefit from flow control. C4 through C10 will greatly benefit those with disabilities; C2 may not provide all the assistance they need. The concepts are rated on reducing trip times similarly to the Increase Throughput ratings. The Enhance Mobility ratings are seat-of-the-pants average of the three components.

2.1.5.4. More convenient and comfortable highway traveling

This rating focuses on the degree of reduced stress and feeling of security, which is assumed to be higher with increasing control of safety related issues by the AHS, but which may be significantly decreased with platooning until people become accustomed to it. All four of the fully automated concepts have the potential to make users feel secure if they are implemented well. However, this is not just a matter of safety statistics. Many people feel less secure in a commercial airliner than in their family car despite demonstrably better safety statistics.

2.1.5.5. Reduce environmental impact

This rating focuses on reduced emissions through smoother vehicle operations and reduced congestion. C6, C8 and C10 will surpass the other concepts in reducing emissions due to their superior flow control. C8 and C10 may have a slight advantage in smoothness of vehicle operations because maneuvers are centrally choreographed under these concepts.

Table 2.1.5-I. Comparison of Evolutionary Alternatives

	Baseline	Adaptive Cruise Control	Locally Cooperative	Infrastructure Supported	Infrastructure Managed	Infrastructure Controlled
Concept Designator	C1	C2	C4	C6	C8	C10
Improve Safety	1	0-2	3	3-4	3-4	2-4
Increase Throughput	1	2	3-4	4-5	4-6	4-6
Enhance Mobility	1	2	3	3-4	3-4	3-4
• More Predictable Trip Times	1	2	2	3	3	3
• Assist Those with Disabilities	1	1-2	3	3	3	3
Convenient/Comfortable Highway Traveling	1	2	0-3	0-3	0-3	0-3
Reduce Environmental Impact	1	2	3	4	4-5	4-5
Operate in Inclement Weather	1	1-2	3	4	4	4
Affordable Cost/Economic Feasibil.	5	4	2-3	1-2	1-2	1-2
Benefit Conventional Roadways	1	2	3	3-4	3-4	2-3
• Increase safety on conventional roads	1	2	4	3-4	3	1
Easy to Use	DNA	DNA	DNA	DNA	DNA	DNA
Infrastructure Compatible	5	4	3	2	1-2	1
Facilitate Intermodal/Multimodal Transportation	DNA	DNA	DNA	DNA	DNA	DNA
Ensure Deployability	5	4	3	2	2	1
Provide High Availability	DNA	DNA	DNA	DNA	DNA	DNA
Apply to Rural Highways	5	5	4	3	3	3-4
Disengage the Driver from Driving	1	2	3	3	3	3
Support Travel Demand Management Policies	1	1	2	2	2	2
Support Sustainable Transportation Policies	DNA	DNA	DNA	DNA	DNA	DNA
Provide Flexibility						
• Architectural Flexibility	1	2	3	4	4	3
• Flexibility in Local Traffic Management	1	2	2	3	3	4
Operate in Mixed Traffic with Non-AHS Vehicles	5	5	3	3	3	3-4
Support a Wide Range of Vehicle Classes	5	5	3-4	3-4	4	4
Enhance Operations for Freight Carriers	1	2	3	3-4	3-4	3-4
Support Automated Transit Operations	1	2	3	4	4	4
Provide System Modularity	DNA	5	4	3	2	1

2. Concept Characteristics

2.1.5.6. Operate in inclement weather

This rating focuses on automation for sensing, judging speed and stopping distance, braking and steering. C4 benefits from improved sensors for lane-keeping and speed/braking control in poor visibility. If these sensors cannot adjust for increase braking distances on wet pavement this could be a major disadvantage, however. C6 derives further benefits from the capability of the infrastructure to sense roadway obstacles beyond the line-of-sight of the vehicle.

2.1.5.7. Affordable cost/economic feasibility

This rating is one of the more difficult ones to score based on intuition. The assumption was made that cost increases with the degree of automation. The cost trade-off between intelligence in the vehicle and intelligence in the infrastructure is much too complex to be guessed at, and is left to more comprehensive analysis.

2.1.5.8. Benefit conventional roadways

This rating is based on AHS throughput, which will draw vehicles from conventional highways, and on the ability of AHS vehicles to enhance the safety of conventional roadways when they operate on them. The throughput scores are taken from the second Objective/Characteristic. C2 has safety enhancement intended for conventional roads. C4 adds vehicle-based fully automatic control. C6 is similar, but may offer less capability for sensing obstructions and flow control in the absence of the infrastructure. C8 has the position-keeping of local cooperative but few of the other enhancements in the absence of the infrastructure. C10 is highly infrastructure dependent, and probably offers only basic manual control in its absence.

2.1.5.9. Infrastructure compatible

This rating is based on the degree of changes required to the roadway and supporting equipment and facilities. C2 and C4 are vehicle-based systems, and should require

few changes, though C4 will probably segregate AHS vehicles, and check them in and out. C6 requires many more infrastructure-based sensors than its predecessors. C8 will probably require more infrastructure than C6, and C10 definitely will, since the infrastructure performs virtually all the detection and processing.

2.1.5.10. Ensure deployability

This rating is based on the technological and economic "distance" between practical, stepping-stone AHS configurations which can be used to attain the chosen architecture. C4 can use C2 as a stepping-stone, making it relatively deployable. C6 and C8 require quite a bit of infrastructure to go beyond the capabilities of C2. C10 is the worst, since the system cannot work without a large amount of infrastructure support, and C2 is not usable as a stepping-stone.

2.1.5.11. Apply to rural highways

This rating is based on how well a concept will work if only one lane is available in each direction, AHS and regular vehicles are mixed, and support equipment is more sparsely located than in urban areas. Any concept which relies on platooning will work poorly under these conditions. C2 suffers no disadvantages since it depends only on the vehicle carrying the system. C4 should operate well in a slightly degraded mode - the only imperative is that maneuver coordination recognize vehicles which are not responding and work around them. C6, C8 and C10 require sensor and communications coverage of every foot of roadway to spot obstructions - expensive in rural areas. C10 has a slight advantage in not being a cooperative system and in doing vehicle tracking - it can treat non-AHS vehicles like moving obstacles, and work around them.

2.1.5.12. Disengage the driver from driving

This rating is based on the extent to which the vehicle is automatically controlled. C2 provides semi-automatic control of the vehicle; C4 through C10 provide automatic control.

2.1.5.13. Support travel demand management policies

This rating is based on the concept's ability to support congestion pricing. The sole differentiator here was whether the infrastructure could support billing as a function of time, i.e., whether it checks vehicles in and out of AHS. C2 does not; the other concepts are expected to do so.

2.1.5.14. Provide flexibility

The description of this rating is ambiguous. It may refer to architectural flexibility, which is whether the concept can be modified easily by adding options (e.g., platooning), or by moving responsibility for a function from the vehicle to the infrastructure or vice versa. C4 through C10 can accept platooning, and C6 and C8 have several functions which could be either vehicle or infrastructure-based. It may also refer to flexibility in local traffic management, which is the ability of a system to be used by local authorities to support their particular traffic management strategy. C2 and C4 give minimal capability here through ITS. C6 and C8 allow traffic management through their flow control function, and C10 gives authorities as much control as the law and the driver will allow.

2.1.5.15. Operate in mixed traffic with non-AHS vehicles

This rating is based on throughput and safety in an environment where there are a substantial number of non-AHS vehicles. C2 suffers no disadvantages since it depends only on the vehicle carrying the system. C4, C6 and C8 should operate well in a slightly degraded mode - the only imperative is that maneuver coordination and flow control functions recognize vehicles which are not responding and work around them. C10, while subject to the same constraints, has a slight advantage in doing vehicle tracking — it can treat non-AHS vehicles like moving obstacles, and work around them.

2.1.5.16. Support a wide range of vehicle classes

This rating is based on the concept's ability to support passenger cars, trucks, and transit vehicles, among others. C2 can be implemented without difficulty on all vehicle classes, as long as the on-board computer knows the characteristics of the vehicle. C8 and C10 can handle multiple vehicle classes; all that is required is for the vehicle to communicate its class, and for the system to look up the appropriate characteristics in a table. This is also possible for C4 and C6, which require inter-vehicle coordination, but may be more difficult given limited on-board data storage and processing capacity.

2.1.5.17. Enhance operations for freight carriers

This rating is based on the concepts ability to reduce trip time, reduce trip time variation, disengage the driver, and guide freight vehicles through weighing and inspection stations. The first three are expected to dominate, and therefore this rating is a seat-of-the-pants average of Disengage the Driver and Enhance Mobility.

2.1.5.18. Support automated transit operations

This rating is based on the concept's ability to reduce trip time, reduce trip time variation, and facilitate transfers to other modes. ITS can provide schedule and location information on other modes of transportation under all concepts. However, the automated systems (C4 through C10) could choose a transit mode and line, and deliver the traveler to the appropriate parking. C6 through C10 rate slightly higher on the basis of reduced trip time and increased predictability.

2.1.5.19. Provide system modularity

This rating is based on a concept's ability to have one or more subsystems modified or upgraded with a minimum of impact to the remaining subsystems. C2 has two subsystems which have no infrastructure dependencies, and are potentially independent of

each other. C4 has potentially four subsystems of which the same can be said, except that they dependent on equipment installed in other vehicles. C6, C8 and C10 have an increasing degree of interdependency between vehicle-based subsystems and the infrastructure.

2.2 COMMUNICATIONS

2.2.1 Characteristic Description

The communications requirements of the AHS system are interdependent with several related functions. AHS functions such as position control, navigation/route guidance, maneuver coordination, and traffic operations may be implemented with one or more types of communications links to provide data transfer. AHS operations may be enhanced through integration of communications capabilities including vehicle-to-vehicle, vehicle-to-infrastructure/infrastructure-to-vehicle, and infrastructure-to-infrastructure data links. The AHS functions are discussed in terms of the expected data link requirements. Communications systems which can be used for vehicle-to-vehicle, vehicle-to-infrastructure – infrastructure-to-vehicle, and infrastructure-to-infrastructure data links are also described.

2.2.1.1. Data link requirements to support AHS functions

Various communications technologies may be used to support four general AHS functions: periodic update of vehicle control loop data, vehicle maneuver coordination, transfer of origin/destination and navigation data, and dissemination of zone or region traffic management information. The operating requirements of a specific communications system are based on several factors, including message latency, access protocol, and data rate. The communications capabilities expected to support each function are described in the following paragraphs.

Position control

The headway control loop algorithm may require exchange of velocity and accelera-

tion information for each vehicle within an assigned coordination unit to support close-following modes. Key technical requirements include strict timing and contention-free bandwidth access. Vehicle control loop data transfers may require short, deterministic latencies as small as 10 msec. Vehicles in close-following configurations will require a dedicated transmit opportunity every 20 msec to 50 msec. The ability to override the normal velocity and acceleration message update rate may be necessary to optimize emergency braking capabilities. The quantity of information contained in each data transfer is expected to be less than 100 bits. The safety-critical nature of the control loop data will also require highly reliable communications channels to increase the probability of error-free data transfer. A significant percentage of the message bandwidth may be consumed by error detection and/or correction protocols. The selected communications technology will be subject to requirements set by the control loop function to a large extent.

Direct communication of velocity and acceleration data between vehicles is one approach to headway control. Velocity and acceleration information may also be obtained by using radar detection. A following vehicle equipped with Doppler radar can sense range to a leading vehicle. Velocity and acceleration can be obtained through processing of successive radar return signals.

Maneuver coordination

Functions including merge, separation, lane change, enter, and exit maneuvers will be automated in a mature AHS. Both steady-state and emergency (collision avoidance) conditions must be supported; the requirements differ since emergency maneuvers are safety-critical, increasing time restrictions on data transfers. Communications will be required to provide time-critical data transfers necessary for emergency maneuvers such as lane changes to avoid obstacles. The steady-state message channel may be compatible with a contention access protocol, as long as the maximum access time meets the required limits. Emergency maneuvers may require access times in the

range of 20 msec to 50 msec. Bandwidth access methods must be capable of assigning priority to emergency messages if necessary to meet safety-critical latency requirements. Packets are expected to be on the order of 50 to 100 bits. The relatively low update rate of steady-state maneuvers may be compatible with message protocols which incorporate repeat transmissions to meet data error rate requirements. This type of communication link may be satisfied by either vehicle-to-vehicle or two-way vehicle-to-infrastructure systems.

Route guidance

The navigation aspect of this function is expected to be available as a subset of ITS capabilities in the time frame projected for AHS implementation. The most significant issues in the area of navigation are the resolution, accuracy, interface, and update rate of available technologies. AHS should expect to influence navigation technology to permit straightforward integration of functionality. The ability to communicate origin/destination information may also be required to support real-time trip modification. Message size and latencies are yet to be determined. This task is compatible with two-way infrastructure-to-vehicle link capabilities. Contention access as well as non-deterministic latency can be tolerated. Packet sizes may vary, and standard packet protocols may be used. Both point-to-point and broadcast modes must be supported. Point-to-point links will allow the vehicle to transfer origin or destination requests to the infrastructure, for example. A broadcast message may be used to transfer traveler information from the infrastructure to a group of vehicles in a coordination unit simultaneously.

Traffic operations

The traffic operations function will include traffic flow management within a network of automated lanes. Communications may be required to support transfer of incident or environment information from roadside sensors to the TMC and the dissemination of route availability data along the infrastructure to roadside processors. Existing protocol and packet switching standards are expected to be compatible with traffic

operations information exchange requirements. Message size and latencies are yet to be determined. The tasks will be supported by one-way infrastructure-to-vehicle and infrastructure-to-infrastructure communication links.

2.2.1.2. AHS communications links

Data transfers which support various AHS functions may be communicated via one or more paths. The individual communications systems may be capable of point-to-point, point-to-multipoint, or broadcast data transfers. The capabilities of each type of communications link are outlined in the following paragraphs.

Vehicle-to-vehicle

Vehicle-to-vehicle control loop data transfers are expected to include velocity and acceleration information. The data link can be accomplished using one-way point-to-point transfers from a leading vehicle to the vehicle immediately following. It is also possible to implement this function using one-way point-to-multipoint transfers from the lead vehicle to all vehicles within its assigned coordination unit. Minimum vehicle headway and elimination of low-differential-velocity collisions in ultra-close vehicle following may be possible by providing two-way point-to-point communications between a leading vehicle and the vehicle immediately following. A feedback loop which provides following vehicle deceleration information to the lead vehicle in emergency braking maneuvers may allow stopping distance to be minimized while preventing collisions. This concept was introduced in the PSA as coordinated braking.

Vehicle-to-vehicle data transfer can be supported by RF radio or infrared signal technologies. The mobile RF communication channel is subject to multipath fading, interference due to high numbers of users, and rapidly varying coordination unit location. Radio communication protocols can support the full range of one- or two-way links, point-to-point or -multipoint, and broadcast communications. Addressing may be included in the message overhead to

allow selective transfer of vehicle-specific data. Infrared signals are not susceptible to interference, but are subject to degradation under conditions of decreased visibility such as fog, rain, or dust. Infrared links are limited to one-way point-to-point communication, introducing propagation delays in transferring information from the lead vehicle to all vehicles within a coordination unit.

Vehicle-to-infrastructure

The vehicle-to-infrastructure link may be used to transfer real-time trip planning information in support of entry and exit requests. Vehicle instrumentation must allow user input of origin and/or destination information and implement transfer of this data from the user interface via a communications device to the roadside. Two-way point-to-point links are expected to be well suited to this application, allowing the vehicle to transmit requests and receive entry or exit commands from the roadside. One candidate technology is Vehicle-Roadside Communications (VRC) using a tag in the vehicle and a beacon at the roadside. VRC is coming into use for automated toll collection and commercial vehicle operations, and incorporates a vehicle tag which is capable of serial interface to a data bus and active data transfers to roadside beacons. Many vehicle-vehicle RF communication links are also capable of supporting the two-way link with the infrastructure.

Infrastructure-to-vehicle

The infrastructure-to-vehicle link may be used to transfer coordination information in support of join or split maneuvers. One-way, broadcast communications links from the infrastructure to vehicles within a localized area may be used to disseminate traffic flow information such as route or lane closures. This feature is expected to become available as an ITS technology prior to deployment of full AHS functionality.

Infrastructure-to-infrastructure

Infrastructure-to-infrastructure communications will link roadside devices with one another and with the Traffic Operations

Center (TOC). Leased telephone lines or fiber optic cable can provide connectivity for this link in areas where infrastructure exists or is installed at the time the roadway is constructed. RF communication technologies such as microwave or unlicensed spread spectrum can be used in areas where land lines are prohibitive or short links are needed to connect existing infrastructure instrumentation.

The applicability of specific technologies depends on the type of data required for the AHS specific function, such as position location, route guidance, or control loop information. The accuracy and resolution required will determine one aspect of the link requirements. The rate at which information must be updated is another important parameter. The ability to uniquely identify individual vehicles with methods such as time slot assignments or unique codes may be another factor. Susceptibility to interference and the ability of a particular technology to operate in inclement weather will affect the data error rate and must be considered. The security of the communications system may be important to prevent transmission of corrupted data, and may be addressed using methods such as data encryption.

2.2.2 Possible Solutions

The teams will describe and contrast each reasonable solution for this characteristic. The teams will describe the significant aspects of each solution. For a technology characteristic, this involves a description of the hardware and software components needed to support the solution and a description of the relative strengths and weaknesses (pros and cons) of each component. For an architecture characteristic, this involves a description of the strengths and weaknesses of each architectural option and of the implications of the design components. For an operating requirement characteristic, this involves describing the strengths and weaknesses of the performance of each solution as well as describing the design and architecture implications of each solution.)

Five baseline solutions are presented, including:

- 1) **ITS Technology:** an approach in which AHS does not add communications capability beyond the technologies brought to market by related ITS developments.
- 2) **Commercial Technology:** existing and emerging commercially available communications infrastructure is exploited to support AHS communications requirements.
- 3) **Existing Technology:** communications products which have been developed for related ITS services are assigned to support specific AHS functionality.
- 4) **Advanced Technology:** communications products under development or deployment are assigned to support specific AHS functionality.
- 5) **Dedicated Technology:** dedicate specific frequency bands to AHS use for operation of spread spectrum communications based on existing unlicensed operations technology.

2.2.2.1. ITS technology

The first approach proposes a solution in which vehicle position control, route guidance, and maneuver coordination are performed within the individual vehicle. No vehicle-to-vehicle, vehicle-to-infrastructure, or infrastructure-to-infrastructure communications are used to link vehicles within a coordination unit or with the TOC. The vehicle operates as an autonomous unit using emerging ITS technologies to implement AHS capabilities.

Position control

Radar in following vehicle obtains range and range rate data by detecting reflected signals returned from leading vehicle. Doppler ranging employs measurement of the vehicle's Doppler frequency, which is directly proportional to the velocity. The Doppler frequency is determined by filtering the reflected signal and measuring the offset between signals applied in two parallel filters. The Doppler method can be extremely precise because errors in the measured location are not inadvertently

included in the differentiation calculations made to determine velocity and acceleration. The result of Doppler measurements is nearly instantaneous, minimizing signal processing delays associated with measuring the rate of change of location. Ranging radars are in development for use in adaptive cruise control applications.

Maneuver coordination

Absolute position location determined by GPS receiver. Entry and exit maneuvers must be performed using map-matching between known geographic locations and absolute position of the vehicle. Merge and split maneuvers must rely on obstacle detection/collision avoidance capabilities since inter-vehicle coordination is not provided. Emergency maneuvers are restricted at this level of instrumentation to in-lane braking.

Route guidance

Absolute position location determined by GPS receiver. Position accuracy can be determined to within 5-15 meters using differential GPS. Differential receivers are currently available and becoming cost competitive. GPS coverage is comprehensive within the continental United States and is currently implemented to provide Automated Vehicle Location (AVL) ITS services. GPS is a line-of-sight location determination system. The GPS system may be inhibited when used in center city areas where tall buildings will obstruct the view of the satellite system. Pseudo-satellites may be used to overcome this difficulty, adding cost by requiring infrastructure instrumentation.

Traffic operations

Existing ITS services may be exploited to obtain route availability and lane closure information. FM Radio Broadcast Data System (RBDS) is coming into use in the US, and has been introduced in Europe (known as RDS). The RBDS system allows co-transmission of digital data along with an FM radio signal. Traffic information is relayed to the FM radio station which in turn encodes the data and transmits it out on the subcarrier frequency (57 kHz).

RBDS transmission range is limited to the transmission range of the FM station, limiting use to areas within range of the transmitting station. RBDS is designed to transfer limited text data or message information to the motorist from the infrastructure. The data rate is up to 1200 bps. RBDS receivers are available from a number of sources, including Delco Electronics. These receivers typically display information received on the RBDS subcarrier on an alphanumeric readout on the face of the radio. Interface to vehicle processing and format of messages are key factors to integration of traffic flow information into automated vehicle control.

Advantages

- Infrastructure instrumentation to support communications backbone is not required.
- Majority of functionality transportable to non-AHS roadways.

Disadvantages

- Minimum headway dependent on sensitivity, accuracy, and response time of ranging sensors.
- Maximum lane capacity is constrained by headway limitations.
- Majority of instrumentation cost born directly by vehicle/owner.

2.2.2.2. Commercial technology

The second approach proposes a system in which commercially available public access communications systems are used to provide vehicle-infrastructure and infrastructure-infrastructure links. This solution builds on the ITS-based technology by adding coordination of maneuvers, entry/exit functions, and traffic flow.

Position control

Vehicle is autonomous, using adaptive cruise control technology based on radar ranging to maintain vehicle headway. No communication between vehicles is used to coordinate braking or acceleration.

Maneuver coordination, route guidance, traffic operations

These functions can be implemented through integration of mobile wireless radio such as

analog or digital cellular with land based networks. A currently emerging information transfer protocol, Cellular Digital Packet Data (CDPD) technology transfers data over a digital packet switched network overlaid onto the cellular radio network. Connectivity to land networks such as the internet is used to provide direct access to host databases, such as centralized navigation information. CDPD can support non-time critical data transfers between a vehicle and the infrastructure to download navigation information and transfer origin/destination requests. The route guidance function is tolerant of the relatively long message latency inherent in the CDPD protocol, which inserts message traffic in idle spaces within analog or digital cellular networks.

CDPD can also provide intra-vehicle coordination for non-emergency lane changes, entry/exit, join and split maneuvers. The response time for emergency maneuvers is limited by the access times of the system, which must wait for a lull in message traffic to transmit data. Emergency maneuvers may be limited to stopping without changing lanes to avoid collisions. The latencies and access times also limit the applicability of CDPD to control loop data transfers, so headway maintenance is not expected to be compatible with this communication technology.

Advantages

- Low cost commercially available technology which provides two-way link between vehicle and infrastructure.
- Provides non-emergency vehicle-vehicle coordination.
- Increased capability over ITS/autonomous vehicle solution with little added cost.

Disadvantages

- No improvement in vehicle headway over autonomous vehicle.
- Increased infrastructure cost due to support of data base and access to land lines.

2.2.2.3. Existing technology

The third approach proposes a system in which existing vehicle-to-vehicle and vehicle-to-infrastructure communication technologies are implemented. Infrastructure-to-infrastructure communications are not used to link vehicles with the TOC. This solution allows transfer of velocity and acceleration information between vehicles in addition to coordination of maneuvers, entry/exit functions, and traffic flow.

Position control

Velocity and acceleration data are communicated to a following vehicle by the vehicle immediately in front using an infrared link. Information is transmitted at infrared light frequencies through the atmosphere. The infrared link is limited to short point-to-point transfers, allowing transmissions to be confined to a limited reception area ideal for vehicle-vehicle communications. All vehicles in the system can use the same IR frequency, since the infrared receiver must be within the line-of-sight range of the infrared transmitter. Each vehicle within a coordination unit must receive information from the vehicle in front of it and retransmit the information to the vehicle behind it as necessary. Analysis by PATH has shown that the propagation delay introduced by the daisy-chain information path will not impact the expected control loop performance for close vehicle following.

Maneuver coordination and route guidance

Introduction of two-way infrastructure-vehicle communications allows origin and destination requests to be coordinated to optimize traffic flow. Autonomous vehicles may enter the automated lanes and merge with the traffic flow safely using absolute vehicle position and obstacle detection, but accommodation of the entering vehicle may have a negative impact on traffic flow. Communications will allow surrounding vehicles to adjust vehicle spacing and velocity in a coordinated manner to optimize traffic flow.

Vehicle-roadside communications (VRC) is an existing technology which employs a roadside transceiver (beacon) which interrogates and accepts responses from a small,

inexpensive vehicle based transceiver (tag). VRC systems provide low power data transfers which are localized to within about 100 feet of each beacon. Beacons can be placed at intervals along the roadway or at specific points where communications are necessary, such as AHS entry and exit points. VRC technology is currently under deployment for both automated toll collection and commercial vehicle operations. It is compatible for adaptation to AHS because the active tags permit two-way communications. Passive tags associated with other toll-tag technology rely on reception of back-scattered energy from passive tags, which will not support entry and exit requests transmitted actively by a vehicle to the roadside beacon.

Continuous communications connectivity between the vehicle and the infrastructure will require installation of roadside beacons at close intervals. The infrastructure investment may not be cost effective in rural areas due to lower traffic volumes. It may be expected that coordination of join and split maneuvers would be less capacity critical in less dense population centers, obviating the need for continuous connectivity.

Traffic operations

Integration of TOC processors with roadside beacons can provide route availability and lane closure information to vehicles enroute. The VRC link permits two-way communications with the vehicle, and real-time speed, headway, or other traffic flow commands can be transmitted to vehicles to adjust traffic flow to existing conditions.

Advantages

- Vehicle-vehicle link allows close-vehicle-following to be implemented inexpensively.
- Technologies are low cost, proven, available.

Disadvantages

- Possible degraded performance of infrared in low visibility.
- Increased infrastructure cost to implement beacons at close intervals.

2.2.2.4. Advanced technology

The fourth approach proposes a system in which developing advanced radio technology is used to support vehicle-vehicle and two-way vehicle-infrastructure communications. Fiber optic cable is currently being deployed and is proposed to support the infrastructure-infrastructure link. This solution allows transfer of velocity and acceleration information between vehicles in addition to coordination of maneuvers, entry/exit functions, and traffic flow.

Position control

Velocity and acceleration data are communicated to a following vehicle by the vehicle immediately in front using RF radio link. Advanced digital radio techniques are being developed which allow system integrators to select modulation techniques and message protocols with a standard hardware configuration. This technology is in development for deployment to passenger vehicles. The potential for interference between users must be considered in the communications link design. This issue can be addressed by implementing frequency hopping to allow simultaneous use by multiple, independent networks. The control loop algorithm will require low message latency, which can be achieved amongst multiple users by implementing a time-slot access architecture.

Maneuver coordination

The digital radio which supports vehicle-vehicle communications for the control loop function can be extended to handle steady-state and emergency maneuvers within a coordination unit. The access protocol design would assign access slots in a manner which provides priority processing for emergency commands. Maneuver coordination which is limited to vehicle-vehicle communication of maneuvers may be restricted to single lane AHS applications. The ability to change lanes or swerve outside of a lane boundary will require intra-coordination-unit transfer of maneuver commands. Integration of the infrastructure-vehicle and vehicle-vehicle links would allow emergency maneuvers to be coordinated among multiple coordination

units and across multiple lanes. This can be accomplished by providing connectivity between the vehicle-vehicle link and the infrastructure by placing radio transceivers at periodic intervals along the roadside.

Route guidance

The infrastructure connectivity provided to support maneuver coordination can also be used to transfer route guidance information. The two-way infrastructure-vehicle link permits transfer of origin/destination data from the vehicle to roadside processors. The entry/exit commands can be processed at the roadside and returned to the vehicle. Supporting several communication paths with a single radio technology will reduce vehicle instrumentation and minimize the number of interfaces.

Traffic operations

Data collected at roadside sensors can be transmitted to the TOC via fiber optic cable providing the infrastructure-to-infrastructure link. Land lines may also be used to disseminate traffic flow information such as route availability, lane closure, travel speeds, and headways for automated vehicle control. Dedicated fiber optic lines provide a very high bandwidth (up to several gigabits per second) connection between infrastructure elements. Benefits of fiber optic include low equipment and maintenance costs, and data transfer that is reliable and immune to interference. Fiber optic is also capable of transmitting uncompressed video over several channels simultaneously, an ideal feature for transfer of incident detection and environmental sensor outputs. Installation can be expensive, time consuming, and disruptive due to trenching for conduit burial for retrofit applications. Another negative feature is the susceptibility of cable to damage during maintenance operations.

Advantages

- Coordinated braking is possible with vehicle-vehicle RF communications, allowing minimum headway and maximum capacity.
- Supports coordination of traffic flow over network of AHS lanes, entries, exits, and interchanges.

Disadvantages

- Higher risk approach due to developmental stage of radio communications.
- Increased infrastructure cost and system complexity.
- Increased infrastructure maintenance and operation responsibilities.

2.2.2.5. Dedicated technology

The fifth approach proposes a system in which existing spread spectrum radio technology is used to support vehicle-vehicle and two-way vehicle-infrastructure communications. This solution may be dependent on procuring frequency assignments for AHS use, similar to recent assignments for ITS communications at 220 MHz.

Position control

Velocity and acceleration data are communicated to a following vehicle by the vehicle immediately in front using spread spectrum RF radio link. Inexpensive transceivers operating in several unlicensed bands are commonly available. The use of different spreading codes enables multiple radios to share the same frequency band with minimal interference. Operation in these bands eliminates the need for frequency planning and coordination associated with conventional radio and microwave links. Some of the commercially available transceivers provide an interface to the RF front end, allowing unique access protocols to be developed. The control loop communications function is expected to require short duration, dedicated access time slots, for example.

Maneuver coordination

The spread spectrum radio which supports vehicle-vehicle communications for the control loop function can be extended to handle steady-state and emergency maneuvers within a coordination unit. The protocol design would assign access slots in a manner which provides priority processing for emergency commands. Integration of the infrastructure-vehicle and vehicle-vehicle links can be accomplished by providing connectivity between the vehicle-vehicle link and the infrastructure by placing

spread spectrum transceivers at periodic intervals along the roadside.

Unlicensed spread spectrum transmissions are currently restricted to 1 watt output power, limiting range to 1 to 2 miles between radios depending on local topography, vegetation, and structures. For communications between vehicles and the infrastructure, this limitation will dictate a spacing of 1/2 to 1 mile between infrastructure radios. Interference from other spread spectrum radio sources such as a wireless LAN in a building near the highway is possible since anyone is able to operate in this unlicensed band. Dedication of a portion of the available bandwidth to AHS would eliminate the potential for unintentional interference from other users.

Route guidance

The infrastructure connectivity provided to support maneuver coordination can also be used to transfer route guidance information. Implementation of contention access or round robin protocols may be suitable for this function. The two-way infrastructure-vehicle link permits transfer of origin/destination data from the vehicle to roadside processors. The entry/exit commands can be processed at the roadside and returned to the vehicle. Supporting several communication paths with a single radio technology will reduce vehicle instrumentation and minimize the number of interfaces.

Traffic operations

Connectivity between roadside transceivers and the TOC can be implemented to support the infrastructure-to-infrastructure link. The spread spectrum radio link can be used to disseminate traffic flow information such as route availability, lane closure, travel speeds, and headways for automated vehicle control. The bandwidth of commercial spread spectrum technology is expected to support compressed video for transfer of incident detection and environmental sensor outputs.

Advantages

- Technology is low cost and readily available.

- Coordinated braking is possible with vehicle-vehicle RF communications, allowing minimum headway and maximum capacity.
- Supports coordination of traffic flow over network of AHS lanes, entries, exits, and interchanges.

Disadvantages

- Some risk of unintentional interference unless dedicated band is assigned.
- Commercially available transmitters have limited output power and short range, requiring frequent spacing along infrastructure.
- Similar infrastructure maintenance and operation responsibilities to solution 4.

2.3 LONGITUDINAL SEPARATION POLICY

2.3.1 Description of Characteristic

2.3.1.1. Definition

This concept characteristic specifies the distance two longitudinally adjacent automated vehicles on an AHS should be separated from each other. The longitudinal separation can be specified in either spatial or temporal term, i.e. spacing or headway respectively. Note that an AHS is defined as a vehicle-freeway system that supports fully automated driving on a dedicated lane. Consequently, the focus of this Concept Characteristic is on such an AHS.

2.3.1.2. Mixed traffic or deployment addressed elsewhere

Longitudinal separation policies during possible intermediate AHS deployment steps are beyond the scope of this discussion. Some of these stages may involve mixing automated vehicles with manually driven vehicles in the same lane. More detailed discussion can be found under the Concept Characteristic of Mixed Traffic Capability.

2.3.1.3. One vehicle class only

If multiple classes of vehicle share a common lane, then two adjacent automated vehicles may be of different classes. The

longitudinal separation policy should also address their separation but this is addressed in the Concept Characteristic of Vehicle Classes in a Lane. The focus of this Concept Characteristic is the separation of longitudinally adjacent vehicles of a common class. Vehicle classes include automobiles, buses, trucks, etc. (Automobile carriers, such as those required in driveless Pallet systems, are considered as trucks in the following discussion.)

2.3.1.4. Effect on other operating requirements omitted

This policy has many implications on other operating requirements, e.g., merging, entering, lane-changing, diverging, and exiting. The longitudinal separation policy not only needs to specify how far automated vehicles should be separated during these events but also impacts how the companion maneuvers are performed. Such implications will not be considered here but will be considered in the Concept Synthesis stage.

2.3.2 Importance

Longitudinal separation policy is a fundamental operating requirement for an AHS. It impacts many overall AHS Objectives and Characteristics, most notably safety, capacity, environmental impact, human factors.

Major Benefits: Longitudinal Separation for Reduction of Rear-end Crashes and Capacity Gain

As the density and speed of vehicles using the road system increase, the likelihood and the likely severity of collisions will increase. The capabilities of drivers are the principal limitation. Automated longitudinal separation has a direct impact on a major collision type: rear-end collision.

It has been estimated that driver errors are responsible for from 70% to 90% of the collisions that occur on the current US roadways. Let us concentrate on those rear-end collisions occurring on the US Interstate Highways. Out of the 5,992,937 crashes that occurred on the US roadway system during 1992, 287,453 (4.8%) of them occurred on US Interstate Highways.

Among these 287,453 crashes, 103,578 (36%) were rear-end crashes. Out of the 3,788 fatal crashes that occurred on those highways during the same year, 454 (12%) of them were rear-end crashes. Although these interstate rear-end crashes tend to be low injury producing events and tend to result in minor to moderate vehicle damage, they are a major safety problem and create much traffic congestion. Causal factor analyses (Collision Avoidance Studies) estimated that 82% of these rear-end crashes are due to driver inattention and following too closely. (See Calspan PSA Reports.) The longitudinal separation policy, supported by the automation technology, can contribute directly to the reduction of such crashes and the resulting fatalities, injuries, property damage and traffic congestion.

Limited ability of drivers to follow other vehicles produces a major limitation on lane capacity. The limitation of drivers' ability to perceive changes in vehicle spacing, relative motion and acceleration and their limited speed and precision of response ensure that lane capacity cannot generally exceed 2200 vehicles per hour under manual control. Traffic flow is the product of speed and density. The longitudinal separation policy, supported by the automation technology, addresses directly the density and hence, can contribute directly to the increase of lane capacity.

Note that longitudinal separation may depend on speed, weather, traffic conditions, lighting conditions, etc.

2.3.3 Describe All Realistic Solutions

- i) Realistic Solutions and Their Performance Strengths and Weaknesses
- ii) Design and Architecture Implications

2.3.3.1. Realistic solutions

- i) Free-Agent
- ii) Platooning
- iii) Free-Agent with Gap Management
- iv) Platooning with Gap Management
- v) Slotting

The Free-Agent and Platooning policies have received much attention in the literature. Their impacts on the longitudinal flow

of an AHS lane have been the primary focus. However, AHS lanes need to accommodate lateral flow too, i.e. lane changes for flow balancing or successful exiting. To facilitate lateral flow of traffic, the distribution of vehicles and gaps on an AHS lane can be tracked, manipulated and managed. This leads to the enhanced longitudinal separation policies of Free-Agent with Gap Management and Platooning with Gap Management. The concept of slotting was heavily studied during the 60's and 70's. We consider only the quasi-synchronous slotting concept as a realistic solution.

Free-agent vs. platooning

The free-agent separation policy has two main characteristics:

- i) a vehicle travels at speed limit or a lower but safe speed if there is no vehicle within the safety distance in front;
- ii) otherwise, it follows the vehicle in front at a safe distance or travels at a lower but safe speed.

This has been viewed by many as the "basic" longitudinal separation policy that any AHS should support. Platooning and free-agent policies are contrasted as follows. Free-agent policy can be viewed as a special case of platooning having only one vehicle per platoon but a "safe" free agent vehicle spacing may be different from a "safe" inter-platoon spacing. We focus our attention on the additional features required by the platooned operations.

In platoon operations, vehicles are clustered together in groups of up to 20 vehicles, with short spacings between the vehicles within a platoon and a long spacing between two platoons. Intra-platoon spacings as short as 1m have been contemplated by proponents of platooning. This mode of organizing the movements of vehicles was conceived as a way of expanding the envelope of capacity and safety that can be achieved by road vehicles. The goals are as follows. There should be no collisions in the absence of malfunction. The short intra-platoon spacings are intended to ensure that when a collision between two longitudinally adjacent vehicles does occur (due to a

malfunxion), the relative speed at collision time and hence, the collision severity are both low. Note that the collision refers to only the initial collision and the initial low-impact collision may lead to more serious subsequent collisions. The long inter-platoon spacings are intended to guarantee no inter-platoon collisions. Under the free-agent separation policy, vehicles move without any clustered formation and the minimum longitudinal spacing is significantly longer than typical intra-platoon spacings, but maybe significantly shorter than typical inter-platoon spacings.

A major difference between the two different solutions is the short spacings between two adjacent vehicles in a platoon. Although these short spacings provide a high potential for a large capacity gain, the safety issues remain unresolved. Most of the technical results about the pros and cons of platooning are preliminary and much more research is required before definitive evaluation can be done. Particularly, models developed for studying platooning safety are far from being able to prove the safety of platooning in the real-world. In the existing studies on the impact of the initial collision, based on either analytical or simulation modeling, variations in values of model parameters can have dramatic effects on the shape, magnitude and distribution of impact speed of the initial collision between two longitudinally adjacent vehicles. Few computer simulation models have been developed to evaluate emergency maneuvering strategies and to simulate the possible subsequent collisions after the initial low-relative-speed impact. The proponents of platooning believe that platooning will be most likely able to provide more safety and capacity than the free-agent policy. The critics do not believe in the safety of platooning.

Lane capacity under platooning hinges upon the inter-platoon and intra-platoon spacings. That under the free-agent policy depends on the inter-vehicle spacings. Until such spacings have been selected, it is difficult to estimate the capacity that the corresponding AHS lane can achieve. Note that lane capacity alone does not determine the highway capacity. In those AHS that have

more than one lane and require lane-changing, some lane capacity may have to be sacrificed to accommodate vehicles' lateral movements from one lane to another.

The platooning policy has several important parameters. First of all, the maximum allowable number of vehicles of a platoon, i.e. maximum platoon size, may vary according to, for example, traffic conditions, weather and safety requirements. The spacings, either the intra-platoon spacings or the inter-platoon spacings, may also vary with respect to, for example, the vehicle class, type of longitudinally adjacent platoons, weather conditions, and safety requirements. These spacings may change in real-time to accommodate speed changes or vehicle maneuvers. Variations of platooning exist. For example, platooning may be compulsory and planned; it may also be optional and spontaneous. In the former case, all vehicles on an AHS lane are required to platoon and the operating rules stipulate how a vehicle should relate to other vehicles in the clustered formations throughout its trip. In the latter case, however, a vehicle's driver decides if he or she wants to travel in a platoon and, after so deciding, he or she can break out of the platoon at any time. This variation is often called spontaneous platooning. In mixed traffic where automated vehicles are intermixed with manually driven vehicles in the same lane, only automated vehicles that happen to be longitudinally adjacent can form a platoon. Platooning in this mixed traffic has also been referred to as spontaneous platooning.

Free-agent and platooning policies with gap management

The idea behind gap management is to better organize and more efficiently utilize the space on an AHS lane. It is also to increase traffic flow stability. Recall that both free-agent and platooning policies do not address the unused gaps between two free-agents and platoons, respectively.

The physical distribution of vehicles and gaps has a great impact on the ability of vehicles to change lane and on the time needed to complete a lane change. Proper distribution can improve the lateral and

hence, the overall AHS capacity. This function (i) plans for the proper distribution of vehicles (platoons, if applicable) and gaps. (ii) monitors and manages the position and the length of individual gaps between the traffic units to maximize the lateral capacity. (The traffic unit may be a platoon or an individual vehicle.) With platooning, this function also plans and determines whether and when to split one platoon into two (or more) or merge two (or more) platoons into one. It also determines where the split(s) should occur within a platoon.

Slotting

The idea behind slotting is to more simply organize the use of space on an AHS. It is also to increase traffic flow stability. The roadside control system creates and maintains moving slots on an AHS lane that partition the AHS lane at each moment in time. Each slot is occupied by a single vehicle or left empty. In a basic slotting concept, slots are always of a single fixed length, not variable. The single fixed length may be determined based on safety requirements, weather conditions, roadway conditions, lighting conditions, etc. Other than the safety spacings and the space physically occupied by the vehicle, there may be extra space within a slot set aside for maneuvering, e.g., lane changing. Variations of this basic slotting concept exist.

Other solutions

There are other possible solutions for longitudinal separation, e.g., platooning with mechanical intra-platoon linkage. In this longitudinal separation concept, two longitudinally adjacent automated vehicles in a platoon are physically linked by a rigid bar, instead of being electronically linked through sensing, communication, computing and actuation. Since the Request for Application (RFA) called for AHS concepts and designs involving only electronic linkage, as opposed to mechanical linkage, this concept is beyond the scope of Concept Characteristic Analysis and is not considered as a realistic solution. Note that this solution still requires the technological support for all other characteristics of platooned operations, e.g., longitudinal separation between two adjacent platoons in the same lane.

2.3.3.2. Design and architecture implications

Platooning vs. free-agent

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);
- ranging sensors with accuracy of several centimeters within the range of a few meters;
- software logic for joining and splitting platoon.

Platooned operations also impose more severe 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.

Vehicle-following vs. point-following technologies

There are at least two fundamentally different ways of implementing any longitudinal separation policies: vehicle-following and point-following. In the former paradigm, longitudinal separation of a vehicle from its predecessor is directly observed by the vehicle. In the latter, a vehicle follows a moving point, i.e. a trajectory, that is calculated and instructed by the roadside control system. In this paradigm, proper longitudinal separation is achieved indirectly through proper functioning of the point-following mechanism. These two paradigms, due to their technological nature, are discussed in more detail under Longitudinal Control Approach. It should be apparent that, in general, the vehicle-following approach requires higher vehicle intelligence but lower infrastructure intelligence than the point-following approach. In other words, the former is vehicle-centered while the latter is infrastructure-centered. The latter paradigm

requires sophisticated centralized sensing (for traffic and driving conditions) and control systems and hence, tends to be vulnerable to single-point failures on the roadside. In addition to the centralized sensing, separate obstacle detection capability is nevertheless needed on the vehicle.

Although in theory both platooning and free-agent policies can be implemented with either of the two paradigms, it is generally believed that, due to the short intra-platoon spacings, the vehicle-following approach is absolutely required for platooning. The free-agent policy may not absolutely require the vehicle-following approach and may be amenable to the point-following approach. Point-following has received much less attention than vehicle-following and it is unclear at this stage how strongly the free-agent policy is related to either of the two approaches.

Gap management

Gap management is a roadside function that addresses both longitudinal separation and system flow control. The primary purpose is system efficiency or capacity, rather than safety. Gap management involves a certain degree of centralized control and requires extra roadside intelligence that monitors, plans and manages vehicle/gap distribution on an AHS lane, but does not absolutely require the sophisticated centralized sensing of the point-following paradigm.

Slotting

The slotting policy absolutely requires point-following longitudinal control technologies, particularly the sophisticated centralized sensing. Due to the need to set conservative slot lengths, slotting tends to have limited capacity potential.

2.3.4 Evaluate Solutions to Concept Characteristic

- i) Against AHS Objectives and Characteristics
- ii) Against Baseline Functions
- iii) Against Uses for an AHS

2.3.4.1. Against AHS objectives and characteristics

Safety ranking

free-agent 5; platooning 6; free-agent with gap management 5; platooning with gap management 6; slotting 4

As indicated earlier, safety and capacity (and hence, mobility) differences between the platooning and the free-agent policies are unclear at this stage. Much more research is required. Gap management should not affect the safety of either the free-agent or the platooning policy. The vulnerability of the slotted systems to single-point failures on the roadside makes them somewhat less safe.

Capacity and mobility ranking

free-agent 5; platooning 9; free-agent with gap management; platooning with gap management 10; slotting 4

Platooning should provide considerably higher capacity than the free-agent policy if proven safe. Gap management should enhance capacity and mobility. Slotting always costs capacity because of the rigid space partitioning.

Convenience and comfort ranking

free-agent 6; platooning 3; free-agent with gap management 6; platooning with gap management 3; slotting 7

Platooning, when compared to the free-agent solution, may make some users feel uncomfortable, due to the short intra-platoon spacings. Gap management should not affect convenience and comfort levels. Slotting, due to the larger longitudinal spacings involved, may provide more user comfort.

Environmental impact

free-agent 5; platooning 7; free-agent with gap management 5; platooning with gap management 7; slotting 5

Platooning has been shown, through wind-tunnel simulation, to reduce aerodynamic drag by as much as 50%. The corresponding reduction of fuel consumption and pollutant emissions is estimated to be between 25% and 50%. (The ranking is based on per

vehicle mile traveled on AHS. These reductions may be offset by the increase of fuel consumption and environmental impact due to increased traffic.) Gap management should not affect the environmental impact. Slotting should have similar environmental impact as the free-agent policy.

Cost ranking

free-agent 6; platooning 4; free-agent with gap management 5; platooning with gap management 3; slotting 32

Due to the higher technological requirements, platooning may incur higher vehicle costs as well as infrastructure costs than the free-agent policy. Gap management needs higher roadside intelligence and may increase the infrastructure costs. Although slotting can reduce somewhat the need for certain vehicle intelligence, it requires much more infrastructure intelligence.

Deployability ranking

free-agent 6; platooning 3; free-agent with gap management 5; platooning with gap management 2; slotting 3

Due to the extra features of platooning, compared to the free-agent policy, its deployment could be more difficult or requires a longer time. Gap management is an additional feature and hence, may require extra time for deployment. Slotting is generally considered difficult to deploy because the infrastructure needs to be extensively modified before demand buildup.

Availability ranking

free-agent 6; platooning 5; free-agent with gap management 6; platooning with gap management 5; slotting 3

Due to the higher complexity of the platooning system, its availability could be lower than its free-agent counterpart. Gap management is not essential for safe operation of AHS. Therefore, it should not affect the system availability. Slotting increases the vulnerability of the roadside system and hence, decreases the availability, although the reduced vehicle complexity may increase the vehicle availability for a slotted free-agent system somewhat (but not for a slotted platooning system).

Supported vehicle classes ranking

Free-agent 6; platooning 4; free-agent with gap management 6; platooning with gap management 4; slotting 4

It is in general a consensus that mixing different vehicle classes in the same platoon is unsafe. Therefore, if the AHS does support a wide range of vehicle classes, grouping vehicles to form large platoons may be difficult and system operations could be more complicated. Gap management should not have any bearing on supported vehicle classes. Multiplicity of supported vehicle classes may increase the complexity of slotting. In this case, the slot length may be set for the shortest vehicle class, e.g., the automobile, and a long vehicle, e.g., a truck, may occupy more than one slot.

2.3.4.2. Against baseline functions

Check-in ranking

free-agent 6; platooning 5; free-agent with gap management 6; platooning with gap management 5; 7

Due to the higher complexity of the platooning system, check-in function, if required, may involve more checking than the free-agent policy. The gap management feature should have any negative impact. The slotting policy may require somewhat less of the check-in function, when compared to the free-agent policy, due to the reduced complexity of on-board functions.

Maneuver Planning and Execution Ranking

free-agent 6; platooning 5; free-agent with gap management 8; platooning with gap management 7 slotting 9

Maneuver planning and execution under platooning could be more complicated than under the free-agent policy. Gap management, due to its very nature, is conducive to maneuvering planning and execution. Due to its rigid space organization, slotting should be even more conducive to maneuvering planning and execution.

Flow control ranking

Free-agent 6; platooning 5; free-agent with gap management 8; platooning with gap management 7; slotting 9

Flow control for platooning could be more complicated than its free-agent counterpart. Gap management, again due to its very nature, is conducive to flow control. Slotting, again due to its rigid space organization, is even more conducive to flow control.

Malfunction management

Free-agent 6; platooning 5; free-agent with gap management 6; platooning with gap management 5; slotting 3

Due to the higher complexity of the platooning technologies, malfunction management could be more complicated than their free-agent counterpart. The gap management feature should not negatively impact malfunction management. The slotting policy is heavily dependent upon the proper functioning of the roadside sensing and control systems. In the presence of roadside failures, malfunction management may be severely affected.

Emergency handling

Free-agent 6; platooning 5; free-agent with gap management 7; platooning with gap management 6; slotting 4

Due to the short intra-platoon spacings, emergency handling in platooned operations could be more difficult than its free-agent counterpart. The presence of gap management should not have any negative impact on emergency handling. Moreover, it should make traffic coordination, either as a means to avoid collisions or as a way to manage traffic after collisions, easier. Due to the heavy reliance on the proper functioning of the roadside sensing and control systems, emergency handling under slotting, in the presence of roadside failures, may be more difficult than their non-slotting counterparts.

Against uses for an AHS

These five solutions fare identically with respect to the six Uses described in Table 2.1 of the System Objectives and Characteristics document. Therefore, rankings for all five solutions are identically 5. However, if the platooning is proven safe, then it should perform better in the heavily congested urban freeways due to its

ability to provide much higher capacity, in which case rankings would be 7 and 5 for platooning and free-agent policies respectively. Their gap management counterparts would rank 8 and 6 respectively. Assuming that the slotting policy is safe and reliable, since it has lower capacity potential, it would rank 4.

2.3.5 Description of Correlation Between the Solutions

The correlation is discussed in the following subsections, each corresponding to the concept characteristic as numbered.

1) Platooning is strongly related to two solutions: a) Vehicle only and b) Vehicle Predominant with Some Infrastructure solution. The features and vehicle performance required by platooning discussed earlier would likely require more vehicle intelligence. The Free-agent policy can be implemented within either the vehicle-following or the point-following paradigm. If implemented by the former, it is also related to the two solutions above, but only weakly related. If implemented by the point-following approach, then it is strongly related to the solution of Infrastructure Predominant. The two policies with gap management relate to the Distribution concept characteristic in a similar way. However, gap management requires more infrastructure intelligence for additional centralized control. The Slotting policy is strongly related to the solution of Infrastructure Predominant.

2) Platooning absolutely requires Vehicle-to-vehicle Communication but is strongly related to Vehicle-to-infrastructure Communication. The Free-agent policy is strongly related to both Vehicle-to-vehicle Communication and Vehicle-to-infrastructure Communication. Gap management absolutely requires Vehicle-to-infrastructure Communication. The Slotting policy absolutely requires Vehicle-to-infrastructure Communication but is weakly related to Vehicle-to-vehicle Communication.

3) All five solutions are independent of the Roadway Interface solutions.

4) All the solutions for the Obstacle Response policy for sensing and avoidance, including sensing, prevention, avoidance, and response, are absolutely required. The requirements on these solutions are more stringent for Platooning and Platooning with Gap Management due to the hazard involved in a collision between a platoon with an obstacle. The response to a detected obstacle under either of these two policies may include "coordinated braking", in which the lead vehicle may delay its braking to ensure minimal likelihood of intra-platoon collisions. Under Slotting, obstacle detection and response heavily involves the roadside intelligence.

5) Both Platooning and Platooning with Gap Management are weakly correlated with the solution of One Vehicle Class for the Concept Characteristic of Vehicle Classes in a Lane. This is because accommodating multiple vehicle classes in a lane makes grouping of vehicles of a common type more difficult. The Free-agent and the Free-agent with Gap Management policies are independent of Vehicle Classes in a Lane. Slotting is at least weakly related to the solution of One Vehicle Class.

6) The solutions associated with the concept characteristic of Mixed Traffic Capability include segregation (physical isolation) of automated traffic from manual traffic ("segregation" for short), non-segregated AHS but dedicated AHS lane ("dedicated lane" for short) and mixing automated vehicles with manually driven vehicles in the same lane ("mixing in lane" for short).

All five solutions are weakly correlated with Segregation because accidents spilling into the automated lane of a non-segregated AHS have been shown to create significant safety hazards. This is under the assumptions that such spill-overs are not detected by the automated vehicles, not to mention collision avoidance, and that no safe driver intervention is possible. (Compared to Platooning and Platooning with Gap Management, the correlation between the Free-agent/Free-agent with Gap Management policies and segregation may be somewhat weaker because, with larger spacings typical of the Free-agent and Free-agent with Gap

Management policies, drivers may serve as sensors and may be able to intervene more safely than they may under Platooning or Platooning with Gap Management.)

Slotting absolutely requires Dedicated Lane because it is very unsafe to mix automated vehicles with manually driven vehicles without sophisticated vehicle intelligence/sensing/processing. All other policies are strongly correlated with Dedicated Lane in that without lane dedication (i.e. mixing in lane) safe automation requires much more sophisticated technologies. Also, without lane dedication, an automated vehicle can join a platoon only if at least one of its two longitudinally adjacent vehicles is also automated. Platooning in such a mixed traffic has been referred to as Spontaneous Platooning. As pointed out earlier, the longitudinal separation between an automated vehicle and a manually driven vehicle is addressed in more detail in the Concept Characteristic of Mixed Traffic Capability.

7) All five solutions are independent of the Lateral Control Approach.

8) Due to the short intra-platoon spacings, both Platooning and Platooning with Gap Management absolutely require those approaches that include vehicle-to-vehicle communication system capable of transferring reasonably high bandwidth control information (in the range of kilobytes per second) and ranging sensors with accuracy of several centimeters within the range of a few meters, and very fast and precise throttle and brake control actuators. The Free-agent policy is weakly related to both the Vehicle-following and Point-following longitudinal control technologies. The Free-agent with Gap Management policy needs additional infrastructure intelligence. Slotting absolutely requires the Point-following longitudinal control technologies.

9) Platooning and Platooning with Gap Management are weakly related to the solution of Platooned Entry, either through a Transition lane or a Dedicated Station, for the Concept Characteristic of Entry/Exit. With the longitudinal separation policy of Platooning or Platooning with Gap Management, entering vehicles can form a platoon first before entering the automated

lane. By the same token, exiting vehicles can exit the automated lane in a group, as long as they have the same destination.

Free-agent, Free-Agent with Gap Management, and Slotting policies are independent of all the Entry/Exit solutions.

10) All five longitudinal separation policies are independent of the Lane Width Capability.

11) Although the actual separation under all five policies may be dependent upon the actual operating speed, all of them are independent of the design speed.

2.4 ROADWAY INTERFACE

2.4.1 Description of the Characteristic

The two core physical components of an Automated Highway System (AHS) are the vehicle and the roadway. The concept characteristic, Roadway Interface, designates the linkage or the connection between these two core components.

2.4.2 Description of all Realistic Solutions

Solutions to the vehicle/roadway interface characteristic depict the extent of interaction between the vehicle and the roadway. First order solutions for this characteristic consist of the following:

- 1) standard or normal interface
- 2) pallet
- 3) RPEV (roadway-powered electric vehicle)

2.4.2.1. Basic description

This section gives a brief description of each of the three vehicle/roadway interface characteristic solutions.

Standard or normal interface

The standard or normal interface simply consists of the vehicle tires on the roadway surface.

Pallet interface

The pallet interface consists of the vehicle attached to a pallet which would operate on

the AHS roadway. The pallet could be sized for a single-vehicle or multi-vehicle configuration. A second order roadway interface, namely, the interaction between the roadway and the pallet system could be the standard interface of the pallet's tires on the roadway.

RPEV interface

The roadway-powered electric vehicle is an electric-electric hybrid vehicle. It has two power sources, both of whom are electric, the on-board battery and the inductive coupling system (ICS). The ICS consists of the roadway inductor, buried just beneath the road surface, and the pickup inductor, mounted on the underside of the vehicle. The coupling consists of the inductive power transfer from the roadway inductor to the pickup inductor. No physical contact exists between these two inductors. The on-board battery can store power emanating from (a) a conventional wall-outlet, for example, while the battery is being recharged overnight, (b) the ICS, as excess power during dynamic roadway charging, or (c) the ICS, as static roadway recharging, while the vehicle is parked over a roadway inductor segment. In addition to the roadway and pickup inductor, other RPEV system components include the distribution links to the electric utility grid, power conditioner located near the roadway, distribution network that carries power from the power conditioner to the roadway, onboard controller, onboard battery, motor controller, and electric drivetrain.

Energy from electrified roadway charging during driving may go directly to the onboard motor controller, and then to the motor. When the vehicle motive requirement is less than the power drawn from the roadway, the excess power would be directed to the onboard battery for later use. The amount of battery recharging from the roadway changes from day to day, as well as by time of day, by vehicle characteristics, and by driving cycle.

One desirable feature of RPEVs is that the electrified roadway can be shared by electric and non-electric vehicles. That is, nothing about the technology precludes the shared use of the roadway by RPEVs as well as non-RPEVs.

Roadway electrification, while being considered here as a solution to the vehicle/roadway interface characteristic, is more fundamentally an alternative means of propulsion that also requires an additional vehicle/roadway interface, namely, the ICS, relative to the standard interface. For RPEV there are thus, actually two types of interaction between the vehicle and the roadway. One interaction is the standard interface of the vehicle tires on the roadway surface; the second interaction, which does not involve any physical connection, is the inductive coupling system (ICS) consisting of the transfer of power from the roadway inductor to the pickup inductor.

In essence then this solution set is really a combination of two non-mutually exclusive characteristics, one being the vehicle/roadway interface and the second being the power source. This mixing allows the formation of the following additional solution alternatives:

(1) + (3) = hybrid vehicle powered by both an internal combustion engine (ICE) and roadway power. The interface is the standard one when power is drawn from the ICE and the pickup inductor is in its retracted position and is the ICS when power is drawn from the roadway.

(2) + (3) = roadway-powered pallet system in which the pallet interfaces with the roadway via its tires as well as the ICS.

Focus will be placed on the first three "pure" characteristic solutions.

2.4.2.2. Comparison of solutions

The comparison among the three alternative solutions is accomplished in two stages. Since the difference between the RPEV solution and the standard interface is the alternative means of propulsion associated with RPEV, the first comparison is made of RPEV relative to the standard interface concentrating on the additional features associated with or required of an RPEV. The second comparison will be made of the pallet alternative relative to both the standard and the RPEV solution. A more complete discussion of the alternative solutions follows.

Standard interface vs. RPEV

As indicated above, the core difference between the standard interface and roadway-powered electrification is that an RPEV is an alternative propulsion vehicle and it adds a second vehicle/roadway interface to the standard or normal one. It is assumed that the means of propulsion used relative to the standard or normal interface is the usual or standard internal combustion engine vehicle (ICEV).

The potential primary advantages/strengths of roadway electrification (AHS) over the standard interface/ICEV-AHS is the possibility for:

- obtaining environmental benefits beyond those that could be obtained by AHS alone
- providing support for sustainable transportation policies
- greater reliability of RPEVs over ICEVs in certain respects and resulting impact on maintenance requirements
- ability of magnetic field generated by inductive power transfer to form a good position reference for a steering control system; this would help keep the vehicle more directly above the centerline of the lane to received the maximum amount of power transfer.

Environmental benefits would be reductions in pollution and decreases in usage of certain fuels (petroleum-based). Whether such benefits are realized and the extent of the benefit is dependent on site as well as on several factors such as primary fuel source for generating the electricity used to power the RPEVs and user acceptance/market penetration.

The potential drawbacks/weaknesses associated with RPEVs compared to ICEVs are in the areas of:

- environmental concerns (EMF, acoustic noise, and battery disposal)
- cost/financing/ability-to-pay issues associated with building up of an electric vehicle market in addition to an AHS-market.
- ensuring deployability (user acceptance/market penetration)

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- operation in inclement weather conditions (snow or ice)
- roadway inductors not likely to be present for entire length of AHS lane (cost reasons), and so would not provide lateral control for the entire trip length on the AHS. While AHS (non-RPEV) lateral control system can be used to track the vehicle to help insure that it closely lines up with the roadway inductor to maximize inductor power transfer, could have compatibility problems between AHS lateral control system and roadway inductor if lateral control solution is primarily infrastructure based.

Regarding deployability, the electric vehicle market may blossom in certain parts of the country, e.g., California or the Northeast, yet generate little if any interest in other parts of the nation. AHS would have to be flexible enough to accommodate both. As indicated above, an attractive RPEV feature is that the electrified roadway can be shared by electric and non-electric vehicles, i.e., no technological reason precludes the shared use of the roadway by RPEVs (AHS) as well as non-RPEVs (AHS).

Pallet interface vs. standard

The core difference between the pallet system and either the standard interface or the RPEV interface is the fact that the traveling unit is no longer the usual vehicle, but the pallet.

The primary advantage of the pallet system is its potential to provide much wider access to the AHS than with the use of standard vehicles. No retrofitting or purchasing of a new AHS-ready vehicle would be necessary, so everyone could potentially access the system. To use the system, however, would require some fee. The primary disadvantage of the pallet system is that it would require additional space, time, and facilities for storage, loading, unloading, and circulation throughout the AHS system. This difference is an important disadvantage relative to the standard or RPEV solution. A more complete set of strengths and weaknesses are provided as follows:

The potential advantages/strengths of the pallet-based system over the standard interface is the possibility for:

- safety-related benefits could accrue: improved control over system design could increase similarity/consistency/uniformity of traveling units and their operating characteristics; improved control over traveling unit maintenance would reduce likelihood of degraded performance, reduced interruption due to automatic check-in and -out being handled off-line; virtual elimination of problem of transferring control to the human operator, as transfer would be conducted under stopped conditions
- ease of use (no manual-to-automated-to-manual transfer in motion)
- universal access — all potential AHS users can access a pallet based system with their existing vehicles; pallet, not the vehicle attached to the pallet that would have to be AHS-equipped; a substantial social equity advantage over possibly requiring expensive equipment on-board the vehicle. Would possibly substitute a pay-as-you-use or rent-a-pallet system for purchasing an AHS-vehicle up front
- would immediately be a high number of “AHS-ready-and-capable” vehicles, i.e. no need to wait for uncertain rates of market penetration development, and construction of pallets is still necessary and depends on market demand, but sharing of pallets among users eliminates the 1-to-1 correspondence between users of system and AHS-traveling units
- pallets would provide a portable AHS technology, pallets could be moved from one location to another
- high utilization factor (assisted by sharing of pallets by users) should justify better and more robust AHS features than an occasionally used, private AHS vehicle
- use of pallet system owned and maintained pallets should yield safer and better maintained AHS traveling units
- pallet-based system could be dedicated to using alternative/cleaner fuels even

when the vehicles being carried are still ICEVs

- could be valuable in applications where it is desirable to prevent potential driver intervention or tampering

The potential drawbacks/weaknesses associated with pallets compared to the standard interface are in the areas of:

- heavy consumer of land space for storage and performing entry/exit functions
- delays at entry/exit points due to load, attach, detach, unload, and circulate activities of vehicles would lead to bottlenecks and problems to achieve and maintain desired level of throughput, mobility, and convenience
- vehicle-pallet attachment could affect comfort of ride, especially at high speeds
- storing and maintaining a large pallet inventory (of different size pallets!) as well as recirculating empty pallets will be a complex logistical endeavor, made more complex for rural application because of longer trip lengths associated with such driving
- concentrate equipment investment costs and liability onto the pallet system entity/authority
- probably use more energy for a given trip than the vehicle being carried; significant volume of deadhead (empty) return trips complete waste of energy
- vehicle/pallet combination traveling unit heavier than vehicle alone and have a higher center of gravity, which would tend to make traveling unit less stable in lateral maneuvers
- emergency handling would have very complex logistics--could have stranded vehicle-carrying pallets on highway; if vehicle has way to remotely control pallet during emergencies (to move pallet) then this could detract from universal access aspect; alternatively, mechanism for manually detaching and unloading vehicle from pallet could help, but still must contend with

stranded pallets on highway as well as driving around them

- ability to operate in partially automated mode with non-AHS vehicles could be very complex logistically
- added logistical complexities associated with non-uniform pallet sizes

An RPEV pallet-based system would combine the strengths and weaknesses outlined above for RPEV systems with those of the "pure" pallet system just described.

2.4.3 Evaluation of Solutions to Concept Characteristics

The three solutions to the vehicle/roadway interface characteristic are evaluated with respect to the following three sets of evaluation criteria: (1) AHS Objectives and Characteristics as detailed in the Automated Highway Systems (AHS) System Objectives and Characteristics 2nd Draft (May 22, 1995), (2) Baseline Functions listed in the Concept Development and Analysis Guidelines, and (3) example uses for an AHS as listed in Table 2-1 of the AHS System Objectives and Characteristics document. At this initial stage in the development of AHS concepts, i.e. individual characteristics not yet integrated with each other to form whole concepts, only a ranking of each solution relative to other solutions will be meaningful. In particular, since the pallet and RPEV solutions are the unusual or different solutions compared to the standard or normal vehicle/roadway interface, the ranking for the standard interface will be given a "5" unless otherwise ranked. Rankings given as a range instead of a single value was necessary when both advantages and disadvantages were present and no available and confident means to quantify the tradeoffs among them.

2.4.3.1. Evaluation relative to AHS objectives and characteristics

The three vehicle/roadway interface characteristics are evaluated against the twenty-three AHS objectives and characteristics and in relative terms with respect to each other.

2. Concept Characteristics

Improve safety

	Ranking
Standard	5
Pallet	7
RPEV	5

The use of an AHS with pallets would cause a shift of safety management from individual vehicles to the infrastructure. Several benefits could accrue: (1) improved control over system design could increase similarity/consistency of vehicles (i.e. traveling units) and their operating characteristics, (2) improved control over vehicle/traveling unit maintenance would reduce the likelihood of degraded performance, reduced interruption due to ACI/ACO being handled off-line, and (3) virtual elimination of the problem of transferring control to the human operator, as transfer would be under stopped conditions. Because of improved control over the designed-in capabilities, maintenance, and check-out of the critical on-board AHS systems, pallets should result in a net increase in safety over the standard interface. The pallet, however, could be more susceptible to breakdowns if it were to have more mechanical equipment than the standard interface. Roadway electrification would be rated the same as the standard interface. The concern that an RPEV would run out of battery power to complete its trip, thus, causing an added safety hazard on the AHS could be addressed during the check-in procedure, as the RPEV would be allowed to enter the AHS only if the vehicle had enough battery power to complete its trip. If the on-board battery was at too low a charge state, the vehicle would be denied access to the AHS.

Increase throughput

	Ranking
Standard	5
Pallet	2
RPEV	5

Roadway electrification would be rated the same as the standard interface. The pallet alternative is rated substantially below the

standard because there could be significant entry-exit issues that could lead to bottlenecks and problems to achieve and maintain the desired increased level of throughput. Entry/exit issues are where and how pallets would be loaded, unloaded, and circulated throughout the AHS system.

Enhance mobility

	Ranking
Standard	5
Pallet	2
RPEV	5

There should be no constraint on the Rev's ability to enhance mobility relative to the standard interface. The pallet alternative is rated substantially below the standard because there could be significant entry-exit issues that could lead to bottlenecks and problems to achieve and maintain the desired enhanced level of mobility, specifically, shorter and predictable travel times. Entry/exit issues are where and how pallets would be loaded, unloaded, and circulated throughout the AHS system.

More convenience and comfort

	Ranking
Standard	5
Pallet	4
RPEV	5

There should be no constraint on the Rev's ability to provide comfort and convenience relative to the standard interface. Comfort could be slightly less in the pallet case depending on the exact nature of the vehicle-pallet attachment. Moreover, convenience could suffer due to potential delays at entry/exit points as discussed above.

Reduce environmental impact

	Ranking
Standard	5
Pallet	3-7
RPEV	8

The areas of environmental impact that need to be considered are (1) pollution, (2) fossil fuel usage, (3) electromagnetic field (EMF)

exposure, (4) acoustic noise levels, and (5) battery disposal.

Emissions—Relative to an ICE (standard interface), considering only vehicle-source emissions, an RPEV's emissions are extremely low, basically a zero-emission vehicle, on a gram per kilometer basis. One has to take into account, however, contributing stationary-source emissions as well to develop a more complete emissions picture, i.e. contributing stationary-source emissions for both the RPEV and the ICEV. While it is much easier to monitor and control the emissions of relatively few power plants compared to millions of ICEVs, the fuel source at the power plants will play a significant role in determining the overall emissions picture for an RPEV. A power plant using coal or oil to fuel it will emit substantially higher pollution levels than a natural gas-fueled power plant. For the PATH-SCAG study (1989-1992) investigating the emissions and utility industry impacts of roadway electrification in which roadway electrification was deployed on a subset of the Los Angeles metropolitan area freeway system, it was assumed that natural gas would be the fuel source for over 80% of electricity-generated for Southern California in the year 2025. The result was a moderate reduction in emissions across all major pollutants (hydrocarbons, carbon monoxide, nitrogen oxides, sulfur oxides, and particulate matter). Further research is required to account for the variation in powerplant fuel sources in order to determine with more certainty the extent of the emissions reductions associated with RPEV.

Fossil Fuel Consumption—Fossil fuel usage depends primarily on the fuel source used in the electric power plant. In the case study cited above with natural gas providing over 80% of the fuel source for the electricity generated for the SCAG region, the net impact on fuel usage was that petroleum consumption decreased moderately, whereas natural gas usage increased more substantially. The reduction in petroleum-based fuels helps reduce the U.S.'s dependence on foreign sources of these fuels.

Electromagnetic Fields—While tests conducted during the PATH/SCAG research effort, however, provide evidence that RPEVs are EMF safe, more EMF exposure research and its biological impacts on humans is needed. There is no irrefutable proof either way that EMF is safe or causes harm.

Tests were performed on the roadway powered bus at Richmond Field Station (RFS) at U.C. Berkeley. The strength of the magnetic field through which the ICS transfers power from the roadway to the vehicle varies depending on roadway current and distance from the roadway centerline. EMF measurements were studied from both static and dynamic testing of the PATH roadway powered bus and conventional vehicles on the Richmond Field Station test track.

Test results from the PATH bus and conventional vehicle powered roadway experiments indicated that in a unshielded situation, the magnetic flux density (the measure of EMF strength) was 300 milligauss (mG), and 1.5 to 3.0 mG for a shielded position for a 240 amp roadway. These measurements were taken at 40 inches above the roadway to approximate the EMF exposure at the driver's position in the vehicles. Shielded test findings indicated lower EMF exposure for the roadway powered vehicle since the magnetic field passes through the pick-up unit in an RPEV whereas it passes through the steel chassis in a conventional vehicle.

To put these powered roadway EMF readings in perspective, the magnetic flux density for several electrical appliances and electrical power delivery by field strength and degree of EMF exposure (in mG), are compared to both the shielded and unshielded powered roadway cases. The results indicate that for an electric shaver, electric blanket, toaster, transmission line at 115-230 kv, and the center of a living room, the EMF exposures are respectively 1,000-10,000 mG, 75-150 mG, 75-150 mG, 10-100 mG, and 0.5-10 mG. Unshielded and shielded conditions on the powered roadway yield approximately 200-800 mG and 1-5 mG, respectively. The unshielded situation

is one in which a human being is exposed to the magnetic field directly without the normal shielding offered inside the vehicle by the steel of the pickup inductor or the vehicle floor and sides. The RPEV estimates of EMF were also found to be significantly below the standards for EMF exposure set by the International Radiation Protection Association (IRPA) and the International Non-Ionizing Radiation Committee (INIRC). Thus, at this time evidence regarding EMF exposure with respect to the powered roadway suggests that there is little need for environmental concern.

Acoustic Noise—As in case of emissions, fuel usage, and EMF, more work is needed in the area of acoustic noise impacts. Acoustic noise levels were investigated on the test track for the roadway powered bus at RFS. In these tests, the interior noise level was found to be 40-45 decibels. Conventional vehicles of different makes and sizes were also examined for acoustic noise under test track driving conditions. For the conventional vehicles 40-70 decibel readings were experienced. To put this in perspective, a library has an acoustic noise level of approximately 35 decibels, an office - 65 decibels, a heavy truck - 90 decibels, a jack hammer - 105 decibels, and a jet plane - 125 decibels. Experts consider noise levels of 135 decibels to be painful to the ear. The acoustic noise measurements for conventional vehicles were considered high enough to warrant further testing of lower roadway currents and higher frequencies. The use of higher frequencies in the inductive coupling design would lower interior noise levels since it permits use of lower roadway currents, and humans are less sensitive to higher frequencies.

Battery Disposal—Whether lead acid or other batteries are utilized in RPEVs, increased unrecycled battery disposal is likely to produce more impacts on the environment. The concern for water quality that would be jeopardized by the increased likelihood of battery leach water in groundwater supplies warrants attention for

“cradle-to-grave” battery management. Similarly, incineration of lead waste products raises questions regarding air quality deterioration and associated health damages. Thus, it is important that behavior be reinforced towards participation in currently established recycling efforts to offset the potential for increased hazardous waste from illegal disposal of batteries.

The ranking for pallets vary depending on whether they are battery/roadway powered themselves or powered by an ICE. Thus, if roadway powered then the pallet would experience at least some of the environmental benefits as an RPEV. Pallets will, however, probably use more energy for a given trip than the vehicle being carried. Moreover, they may also have to make a significant number of trips empty, deadhead trips, which would be a complete waste of fuel/energy. There is also a tradeoff between energy use and the size of the available pallets. If pallets were available in all sizes (e.g., pallet platoons to hold from 1 to 15 vehicles) to meet the demands of any particular situation then this would make for very complex logistics. If, however, there were a “one size pallet fits all” then this would use more energy. That is, it is more energy efficient to have a 1-vehicle pallet transport 1 vehicle then for a 10-vehicle pallet to transport that single vehicle.

Operate in inclement weather

	Ranking
Standard	5
Pallet	4
RPEV	4

A potential problem area with RPEV is its ability to perform in bad weather, in particular, in snowy weather and its impact on the transfer of power from the roadway to the pickup inductor. A major question is how will snow affect power output? The complex logistics associated with entry/exit for pallets could be exacerbated during inclement weather, in particular during snowy conditions.

Ensure affordable cost & economic feasibility

	Ranking
Standard	5
Pallet	5?
RPEV	5?

A recent study of the regional impacts of roadway electrification (PATH/SCAG Study) included an economic analysis of RPEVs compared to their gasoline counterparts. Assumptions were made about the specifics of an RPEV scenario deployed on a subset of the freeway system in the metropolitan Los Angeles region in the year 2025. Baseline user cost comparisons of gasoline vehicles and RPEVs indicated that RPEVs may offer some economic advantage to users over the life of the vehicle if roadway infrastructure costs were subsidized. Of course, the capital costs associated with the roadway infrastructure modifications associated with implementing the technology could be sizeable. Recent Precursor Systems Analysis (PSA) estimates are in the range of \$500 thousand-\$1.5 million per lane mile. Much further work is necessary in this area. No cost analysis was performed on pallet-based AHS systems in the PSA set of projects. While the pallet-based scenario developed in the PSA research envisioned the pallet as the traveling unit, thus, no changes necessary to any vehicle, there would likely be pay-as-you-use costs associated with the pallet-based systems. This whole area requires much further research.

Beneficial effect on conventional roadways

	Ranking
Standard	5
Pallet	3
RPEV	5

There should be no constraint on the RPEV's ability to support a beneficial effect on conventional roadways adjacent to the AHS facility compared to the standard interface. A pallet-based system will likely be a heavy consumer of land space adjacent to entry/exit points to the AHS facility for

storage and for achieving the entry and exit functions. This effect of pallet-based systems would likely have a detrimental impact on conventional roadways.

Easy to use

	Ranking
Standard	5
Pallet	3-7
RPEV	5

There should be no constraint on the RPEV's ability to support an easy-to-use system compared to the standard interface. In some respects, the pallet-based system will be much easier to use than the standard vehicle/roadway interface, since the driver does not have to worry about any transition from manual to automated and back again while the vehicle is in motion. Performing entry and exit functions could involve complex logistics and detract from ease of use. In circumstances of extreme malfunction, the pallets could become stranded on the highway waiting for external assistance for egress from the AHS (See Disengage the Driver from Driving category below) unless there were a way for the driver to manually unload the vehicle from the pallet and drive away manually. Of course, even under such circumstances, working one's way through the obstacle course of stranded pallets would be a challenge.

Infrastructure compatible

	Ranking
Standard	5
Pallet	5
RPEV	5

No differences among the three solutions is apparent at this time relative to the criteria of infrastructure compatibility.

Facilitate intermodal/multimodal transportation

	Ranking
Standard	5
Pallet	4
RPEV	5

There should be no constraint on the RPEV's ability to facilitate intermodal/multimodal transportation relative to the standard interface. The more that pallets (whether ICEV or RPEV based) support vehicles of different classes, the more complex the logistics become (See discussion in the following categories: Reduce Environmental Impact, Support TDM Policies, Support Wide Range of Vehicle Types, Enhance Operations for Freight Carriers, and Support Automated Transit Operations).

Ensure deployability

	Ranking
Standard	5
Pallet	4-6
RPEV	4

The chicken-or-the-egg problem concerning the linkages between market penetration and available AHS-ready vehicles is exacerbated in the case of RPEV since now the linkage also includes building up of an electric vehicle market (public acceptance). With respect to pallets there is universal access as all potential AHS users would be able to access a pallet based system with their existing vehicles. There would immediately be a high number of AHS-ready-and-capable vehicles without having the need to wait for uncertain rates of market penetration. Development and construction of pallets is still necessary and depends on market demand, but sharing of pallets among users eliminates the 1-to-1 correspondence between users of system and AHS-traveling units. There would, however, be issues associated with partially automated pallet based systems that would be necessary in the early stages of deployment (See Operate in Mixed Traffic with Non-AHS Vehicles category below).

Provide high availability

	Ranking
Standard	5
Pallet	3
RPEV	5

There should be no constraint on the RPEV's ability to provide high availability relative to the standard interface. For pallets, under the universal access assumption that there would be no mechanism for transferring control from the pallet to the "on-board" vehicle, access to emergency vehicles and accommodation of rapid removal of disabled vehicles from the traffic stream would be made much more difficult a task.

Apply to rural roadways

	Ranking
Standard	5
Pallet	2
RPEV	5

There should be no constraint on the RPEV's ability to support the application of AHS to rural roadways relative to the standard interface, except that the longer distances associated with rural driving would require more capital outlay for roadway modifications. Relative to the standard interface, pallets would likely exhibit an inferior performance. The longer distances associated with rural roadway driving would tend to exacerbate the dead-head or empty-pallet-return-trip event. Some of this empty trip problem could be remedied through extensive coordination of regional or state trips. Moreover, since commercial vehicles are major users of rural roadways, especially the interstates, the complexity associated with adapting pallets to such large vehicles as heavy-duty trucks would be exhibited here too (See Support Wide Range of Vehicle Classes category below). The issues associated with partially automated lanes and use of pallets would also be present here as well (See Operate in Mixed Traffic with Non-AHS Vehicles category below).

Disengage the driver from driving

	Ranking
Standard	5
Pallet	3
RPEV	5

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There should be no constraint on the RPEV's ability to support the driver disengagement feature of an AHS relative to the standard interface. PSA pallet research developed a scenario in which there would be no transfer from manual to automated control and back again as in the case of the standard interface. Either the pallet would not be moving, e.g., during vehicle/pallet loading/unloading procedures, or it is moving, yet always under AHS/pallet system control. This situation would make for a safer environment than the standard interface in non-emergency situations, and truly the driver would be disengaged from the driving task. However, during emergency conditions when automated control is stopped, how would the vehicle/pallet get off the AHS unless there were some mechanism for transferring control of the pallet to the driver of the vehicle or some means to insure that the driver could manually unload the vehicle from the pallet and drive away? Communication between the driver/vehicle and the pallet or the pallet authority would also be crucial. The addition of such vehicle capabilities then puts limits on the universal access feature of the pallet technology. Having all control in the pallet means that any vehicle would be able to use the AHS since there would then be no need for any retrofitting of existing vehicles or purchasing of new AHS-ready vehicles. There is thus, a tradeoff between degree of access and ability to resume control during emergency situations.

Support TDM policies

	Ranking
Standard	5
Pallet	4
RPEV	5

There should be no constraint on the RPEV's ability to support TDM policies relative to the standard interface. Ensuring pallets of varying sizes to accommodate and enhance transit use would make pallet logistics more complex not because of the need for a large pallet but for the need for non-uniformity in pallet sizes.

Support sustainable transportation policies

	Ranking
Standard	5
Pallet	3-5
RPEV	6-7

RPEV may have advantages over the standard vehicle/roadway interface in the areas of its ability to support deployments that have long-term sustainable impacts on resources and the environment, compatible with policies to couple AHS with programs that encourage fuel efficiency and renewable energy technologies, implementing AHS on advanced propulsion system vehicles first, and emphasizing AHS support for public transportation. Pallet-based systems may also experience these benefits if they were roadway powered instead of ICEVs. However, another aspect of showing support for sustainable transportation systems is its ability not to lead to increased congestion and traffic burden in neighborhoods adjacent to entry and exit points to/from the AHS facility. Pallet-based systems would likely have difficulty in this area as such systems would be a heavy consumer of land space adjacent to entry/exit points for storage and for achieving such entry and exit functions (See Beneficial Effect on Conventional Roadways).

Provide flexibility

	Ranking
Standard	5
Pallet	5
RPEV	5

No differences among the three solutions is apparent at this time relative to the criteria of flexibility. The choice to use roadway electrification may be very site-dependent, yet the technology is flexible enough to allow non-RPEVs to travel on roadway electrified lanes. Given that the system consists of an RPEV/AHS and given that a particular region or state chooses to implement this system, neither of the three solutions exhibits any flexibility advantage or disadvantage over the other two solutions.

Operate in mixed traffic with non-AHS vehicles

	Ranking
Standard	5
Pallet	3
RPEV	5

One desirable feature of RPEVs is that the electrified roadway can be shared by electric and non-electric vehicles. That is, nothing about the technology precludes the shared use of the roadway by RPEVs as well as non-RPEVs. The vehicles operating in at least partially automated mode are assumed to nevertheless be traveling under roadway power. The mixing of vehicle-carrying pallets with ordinary vehicles again seems to make an already complex logistical situation more complex. Fully automated pallets would be driverless, whereas partially automated pallets would place more control with the driver of the vehicle being carried. Exclusive entry/exit facilities with barriers between the automated lane and conventional lanes for fully automated pallets have been suggested to avoid having vehicle-carrying pallets needing to weave through conventional traffic to access the automated lane, and generally make entry and exit simpler. With a partially automated pallet, how would entry/exit be handled? The same as before? That would mean that conventional vehicles sharing the automated lane would be completely separated from their counterparts on fully conventional lanes. Should partially automated vehicle-carrying pallets be allowed to weave through conventional lanes for automated lane access? such complex logistics and tradeoffs need to be thoroughly understood and evaluated.

Support wide range of vehicle classes

	Ranking
Standard	5
Pallet	4
RPEV	5

There should be no constraint on the RPEV's ability to support a range of vehicle classes relative to the standard interface. While certain types of freight and cargo may

be carried in light-duty vans and light-duty trucks which are comparable to standard-sized passenger vehicles, the already complex logistics associated with pallets could be made substantially more complex when associated with the largest of the heavy duty vehicles, such as 18-wheelers. The tendency for more complex logistics is not necessarily associated with the size of the vehicle, but the non-uniformity in the size of the vehicles that require pallets, as pallets of various sizes must be available as demanded.

Enhance operations for freight carriers

	Ranking
Standard	5
Pallet	4
RPEV	5

There should be no constraint on the RPEV's ability to support freight carrier operations relative to the standard interface. While certain types of freight and cargo may be carried in light-duty vans and light-duty trucks which are comparable to standard-sized passenger vehicles, the already complex logistics associated with pallets could be made substantially more complex when associated with heavy duty vehicles, such as 18-wheelers. The tendency for more complex logistics is not necessarily associated with the size of the vehicle, but the non-uniformity in the size of the vehicles that require pallets as pallets of various sizes must be available as demanded.

Support automated transit operations

	Ranking
Standard	5
Pallet	4
RPEV	5

There should be no constraint on the RPEV's ability to support automated transit operations relative to the standard interface. The already complex logistics associated with pallets could be made more complex when associated with larger vehicles such as buses, although the number of entry/exit points for buses that service freeways would tend to be considerably fewer than ordinary

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passenger vehicles and this would help simplify pallet logistics. The tendency for more complex logistics is not necessarily associated with the size of the vehicle, but the non-uniformity in the size of the vehicles that require pallets as pallets of various sizes must be available on demand.

Provide system modularity

	Ranking
Standard	5
Pallet	5
RPEV	5

No differences among the three solutions is apparent at this time relative to the criteria of system modularity.

2.4.3.2. Evaluation relative to baseline functions

The three vehicle/roadway interface characteristics are evaluated relative to the list of Baseline functions given in the Concept Development and Analysis Guidelines.

Check-in

	Ranking
Standard	5
Pallet	8
RPEV	5

The check-in procedure for RPEV will be only slightly more detailed than for the standard interface, as the RPEV would be allowed to enter the AHS only if the vehicle had enough battery power to complete its trip. If the on-board battery was at too low a charge state, which would be measured upon check-in, the vehicle would be denied access to the AHS. Check-in requirements for pallets would be reduced substantially relative to the standard interface as the vehicle is not checked-in, the pallet is; and the pallet would always be under automatic control. Check-in would be handled off-line, i.e. the pallet is checked-in while in a stationary position.

Transition from manual to automatic control

	Ranking
Standard	5
Pallet	8
RPEV	5

The RPEV's ability to transition from manual to automatic control should be comparable to that of the standard interface. The pallet would always be under automatic control, either in a stationary position or in motion. The pallet moves after the vehicle is loaded, attached, and locked into position on the pallet off the AHS facility in a pallet attach area adjacent to the entry/exit area. The vehicle/pallet unit would not be in motion during this transfer. This would be safer than for the standard interface.

Automated driving: sensing of roadway, vehicles, obstructions

	Ranking
Standard	5
Pallet	5
RPEV	5

No differences among the three solutions is apparent at this time relative to the baseline function of sensing.

Automated driving: hazard detection

	Ranking
Standard	5
Pallet	5
RPEV	5

The RPEV must be aware of more potential hazards on the road than in the standard case, e.g., deep snow or ice over the roadway inductor. Its ability to detect these additional hazards should not be any less than for the standard interface. No differences between the pallet solution either is apparent at this time relative to the baseline function of hazard detection.

Automated driving: maneuver planning and execution

	Ranking
Standard	5
Pallet	4
RPEV	5

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The RPEV's ability to perform maneuver planning and execution should be comparable to that of the standard interface. The pallet-based system could find it more difficult as it has to perform such functions for a pallet+vehicle(s) system, not just a vehicle(s).

Transition from automatic to manual control

	Ranking
Standard	5
Pallet	8
RPEV	5

The RPEV's ability to transition from automatic to manual control should be comparable to that of the standard interface. The pallet would always be under automatic control while in motion. After the pallet is brought to rest, the vehicle(s) is(are) unlocked, detached, and unloaded. This activity is performed off the AHS facility in a pallet detach area adjacent to the entry/exit area. This would be safer than for the standard interface.

Check-out

	Ranking
Standard	5
Pallet	8
RPEV	5

The check-out procedure for RPEV should be comparable to the standard interface, as the RPEV would have been queried about its available battery power during check-in. Check-out requirements for pallets would be reduced substantially relative to the standard interface as the vehicle is not checked-out, the pallet is; and the pallet would always be under automatic control. Check-out would be handled off-line, while the pallet is in a stationary position.

Flow control

	Ranking
Standard	5
Pallet	4
RPEV	5

The RPEV's ability to perform flow control should be comparable to that of the standard interface. The pallet-based system could find it more difficult as it has to perform such functions for a pallet+vehicle(s) system, not just a vehicle(s).

Malfunction management

	Ranking
Standard	5
Pallet	7
RPEV	6-7

For RPEVs there certainly would be additional items to manage under malfunction conditions compared to the standard interface situation, such as the roadway inductor or the pickup inductor. However, the RPEV would obtain access to the AHS facility upon check-in only after the system verified that the on-board battery had sufficient power to complete the entire trip. The RPEV is an electric vehicle, however, and EVs are considered more reliable than ICEVs in numerous respects because they contain fewer components and require less maintenance. There are advantages and disadvantages of pallets over the standard interface with respect to the criteria of malfunction management. Advantages include (1) control of pallet maintenance by a central authority results in better maintained pallet compared to a privately owned AHS vehicle (standard interface), (2) higher utilization of the pallet compared to a private AHS vehicles allows greater investment in each pallet (i.e. one can afford more redundancy and/or more expensive/higher reliability systems), and (3) because pallets only operate on the AHS, they can be optimized for that environment. Disadvantages include (1) higher center of gravity which likely results in a less stable "traveling unit", i.e. vehicle-pallet, (2) additional functions (e.g., vehicle load/unload and associated facilities, vehicle lockdown on the pallet, etc.) that are pallet-unique provide additional opportunities for malfunctions, and (3) there will probably be a need for additional response teams to recover pallets with minor malfunctions. On the whole picture, advantages likely outweigh disadvantages. Other advantages would be associated with the pallets if they were RPEV as well.

Emergency handling

	Ranking
Standard	5
Pallet	3
RPEV	5

The RPEV solution may encounter additional situations of an emergency type that would not ordinarily be encountered by the standard interface, e.g., a large scale electrolyte spill from the battery, but its ability to perform emergency handling should not be inferior to that of the standard interface. For example, if automated control should temporarily cease as well as roadway power, then the RPEV should be able to egress from the AHS facility under manual control using its on-board battery for power, since permission to access the AHS facility was given only if the vehicle had sufficient battery power to complete its journey. Emergency handling for a pallet-based AHS is rated inferior to that of the standard interface solution. It is assumed that the pallets are driverless and that the on-board driver/vehicle would not gain control of the pallet. A shut down of the AHS facility would then result in stranded pallets with attached vehicles that would require some means of removal from the AHS facility unless there were available to the driver the means through which he/she could manually unload the vehicle from the pallet and drive away. There would still be the gauntlet of stranded pallets around which the vehicles would have to maneuver. Major delays could be likely.

2.4.3.3. Evaluation relative to uses for an AHS

The three vehicle/roadway interface characteristics are evaluated relative to the list of example uses for an AHS listed in Table 2-1 of the AHS System Objectives and Characteristics.

Heavily congested urban highway

	Ranking
Standard	5
Pallet	3
RPEV	5

The RPEV's ability to support the use of AHS in a heavily congested urban highway environment should be comparable to that of the standard interface. The pallet-based system is rated inferior to that of the standard interface because of the very complex logistics at and near entry and exit facilities associated with loading, unloading, storing, and recirculating the pallet around urban area. Such disadvantages for the pallet would still exist even with an RPEV-based pallet. In addition, without exclusive entry and exit facilities, pallet-carrying vehicles would have to weave through ordinary conventional traffic streams which could pose additional problems. So the need for exclusive entry/exit facilities would require infrastructure modifications and possibly additional land.

Exclusive transit vehicle lanes

	Ranking
Standard	5
Pallet	3
RPEV	5

The RPEV's ability to support the use of AHS in an exclusive transit vehicle lane environment should be comparable to that of the standard interface. Generally, pallet-based systems should be able to support this use for an AHS, however, the process of loading, attaching, unloading, and detaching such a large vehicle as a bus could pose some logistics challenges. Issue of need for exclusive entry/exit facilities as in "Heavily Congested Urban Highway" use above is also issue here. Another issue making the logistics more complex is that of the short-haul/long-haul aspects of the bus trip. That is, the trip from origin to destination may include several short-haul runs along the route to pickup passengers. There could be bus stops on the highway (which would require infrastructure modifications to build) or the bus could exit the facility as needed to pickup passengers then get back on. This latter approach, however, would require entry/exit facilities at each of these points as well as having a bus-carrying pallet negotiate the arterial network to pickup passengers and return to the highway. Further research is needed to fully

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understand the complex logistics and tradeoffs associated with this scenario.

Only HOVs in rush hour

	Ranking
Standard	5
Pallet	3
RPEV	5

The RPEV's ability to support the use of AHS in an only HOV-in-rush-hour environment should be comparable to that of the standard interface. The same problems associated with the complex logistics of pallet-based systems described above in the "Exclusive Transit Vehicle Lanes" category are also present in this case with the additional issue of requiring pallets of different sizes (buses, vans, passenger vehicles) (See "Support Wide Range of Vehicle Classes" category) that could make already complex logistics associated with pallets substantially more complex when associated with the non-uniformity in the size of the vehicles that require pallets. Pallets of various sizes must be available as demanded.

Exclusive commercial vehicle lanes

	Ranking
Standard	5
Pallet	3
RPEV	5

The RPEV's ability to support the use of AHS in an exclusive commercial vehicle lane environment should be comparable to that of the standard interface. Generally, pallet-based systems should be able to support this use for an AHS, however, the process of loading, attaching, unloading, and detaching such a large vehicle as some heavy-duty trucks could pose some logistics challenges. Issue of need for exclusive entry/exit facilities as in "Heavily Congested Urban Highway" use above is also issue here. Docking facilities would require modifications for detachment and unloading of the vehicles from the pallets. The truck-carrying pallet would still have to travel from the highway exit to the docking facility through the arterial network. Further research is needed to fully understand the

complex logistics and tradeoffs associated with this scenario.

Sparse rural areas

	Ranking
Standard	5
Pallet	2
RPEV	5

There should be no constraint on the RPEV's ability to support the application of AHS to rural roadways relative to the standard interface except that the longer distances associate with rural driving would require more capital outlay for roadway modifications. Relative to the standard interface, pallets would likely exhibit an inferior performance. The longer distances associated with rural roadway driving would tend to exacerbate the dead-head or empty-pallet-return-trip event. Some of this empty trip problem could be remedied through extensive coordination of regional or state trips. Moreover, since truck traffic are major users of rural roadways (interstates) the complexity associated with adapting pallets to such large vehicles as heavy-duty trucks would be exhibited here too (See Support Wide Range of Vehicle Classes category below). The issues associated with partially automated lanes and use of pallets would also be present here as well (See Operate in Mixed Traffic with Non-AHS Vehicles category below).

Roadway-powered electric vehicle

	Ranking
Standard	1
Pallet	1
RPEV	10

This category is unusual since the category itself is identical with one of the solutions. Obviously, the RPEV gets the highest ranking for its own category. As previously discussed, another solution to this vehicle/roadway characteristic could be a hybrid case for both the vehicle as well as the pallet system, i.e. to use roadway power for a portion of their means of propulsion. In these cases, the rankings for both the standard and pallet solutions would be 10 if

roadway power is used for traveling on the AHS. Otherwise, the vehicle associated with the standard vehicle/roadway interface is assumed to be a “standard” internal combustion engine vehicle and so would earn the lowest ranking; and the pallet would be assumed not to be powered by roadway electrification and would also receive a ranking of 1.

2.4.4 Description of Correlation Between Solutions

The level of correlation and compatibility between each of the solutions for the vehicle/roadway interface with any of the suggested solutions listed in the Concept Development and Analysis Guidelines are listed below with justification and analysis. Values for the correlation levels are given, according to the guidelines as follows: AR (absolutely required), SR (strongly related), WR (weakly related), and I (independent).

2.4.4.1. Distribution of intelligence/sensing/processing

	Level of Correlation
Standard	SR-AR
Pallet	SR-AR
RPEV	SR-AR

Most important compatibility issue to consider is the additional complexity associated with the RPEV (vehicle or pallet) vis-à-vis the buried roadway inductor and also having intelligence embedded in the roadway infrastructure.

2.4.4.2. Communications

	Level of Correlation
Standard	SR-AR
Pallet	SR-AR
RPEV	SR-AR

No apparent incompatibility problems associated with any of the solutions to this characteristic. Communications between the vehicle and the roadway will make much stronger the ties between them.

2.4.4.3. Separation policy

	Level of Correlation
Standard	SR-AR
Pallet	SR-AR
RPEV	SR-AR

Pallets and platoons, while not necessarily incompatible, certainly make for more complex logistics as pallets of different, non-uniform lengths would be required to accommodate vehicle platoons of varying lengths. A single pallet long enough to accommodate the longest platoon of vehicles allowed would reduce the logistics issue but would use more energy (e.g., a fifteen vehicle pallet carrying a single vehicle).

2.4.4.4. Obstacle response policy

	Level of Correlation
Standard	SR-AR
Pallet	SR-AR
RPEV	SR-AR

Almost all suggested solutions are vehicle-based. Should probably speak more generally in terms of the traveling unit and not the vehicle, at least until pallets are eliminated from consideration for inclusion in AHS concept. For the pallet alternative, all such traveling unit-based solutions need to be pallet-based solutions instead of vehicle-based solutions.

2.4.4.5. Vehicle classes

	Level of Correlation
Standard	WR-I
Pallet	SR-AR
RPEV	SR-AR

Vehicles of different classes (passenger cars, vans, light-duty trucks, buses, heavy-duty trucks) are associated with vehicles of different sizes and the need for non-uniform size of pallets, again a more complex logistics scenario.

2. Concept Characteristics

2.4.4.6. Mixed traffic capability

Level of Correlation

Standard	WR-I
Pallet	SR
RPEV	SR

While there are no compatibility problems associated with RPEV, another mode is present to consider when studying the capability of mixed traffic travel. There is AHS/RPEV, non-AHS/RPEV, AHS/non-RPEV, and non-AHS/non-RPEV. Nothing in the roadway electrification technology precludes RPEVs and non-RPEVs from sharing the same lane. Mixing pallets and non-pallets (standard vehicles), however, has problems (See Operate in Mixed Traffic with Non-AHS Vehicles).

2.4.4.7. Lateral control

Level of Correlation

Standard	WR-I
Pallet	WR-I (ICE pallet) or SR-AR (roadway powered)
RPEV	SR-AR

The inductive coupling system can transfer the maximum current to the vehicle when the vehicle is properly centered above the roadway inductor. The magnetic field created by the roadway inductor is very strong and distinctively shaped. It forms a good position reference for a steering assistance or control system. This would help keep the vehicle more directly above the centerline of the lane to receive the maximum amount of power transfer. The roadway inductor, however, would likely not be present for the entire length of the AHS lane, and so it could not provide lateral control for the entire trip length on the AHS. Alternatively, the AHS (non-RPEV) lateral control system can be used to track the vehicle to help insure that it closely lines up with the roadway inductor to maximize inductor power transfer. If lateral control solution is primarily infrastructure based then potential conflicts between the two technologies using the same roadway need to be addressed. This subject needs to be more thoroughly investi-

gated as a means for automatic vehicle steering.

2.4.4.8. Longitudinal control

Level of Correlation

Standard	WR-I
Pallet	WR-I
RPEV	WR-I

No apparent compatibility problems associated with the three vehicle/roadway interface solutions (primarily vehicle-based). Such vehicle-based solutions would need integrating with the pallet for that solution.

2.4.4.9. Entry/exit

Level of Correlation

Standard	WR
Pallet	AR
RPEV	WR

The pallet-based alternative leads to complex logistics problems at entry/exit points. If the pallet solution were used in conjunction with non-exclusive entry/exit facilities using a transition lane to access the AHS lane after weaving through conventional traffic lanes (See Operate in Mixed Traffic with Non-AHS Vehicles category), the logistics of handling such a scenario would be very complex. As indicated in the discussion above on "Beneficial Effect on Conventional Roadways", a pallet-based system will likely be a heavy consumer of land space adjacent to entry/exit points to the AHS facility for loading, attaching, unloading, detaching, and storage and for achieving the entry and exit functions.

2.4.4.10. Lane width

Level of Correlation

Standard	WR-I
Pallet	WR-I
RPEV	WR-I

Compatibility problems associated with the three vehicle/roadway interface solutions are more directly associated with the use of alternative vehicle types.

2.4.4.11. Design speed

	Level of Correlation
Standard	WR-I
Pallet	WR (ICE pallet) or SR (roadway powered)
RPEV	SR

While power can be drawn inductively with no problem at high speeds, there is a tradeoff among speed, length of roadway inductor, and amount of power transferred. For example, a bus with a 10 foot pickup inductor sitting in a stationary position for one second over a 10 foot roadway inductor will draw a certain amount of power, P. The same bus traveling 60 mph (88 feet per second) passing over a 10 foot roadway inductor will take 0.11 second and thus, will draw less than P power. Alternatively, to draw the same amount of power will require a considerably longer roadway inductor (higher capital costs!). These tradeoffs must be studied in order to make more informed decisions about design speed.

With respect to pallets, the kind of vehicle-to-pallet attachment and locking mechanism could be affected by pallet speed. An RPEV-pallet would encounter the same design speed-related problems as an ordinary RPEV.

2.4.5 Conclusions

Based on this investigation of the roadway interface concept characteristic considering in detail the three solutions (standard, pallet, and roadway electrification) as well as the follow-up discussion of these issues at the Concept Characteristics Review Meeting during the June 27-28 meeting, it was decided by the C! Team that both pallets and roadway electrification would not be recommended for continuing study as a potential concept discriminator during the remainder of the concept downselect process of WBS C1. This would not, however, mean that either pallets or roadway electrification would or should not be studied further in the context of applications of various AHS concepts. Indeed, roadway electrification is specifically enumerated as an application scenario in the Objectives and Char-

acteristics document. Regarding pallets, however, there are numerous issues to resolve regarding the apparently very complex logistics and the formidable setup requirements to handle the entry/exit activities required to minimize chances of a delay or at least of prospects of a sizeable delay with pallets. The smaller the delay the larger the size of the logistics operation necessary to handle pallet entry/exit operations. The smaller the logistics operations the larger the time delay would likely be. A complex and sizeable logistics operation would be a big land use consumer. Thus, land use is involved to a great degree in the tradeoffs that need to be made. Also, a large logistics operation would likely be very costly with the potential requirement to purchase additional real estate. Moreover, additional delay means increased travel times which also means increased cost. A rural application could have more logistics problems than for an urban application, jurisdictional issues associated with interstate crossings, competition with Amtrak.

2.5 OBSTACLE RESPONSE POLICY

There were three main considerations in deciding obstacle response policy. The first involves trade-offs in the amount of prevention vs. detection of obstacles. The second involves trade-offs in the amount of manual vs. automated detection. The third involves the vehicle maneuver capability in an obstacle avoidance response. As in longitudinal and lateral control, the technology to perform the obstacle detection task was not specified since development of this technology is still in its early stages (i.e. for the reliability required in AHS).

In considering prevention vs. detection, the most difficult type of obstacle that could occur in each particular case was examined. It was immediately apparent that there are many difficult obstacles (e.g., tire and vehicle parts, large birds, animals, fallen or wind-blown objects) which cannot be fully prevented, even though the probability of their occurrence could be made very small. Thus, any concept must retain full object detection capability for all types of objects,

regardless of the degree of attempted obstacle prevention.

A similar examination led to the conclusion that there are few choices in the amount of manual help in the detection process. The natural tendency is to automate the detection of "easy" obstacles, and let humans detect the "hard" ones. The fallacy in this is that humans would have to detect all obstacles in order to decide which ones are the "hard" ones. This would make automatic obstacle detection redundant at best. Thus, the only possible choices are fully manual detection or fully automated detection.

The obstacle avoidance maneuver capability is related to the sensing capability. The possibilities are: (1) remain in the lane and stop or overrun the obstacle; and (2) steer around the obstacle. With manual obstacle detection, either choice is valid. With automated obstacle detection, the ability to steer around an obstacle is related to the field of view of the sensing system. Forward-looking, side-looking, and possibly rearward-looking sensors would be required for fully automated obstacle avoidance with steering capability. The trade-off is to use only forward-looking sensors for fully automated detection of obstacles in the vehicle lane. Once an obstacle is detected, the vehicle would have to stop and temporarily switch to manual detection to steer around it, or wait for the obstacle to be removed.

The above considerations led to the following three choices for the obstacle response policy:

2.6 VEHICLE CLASSES IN A LANE

This concept characteristic is an operational characteristic that defines one facet of the operational system requirements. This particular facet concerns whether or not an AHS lane should be restricted to a single vehicle class.

Possible solutions include:

Single Class Only—Only one class of vehicle is allowed into a given lane. A class definition would need to be specified.

Mixed Class—Different class vehicles could freely mix within a lane.

Platoon (Homogeneous)—Packets would be composed of a single class of vehicles, but mixed platoons would be allowed in the same lane.

Platoon (Sorted)—Packets would be composed of mixed classes of vehicles, but would be sorted on some key characteristic such as stopping distance. The length of platoons would vary as a function of the Markovian arrival of different classes of vehicles.

Note that if platooning is not allowed, then the first two solutions are the same as the last two. (In other words, if separation speeds are set independent of modes of operation (e.g., predefined separation (15 ft.), etc.) then "platoon" is undefined)

2.6.1 Solution Description

This section will describe the four possible solutions identified above. Each solution description will include a discussion of the solution definition, estimated performance, and any implication for the overall system architecture.

2.6.1.1. Single class only

Description

This solution would require all vehicles in a single lane to be of a common class. Class would be identified during check-in at which point a lane assignment would be made.

Estimated performance

This system could obtain high systems performance in terms of speed and safety, although it would get limited use by restricting itself to a subset of the desired users.

Architecture implications

The check-in station must be able to identify vehicle characteristics and/or Class to grant entrance approval or lane assignment. Inter vehicle communications are minimized as individual vehicles do not need to cooperate or be aware of special vehicle classes. Road Infrastructure requirements can be optimized

for the particular vehicle class. Operational limits and system performance can be optimized for a restricted set of parameters.

2.6.1.2. Mixed classes

Description

In this solution, more than one class of vehicles could operate in any lane. Vehicles may need to transfer information to surrounding vehicles on stopping distance, obstacle sensing fields, etc. to assure safe operations. No additional requirements are placed on the check-in station sort incoming traffic.

Estimated performance

This would give the highest number of users access to the system. However, the system would have to operate at the lowest common denominator of the vehicles currently in the lane.

Architecture implications

Vehicles may need to transfer information to surrounding vehicles on stopping distance, obstacle sensing fields, etc. to assure safe operations. No additional requirements are placed on the check-in station sort incoming traffic.

2.6.1.3. Platoon (homogeneous)

Description

During entrance check-in, vehicle classes would be noted. Information would be returned to the entering vehicle regarding the vehicle(s) in front to allow platooning. Incompatible vehicles would have to maintain greater than normal operational separation. In this fashion compatible platoons could be assembled with homogeneous vehicles, and differing platoons could be separated appropriately.

Estimated performance

All vehicle classes can be accommodated. The operational envelope (speed, etc.) would be between an optimally set number and a lowest common denominator although biased toward the lower end because of platoon passing/resorting constraints.

Architecture implications

Additional software would have to be added to the check-in station for platoon sorting and to the vehicles to remember their relative operating position vis a vis the rest of the platoon. Inter vehicle communications may be required. Roadway design would need to accommodate the lowest common denominator in terms of width, control frequency, etc.

2.6.1.4. Platoon (sorted)

Description

During entrance check-in, vehicle class would be noted. Information would be returned to the entering vehicle regarding the vehicle(s) in front to allow platooning. Vehicles would be sorted inversely according to a primary parameter such as stopping distance so that they could be platooned without violating operating constraints. In this fashion sorted platoons could be assembled with heterogeneous vehicles sorted by a primary feature such as stopping distance, gross weight, height, etc. Any negative discontinuity in the primary parameter would cause a new platoon to form with the lead vehicle noting the additional separation parameters. In this fashion, all vehicle classes could be accommodated with maximum efficiency while maintaining safe operations.

Estimated performance

All vehicle classes can be accommodated. The operational envelope (speed, etc.) would be between an optimally set number and a lowest common denominator although biased toward the lower end because of platoon passing/resorting constraints.

Architecture implications

Additional software would have to be added to the check-in station for platoon sorting and to the vehicles to remember their relative operating position vis a vis the rest of the platoon. Inter vehicle communications may be required. Roadway design would need to accommodate the lowest common denominator in terms of width, control frequency, etc.

2.7 MIXED TRAFFIC OPERATION

2.7.1 Description

Mixed traffic operation refers to the degree to which vehicles under manual control and those under automated control simultaneously share one or more lanes of a vehicle-highway. Figure 2.7.1-1 shows the spectrum of mixed-Traffic operation. At one end of the spectrum, there is no mixing: manually controlled vehicles (MCV) and automatically control vehicles (ACV) are segregated, with MCV assigned to MCV-dedicated lanes and ACV assigned to ACV-dedicated lanes. At the other end of the spectrum there is full mixing of MCV and ACV traffic: there are no dedicated lanes. In between these two extremes lie combinations of dedicated lanes and shared lanes.

Given this spectrum, the extreme and closed interval between the extrema correspond to isolation categories in terms of AHS concept characteristics: (i) no mixing, (ii) partial mixing, and (iii) full mixing of MCV and ACV. The relationship between each solution category and the existence of dedicated and shared lanes in a vehicle-highway system are shown in Table 2.7.1-I.

Note that these solution categories do not exclude the possibility of dynamically changing the designation of a lane from dedicated to shared and vice versa. That is, mixed traffic operation can have a temporal component. For example, during peak-hour usage of a vehicle-highway system in an urban area or in the event of an accident on either a dedicated or shared lane, it may be necessary to reallocate the number of lanes designated as dedicated and shared.



Figure 2.7.1-1. Spectrum of Mixed Traffic Operation Alternatives

Table 2.7.1-I. Relationship Between Each Solution Category and the Existence of Dedicated and Shared Lanes in a Lane

	Dedicated Lanes	Shared Lanes
No mixing	yes	no
Partial mixing	yes	yes
Full mixing	no	yes

2.7.2 Description of Realistic Solutions

An objective determination of whether a specific solution within one of the three mixed traffic operation solution categories is realistic cannot be performed in a void. Rather, a specific solution or category of solution is realistic in terms of a specific system context. Consider, for example, a rural and an urban segment of a vehicle-highway system. A solution characterized by full mixing may be deemed pragmatic for the rural portion of the vehicle-highway system due to cost considerations: it may be hard to justify on a per-kilometer basis the cost to build additional dedicated AHS lanes

if the volume of traffic on these lanes is expected to be low. However, the same solution may not be pragmatic for use in the urban segment of the vehicle-highway system: the risk associated with system hazards introduced by fully mixed lane operation in high-density traffic may be too high from a public policy perspective. Hence, the same mixed lane operation solution may be realistic for zero, one, or more specific system contexts for the same candidate concept AHS.

2.7.2.1. No mixing

Pros: The sensing and control functions required of the vehicle-highway system may be less stringent than those for partial- or full-mixing lane operations due to the absence of manually driven or malfunctioning AHS-equipped vehicles in the dedicated AHS lanes under nominal conditions.

Cons: The AHS must be able to detect and compensate for rogue users of a dedicated AHS lane; a rogue user of a dedicated AHS lane is a vehicle that enters a dedicated AHS lane when it is either not AHS-equipped or failed or deceived the check-in test to enter the dedicated AHS lane. The rogue user of a manual-only lane is a vehicle operated under automatic control.

Strict separation of MCV and ACV can make it difficult to respond to an accident (e.g., vehicle-vehicle crash) or failure (e.g., AHS-equipped vehicles communication system fails or debris, such as a piece of wood falls onto the dedicated lane) occurs within a dedicated lane apprehend a reach the accident scene, rogue vehicle (for enforcement purposes), or malfunctioning vehicle.

The level of usage of lanes dedicated to AHS-equipped vehicles will be low in the early stages of AHS deployment. Moreover, in rural areas, it can be difficult to justify on a per-kilometer basis the cost to build additional dedicated AHS lanes or convert existing manual lanes to dedicated AHS lanes if the volume of traffic on the dedicated lanes is not expected to exceed a certain threshold.

2.7.2.2. Partial mixing

Pros: Partial mixing permits some degree of flexibility in making tradeoffs among system safety, cost, and throughput-capacity. For example, commercial and transit vehicles under manual or automatic control can be relegated to lanes reserved exclusively for their use, while all other vehicles, irrespective of their mode of control, share the remaining lanes. From a system safety perspective, such an arrangement removes the hazard characterized by two vehicles of

greatly differing masses colliding at highway speeds.

In comparison to no-mixing lane operation solution, shared lanes can be used to reroute traffic, respond to an accident (e.g., vehicle-vehicle crash) or failure (e.g., AHS-equipped vehicle is communication system fails or debris, such as a piece of wood falls onto the dedicated lane), or apprehend a rogue vehicle (for enforcement purposes).

Cons: As in the no-mixing lane operation solution, there needs to be a capability in any existing dedicated lanes to detect rogue users.

The sensing and control functions required of the vehicle-highway system may be more stringent than that of no-mixing lane operation for the following two reasons: (i) in shared lanes, ACV must compensate for the unexpected or incorrect behavior of human drivers and (ii) MCV must compensate for unexpected or incorrect behavior of the ACV.

2.7.2.3. Full mixing

Pros: Manual-use lanes on existing highways can be used for AHS traffic.

Cons: As with no mixing, there is less flexibility to accommodate system safety, cost, and throughput-capacity issues than with partial-mixing lane operation solutions.

The sensing and control functions required of the vehicle-highway system may be more stringent than those for no- or partial-mixing lane operations for the same reasons cited above.

2.8 LATERAL CONTROL APPROACH

2.8.1 Characteristics

The purposes of lateral control are to automatically maintain the vehicle's position within a line, change lanes, help to avoid obstacles, or merge into or out of the automatic highway system.

To facilitate the above goals, the lateral control will need to perform the following

basic functions: roadway definition, sensing, signal processing, control, and actuating. The AHS roadway is either defined by some kind of markers on the roadway or stored as a map in some devices. The raw information of the absolute, or relative vehicle position is recognized and transmitted through some media to the sensing devices. Based on the characteristics of the media, the raw information is then signal processed to obtain the necessary control variables. One common such variable is the current lateral deviation of the vehicle with respect to the road center. The number and nature of the variables depend on the requirements of the inputs of the control algorithm. The control algorithm takes this (these) input(s) and produce steering command based on a set of designed procedures. The algorithm is developed primarily based on the overall AHS lateral control system/operating requirements. An automatic steering actuator then interacts with the manual steering mechanism to perform the desired steering function. The vehicle reacts based on its dynamic characteristics, and the environmental disturbances.

The design and the complexity of the control function depends on the overall lateral functional requirements, such as maximum tolerable lateral deviation, minimum emergency response time. The major difficulties involving are 1. good tradeoff between lane-tracking accuracy and ride comfort when small lateral error is demanded, 2. good robustness against environmental disturbances and system uncertainties, and 3. high reliability for emergency responses. Additional control inputs such as incoming road curvature, relative vehicle orientations may be required to meet stringent functional requirements.

The choice of the automatic steering actuator depends on the control requirement flow-down, the ease of both user and manual system interfaces, as well as the cost and reliability.

The majority of the variations of the lateral control lies on the sensing system and the corresponding signal processing. There are many systems suggested based on different detection devices, media, and technologies.

They are of different maturity level today, nevertheless most of them have the potential to provide the basic information necessary for the automatic lateral control. Although the selection of such sensing and signal processing system depends somewhat on the control function requirements, the eventual decision will be based more heavily on the *maturity* of each technology, future *potential* (e.g., upgradability) of each system, overall *reliability*, the total *cost* (or the marginal cost) of the sensing/processing system together with that of the corresponding infrastructure modification/maintenance, as well as the *schedule* of the product development.

It is of course preferable to require no additional infrastructure modification for the roadway definition. However, the schedule, the maturity, and the reliability of the corresponding sensing/signal processing system may demand some form of roadway infrastructure modifications.

2.8.2 Realistic Solutions

There are many possible solutions of the lateral control approach. They can be grouped in different ways. For example, grouped by where the control and sensing devices located, we have vehicle centered (located in the vehicle), or infrastructure centered lateral control. By the road markers: magnet nail, magnet strip, electric wire, resonance coil, guard rail, ... By the sensor transmitting media: magnetic field, electro-magnetic waves with different wave length, sound wave. By the power transmitted: active and passive. By the direction the sensor is pointing at: look ahead, look down, and look sideways. By the technology: vision, GPS, Differential GPS, frequency selective strip, acoustic, wireless communication, Infrared Beacon,...

To address the fundamental difference in the approaches of lateral information acquisition, the following method of grouping is chosen:

- Mechanical Guided Roadway: There is a physical link between the vehicle and the roadway in this category, for example, rail road is one of such case.

This is not a realistic solution of the lateral control approach.

- **Indirect Guided Roadway:** There is no physical link between the vehicle and the roadway in this category. The road is defined by markers either on the center/side of the roadway or on the roadside. The markers can be magnet nails or strips, electric wires, resonance coils, guard rails, different radar reflectors (strips, paints, mesh), optical or electro-optical reflectors, acoustic or ultrasonic reflectors, or even ordinary lane markers. The appropriate devices are used to detect the field strength, or to compare the incident and reflected signals. The corresponding physical properties are then used by some signal processing algorithm to determine the relative distance between the sensor and the markers. Some of the marker systems, such as the magnetic systems, have inherited ability to code information (e.g., future road map) on the roadway. Some of the systems requires active elements either on the roadway or in the vehicle. Some are totally passive. However, they are similar in terms of their eventual potentials and basic limitations. This is a realistic solution of the lateral control approach.
- **Direct Imaging:** There is no physical link between the vehicle and the roadway in this category. This category involves primarily machine/ computer vision systems with cameras and image processing. Relative geometrical relationships between the vehicle and the roadway can be extracted from the image of the roadway divided markings captured by the camera. Besides the information similar to those obtained from the indirect guided roadway system, direct imaging systems have the potential to apprehend more roadway knowledge, such as roadway obstacle detection and sign recognition. Furthermore, the extensive research conducted on this lateral control approach warrants its consideration separately from the indirect guided roadway category. This is a realistic solution of the lateral control approach.

alistic solution of the lateral control approach.

- **Beacon System with Road Map:** There is also no physical link between the vehicle and the roadway in this category. Instead of obtaining the relative vehicle information with respect to the roadway markers, the systems in this category acquire absolute vehicle locations through some kind of global or roadside beacon systems, for example, GPS, Differential GPS, or wireless communication. Relative geometrical information between the vehicle and the roadway can be obtained by comparing the current and previous absolute vehicle locations with respect to the map. It can also be a realistic solution of the lateral control approach.
- **Dead Reckoning with Inertial Navigation:** These systems utilize vehicle based motion sensors such as gyros, accelerometers and wheel encoders to estimate the vehicle's location on the roadway. To function as a lateral control system, this technology would be combined with a map or some discrete beacon system to obtain the vehicle's absolute position. Due to the error accumulation in these sensor over time, it is unlikely this type of system alone could solve the entire lateral control problem. However such a system may be effective when combined with other lateral control alternatives, particularly those which provide vehicle position estimates that are relatively widely spaced in time or distance. To that effect, we still consider it to be a realistic solution of the lateral control approach.
- **Infrastructure Based Lateral Control:** This concept involves systems which individual vehicles' lateral sensing and/or control functions are the responsibility of the infrastructure. Although centralized sensing/control capability seems to be attractive from the simplicity point of view, it is in fact a non-efficient method of performing the automatic lateral control functions. Moreover, the infrastructure based lateral control approach.

eral control system requires several communication technologies that are not currently available and will not be available in the near-term. These requirements include continuous communication for real-time control of the vehicles with absolutely no interruptions or loss of information; and a sophisticated network of computers able to 'hand-off' sensing/control functions of vehicles with absolutely no interruptions or loss of information. Furthermore, the latency of the communication as well as the 'local' uncertainties and variations of each vehicle/components/environment make the infrastructure based lateral control system more costly than any of the above suggested systems. As a general rule, remote servo control system is always more costly and difficult to build. Combining the above arguments and the possibility/ability of simultaneously creating thousands of accidents should a failure in the infrastructure occur disqualify this system to be a realistic solutions.

Why the possible solutions are defined as above? Notice that the members in each generic group possess similar system potential and have common limitations. For example, the best can be obtained from the indirect guided roadway system will be the exact knowledge of the current vehicle geometric relationship with respect to the road marker along with an incoming road map. On the other hand, the direct imaging systems have more potential simply because the image contains more information than just the relative relationship. But the complexity of imaging processing and the reliability in the inclement weather will be a common problem area for the direct imaging system for some time to come. The differences of future potential among system within a group are not very significant. The eventual choice among one group, should it be chosen as a candidate, will be based on the tradeoff of the level of maturity, the ease of coordination with other components in the vehicle or roadway,

the overall reliability, the total cost of the sensing/processing system together with that of the corresponding infrastructure modification and maintenance, as well as the schedule of the AHS development.

Moreover, the above categories are not absolutely exclusive. For example, a member of the direct imaging category that looks directly down at the lane maker next to the vehicle during bad weather very much resembles an indirect guided roadway system. A beacon system with long sampling interval and a discrete marker system with very low vehicle speed are similar in nature to a dead reckoning system without inertial navigation. A system in the indirect guided roadway category may resemble a dead reckoning system during lane change maneuvers if the lateral position sensor has a restricted sensing range. If we bring in the fact that each solution group has similar limitations, a tentative conclusion may be that some combination of the above realistic solutions is yet another feasible solution.

The realistic solutions of the lateral control approach are the following vehicle centered approaches:

- Indirect Guided Roadway
- Direct Imaging
- Beacon System with Road Map
- Dead Reckoning with Inertial Navigation
- Some form of Combination of the Above.

2.8.2.1. Pros and cons

Indirect guided roadway

Pros:

- This category presents the most effective methods to obtain precision relative geometric information between the vehicle and the roadway.
- Most members of this category have less complicated components and rela-

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tive simple signal processing algorithm.

- Most members can perform equally well at inclement weather or at low visibility.
- Several members can code information on the roadway with relative ease (e.g., road map).
- Most members are robust in terms of relative roadway information acquisition.
- Most members in this category can become mature in relative short period of time.

Cons:

- Most members of this category require some form of roadway infrastructure modification and maintenance.
- The systems in this category can at best provide the precise relative roadway/vehicle knowledge, and other geometric related information coded on the roadway. It can not really 'see' the roadway and surroundings. They all need other system's support for obstacle detection and emergency maneuvers.

The eventual choice among the members of this category will be based heavily on the maturity of each technology, future potential (e.g., upgradability) of each system, overall reliability, the total cost (or the marginal cost) of the sensing/processing system together with that of the corresponding infrastructure modification/ maintenance, the schedule of the product development, as well as some marginal effects such as the ease of road information coding, the range limitation of the measurements, and passive or active components.

Direct imaging

Pros:

- This category have the most potential of capturing roadway information for lateral lane control, obstacle detection and emergency control, roadway sign recognition, as well as longitudinal spacing control.

- This system requires almost no infrastructure modification, except maintenance.
- This system can detect small relative angle between vehicle and the roadway through vision geometric amplification.

Cons:

- There would be no information acquired from this system when it can not 'see'. The robustness of this lateral information acquisition system during inclement weather condition, low visibility situations, or poor lighting environment can not be guaranteed.
- The complexity of the image processing algorithm requires large computation power to achieve fast sampling rate, better accuracy, or higher robustness.
- The capability of this system in small longitudinal spacing situation (e.g., platooning) may be limited.
- The time for the fully maturity of the system in this category will be long.

Beacon system with road map

Pros:

- There may be no infrastructure modification and maintenance on the roadway.
- It is relative easy to implement roadway modification (e.g., detour) since the roadway is defined by the map,
- The system is available at bad weather (except when beacon system transmission has been affected) and low visibility.

Cons:

- Good accuracy and fast sampling rate depend on the development and availability of the beacon system.
- Accurate map is also necessary for tight control.

- Higher noise to signal ratio for the relative geometric information (especially relative angles) derived from the absolute knowledge of locations.

Dead reckoning with inertial navigation

Pros:

- The inertial sensors provides direct vehicle dynamic information for servo controls.
- Most inertial sensors can have multiple usage for other vehicle control functions.

Cons:

- Low robustness against sensor noise and environmental uncertainties because of the noise accumulation.
- Low robustness against road hazard and when perform emergency maneuvers.
- Some members of this category need roadside beacon installation.
- It could be costly to increase the accuracy of the roadside beacon system.

2.9 LONGITUDINAL SENSING AND CONTROL APPROACH

Options include:

1. Vehicle-based radar, with wide field of view, supplemented by video for longitudinal control and forward obstacle detection. Side-looking radar (proximity sensors) and vehicle-vehicle communications for steering around obstacles.
2. Vehicle-based video using cooperative target, supplemented by vehicle-vehicle communication for longitudinal control and vehicle avoidance. Down-looking infrastructure video, or side scanned infrastructure radar/laser for non-cooperative targets.
3. Down-looking infrastructure video, or side scanned infrastructure radar/laser for all targets (together with communi-

cations and control intelligence for infrastructure guidance of vehicles).

4. Vehicle-based radar in lead vehicle (as in 1 above). Cooperative target video for other vehicles.
5. Human driver in lead vehicle. Cooperative target video for other vehicles.
6. Vehicle-based video using cooperative target, supplemented by vehicle-vehicle communication for longitudinal control and vehicle avoidance. No detection of uncooperative targets.
7. GPS or beacon based vehicle position sensing and vehicle-vehicle communications for longitudinal control and vehicle avoidance. No detection of uncooperative targets.

2.10 ENTRY/EXIT

2.10.1 Objective

This section discusses the physical requirements and operational characteristics necessary to accommodate AHS operation and that may have an influence on technology selection and/or evaluation.

2.10.2 Roadway Configuration

AHS deployment can be implemented in one of the following configurations:

2.10.2.1. Configuration 1

A dedicated highway with all lanes automatically controlled.

2.10.2.2. Configuration 2

A dual-use highway with automatically-controlled vehicles (ACV) that would be operated only on dedicated automatically-controlled lanes (ACL) and manually controlled vehicles (MCV) that would be operated only on dedicated manually-controlled lanes (MCL). A MCL may have to accommodate ACV's for a certain length along the route.. Such a lane will be referred to as a Mixed Type Lane (MTL).

Each of the above configurations can be deployed in an urban setting or in a rural setting.

2.10.3 Base Line Functions

The following baseline functions will be involved in the operation of the AHS System:

1. Physical access to the automatically-controlled lane(s) from the surrounding roadway network.
2. Check-in procedures; i.e. verification that the vehicle is properly equipped to be operated on the ACL and meets certain safety and reliability standards.
3. Transition from manual to automatic control and merging into an ACL.
4. Exiting the ACL and transition from automatic to manual control.
5. Physical egress from the automated lane(s) to the surrounding roadway network.
6. Malfunction and emergency management; physical and operational accommodation of malfunction in one or more system's components and in dealing with emergency situations.

2.10.4 Alternative Solutions

2.10.4.1. Physical access to the ACL

ACV's can access the AHS system via one of the following options:

Option 1A: Dedicated ramps that directly feed the ACL. Applicable to all configurations.

Option 1B: Common ramps used by all vehicles; automatically-equipped as well as manual. Applicable to Configuration 2 only.

The adopted system concept will have to accommodate either option. As such, this function is not a concept discriminator.

2.10.4.2. Check-in procedures

It is assumed that ACV's will be tested and certified for operation on ACL's off-site. Some means of certification will be tagged to the vehicle. Options available for check-in ACV's to the AHS system include:

Option 2A: Automatic check-in. On the fly check-in through electronic reading of a magnetically-coded tag placed in or on the vehicle. *A vehicle-based or an infrastruc-*

ture-based verification system would indicate to the driver whether the vehicle is or is not fit to use the AHS.

This process should preferably take place before the vehicle reaches the AHS facility to allow the driver to take the necessary action (i.e. proceed to use the AHS facility, proceed as a MCV, or abort and go back) without impinging on the operation of the highway.

Option 2B The ACV would be equipped with self-diagnosing instrument(s) that the driver can test before approaching the AHS facility, i.e. similar to an airplane's "check-in" before take-off.

If all systems are O.K. the driver can proceed to use the AHS facility. Otherwise he or she can proceed as an MCV, or abort.

The above two options are believed to be concept discriminators.

2.10.4.3. Transition from manual to automatic control and merging into ACL

The ACV would transition from manual control to fully automatic control and merge into the ACL under the AHS system in accordance with one of the following options:

Option 3A: on the entry ramp while the vehicle is stationary. The ACV would come to a complete stop on the entry ramp, wait for a *vehicle-based or an infrastructure-based* sign or signal to switch to automatic control and proceed to merge into the first ACL. If there is more than one ACL, then a separate mechanism would need to be developed to accommodate inter-ACL switching. This option would only be applicable to the dedicated ramp option (1A) discussed above.

Option 3B: on the entry ramp as the vehicle is in motion. Again a *vehicle-based or an infrastructure-based* sign or signal should be communicated to the driver to switch to automatic control and proceed to merge into the first ACL. Since this would be on the fly operation, a transition lane (similar to acceleration lanes associated with regular entry ramps) should be provided. This option would also be only applicable to the dedicated ramp option (1A) above.

Option 3C: .on a transition lane as the vehicle is in motion. This option would be applicable to the common ramp option (2A) discussed above. The ACV would enter the roadway on a common ramp with all other vehicles, maneuver its way to a transition lane next to the ACL. A *vehicle-based or an infrastructure-based* sign or signal would instruct the driver to switch to automatic operation and proceed to merge into the first ACL. Whether this transition lane would be dedicated to ACV's or used by all vehicles is dependent on the mode of operation of the ACL lane (i.e. free agent, single-class platoon, mixed platoon, etc.), on the number of ACL lanes, and on the speed of traffic on one or more of the ACL's.

The adopted system concept should accommodate either option 3A or 3B, and option 3C.

2.10.4.4. Exit from the ACL and transition from automatic to manual control

The exiting process is initiated by the trip planning function through which the vehicle and the driver are notified that they are approaching the desired exit or the terminus of the AHS system. Such notification can be *vehicle-based or infrastructure-based or both*. Since ACV's would be traveling at a high speed on the ACL, a transition/deceleration lane should be provided for both roadway configurations, i.e. it would not be possible to exit the ACL directly to an off ramp in case of Configuration 1.

Transition from automatic to manual control could take place on the transition lane or, in the case of a dedicated AHS facility, on the exit ramp as the vehicle is in motion or when it comes to a complete stop.

The length and use of the transition lane in function 3 and 4 above is believed to be a critical element in the development of the AHS system, especially in urban applications where inter-spacing between interchanges would be relatively short.

2.10.4.5. Physical egress from the AHS to surrounding roadway network

Options available for egress from the AHS are similar to those available for access, i.e.

dedicated ramp in case of Configurations 1 and 2 or common ramp in case of Configuration 2 only.

2.10.4.6. Malfunction and emergency management

Depending on the type and nature of the malfunction or emergency, options available for malfunction and emergency management range from shutting down the AHS operation entirely or partially, reverting to manually-controlled operation, or directing disabled vehicle to an emergency lane or shoulder.

2.10.5 Evaluation of Alternative Solutions

Table 2.10.5-I presents a brief listing of advantages and disadvantages of pertinent options.

2.11 LANE WIDTH CAPABILITY

2.11.1 Describe the Characteristic

This concept characteristic addresses the width of an automated lane. Three general solutions exist — normal (current) width, narrower than normal (current) and wider than normal (current). Only the first two are considered realistic. Due to lack of specifics about technology capabilities, Narrower Than Normal, instead of the possible actual narrower lane widths, is considered a solution.

2.11.1.1. Importance

This concept characteristic addresses lateral separation but indirectly. Unlike longitudinal separation policy where the actual separation can be adjusted in real-time according to weather condition etc., lane width is considered part of infrastructure and cannot be adjusted easily in real-time.

Operations of AHS impose requirements on AHS lane width. The lane width, in turn, directly imposes requirements on the lateral control capability of an AHS vehicle. Note that lateral control is closely related to longitudinal control. For example, lateral control at low speed is easier than that at high speed. In other words, lane width, together with lateral control capabilities, may limit the operational speed of the AHS

Table 2.10.5-I. Entry/Exit Option Comparison and Evaluation

Function	Option	Advantages	Disadvantages
1. Physical Access	1A	Better control of AHS operations. Improved safety Control of interchange spacing. Control of length and operation of transition lanes	Could be very expensive Disruptive to highway operation during construction.
	1B	Low cost option	Disruptive to MCL's operation all the time Possible disruption to ramp operation
2. Check-in Procedures	2A	Automation compatible Assures driver of vehicle status Reasonable operating cost	System assumes responsibility for misdiagnosis Difficult to enforce
	2B	Automation compatible Relatively low capital and operating cost Driver assumes responsibility for vehicle status	Difficult to enforce
3. Transition to/from automatic controls	3A	Provide time for driver to adjust to transferring control to/from automatic operation Automation compatible	Potential time delays Need for queuing space
	3B	Fast, efficient and automation-compatible	May require more sophisticated drivers
	3C	Required for configurations 2 and 3 Compatible for mixed operation	Disruptive to MCL's operations Reduces throughput of MCL's

traffic on that lane. What follows concentrates on the operational requirements on AHS lane width.

The Operational Requirements Affecting Lane Width: Vehicle Type, Weather, Loss of Lateral Control, Emergency Manuevering, and Degraded-Mode Operation (Manual Driving)

A lane must be sufficiently wide so that, in the absence of malfunction, any automated vehicle traveling in that lane stays completely within that lane. Note the effect of vehicle classes accommodated. A lane may be dedicated to the use of one particular vehicle class during certain hours, e.g., automobiles during commute hours, but may be shared by other vehicle classes during the rest of the day. Also note the effect of weather condition, especially the reduced

tire-pavement friction and wind-gust, on the lane width requirements.

The possible safety hazards resulting from loss of lateral control, i.e. lateral control failure, during automated traveling should also be considered in determining the lane width. Emergency maneuvers for avoiding collisions after a failure, even with perfectly functioning lateral control, may require a wider lane width for safety.

The lane width should also be wide enough to support the degraded operating modes. In the extreme case of system shutdown, if automation-equipped vehicles are allowed to operate on AHS lanes manually during the system downtime, then those lane must be sufficiently wide for safe manual driving at a reasonable speed.

2.11.2 Describe All Realistic Solutions

- i) Realistic Solutions and Their Performance Strengths and Weaknesses
 - ii) Design and Architecture Implications
- #### 2.11.2.1. Realistic solutions

- i) Normal Width (for all vehicle classes)
- ii) Narrower Than Normal for automobiles and light-duty vehicles only

The current standard lane width is 12 feet (3.7 meters). This width will be referred to as the Normal width. Since very little theoretical or empirical work has been done on the performance of possible lateral control technologies on heavy-duty vehicles, it is assumed that it is not realistic or beneficial to consider setting lane width at any value narrower than 3.7 meters for those lanes that will accommodate heavy-duty vehicles like trucks and buses. Therefore, the solution of "Narrower Than Normal" refers to the lane width for ONLY those AHS lanes that are dedicated to the use by automobiles or other light-duty vehicles. Due to lack of specifics about technology capabilities, Narrower Than Normal, instead of the possible actual narrower lane widths, is considered a solution. For convenience, a Narrower Than Normal lane should be at least 10% narrower than 3.7 meters and therefore should be at least one foot narrower than the normal width.

The only advantage of Narrower Than Normal width is the reduced land requirement. This should be weighed against its many potential disadvantages, which will become clear when these two solutions are evaluated against the Goals and Objectives, Baseline Functions, Uses and the solutions for other Concept Characteristics.

Other solutions

One other solution exists — Wider Than Normal (Current) Width. However, it is considered unacceptable. In other words, it is a requirement that the width of an AHS lane should not exceed the current standard. This means that the AHS technologies must be advanced enough and the operating rules must be conservative enough so that the AHS is safe while providing sufficient capacity gain. Given the assumption that it

is not realistic or beneficial to consider setting lane width at any value narrower than the current standard, the current standard width is effectively the only solution for heavy-duty vehicles.

2.11.2.2. Design and architecture implications

The operational requirements that affect lane width include:

- a) vehicle classes accommodated on the lane,
- b) operation under inclement weather, particularly poor tire-pavement friction and gusting winds,
- c) safety requirements after failures of lateral control,
- d) safety of emergency maneuvering, and
- e) safety and efficiency of degraded-mode operations (e.g., manual driving).

2.11.3 Evaluate Solutions to Concept Characteristic

- i) Against AHS Objectives and Characteristics
- ii) Against Baseline Functions
- iii) Against Uses for an AHS

Recall that Narrower Than Normal refers to only those AHS lanes that are dedicated to the use by automobiles and light-duty vehicles. Therefore, the rankings provided below effectively addresses lane width issues with respect to ONLY automobiles or other light-duty vehicles.

2.11.3.1. Against AHS objectives and characteristics

Safety ranking

Normal 6; Narrower Than Normal 4

Capacity and mobility ranking

Normal 5; Narrower Than Normal 6

The reduced land requirement provides the opportunity for accommodating more lanes. However, on a two-lane AHS (i.e. two automated lanes in each direction) where only one lane is dedicated to automobiles, the impact on capacity gain could only be a small fraction of the total capacity. If the AHS requires a break-down lane, then the

fraction will even be smaller. However, if land becomes so scarce that any marginal reduction of land requirement becomes crucial, then Narrower Than Normal should be very desirable.

Convenience and comfort ranking

Normal 5; Narrower Than Normal 4

Narrower lanes may create discomfort for automobile users.

Environmental impact ranking

Normal 5; Narrower Than Normal 5

The ranking is based on per vehicle mile traveled on AHS. These reductions may be offset by the increase of fuel consumption and environmental impact due to increased capacity and hence, traffic.

Cost ranking

Normal 5; Narrower Than Normal 5

There are two different cost perspectives: infrastructure (land) costs and vehicle costs. If land becomes so scarce that any marginal reduction of land requirement becomes crucial, then Narrower Than Normal should reduce lane requirement and could be very desirable. However, Narrower Than Normal lane width would impose performance constraints on the vehicle and hence, make vehicle potentially more costly. How these two conflicting factors would determine the total costs is unclear at this stage.

Deployability ranking

Normal 5; Narrower Than Normal 4

Narrower lane Normal lanes would limit the vehicle classes that can be safely and efficiently accommodated. Also, lane narrowing may involve infrastructure modification.

Availability ranking

Normal 5; Narrower Than Normal 4

The more stringent lateral control requirements may result in more complex lateral control system and hence, vehicle availability may be lower.

Supported vehicle classes ranking

Normal 9; Narrower Than Normal 3

The normal lane width may not be able to accommodate some forms of Pallets. (For some pallet system designs, automobiles are loaded on the pallets sideways, i.e. the automobiles are facing side of freeway. Narrower Than Normal lanes will likely not be able to accommodate heavy-duty vehicles.

2.11.3.2. Against baseline functions

Check-in ranking

Normal 5; Narrower Than Normal 4

Due to the potential higher complexity of the lateral control system required for safe automated driving within narrower lanes, check-in function, if required, may involve more checking than its Normal counterpart.

Maneuver planning and execution ranking

Normal 5; Narrower Than Normal 5

Lane width should have minimum impact on maneuver planning and execution.

Flow control ranking

Normal 5; Narrower Than Normal 4

Since Narrower Than Normal lanes cannot accommodate heavy-duty vehicles, they restrict flow of the corresponding traffic and hence, may make flow control more difficult.

Malfunction management

Normal 5; Narrower Than Normal 3

Due to the narrower lateral separation between two adjacent streams of traffic, failures, especially those of lateral control, occurring on a Narrower Than Normal lane may create more serious safety hazards than their Normal counterpart.

Emergency handling

Normal 5; Narrower Than Normal 3

Due to the narrower width, emergency vehicles may have difficulty reaching the scene of an incident/accident.

2.11.3.3. Against uses for an AHS

Heavily-congested urban highway

Normal 5; Narrower Than Normal 7

With respect to the Use in Heavily Congested Urban Highway, Narrower Than Normal (automobile) lanes will reduce land requirement and hence, may in turn increase throughput.

Exclusive transit vehicle lanes

Normal 9; Narrower Than Normal 3

Narrower Than Normal lanes may be able to accommodate only vans and mini-buses.

Only high-occupancy vehicles in rush hour

Normal 9; Narrower Than Normal 3

Narrower Than Normal lanes cannot accommodate heavy-duty buses, as assumed earlier.

Exclusive commercial vehicle lanes

Normal 9; Narrower Than Normal 3

Narrower Than Normal lanes cannot accommodate heavy-duty buses, as assumed earlier.

Sparse rural areas

Normal 9; Narrower Than Normal 3

In sparse rural areas, there could be only one AHS lane in each direction. If the lane is Narrow Than Normal, then heavy-duty vehicles may have difficulty using the AHS.

Roadway power electric vehicles

Normal 5; Narrower Than Normal 5

Lane width should have no impact on this particular Use.

2.11.4 Description of Correlation Between the Solutions

The correlation is discussed in the following subsections, each corresponding to the concept characteristic as numbered.

1) Both Normal width and Narrower Than Normal lane width are correlated with a) Vehicle only and b) Vehicle Predominant with Some Infrastructure solution. But Narrower Than Normal is more so than Normal lane width.

2) Lane width is independent of Communication.

3) Lane Width is independent of Longitudinal Separation.

4) Lane Width is independent of Roadway Interface, except that some pallet systems may require Normal or even Wider Than Normal width.

5) Lane Width is correlated with the Avoidance Response solution of Obstacle Response Policy. The narrower the lane, the more difficult to safely avoid the obstacle.

6) Accommodation of heavy vehicles on a lane is strongly correlated with, if not absolutely require, Normal Width.

7) Mixing of automated automobiles with manually driven automobiles in a common lane is strongly correlated with, if not absolutely requires, Normal width.

8) Lane Width directly imposes performance constraints on the lateral control technologies.

9) Lane Width is independent of the Longitudinal Control Approach.

10) Lane Width is independent of the Entry/Exit policies.

11) Due to the correlation between lane width and operating speed, Narrower Than Normal lane width may allow a lower operating speed than otherwise. This in turn may warrant a lower design speed.

2.12 DESIGN SPEED

2.12.1 Description of Concept Characteristic

Design speed is an operating characteristic that defines the maximum allowable speed of traffic flow on a highway system under normal operating conditions. Specification of a design speed for an automated highway system (AHS) imply that the infrastructure and the automated vehicles within the system are capable of performing desired functions up to the selected speed. It also indicates that the goals and objectives of AHS can be met up to the design speed. Design speed has a considerable impact on the social and technical properties of an AHS concept.

The selection of a design speed does not assume that all traffic in an AHS must operate at the design speed at all times. Rather, the traffic speed in a specific location at a certain time is determined by the operating scenarios, vehicle, roadway and weather conditions. A higher design speed does suggest that an AHS operate at a higher speed for the majority of use. A higher design speed may increase the potential capacity of a highway system and reduce travel time but it also demands a higher level of performances and associated costs for all system components.

The design speed of AHS is critical with regards to its consequences on the operation of AHS because the traffic flow in AHS is closely coordinated and tightly controlled. For instance, a small percentage of relatively slow-moving vehicles in an AHS that fail to operate at a high design speed may potentially affect or paralyze a significant portion of AHS traffic. On the other hand, if a high design speed is successfully implemented and executed, the benefits of AHS will be highly visible and appealing.

Current interstate highway systems are designed for a speed of 65 mph or higher. The typical speed limits imposed on highways are not necessarily the design speed of the infrastructure. The determination of speed limits requires extensive and thorough consideration of social, economical and technical consequences. For example, highway safety and environmental impacts are the most frequently discussed factors in deciding a proper speed limit for highways. The same scrutiny should be applied in selecting the design speed for an automated highway system with the investigation of all relevant issues.

The selection of design speed should be based on the evaluation of the following factors:

- 1) Safety considerations, which includes
 - effects of design speed on failure behaviors
 - sensitivity of control systems to design speed

- evaluation of safety measures in collisions
- requirements of occupant restraint systems
- speed difference between AHS and adjacent manual traffic

- 2) Performance requirements and feasibility of vehicles and its components
- 3) Implementation and maintenance costs of vehicles and its components
- 4) Environmental impacts, such as fuel consumption and noises.
- 5) Achievable highway throughput
- 6) Potential reduction of travel time
- 7) Operational variables, such as classes of vehicle and mixing of traffic.
- 8) Requirements and feasibility of infrastructure
- 9) Construction and maintenance costs of infrastructure

2.12.2 Description of Solutions

2.12.2.1. 29 m/sec (65 mph)

It is appropriate to assume that an automated highway system should operate at a speed no lower than the current highway speed limit, 65 mph, or 55 mph in some urban areas. The AHS objective of increasing highway capacity is accomplished by automation (such as vehicle platooning and traffic management) without elevating the operation speed from the current system. Selecting a design speed close or equal to the current highway system also allows the interchange or mixing of automated and manual traffic if such mixing is desirable. A design speed of 65 mps is therefore chosen as one solution.

2.12.2.2. 43 m/sec (95 mph)

This solution is proposed as a potential solution with an operating speed approximately 50% higher than the current interstate speed limit. Although it will reduce travel time by the same order of magnitude in the absence of congestion, it will not significantly increase the throughput of a

highway system. In fact, it may actually reduce the throughput. (Throughput is generally defined as the product of speed and density. Increasing speed necessitates density reduction for safety.) It is also a driving speed that can be achieved by well-equipped and well-maintained passenger cars.

2.12.2.3. 56 m/sec (125 mph)

A third solution is proposed to approximately double the operation speed from that of current highway systems. This will further reduce the travel time in the absence of congestion. However, the potential throughput is likely to be lower than the level achievable at the speed of 43 m/sec. This speed can be achieved by high-performance passenger cars.

2.13 KEY CONCEPT CHARACTERISTICS

The analysis of the initial set of characteristics allowed the Concepts Team to refine the list. The goal was to focus on the most high level, essential dimensions, so that the number of combination concepts that result is manageable.

2.13.1 Refinement of Concept Characteristics and Alternatives

The specific modifications were as follows:

2.13.1.1. Distribution of intelligence/sensing/processing

This characteristic, also known as Allocation of Intelligence, was determined to be one of the key concept discriminators. The analysis showed that there are a great number of alternatives here, well beyond the original options — all in the vehicle, all in the infrastructure, or some in each. In fact, there are many viable ways to distribute the intelligence between the vehicle and the infrastructure, and the most promising approaches place intelligence in both places. Unfortunately, the 11 different alternatives make the total number of concept alternatives unmanageable. It soon became clear to the Concept Team that it is not feasible to do an exhaustive analysis of all alternatives.

Based on the above analysis (see 2.1), the most promising alternatives were selected, supplemented by enough others to form a broad and representative sample of approaches. This does not mean that those that were not selected were eliminated for all time. The “re-concepting” approach allows the reintroduction of alternatives if the analysis points that way. The alternatives selected for analysis are discussed below.

2.13.1.2. Communications

The communications alternatives were seen to be driven by the allocation of intelligence. For example, a cooperative architecture would require heavy vehicle-to-vehicle communications, while infrastructure controlled would need extensive roadside-to-vehicle communications. Thus, the Concept Team agreed that the communications options discussed above in Section 2.2 would be used to provide a feasibility framework for the concepts, but that communication is not a concept-level characteristic by itself. As the concepts are fleshed out, communications architectures will be developed appropriate to the allocation of intelligence.

2.13.1.3. Separation policy (platoon, free agent, slot)

The analysis of the separation policy showed it to be a key driver in the nature of any concept. Each of platooning and free agent has advantages, so both should be continued as alternative options. The slot approach seemed less promising, in that it introduced complexity without great throughput gains. However, the team felt that further analysis needed be done before it could be definitively ruled out. Hence, separation policy was kept as a concept characteristic, with the original three options.

2.13.1.4. Roadway interface (normal, pallet, RPEV, other)

The normal interface, a rubber-tired, self-powered vehicle riding directly on the road, is a requirement of the AHS by its very nature. Then the issue becomes whether the AHS will also accept pallets and/or RPEVs.

This is an implementation and evaluation issue, to ensure that the concept is not designed in such a way to preclude pallets, or to interfere with the potential delivery of power from the roadway. This was consequently eliminated as a concept characteristic.

2.13.1.5. Obstacle response policy for sensing and avoidance

The analysis showed three approaches. If the technology does not exist for detecting obstacles, the human must be relied on for this function, in which case the vehicle will be automated until the driver sees a danger, at which time he will take over. The second approach is to use the collision avoidance capability that must be an any automated vehicle (that is not infrastructure controlled). If this could be tuned to recognize all hazards in addition to vehicles, this would naturally cause a stop at an obstacle. At that point, the driver would need to assume control, restart the vehicle and drive manually around the obstacle. The third option is full automation, in which the AHS (vehicle, roadside or combination) recognizes and avoids obstacles. The team agreed that this is a concept characteristic.

2.13.1.6. Vehicle classes in a lane (one class only, mixed classes)

Vehicle class mixing (e.g., cars and big rigs) was kept as a concept characteristic since the traffic dynamics change dramatically.

2.13.1.7. Mixed traffic capability (dedicated and mixed, dedicated only)

Whether or not manually operated vehicles are allowed to mix with automated vehicles profoundly changes the nature of the AHS, and hence, was kept as a concept characteristic. However, the analysis showed that there are different levels of mixing. At one extreme are manual vehicles allowed to travel in the same lanes as automated vehicles, but beyond that there are alternatives distinguished by the certainty that the manual vehicles will stay out of the automated lanes. This is based on the physical means for separating the lanes and the technique for the entering and exiting

vehicles to merge. These alternatives are described in the next section.

2.13.1.8. Lateral and longitudinal control approach

Both of these techniques were seen to be implementation issues. The concept-level issues here are already covered in other characteristics, specifically whether or not the vehicles are infrastructure controlled, and whether or not slots (point-following) are used. Hence, both of these were eliminated as concept characteristics at this time.

2.13.1.9. Entry/exit (transition lane, dedicated station)

Of the many entry and exit characteristics, the key ones were dedicated ramp vs. transition lane. The choice of one or the other impacts the nature of the AHS, and so this was kept as a concept characteristic with these two alternatives

2.13.1.10. Lane width capability (normal only, normal or narrow)

The lane width will be determined locally, but each concept should be evaluated as to how well it supports a narrow lane once the concept is sufficiently well defined to estimate lane keeping accuracy. This was not used as a concept characteristic.

2.13.1.11. Design speed (speed limit, higher than speed limit)

This is something that will be imposed from without, rather than a design parameter of the AHS. The ongoing concept development should be sure not to preclude future speed limit increases on the AHS, but the baseline should be targeted at normal highway speeds. This was not used as a concept characteristic.

2.13.2 The Six Concept Characteristics

The evaluated concepts are built around the six key characteristics or dimensions that distinguish essentially different approaches to the Automated Highway System.

2.13.2.1. Allocation 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 requirements on sensing and communications, and on the nature of the AHS system as a whole. The locus of intelligence and control is largely the key description of the architecture. It will impact who pays the costs, how the automated highway evolves and whether a system optimum or individual optimum can be achieved. In this section the word "infrastructure" refers to infrastructure-based electronics, as opposed to vehicle-based electronics.

Autonomous

This is merely an automated vehicle. The infrastructure provides at most the basic ITS services (in-vehicle information and routing, but not control) and something for the vehicle to sense to determine its position in the lane. The vehicle does automatic lane, speed and headway keeping. Example implementations for lane keeping are the use of magnetic nails, a sensor on the vehicle that can read the roadway striping, and GPS with map matching. In any case, the roadway contains no more AHS-specific intelligence than the immediate location of the road. The vehicle senses its surroundings, including adjacent vehicles and lane, but does not communicate with the infrastructure (except possibly for standard ITS features such as routing requests or Mayday). Nor does it communicate with other vehicles.

In the simplest version, the vehicle can maintain steady state once in its lane, but anything else, including entry, exit, lane changes and obstacle detection and response, must be done by the driver. This vehicle senses and reacts (brakes and throttle) to the vehicle it is following in its own lane in order to maintain its fixed spacing. If there is no vehicle ahead of it, it maintains a set speed. If the vehicle carries additional sensors looking to the side or rear, they are only there to alert the driver. Obstacles in the vehicle's immediate path

that are big enough to be seen by the forward-looking sensor will be sensed and cause the vehicle to brake as though another vehicle stopped suddenly ahead. However, there are no additional sensors to detect dangerous, but smaller, obstacles ahead or any obstacles, such as vehicles, approaching from the side.

A more sophisticated version supports automated lane changes, for example by the addition of side-looking sensors. However, there is no way to command the other vehicles to open a space, other than the usual signals between drivers.

Cooperative

This option is similar to the previous, in that there is minimal infrastructure intelligence, but there is the addition of local (e.g., line-of-sight) vehicle-to-vehicle communications for vehicle coordination. This allows coordinated lane changes and platooning. There is no infrastructure support beyond that in the previous alternative. Since this is all done locally, there is no region-wide traffic optimization, other than through digital ITS advisories. There is no entry or exit flow control.

There may be passing of information vehicle-to-vehicle or platoon-to-platoon, for example in an emergency, but they do not routinely act as conduits in a basic cooperative concept. More advanced versions of this option include data passing and aggregation, leading to a distribution of global intelligence throughout the vehicles on the roadway.

Infrastructure supported

This is an enhancement of the previous alternative. Here the cooperating vehicles are given location-specific information from the infrastructure electronics that is monitoring the global situation (flows and trouble spots, not individual vehicles). For example, all of the vehicles at a location may be given the information by a roadside beacon. In any case, the information sent will not be specific to any one vehicle or platoon, though it may be lane-specific. It will be in the form of general parameters, such as target speed or spacing, dependent on the current situation. The information could be static as

well, such as: lane ends, merge left; speed limit 65; slow, curve ahead; exit 165. The vehicles are still maintaining their steady state and negotiating their lane changes, but now these are informed by the broader view maintained by the infrastructure. This allows the vehicles to concentrate on the local view of themselves and the surrounding vehicles, while the infrastructure concentrates on the global view.

Infrastructure managed

The major difference between Infrastructure Supported and Infrastructure Managed is that in this latter alternative, the infrastructure communicates with individual vehicles rather than groups of vehicles. Thus, the infrastructure manages anything other than steady state in the lane. Specifically, the vehicles maintain steady state including lane keeping, headway keeping, speed maintenance and platooning, but for any special request, such as lane change, entry or exit, the infrastructure takes command. Thus, this is a "request-response" approach, in which the individual vehicles ask permission of the infrastructure to perform certain activities, and the infrastructure responds by sending commands to that vehicle or to other vehicles (e.g., open up to allow a lane change). These are high level commands; the vehicles will determine the steering, braking and throttle needed to execute them.

Either the vehicle or the infrastructure may do vehicle navigation. The infrastructure may also take the initiative in emergency situations that it detects, or to reroute individual vehicles for flow control. In particular, individual entering vehicles may be sent to an alternate exit if their destination is congested. This allows much tighter overall system control than the previous alternative, but it requires tracking individual vehicles and extensive communications.

Infrastructure controlled

Here the vehicles are completely controlled by the infrastructure, which will continually track and send commands to individual vehicles. These commands may be in the form of steering, braking and throttle commands, or they may be acceleration, deceleration and turning commands. The

vehicles have no intelligence beyond the ability to translate these commands into corresponding commands for their own actuators, and to monitor and adjust their response. They may not have sensors for roadway geometry or surrounding vehicles; if they do it is only as a means of data collection for the infrastructure.

This approach puts a heavy burden on the infrastructure in terms of real-time knowledge of the roadway and the vehicles, the computing power to manage the vehicles, and the communications power to be in continual control of all the vehicles. The update rate is very high, especially compared with the previous option in which commands were given on an exception basis.

2.13.2.2. Separation policy

The separation policy defines the relationship of each vehicle to the one in front of it. It defines the position that each vehicle will maintain. As such, it has major impacts on safety and throughput.

Free agent

The free agent vehicle maintains a safe distance from the vehicle it is following, and it travels at safe speed. This separation may be spatial (e.g., 3 meters) or temporal (e.g., 1 second). If there is no vehicle ahead within the safety distance, it will travel at the speed limit or at a lower but safe speed.

Even if the vehicles bunch up, with several closely-spaced vehicles following each other, this is not platooning, since the platoons do not operate as units, nor are they managed (e.g., there is no limit to their length), nor are spacings as tight as with an actual platoon.

The term "free agent" should not be construed to mean that they are free of outside influence. They may receive commands from the infrastructure or from other vehicles; the difference is that such commands are directed at individual vehicles rather than at platoons.

Platooning

Platoons are clusters of vehicles with short spacing between vehicles in the platoon and

long spacing between platoons. Platoons as long as 20 vehicles have been considered. Intra-platoon spacings as short as 1m have been contemplated. This ensures that the relative speed is low if a malfunction causes a collision. The longer inter-platoon spacings ensure no inter-platoon collisions. Tight coordination within the platoon is required to maintain the close spacing. The platoon can be treated as a unit by the infrastructure or by other vehicles.

Slot

The roadside control system creates and maintains moving slots on an AHS lane that partition the AHS lane at each moment in time. Slots then are moving roadway segments, each of which holds at most one vehicle at any time. The vehicles are identified and managed by association with their slots. Vehicles that need more space (e.g., heavy trucks) may be assigned multiple slots. In a basic slotting concept, the slots are of fixed length.

Another way to think of slots is as a point-following technique. Vehicles are assigned to follow moving points rather than other vehicles.

2.13.2.3. Mixing of AHS and non-AHS vehicles in the same lane

Mixed traffic operation refers to the degree to which vehicles under manual control and vehicles under automated control share the roadway. At one extreme is full mixing, in which automated and manual vehicles under normal operations share a mainline lane. At the other extreme is dedicated automated lanes, with a physical barrier that makes it virtually impossible for a manually operated vehicle to enter. In between are configurations in which lanes are dedicated to automated use, but there is not complete physical separation. Thus, the distinction among the four alternatives below is the likelihood that a manually operated vehicle will find itself in a lane with automated vehicles.

Dedicated lanes with continuous physical barriers

The automated lane or lanes are physically separated from any manual lanes. For

example, the innermost lane on a freeway may be converted to automated use, with a continuous solid barrier between this lane and the adjacent manual lane. Another example is a fully automated highway that is not adjacent to any manual roadway, either from new construction or by complete conversion to automation. This option generally would be implemented with dedicated automated on and off ramps.

Dedicated lanes with some gaps in the physical barrier

This variation on the previous alternative includes occasional gaps in the physical barrier to allow transition from the adjacent lane. This allows the adjacent lane to be a transition lane (see below). There is potentially greater danger of manual vehicle incursion in this alternative, since the gaps allow the possibility of a manually-operated vehicle entering through driver error or vehicle failure.

Dedicated lanes with virtual barriers

Virtual barriers are any demarcation that separates the dedicated automated lanes from other traffic, but does not physically prevent movement between lanes. The common example is yellow lines. This alternative is similar to HOV (carpool) lanes on many freeways, in which double double yellow lines, warning signs and enforcement prevent vehicles from entering the HOV lane except at designated gaps. In this alternative there is even greater danger of manually operated vehicles in the adjacent (presumably transition) lane inadvertently drifting into the automated lane.

Full mixing

Automated and manually-driven vehicles co-exist in the same through lane at all times. This is the only one of the choices in which the manual vehicles in the lane are not an abnormal or emergency situation.

2.13.2.4. Mixing of vehicle classes in a lane

Vehicle classes refer to levels of performance characteristics, such as passenger cars, heavy trucks and transit. For equity and economic viability the automated highway must accommodate all classes, but

not necessarily in the same lane. Vehicles with poor performance will impact vehicles following; for example, a heavy truck going up a hill will cause the following traffic to slow. It may not be feasible to mix classes within a platoon.

Mixed

This alternative supports all classes in all lanes at the same time. It may or may not mix classes within platoons. It may or may not form vehicles into same-class blocks or otherwise manage the various classes on the lanes.

Not mixed

In this alternative only one class (or group of similar classes) is allowed in each lane. For example, there may be a lane for heavy trucks and buses and another for cars and light trucks. This may change with time of day, for example allocating more lanes for cars during rush hour.

2.13.2.5. Entry/exit

The key issue in entry and exit is how the automated vehicle transitions from manual and how it relates to other traffic on a dual-use highway.

Dedicated

This alternative has on ramps and off ramps that are used solely by automated vehicles and place the vehicles in the automated lane without passing through the manual traffic. The transitions between manual and automated operation occur somewhere on these automated ramps. It may or may not require the vehicle to stop.

Transition

If all vehicles use the same ramps, it is reasonable to assume that the automated vehicles will use the lanes farthest from entry. For example, in a standard freeway conversion, the lane closest to the center divider will be used for automated vehicles. The reason for this is that automated vehicles can operate in a manual mode and so can transition through the manual lanes without disrupting them, but the manual vehicles cannot transition through automated lanes.

A transition lane is the lane next to the first fully automated lane. Automated vehicles will enter this lane under manual control. They may go automated in this lane and then merge into the fully automated lane under automated control. This merge action is similar to that used currently to enter an HOV lane that is the left-most lane of a conventional freeway. The automated lane may be separated from the transition lane by virtual barriers or physical barriers with occasional gaps to allow transition.

2.13.2.6. Obstacle

There is no way to prevent obstacles on the roadway. They include such things as stalled vehicles, manual vehicles from adjacent lanes, dropped cargo, animals, and vehicle parts such as bumpers or hubcaps. Some hazardous objects are small and hard to detect.

Manual sensing and avoidance of obstacles

This alternative is essentially what is done today. The driver watches the road ahead and the sides of the road, and takes evasive action, such as braking, swerving or changing lanes, if a hazard is seen.

Automatic sensing, stop or manually avoid

The vehicle has the capability to detect obstacles in the road ahead and to brake automatically. For large (vehicle size) objects this may be provided by the sensor on the vehicle that maintains headway; it will see the obstacle as a stopped vehicle, and brake. This may be supplemented by other sensors on the vehicle and/or on the roadway. Once the vehicle stops, it is up to the driver to take control to steer around the obstacle if necessary.

Automatic sensing and automatic avoidance maneuver if possible.

Obstacles are sensed as in the previous alternative. If an obstacle is sensed, the vehicle will determine and execute the appropriate response, including braking and/or lane change. A variation would allow a swerve. Another variation would give the driver a "panic button" for those hazards that may be missed by the sensors (e.g., deer about to enter roadway; ladder or nails in the road).

3. CANDIDATE CONCEPTS

3.1 SELECTION OF THE CANDIDATE CONCEPTS

Examination of the concept characteristics allowed the Concepts Team to reduce the eleven key concept characteristics to six. However, few of the alternatives within any characteristic could be definitively eliminated based on studying each characteristic alone, since the various characteristics are closely interrelated. The effectiveness of any characteristic alternative is very dependent on the other characteristics. Hence, it is necessary to compare complete concepts. While the team identified some alternatives that seemed less promising, they were not definitively eliminated, and were kept to evaluate for completeness. This leaves a total of $5 \times 3 \times 4 \times 2 \times 2 \times 3 = 720$ combinations of characteristics, i.e. candidate concepts. This is clearly more than can be reasonably evaluated, so the team developed a manageable set of candidate concepts. Recall that the team already had to limit themselves to a representative, not a complete, set of alternatives for the allocation of intelligence alone.

The team agreed that the set of concepts should consist of between 15 and 30 candidates in order to provide breadth, while being a small enough number to evaluate reasonably. This set of candidates needed to include representatives of the full range of feasible AHS solutions, and all of the most promising solutions.

The first step was to eliminate mismatched combinations. First of all, there is a strong correlation between the entry/exit strategy and the mixing of AHS and non-AHS vehicles, in particular the means to separate the two. Specifically, a transition lane is inconsistent with a continuous physical barrier, simply because the barrier prevents transition. Similarly, dedicated entry/exit only makes sense with a continuous physical barrier in order to maintain a consistent level of separation. It would not be reasonable to

construct an expensive dedicated ramp, and then allow traffic from adjacent lanes to drift in through gaps. The team eliminated other combinations based on mismatches. For instance, both autonomous concepts have a free agent separation policy because vehicle-to-vehicle communications (by definition not a part of an autonomous concept) are by definition required for platoons. As another example, concepts with a slot separation policy by definition require heavy infrastructure involvement.

Next the team identified the most promising characteristic alternatives based on the analysis reported in Section 2. The following were judged to warrant examination in all or nearly all combinations.

Distribution of intelligence

- Cooperative
- Infrastructure Supported
- Infrastructure Managed

Separation Policy

- Free Agent
- Platooning

Mixing of AHS and Non-AHS

- Dedicated Lanes with Continuous Physical Barriers
- Dedicated Lanes with Some Gaps

Mixing of Vehicle Classes in a Lane

- Mixed

Entry/Exit

- Dedicated
- Transition

Obstacle

- Automated sensing and automatic avoidance maneuver if possible

Other characteristics were less promising, based on the analysis.

- Autonomous was addressed in two concepts, with and without automated obstacle avoidance, because the former represents a very minimal capability. It may not even be an AHS system, but

was maintained to allow a consideration of the extremes.

- Infrastructure controlled was kept in two concepts. The initial analysis indicated that lane keeping is far more efficiently managed by the vehicle, and completely centralized control risks single point failure, but this approach was kept as an extreme.
- Slotting was limited to a single concept, since the analysis indicated that it was extremely complex, and did not provide great capacity benefits.
- Dedicated lanes with virtual barriers were limited to two concepts, due to safety concerns.
- Full mixing of AHS and non-AHS vehicles appeared in only three concepts, due to concerns of safety, and loss of many AHS advantages.
- All but five of the concepts allow mixing of vehicle classes, since the stakeholders want access open to all classes, and the provision of dedicated lanes for each class may be prohibitively expensive.
- Only one alternative included manual obstacle avoidance, since a true AHS automates all driving tasks, but this was maintained as an extreme.
- Only three concepts have only the capability to automatic sensing, stop or manually avoid obstacles, since this too violates the spirit of AHS by forcing the driver to take over whenever the vehicle is confronted with a perceived obstacle.

Figure 3.1-1 summarizes the selected concepts. There were originally 23 concepts, but after some adjustments to correct inconsistencies concept 7 was seen to be redundant and eliminated. Subsequently, the evaluations rated concept 3 poor, due primarily to its reliance on an infrastructure controlled approach. Since this was the only slotting concept, a second infrastructure managed slotting concept was created, concept 3a, returning to 23 candidate concepts.

3.2 DESCRIPTIONS OF CONCEPTS

Figure 3.1-1 defines the skeleton of these 23 concepts, but more specifics were needed for estimates of performance, deployability and cost. The next step was to describe the concept in sufficient depth to allow evaluation. Specifically, each was fleshed out with details representative of the range of possibilities in order to provide an evaluatory design. That is not to say that the details are necessarily the only, or even the best, approach. The goal was representative designs to show the richness of the possibilities.

Each of the descriptions was assigned to a particular organization, as indicated in the matrix. Similar concepts were intentionally assigned to different organizations to get a range of viewpoints and approaches. The descriptions presented physical, functional and operational viewpoints. These documents were not only descriptive, but also provided insights into the applicability and limitations of various combinations of concept dimensions.

The following is the suggested outline for these descriptions. The authors were given this outline expanded with examples, and a great amount of latitude in selecting the scope and depth of information presented for an understanding and evaluation of the particular concept. This outline was provided as suggested content; no author was expected to provide all of the information included in it.

1.0 Overview

No more than 1/2 page. Why are we considering this concept? What is its distinguishing feature?

2.0 Selected alternative

From each dimension state the alternative chosen (e.g. autonomous, free agent, full mixing, etc.)

On each option, describe any local tailorability or cases in which the system is operating in different

Table 3.1-1. Twenty-Three Candidate Concepts

Candidate Concept Identifiers	1a	1b	2	3	3a	4	5	6	8a	8b	9	10	11	12a	12b	13	14	15	16	17	18	19	20
Distribution of Intelligence																							
Autonomous	X	X																					
Cooperative						X	X													X	X		
Infrastructure Supported								X	X	X	X						X		X				X
Infrastructure Managed					X							X	X	X	X	X		X				X	
Infrastructure Control			X	X																			
Separation Policy																							
Free Agent	X	X	X			X		X	X	X		X		X	X			X	X		X		X
Platooning							X				X	X				X	X			X		X	
Slot				X	X																		
Mixing AHS & Non-AHS Vehicles in Same Lane																							
Dedicated lanes with continuous physical barriers			X	X	X				X	X	X			X	X	X					X	X	X
Dedicated lanes with some gaps in the physical barriers						X	X	X				X	X				X						
Dedicated lanes with virtual barriers																			X	X			
Full Mixing	X	X																X					
Mixing Vehicle Classes in Same Lane																							
Mixed	X	X	X			X	X	X	X		X	X	X	X			X	X	X	X	X	X	
Not Mixed				X	X					X					X	X							X
Entry/Exit																							
Dedicated			X	X	X				X	X	X			X	X	X					X	X	X
Transition	X	X				X	X	X				X	X				X	X	X	X			
Obstacle																							
Manual sensing and avoidance of obstacles	X																						
Automatic sensing, stop or manually avoid																					X	X	X
Automatic sensing and automatic avoidance maneuver if possible		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			

alternatives at different locations or times. If some alternative does not quite seem to fit, describe what is special about that alternative in this concept.

3.0 Operational Concept

Describe how the system would operate. What happens when things are running regularly? What are the system operations, and how are they achieved? Discuss any special operating modes or behaviors.

4.0 System diagram

Show the vehicles and infrastructure and data flows among them, including sensing. Generally describe the content of each of the shown data flows. Roughly estimate the order of magnitude of the message size, update rate and range. Mention any other requirements or features.

5.0 Functional allocation

For at least the following functions, define its allocation to vehicle, infrastructure, human or combination, and describe the sequence of events for performing the function.

- Check-In
- Transition from manual to automatic control
- Automated driving including:
 - Sensing of roadway, vehicles, and obstructions
 - Lane and headway keeping
 - Detection of hazards
 - Maneuver planning (normal or emergency)
 - Maneuver execution
 - Transition from automatic to manual control
 - Check-Out
 - Flow control
 - Malfunction management
 - Handling of emergencies

6.0 Implementations

Describe at least one implementation of the concept, specifically what will be in the vehicle, the roadside and the AHS traffic operation center, above and beyond the standard and

Intelligent Transportation System. Provide whatever level of detail you feel is necessary for a description of the concept, but be sure to address the following at a minimum:

- What are the options for different standard levels of AHS roads (rural or urban) in this concept?
- Describe the minimal deployable system. Describe what incentive there is to buy an AHS vehicle, given the minimal deployed system. Describe what incentive there is to extend the AHS roadway, or deploy additional AHS infrastructure, given the minimal deployed system.

7.0 General issues and considerations

Discuss any additional issues that should be considered in the evaluation of this architecture [a list of suggested questions was provided].

The descriptions of these 23 concepts are in Appendix H.

3.3 CONCEPTS SUMMARIES

The following tables summarize the 23 alternative concepts developed by the AHS Concept Team. The descriptions in Appendix H provide the basis for this summary. The descriptions are not full designs, and so have different emphases depending on the key characteristics of each concept. Thus, any lists that appear in this summary are not intended to be exhaustive, but merely to indicate the "flavor" of the concept. In particular, nothing should be inferred from blank cells in this summary.

3.3.1 Description of the Rows of the Table

3.3.1.1. Concept ID No.

Each of the 23 concepts was assigned a number. There were originally 20 concepts. Initial work on these suggested other variations, so you will see numbers such as 8a and 8b. Number 7 was eliminated as being redundant. 3a was added after the initial evaluation.

3.3.1.2. Key features

This is a brief summary of the characteristics that made this concept worth looking at and distinguishes it from the others.

3.3.1.3. Allocation of intelligence

Allocation of intelligence indicates whether the intelligence is primarily in the vehicle, in the infrastructure, or some combination (see 2.13).

3.3.1.4. Separation policy

The separation policy states whether platoons, free agency or slotting is used (see 2.13).

3.3.1.5. AHS/manual mix of vehicles

A "yes" indicates that automated vehicles would be able to share the road with manually operated vehicles as well as being able to operate in dedicated lanes. Any other answer indicates that the automated vehicles must have a dedicated roadway, which is distinguished by the type of barrier separating it from adjacent lanes. "Barriers" indicates a solid barrier that would be entered via dedicated ramps, "barriers with gaps" indicates a solid barrier with occasional openings through which vehicles may transition from the adjacent lane, and "virtual barriers" indicate a lack of any physical separation other than yellow lines.

3.3.1.6. Mixed vehicle classes in a lane

A "yes" indicates that various classes of vehicles (e.g., passenger cars and heavy trucks) use the same AHS lane at the same time (although they may not necessarily be in common platoons). A "no" indicates either that there are separate lanes for the various classes, or that only one class uses the AHS at a time (e.g. only passenger cars and small buses in rush hour, only heavy trucks other times).

3.3.1.7. Entry/exit

Entry and exit will occur either by an adjacent transition lane through manual traffic or a dedicated ramp that places vehicles directly on an automated lane.

3.3.1.8. Obstacle detection and avoidance

"Manual" indicates that the driver is fully responsible for seeing hazards and maneuvering around them. "Auto sense & avoid" indicates that the system will detect hazards and avoid them automatically. "Auto sense & stop" indicates that the system will automatically detect hazards and bring the vehicle to a stop, possibly allowing the driver to maneuver around the hazard manually.

3.3.1.9. Vehicle sensors

This indicates either what is being sensed by each vehicle or the actual types of sensors on the vehicle, depending on the approach taken in the write-up. The list depends on the level of detail in the full concept description and may not form an exhaustive list.

3.3.1.10. Infrastructure sensors

This lists the attributes of the traffic or other conditions that are detected by the roadway. Again, these lists are not exhaustive.

3.3.1.11. Vehicle-to-vehicle communications

This indicates the types of information that is passed between vehicles.

3.3.1.12. Vehicle-infrastructure communications

This indicates the types of information that is sent from the infrastructure (roadside or central) to the vehicles. It also may identify information sent from the vehicles to the roadside, or characteristics of the communications path.

3.3.1.13. Driver involvement

This identifies the activities that the driver must or can do while in the automated lanes.

3.3.1.14. Infrastructure modifications

These are the items that need to be added to a standard highway to implement this concept. In some cases there are options or alternatives listed.

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3.3.1.15. Issues and solutions

In some cases, the concept author discussed some problems, issues or concerns that drove the concept design in a particular direction. Each issue and its corresponding solution are separated by a semi-colon -- Issue1; solution1. Issue2; solution2.

3.3.1.16. Reconcept ideas

One goal for the concept team was to identify alternative concepts or variations on these concepts that would perform better. These are described briefly here. In some cases these ideas were incorporated in the concept description, and in other cases they were merely comments on how to improve the concept.

3.3.1.17. Unusual approaches

In some cases, the approach to the development of the concept included a twist that was not the "standard" approach or that set it apart from the other concepts.

3.3.2 Abbreviations Used in the Table

@	at
accel	acceleration
addl	additional
AHS	Automated Highway System
auto	automated
b'cast	broadcast
comm	communications
coop	cooperative
deg	degree
det	detection or detecting
DGPS	differential GPS
dist	distance
FMCW	Frequency modulated continuous wave
GPS	Global Positioning System

incl	including
ind	individual
indiv	individual
inf	infrastructure
info	information
infr	infrastructure
infra	Infrastructure
IR	Infrared
ITS	Intelligent Transportation System
LOS	line-of-sight
mgmt	management
mod	modification
nav	navigation
opp	opposite
opt	optional
parms	parameters
pos	position
poss	possibly
prox	proximity
pt	point
recog	recognition
rel	relative
req's	requires
RF	radio frequency
rng	range
sec	second
sim	similar
std	standard
thru	through
TOC	traffic operation center
veh	vehicle
vel	velocity
w/o	without

Table 3.3.1-I. Summary Comparison of Concepts

Concept ID No.	1a	1b	2	3	3a	4
Key features	Automated cruise control and lane keeping	Automated cruise control, lane keeping, and lane changing	Infrastructure controlled	Slots	Slots	Cooperative flexible
Allocation of Intelligence	Autonomous	Autonomous	Infra controlled	Infra controlled (vehicle lateral control option)	Infra managed	Cooperative
Separation policy	Free agent	Free agent	Free agent	Slot	Slot	Free agent
AHS/manual mix of vehicles	Yes	Yes	Barriers	Barriers	Barriers	Barriers with gaps
Mixed vehicle classes in a lane	Yes	Yes	Yes	No	No	Yes
Entry/exit	Transition	Transition	Dedicated	Dedicated	Dedicated	Transition
Obstacle detection and avoidance	Manual	Auto sense & avoid	Auto sense & avoid	Auto sense & avoid	Auto sense & avoid	Auto sense & avoid (maneuver into transition)
Vehicle sensors	Variation 1: Forward-looking FMCW radar. Variation 2: Fusion of forward-looking FMCW radar and vision sensor.	Forward, backward Doppler radar, GPS, side proximity, IR, vision	Lane & obstacle sensors	Supplemental obstacle (optional); lateral control reference (opt.)	Supplemental obstacle (optional); lateral control reference (opt.)	Lane, headway, adjacent vehicles, roadway, obstacles (forward & side)
Infrastructure sensors	None	None	Sense position & velocity of all vehicles	Vehicle position; hazards	Congestion, environment, hazard info; vehicle position (opt.)	Obstacles
Vehicle-vehicle communications	None	Detection of signals	None	None	None	Signals entry/exit; platoon parameters; coordination among platoons
Vehicle-infrastructure communications	None	GPS	Control signals, 20/sec for each vehicle	One way inf to veh control signals	Vehicle sends position; infra sends position changes	Veh requests permission to enter; infra sends target speed; veh sends exit notice

- Table 3.3.1-L. Summary Comparison of Concepts (Continued)

Concept ID No.	1a	1b	2	3	3a	4
Driver involvement	Obstacle sensor; override at any time; lane change	Command transition out of automated mode			Alert AHS of hazards and malfunctions	Takes/surrenders control in transition lane
Infrastructure mods	Variation 1: Magnetic nails. Variation 2: DGPS ref stations, radar-reflective roadway markings.		Comm, computation, remote servo controller for each section of roadway	Lane markings (optional)	Lane markings (opt.); obstacle detection (opt.); vehicle position (opt.)	
Issues and solutions	Variation 1: Obstacle recognition on curved road; curvature coded in roadway. Variation 2: Obstacle recognition on curved road; curvature through DGPS and map.		Detecting driver intentions; automated brake & signal detectors. Aggressive manual vehicles; sophisticated algorithms	Remote servo control; high bandwidth, high reliability, handoff across sections	Capacity depends on position sensing accuracy; advanced or closely spaced sensors. High update rate; high level of real-time processing.	Capacity depends on ability of vehicle to maintain position in slot. High update rate; high level of real-time processing.
Reconcept ideas	Alarms, manual steering required to keep driver alert	Locally directed vehicle-vehicle comm	Vehicles determine own steering, braking, throttle		This is an infra managed version of Concept 3	Infrastructure approves check-in, tracks routing; pseudo-platoons with front-end comm
Unusual approaches	Auto detection of manual vehicle intentions					Time synchronous vehicle management

- Table 3.3.1-I. Summary Comparison of Concepts (Continued)

Concept ID No.	5	6	8a	8b	9	10
Key features	Cooperative platoons	Free agent with moderate non-AHS exposure	Infra supported free agent, DGPS	Infrastructure supported free agent without mixed classes	Infrastructure supported platooning	Infra managed, no veh-veh comm
Intelligence	Cooperative	Infra supported	Infra supported	Infrastructure supported	Infra support, some infra managed	Infrastructure managed
Separation	Platoon	Free agent	Free agent	Free agent	Platoon	Free agent
AHS/manual mix of vehicles	Barriers with gaps	Barriers with gaps	Barriers	Barriers	Barriers	Barrier with gaps
Mixed vehicle classes in a lane	Yes, unmixed platoons	Mixed	Mixed	No	Yes (local option)	Yes (local option)
Entry/exit	Transition (with check-in)	Transition	Dedicated	Dedicated	Dedicated	Transition
Obstacle detection	Auto sense & avoid	Auto sense & avoid	Auto sense & avoid (veh & opt. infra)	Auto sense & avoid	Auto sense & avoid	Auto sense & avoid
Vehicle sensors	Lane edge, road curvature, junctions, abs position, rel speed & dist, adjacent hazards	Lateral control, distance (radar), obstacles	Distance, passive markers	Adjacent vehicles, lane markings	Sophisticated obstacle sensors, lane, distance & rel vel, adjacent veh's	Longitudinal position & obstacle, lane keeping, right side large object. All ranging
Infrastructure sensors	Traffic flow	Congestion, surface, weather	Std. ITS	Traffic flow	Occupancy, speed upstream from entry; flow; obstacles; ind. veh movements	None
Vehicle-vehicle communications	Within platoon with lead, adjacent lanes, directed or broadcast	Share speed & accel data with adjacent, position & intended maneuver	Substantial data & coordination, including b'cast hazards		Lane position, velocity, coordination, advisory & nav (daisy-chain)	None

- Table 3.3.1-I. Summary Comparison of Concepts (Continued)

Concept ID No.	5	6	8a	8b	9	10
Vehicle- infrastructure communications	Emergency, advisories, static info	Infra to veh only.	DGPS, beacon @ check-in; broadcast beacons elsewhere; use veh-veh comm (opt.)	Advice to vehicles	Infra local b'cast to veh's: lane, speed, exits, hazards, etc. Vehs send hazards	Short range 2 way, complete coverage
Driver involvement		Entry, exit requests; receives status	Command auto, desired exit, take-over in system failure	Exit preference, take over in system failure	Initiate transition	Transfer control at entry, resume control in transition lane (incl. failure)
Infrastructure mods	Magnetic markers, barriers	Sensors for traffic flow, zone controllers, TOC, poss. lane markers	GPS, optional beacons, roadway markers	Lane marking	Section controller, entry controller, road reference, short-rng transmitters	Encoded roadway markers, cameras @ entry
Issues and solutions	Variations in barriers; several alternatives. Selfish maneuvers; cooperative protocols	Access to receive bandwidth in maneuver; addressing	Detection of vehicles & traffic cones, recognition of obstacles; passive markers (obstacles don't have them). Emergency; response protocol	Prevent mishaps; strict check-in & -out (2 gates)	Pure infra support is limited; infra- indiv. veh. comm for entry/exit, dynamic routing, emergency. Two cars changing into same lane from opp sides; query 2 lanes over.	Passing in single lane; use transition lane. Inadequate obstacle detection; driver spotter
Reconcept ideas	More global comm, infra support				Infra-individual veh control on entry, infra req's detected movement of ind. veh's	Driver spotter

- Table 3.3.1-L. Summary Comparison of Concepts (Continued)

Concept ID No.	11	12a	12b	13	14	15
Key features	Infra managed platoons	Infra managed mixed free agents	Infrastructure managed unmixed free agents	Maximum achievable throughput	Infra supported platooning with transition lane	Infra managed, full mixing
Intelligence	Infra managed	Infra managed	Infra managed	Infra managed	Infra support, some infra managed	Infra managed
Separation	Platoons	Free agent	Free agent	Platoon	Platoon	Free agent
AHS/manual mix of vehicles	Barriers with gaps	Barriers	Barriers	Barriers	Barriers with gaps	Yes
Mixed vehicle classes in a lane	Yes	Yes	No	No	Yes (local option)	Yes
Entry/exit	Transition with entry check	Dedicated	Dedicated, separate class ramps	Dedicated, separate class ramps	Transition (with check, poss. stop)	Transition (shared with manual)
Obstacle detection	Auto sense & avoid	Auto sense & avoid	Auto sense & avoid	Auto sense & avoid	Auto sense & avoid	Auto sense & avoid
Vehicle sensors	Forward looking radar, prox sensors for gaps, camera for stripes	lateral prox & lane pos, 2 rng, rng rate longitudinal, platooning controller	lateral prox & lane pos, 2 rng, rng rate longitudinal	lateral prox & lane pos, 2 rng, rng rate longitudinal	Sophisticated obstacle sensors, lane, distance & rel vel, adjacent veh's	Distance to any adjacent vehicles
Infrastructure sensors	Vehicle speed, weather	Traffic flow speed & density; weather	Traffic flow speed & density; weather	Traffic flow speed & density; weather	Occupancy, speed upstream from entry; flow; obstacles; ind. veh movements	All vehicles' locations, obstacles
Vehicle-vehicle communications	None directly	Vel, accel, braking, coordination	Vel, accel, braking, coordination	Vel, accel, braking, coordination	Lane position, velocity, coordination, advisory & nav (daisy-chain)	None

- Table 3.3.1-I. Summary Comparison of Concepts (Continued)

Concept ID No.	11	12a	12b	13	14	15
Vehicle- infrastructure communications	2 way, voice & data short range. Veh receive satellite. Infra tracks vehs thru comm	Broadcast & 2-way individual address	Broadcast & 2- way individual address	Broadcast & 2- way individual address	Infra local b'cast to veh's: lane, speed, exits, hazards, etc. Vehs send hazards	Two-way local
Driver involvement	Initiates lane changes, calls in obstructions, takes over in failure	Optional obstacle spotting. Takes over in emergency. Requests destination, change of exit	Optional obstacle spotting. Takes over in emergency. Requests destination, change of exit	Optional obstacle spotting. Takes over in emergency. Requests destination, change of exit	Initiate transition	Some will drive always
Infrastructure mods		Lane markers	Lane markers, dedicated separate ramps	Lane markers, dedicated separate ramps	Section controller, entry/exit controller facilities, road reference, short-range transmitters	Local controllers, TOC
Issues and solutions	Optimizing inter-veh spacing; spacing is sum of fixed veh parameters & dynamic system parms. In- vehicle computer failure; redundancy					Pure infra support is limited; infra- indiv. veh. comm for entry/exit, dynamic routing, emergency. Two cars changing into same lane from opp sides; query 2 lanes over.
Reconcept ideas		Minimal infra- structure manage- ment (vehicle plans normal maneuvers, platooning)	Minimal infrastructure management (vehicle plans normal maneuvers)	Minimal infrastructure management (vehicle plans normal maneuvers)	Infra-individual veh control on entry, req's det movement of ind. veh's. Dedicated ramp.	May need some mgmt of non-AHS vehicles

- Table 3.3.1-I. Summary Comparison of Concepts (Continued)

Concept ID No.	16	17	18	19	20
Key features	Free agent virtual barriers	Coop platoon, virtual barriers	Cooperative, auto obstacle sense & stop	Platooning, auto obstacle sense & manual avoid	Low risks
Intelligence	Infra supported	Cooperative	Cooperative	Infra managed	Infra supported
Separation	Free agent	Platoon	Free agent	Platoon	Free agent
AHS/manual mix of vehicles	Virtual barrier	Virtual barriers	Barriers	Barriers	Barriers
Mixed vehicle classes in a lane	Yes	Yes	Yes	Yes (mixed platoons)	No
Entry/exit	Transition	Transition (vehicle self test)	Dedicated (veh only check-in)	Dedicated	Dedicated (with stop & at obstacle)
Obstacle detection	Auto sense (veh) & avoid	Auto sense (veh) & avoid	Auto sense & stop	Auto sense & stop, manually avoid	Auto sense & stop, manual avoid
Vehicle sensors		Forward, side, lane marker. Velocity and range of adjacent vehs	360 deg Doppler radar for obstacles, vision system, IR	Distance to vehicle ahead. Roadway, vehicles, obstacles (platoon lead only)	Forward range, range rate; passive marker sensor; side prox
Infrastructure sensors			None	Obstacles	
Vehicle-vehicle communications	Broadcast RF with global addressing, packet.	Short range, 2-way	Beacon. Performance parameters, emergency vehicle notice	None	Short range LOS
Vehicle-infrastructure communications	1 way infra to veh. broadcast RF	Roadside receivers & processors, continuous coverage	None	Roadside beacons.	

- Table 3.3.1-I.Summary Comparison of Concepts (Continued)

Concept ID No.	16	17	18	19	20
Driver involvement	Entry, exit requests, opt. detect hazards & malfunctions	Can request no platoon. Alert button. Request lane change	Tell vehicle to ignore obstacle or manually avoid obstacle	Request entry/exit	Drive around obstacles
Infrastructure mods	Broadcast RF	Reflective lane markers	None	TOC, beacons, controllers	Passive lane markers
Issues and solutions	Sensor blind spot; vehs broadcast speed & position. Obstacle detection; add'l sensors or driver spotter. Obstacle recog; vehs b'cast positions			Rural can't afford continuous comm; have platoon leads carry data to next comm pt.	Obstacles are major disruption; breakdown lanes for breakdowns & driving around obstacles
Reconcept ideas	Physical barriers. Few entry/exit, long trips only	Local processor (sim to infra supported)	Manual obstacle avoid technically insupportable. Use vehicle maneuver capability		Infrastructure check at check-in
Unusual approaches	Veh check-in before entering freeway. Highly vehicle centered	2-way comm veh- roadside, transition lane for passing, platoons formed by destination	Completely vehicle centered	Extremely infrastructure centered, platooning w/o veh-veh comm	

4. CONCEPT EVALUATIONS

Five teams were formed to evaluate and compare the 23 candidate concepts. (Seven External System Concepts are being independently developed by outside contractors. The evaluations of these concepts are discussed in chapter 6.) Rather than assign each team to some group of concepts, each team was tasked to evaluate all of the concepts relative to a major issue area. This approach was chosen to allow greater depth in the evaluations and uniformity across all concepts. Teams were formed to address each of the major issues: Throughput, Safety, Cost, Flexibility/Deployability, and Acceptability. Each team consisted of members from multiple organizations.

Each of the Objectives and Characteristics was assigned to one of these teams, as indicated in the following Table 4-1.

The goals of the evaluations were to:

- Eliminate unpromising candidate concepts
- Eliminate unpromising key characteristics solutions
- Identify additional key characteristics
- Identify trade studies
- Suggest improvements to the candidate concepts
- Suggest additional promising candidate concepts
- Identify six promising concept families.
- Justify selections of the six concept families

Each team developed a plan for evaluation of the concepts that included, but was not limited to, an assessment relative to the Objectives and Characteristics. Each of the five viewpoints required a different approach to the assessment. The challenge was to formulate a plan that allows a broad evaluation of a large number of alternatives in a short period of time, with an eye toward more detailed comparisons in the next phase. The evaluations were performed according to the plans. In general, the evaluations were

qualitative, but were reported as numerical ratings. The evaluation reports, including the plans, are included in the following sections, with detailed background data appearing in appendixes B through G

There was another team charged with ensuring clear and sufficient descriptions of the concepts. Yet another team merged all the evaluation results. This was necessary since the relative ratings of the concepts, as expected, varied across the five viewpoints. The selection and definition of the 6 concept was based on the five evaluation results, relative stakeholder importance of each of the five areas, and stakeholder feedback. This activity and its outcome are discussed in section 4.6, and chapters 5, 7 and 9. The concept definition teams continued to be available during the evaluation process to refine descriptions, answer questions, and generally support the evaluations.

The 23 concepts had been selected as representatives of the possible range of automated highway systems, and did not include all possible solutions. Hence it was seen as unlikely that the final six concepts presented in the Workshop would be exactly like any of the original 23. This meant that the team has gone through a process of re-concepting, rather than of down selection. The re-concepting has occurred through evaluation teams noting deficiencies in the concepts and suggesting ways to modify the concepts. The teams were asked not to reject a concept outright based on the evaluation, but to look for easy fixes that greatly improved the concept. Such ideas are normal by-products of the evaluation process, and greatly support the re-concepting process.

The goal of the evaluation was not just to compare alternatives. In the process of evaluating the alternatives, there were lessons learned about what characteristics drove performance. These lessons are just as important as the comparative evaluations, if not more so. Identifying uncorrectable "show stoppers" that make a concept unacceptable relative to some aspect is especially important, because this allows the

elimination of alternatives before evaluating all dimensions.

The concept descriptions themselves generated insights even before the evaluations began. For example, the

Infrastructure Supported concept write-ups generally included additional infrastructure, while Infrastructure Managed did not use all that it had. This indicated an intermediate level of infrastructure involvement that is probably superior to either of the two.

Table 4-I. Allocation of Objectives to the Five Evaluation Teams

AHS Performance Objectives and Characteristics	Page*	Evaluation Team to which this item is assigned
Improve Safety	17	Safety
Increase Throughput	18	Throughput
Enhance Mobility	20	Acceptability
More Convenient and Comfortable Highway Traveling	21	Acceptability
Reduce Environmental Impact	22	Acceptability
Operate in Inclement Weather	23	Flexibility
Ensure Affordable Cost and Economic Feasibility	23	Cost
Beneficial Effect on Conventional Roadways	24	Throughput
Easy to Use	25	Acceptability
Infrastructure Compatibility	26	Flexibility
Facilitate Intermodal and Multimodal Transportation	26	Acceptability
Ensure Deployability	27	Flexibility
Provide High Availability	28	Flexibility
Apply to Rural Roadways	28	Flexibility
Disengage the Driver from Driving	29	Acceptability
Support Travel Demand Management Policies	29	Acceptability
Support Sustainable Transportation Policies	30	Acceptability (with input from the Cost Evaluation Team)
Provide Flexibility	30	Flexibility
Operate in a Mixed Traffic with Non-AHS Vehicles	31	Flexibility
Support a Wide Range of Vehicle Types	31	Flexibility
Enhance Operations for Freight Carriers	32	Flexibility
Support Automated Transit Operations	32	Flexibility
Provide System Modularity	33	Flexibility

* Page on which description starts in the document, "Automated Highway System (AHS) System Objectives and Characteristics, 2nd Draft", May 22, 1995

It was also noted that two concepts that differ only in one characteristic may differ greatly in their evaluatory design, since they were intentionally assigned to different, independent teams. This indicates that there is great variety in the potential AHS solutions, and the candidate concepts and their evaluatory designs are merely representatives of this variety. Hence the evaluators could not merely assess the alternatives; the best solution may not be among them. A major evaluation goal was the identification of better alternatives. In fact, the evaluations supported this goal; very early in the process there were new characteristics surfacing from the analysis.

Besides looking for conceptual insights, the evaluations were made numerical to facilitate concept-to-concept comparison. This may not be an actual measure of effectiveness, and is more likely a qualitative rating. Each team evaluated the concepts relative to multiple factors, of varying levels of importance. Then they each found some way, such as weighting, to combine these evaluations into a single composite score for each evaluation area (throughput, etc.). This helped the other teams see which were the best and worst concepts in each of throughput, safety, etc. and to gain a better grasp of the results. This also supported the down selection.

4.1 THROUGHPUT

This team evaluated the ability of the different concepts to increase traffic capacity.

4.1.1 Introduction

This section summarizes the throughput evaluation findings as well as down-selection and reconcepting recommendations. AHS throughput, at least that of the mainline, hinges upon the safety spacings between two longitudinally adjacent vehicles. The Team also conducted a parametric study of such spacings (see Appendix B).

The rest of the section is organized as follows. Section 4.1.2 discusses the

methodology, particularly the measures of effectiveness (MOEs) considered, the qualitative nature of the work and the relationship between throughput and other major measure of effectiveness. Section 4.1.3 discusses the throughput implications of the six concept characteristics and compares the impact of each of the solutions. Section 4.1.4 summarizes many potential throughput issues associated with the concept characteristics and solutions. Section 4.1.5 summarizes the evaluation findings for the 22 concepts. Down-selection and reconcepting recommendations are described in Section 4.1.6. Also included in Section 4.1.6 are some down-selection and reconcepting inclinations by the Throughput team members. Section 4.1.7 summarizes the study of the safety spacings.

4.1.2 The Methodology

4.1.2.1. Team Composition

The team composition was as follows:

PATH: D. Godbole, R. Hall, P. Ioannou, A. Kanaris, J. Misener, S. Shladover, J. Tsao

Bechtel: S. Sultan

Caltrans: A. Siddiqui

MITRE: W. Stevens

4.1.2.2. The MOEs Used and Issues Investigated

Longitudinal capacity (vehicles per lane per hour)

- light-duty vehicle
- heavy bus
- heavy truck
 - single-unit
 - tractor trailer
 - articulated truck
 - mixture
- lateral capacity
- merging of two traffic streams into one
- missed exits

Entry rate

- dedicated on-ramps

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- single check-in area and queue
- multiple check-in areas and queues (light-duty & heavy vehicles)
- transition lane
 - continuous
 - limited to entry areas

Exit rate

- dedicated off-ramps
- transition lane
 - continuous
 - limited to exit areas

4.1.2.3. Stages

The evaluation task was divided into the following 4 stages.

1) Perform qualitative evaluation of all original twenty-two Concepts against two basic groups of MOEs, mainline MOEs and interface (entry, exit and transition lane) MOEs. (Note that those MOEs that depend heavily on Application Scenarios are not included in the evaluation but are expected to be evaluated later for the 6 selected concepts as part of Task C2.)

2) Select those concepts that deserve further quantitative throughput evaluation. Due to the limited time and resources, those Concepts not likely to survive the downselect process, either because of insufficient throughput or other reasons (e.g. safety), will not be given significant quantitative evaluation.

3) Develop preliminary models and tools to perform preliminary quantitative evaluation. Due to the limited time and resources, only preliminary models and tools were developed and hence preliminary evaluation performed.

4) Use of those existing or developing models and tools by Jacob Tsao of UCB, Randy Hall of USC, Petros Ioannou of USC and Bin Ran of U. of Wisconsin at Madison were attempted for the preliminary throughput evaluation.

Note the qualitative nature of the work: AHS throughput, at least the mainline throughput, hinges upon the spacings between two longitudinal adjacent vehicles. However, the main determinants for the spacings are safety and risk aversion. The former requires

in-depth study of possible failure modes, their possible consequences, possible responses to them, and their frequencies. The latter involves public policies.

Failure modes, their consequences and responses, frequencies, and policies are beyond the scope of this early concept development work. Consequently, no precise throughput prediction can be made for C1. A parametric study on the safety spacings was performed and is reported in Appendix B. The evaluation of the 22 concepts was partially based on this parametric study. It was also based on other preliminary analysis and, more importantly, PSA results and other results in the existing literature. When accurate quantitative measures were lacking, engineering judgement was used.

4.1.3 Impact of Concept Characteristics on Throughput

This subsection describes the general impact of each of the concept characteristics and their solutions to AHS throughput. It also ranks the solutions, when appropriate, according to their throughput potential.

4.1.3.1. Distribution of Intelligence

In the context of Task C1, intelligence is referred to as what goes beyond ITS intelligence. The five solutions are autonomous, cooperative, infrastructure supported, infrastructure managed and infrastructure controlled. The first four solutions feature increasing vehicle intelligence while the last three involve increasing infrastructure intelligence. In general, the level of total intelligence increases with the the five solutions, except perhaps that the infrastructure controlled solution calls for less vehicle intelligence than infrastructure managed solution.

The total intelligence of a solution has a large impact on the achievable throughput. Since the first four solutions feature an increasing amount of total intelligence, they provide an increasing amount of throughput. However, the throughput achievable by the fifth solution - infrastructure control - hinges upon the technology. Since there is very

little published literature on this subject and also very little on-going research into such technologies, it is very difficult to assess the achievable throughput and compare it with those achievable by other solutions.

4.1.3.2. Longitudinal Separation

There are three different solutions: free-agent, platoon and slot. Fair throughput comparison requires approximate ranges of spacing values, which in turn require thorough evaluation of their safety. At this early stage of concept development and evaluation, such evaluation is yet to be performed. Through an extensive literature review and much discussion between the team members, it was concluded that the platooning policy should provide more throughput than the free-agent policy but slot policy would provide the least throughput improvement over the throughput on conventional highways, if at all. It was concluded that the slot length would be much larger than the average intervehicle spacing required by either the free-agent or the platooning policies. For details, refer to Appendix B.

4.1.3.3. Mixing of AHS vehicles with Non-AHS vehicles

There are four solutions: continuous barriers between the AHS lanes and the manual lanes, physical barriers with gaps, virtual barriers and full mixing. Because of vehicle uniformity and the absence of interaction between the automated traffic and the manual traffic, the solution of continuous barriers offers the most throughput. For similar reasons, AHS with physical barriers with gaps provides more throughput than that with virtual barriers, which in turn offers more throughput than that with full mixing. Note that in all four solutions except the first, all the AHS traffic, including all heavy-duty vehicles, needs to access and egress the AHS lanes through the manual lanes. Therefore, the throughput of the AHS lanes is subject to the ability of the manual lanes to feed traffic into the AHS lanes and to absorb traffic exiting the AHS lanes. If the manual portion of the highway is congested, the congestion may have a tremen-

dous negative impact on the throughput on the AHS lanes.

The interaction between the AHS traffic and the manual traffic incurred by the three latter solutions may necessitate a small to moderate speed differential between these two lane types. In those AHS with virtual barriers, spill-over of accidents from the manual portion of the highway may severely impact the throughput on the AHS lanes and vice versa. Full mixing of automated vehicles and manually driven vehicles will necessitate large spacings between an automated vehicle and its neighboring manually driven vehicles. Therefore, it offers minimum, if any, throughput gain over the conventional highways.

4.1.3.4. Mixing of Vehicle classes

The two solutions are full mixing and no mixing of different classes of vehicle in the same lane. We assume that AHS vehicles will be grouped into two categories - heavy-duty and light-duty vehicles. Due to the different braking capabilities of these two categories of vehicle, full mixing results in less throughput, in terms of number of vehicles per lane per hour. For details, refer to Appendix B. However, given the low percentage of heavy vehicles among current highway users, it may be difficult to justify dedication of even one lane to heavy vehicles.

4.1.3.5. Entry/Exit

There are two solutions - dedicated on/off ramps and transition lane. This concept characteristic is closely related to that of mixing AHS vehicles with non-AHS vehicles, at least from the throughput point of view. The solution of dedicated on/off ramps of the former can be combined with the solution of continuous barriers for the latter. The throughput implication of the transition lane depends on whether there are physical barriers with gaps or only virtual barriers.

4.1.3.6. Obstacle Detection

There are three different solutions - manual detection and manual avoidance, automatic

detection but manual avoidance and automatic detection and avoidance. Since the feasibility of the latter two solutions is yet to be examined and compared to the first solution, it is difficult to make any judgement of their throughput potential and impact.

4.1.4 General Issues

This section summarizes some general issues associated with the concept characteristics and solutions. We group these issues in two categories: mainline and interface.

4.1.4.1. Main Line Issues

4.1.4.1.1. Lane-changing (including transition lane entry) with significant speed differential but without infrastructure assistance:

It is likely, if not inevitable, that there will be a significant difference between the speeds of two adjacent automated lanes. (The same is true between the transition lane and the adjacent automated lane.) In the presence of a significant speed differential, identification of a receiving gap and coordination for safety during a lane change are essential. Such coordination is most likely conducted through communication among vehicles and/or between vehicles and infrastructure. Without any infrastructure assistance beyond the current definition of infrastructure support in the individual lane-change maneuvers, it may be difficult for the lane-change vehicle to identify the neighboring vehicles with which it needs to establish communication. Even when the communication parties can be identified, it may be difficult for the lane-change vehicle to establish a dedicated communication channel (or multiple communication channels) to the communication parties. These issues must be studied in depth in due course.

4.1.4.1.2. Merging without infrastructure assistance

Merging of two streams of traffic into one will take place on AHS, e.g. at the merging

locations where one lane is dropped. Note that merging locations often involve difference in elevation, e.g. the merging locations at highway-to-highway interchanges. Unlike lane-changing, which can be aborted and retried downstream at a later time, merging in general must be performed successfully within a limited amount of space and time. Failure to do so may result in safety hazards and disturbance to AHS traffic. Safe merging will likely require communication among vehicles. However, without any infrastructure assistance (beyond the current definition of infrastructure support), identification of communication parties could be a problem. Also, even if such identification can be made, establishing a dedicated channel (or multiple dedicated channels) could be a problem. If line-of-sight is needed for gap identification or communication, then long ramps or very sophisticated sensors (e.g. concrete-penetrating) will be required, especially for platooning concepts where two streams of long platoons may be involved. It is presumed in this preliminary throughput evaluation, without further analysis, that systems which lack infrastructure support for merging will thus be limited in throughput at merges.

This problem is particularly serious where the AHS has only one lane. Such a single-lane AHS may exist due to limited demand, which may occur at low-demand locations after widespread AHS deployment or occur at early AHS deployment stages. Merging takes place at any location where two streams of traffic are merged into one. Such locations include the merging points at highway-to-highway interchanges and any place where a lane is being dropped. It also takes place at on-ramps. We will use on-ramps as the example in the following discussion.

There exists virtually no literature on the effect of on-ramp merging on a single-lane highway (each direction), although there is a significant amount of existing literature on that effect on multi-lane highways. For multi-lane highways, it has been demonstrated by different research studies that on-ramp merging indeed has negative impact on the mainline throughput but the

impact decreases as the number of lanes increases. In other words, the smaller the lane number, the higher the negative impact of such merging. Perhaps due to the fact that there exists virtually no single-lane highway in the US or elsewhere, no study has been done on the effect of such merging on a single-lane highway. It is also likely that the negative effect of such merging on the mainline throughput on a single-lane highway is so intuitively clear and large that no single-lane highway was even contemplated and no in-depth studies were warranted. As argued earlier, many reasons pointed to the need for a single-lane AHS. Therefore, the merging maneuver deserves much attention because if it is not performed efficiently and safely, the mainline throughput of a single-lane AHS may suffer a big loss. It is possible that safe and efficient merging will be best performed with some degree of infrastructure assistance. This issue should be studied carefully in due course.

A final note on the role of efficient merging in AHS. Unless the AHS can be designed so safe that there will be virtually no lane-blocking incidents and accidents, one needs to study the effect of lane blockage on the throughput of AHS. When a lane is blocked, the traffic already on that lane needs to be directed onto the adjacent lane or the breakdown lane, if any. Consider a multi-lane AHS where one lane is blocked due to an incident. This blockage requires merging of two streams of traffic into one. Note that, at capacity, traffic build-up on AHS is much faster than its conventional counterpart due to the large capacity of AHS. If merging before the blockage is not done safely and efficiently on the AHS, the effect will be exacerbated. This also points to the need to seriously treat the ability of a concept/design to safely and efficiently perform the merging maneuver as a fundamental issue. Note that, unlike the merging taking place at pre-determined merging locations, such merging at blockage may take place anywhere on the AHS. It is possible that safe and efficient merging at random locations on the AHS requires some infrastructure assistance beyond the infrastructure support as currently defined.

4.1.4.2. Interface Issues

Interface issues are grouped into those related to dedicated on-off ramps and those related to the transition lane.

4.1.4.2.1. Dedicated On/Off-Ramps

Spacing Between Entry/Exit Points

Preliminary but quantitative study has shown that frequent entry/exit points are needed to feed high flow rate on the mainline. Given the current trip length distribution, one automated on-ramp with a capacity doubling that of a manual on-ramp is needed for every mile on the AHS in order to feed a three-lane AHS. The same applies to the off-ramps.

Effect of Manual-AHS transition on Ramp Throughput

Since the manual-automatic transition needs to take place prior to entering the automated portion of the on-ramp (i.e. AHS entry lane), approximately two manual lanes are needed to feed one AHS entry lane. If new highway-to-street interchanges are to be built, then the AHS may lead to extensive infrastructure modification at the AHS-City Street interface. This will require augmented conventional on-ramps if the conventional on-ramps are used. However, this may lead to a shift of congestion from the highway mainline to the AHS-city street interface. Therefore, AHS design and deployment should be integrated with the whole roadway transportation system. A high AHS mainline capacity may not be fully used if the interface issues are not resolved. The same applies to the off-ramps.

Effect of on-ramp merging, particularly for those AHS with only one lane

As argued earlier, merging at on-ramps may have a significant impact on the mainline throughput, particularly for sections of the AHS where only one AHS lane is provided. Note that merging may take place on AHS mainline as well as on-ramps.

4.1.4.2.2. Transition Lane

Effect of Congestion on Manual Lanes on Entry Rate and Exit Rate

If the AHS is equipped with only transition lanes but no dedicated on-off ramps, then all AHS traffic needs to travel through the manual lanes in order to access and egress the AHS lanes. Therefore, the entry rate into and exit rate out of AHS hinge on the congestion level of the manual portion of the highway. Particularly, when the manual portion is congested, either due to recurrent congestion or non-recurrent incidents, the AHS lanes cannot be fully utilized and, more importantly, traffic may be spilled back from the congested manual lanes onto the AHS lanes. Note that the resulting blockage may have a tremendous effect on the mainline throughput, as argued earlier about the effect of lane blockage due to incidents or accidents.

Effect of Disruption to Manual Traffic by Traffic Accessing and Egressing Automated Lanes

The AHS can carry a high volume of traffic, including heavy-duty vehicles. The access and egress of the AHS vehicles through the manual portion of the highway may cause significant disturbance to the traffic on the manual lanes.

More importantly, if the transition lane is not continuous throughout the AHS (which is most likely the case if deployed), i.e. the transition lane is provided only at highway-to-street interface locations, the traffic on the ending transition lane at the AHS egress location needs to be merged with the traffic on the leftmost manual lane. Note that since the egressing traffic could be heavy and heavy vehicles also egress from the location, the merging activities at the location may cause much disturbance to the traffic on the manual lanes.

Also, note that providing a continuous transition lane throughout the AHS requires much right-of-way and dilutes the capacity gain of the AHS. If a continuous breakdown lane is also required, it further reduces the AHS potential for capacity gain.

Ability of Manual On-ramps to Feed Sufficient AHS Traffic

If no dedicated AHS on-off ramps or additional conventional on-off ramps are built, then all the AHS traffic, in addition to the manual traffic, has to access and egress AHS from the manual on-off ramps. This puts a heavy burden on the existing manual on-off ramps. Heavy congestion at the on-off ramps may result, unless they are augmented accordingly.

Effect of Speed Differential on Entry Rate

The AHS is expected to have stable and possibly higher speed than the manual lanes, particularly when the manual lanes are congested. This speed differential may lead to the necessity of a large reception gap for an entering vehicle, which in turn may lead to a lower entry rate into the AHS. Or alternatively, due to the interaction between the automated traffic and the manual traffic on or near the transition lane, the actual speed differential may need to be kept below a certain threshold for safety and efficient entry.

Effect of Merging/Lane-changing on Mainline Throughput

Due to the presence of interaction between the automated traffic and the manual traffic on the transition lane, merging/lane changing may have even higher negative effect on the mainline traffic than those AHS with exclusive dedicated AHS on-off ramps. Again, this effect is more serious when the AHS segment has only one lane.

4.1.5 Evaluation Of 22 Concepts

The focus was on normal operations. First described is the format in which the evaluation results are summarized. For individual concepts, concept characteristics and their solutions are first described and followed by the evaluation results. The results are summarized in the following 10 subsections. Note that multiple but similar concepts may be described and compared under one subsection heading. The following format is used in summarizing the results.

Concept #(s): -(The Subsection Header)

Concept Summary:

- common characteristic solutions
- distinct characteristic solutions

Maneuvers:

- longitudinal travel (vehicle following, speed following)
- lane-changing: disturbance to longitudinal flow
- merging: disturbance to longitudinal flow

Flow Optimization:

- optimization by vehicle
- system optimization

Interface:

Others Considerations: including, for example, system flow control functions in response to incidents

Throughput Rating:

- 1 less than conventional
- 2 similar to conventional
- 3 1 - 2 times of conventional
- 4 2 - 3 times of conventional
- 5 3 times or more of conventional

4.1.5.1. Concepts #1a & 1b

Concept Summary:

- Common: Autonomous, free-agent, full mixing with manual, mixed classes, transition lane
- Difference: 1a - manual sensing 1b - automatic sensing

Maneuvers:

- longitudinal
 - conservative control law anticipating erratic manual driver behavior
 - capacity similar to conventional
- lane-changing
 - no coordination at all
 - manual driver can be overly aggressive
 - automated vehicles cannot be aggressive by conservativeness of control
 - gaps may be too small for manual lane-changing; clusters hinder both manual and automated lane-changing

- even if lane changing is manual, the automated vehicles cannot know the lane-changing attempts of vehicles in adjacent lane and hence won't yield, unless turn signal can be recognized and yielding is built in the control law

• merging

- no coordination at all
- sensing itself may not be sufficient and vehicle intelligence may not be adequate, unlike human vision and intelligence, especially for locations where there is only one AHS lane

Flow Optimization:

- no system-level flow control functions beyond ITS functions
- no lane assignment
- lane traffic condition information possibly part of ITS

Others:

- incident management flow control difficult if done automatically
- non-coordinated merging worsens the impact of incidents

Rating: 1a - 1 or 2 depending on technology. 1b - 1 or 2 depending on technology.

4.1.5.2. Concepts #18 & #4

Concept Summary:

- Common: cooperative, free-agent, mixed classes
- Difference: 18 - continuous barriers, dedicated on-off ramps 4 - gaps in barriers, transition lane

Maneuvers:

- longitudinal
 - 1 - 2 times conventional capacity
- lane-changing
 - coordination helps lateral flow
 - flow stability may suffer, if speed differential is significant
- merging
 - major problem because of lack of infrastructure support, e.g. no static geometry information about merging points like highway-to-highway interchanges

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- merge area may have to be extended so that merging can be performed as lane-changing, particularly for those locations where AHS has only one lane; right-of-way and construction problems result

Flow Optimization:

- no system flow control functions
- no lane assignment
- lane traffic conditions possibly part of ITS

Interface:

- difference in throughput mainly because of interface (smaller speed differential between automated and manual traffic assumed for transition lane; limitations on throughput due to access/egress through manual traffic also assumed)

Others:

- no incident management flow control beyond ITS
- merging problem worsens the impact of incidents

Rating: 18 - 3. 4 - 2-3

4.1.5.3. Concepts #5 & 17

Concept Summary:

- Common: cooperative, platoon, mixed classes, transition lane
- Difference: 5 - gaps in barriers. 17 - virtual barriers

Maneuvers:

- longitudinal
 - flow could be twice as much as conventional or higher
- lane-changing
 - flow depends on lane-changing policy; if full platoon-splitting is required, flow and its stability suffers; "minimum-platoon-split" lane-changing helps flow and stability
- merging
 - without infrastructure support and without using vehicles as conduit for information, merging of two streams of platoons efficiently is difficult (particularly for those

locations where AHS has only one lane)

- note that merging of two streams of platoons is more difficult than merging of two streams of free-agents

Interface:

- physical barrier allows higher speed differential
- platooning with virtual barrier could be unsafe

Flow Optimization:

- no system flow control functions beyond ITS
- no lane assignment

Others:

- no incident management flow control beyond ITS
- merging without infrastructure support worsens the impact of incidents

Rating: 5 - 3. 17 - 2 or 3

4.1.5.4. Concepts #8a, 20, 8b, 6, 16

Concept Summary:

- Common: infrastructure supported, free-agent,
- Difference: 8a - continuous barriers, mixed classes. 20 - continuous barriers, no class mixing, (auto sensing obstacle but stop or manually avoid). 8b - continuous barriers, no class mixing (auto sensing obstacle and automatic avoid). 6 - gaps in barriers, mixed classes. 16 - virtual barriers, mixed classes

Maneuvers:

- longitudinal
 - capacity could be twice the current
 - 20 and 8b can have higher capacity due to non-mixing of classes
- lane-changing
 - coordinated
 - identification of communication parties could be a problem
 - establishing a dedicated channel could be a problem
 - merging
 - lack of infrastructure "assistance" at merging points could make merging inefficient, particularly at

those locations where AHS has only one lane

Flow Optimization:

- system flow control available
- lane assignment available

Interface:

- difference in throughput mainly because of interface

Others:

- incident management flow control is available but should call for early lane changes, rather than relying on merging at the lane blockage

Rating: 8a - 3. 20 - 3. 8b - 3. 6 - 2 or 3. 16 - 2

4.1.5.5. Concepts #9 & 14

Concept Summary:

- Common: infrastructure support, platoon, mixed classes
- Difference: 9 - continuous barriers. 14 - gaps in barriers

Maneuvers:

- longitudinal
 - capacity can be 2 - 3 times of current, depending on spacings
- lane-changing
 - coordinated
 - identification of communication parties could be a problem
 - establishing a dedicated channel could be a problem
- merging
 - lack of infrastructure "assistance" at merging points could make merging very inefficient, especially for one-lane AHS
 - inefficiency could be much more serious than its free-agent counterpart
 - actually, safety could be a problem

Flow Optimization:

- system control optimization available, including platoon sizing

Interface:

- difference in throughput mainly because of interface

Others:

- incident management flow control is available, but should not use merging function, unless absolutely necessary; should use early lane changes, whenever possible

Rating: 9 - 4. 14 - 3-4

4.1.5.6. Concepts #12a, 12b, 10

Concept Summary:

- Common: infrastructure managed, free-agent,
- Difference: 12a - continuous barriers, mixed classes. 12b - continuous barriers, no class mixing. 10 - gaps in barriers, mixed classes

Maneuvers:

- longitudinal
 - lane capacity can be twice the current for #12a and 10
 - lane capacity can be even higher for #12b (no class mixing)
- lane-changing
 - fully coordinated
- merging
 - fully coordinated

Flow Optimization:

- full system optimization

Interface:

- continuous barriers allow higher speed differential

Others:

- full incident management flow control

Rating: 12a - 3. 12b - 3. 10 - 3

4.1.5.7. Concepts #15

Concept Summary:

Infrastructure managed, free-agent, full mixing with manual, transition lane, mixed classes

Maneuvers:

- longitudinal
 - spacing must be set conservatively due to the presence of manually driven vehicles in the same lane
- lane-changing

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- no coordination possible between automated vehicles and manually driven vehicles
- merging
 - no coordination possible between automated vehicles and manually driven vehicles

Flow Optimization:

- system flow control virtually ineffective due to the presence of unequipped vehicles

Others:

- incident management flow control ineffective due to the presence of unequipped vehicles
- lack of coordination at merging points worsens the impact of incidents

Rating: 15 - 2

4.1.5.8. Concepts #19, 13, 11

Concept Summary:

- Common: infrastructure managed, platoon,
- Difference: 19 - continuous barriers, mixed classes. 13 - continuous barriers, no class mixing. 11 - gaps in barriers, mixed classes

Maneuvers:

- longitudinal
 - capacity can be 2 - 3 times the current for #19 and #11
 - capacity can be 3 - 4 times the current for #13
- lane-changing
 - fully coordinated
- merging
 - fully coordinated

Flow Optimization:

- fully system optimization

Interface:

- physical barriers allow higher speed differential

Others:

- complete incident management flow control

Rating: 19 - 4 13 - 4-5 11 - 3-4

4.1.5.9. Concepts #3, 3a

Concept Summary:

- Common: Slot, continuous barriers, no class-mixing
- Difference: #3 - infrastructure controlled. #3a - infrastructure managed (variable slot length)

Maneuvers:

- longitudinal
 - capacity depends on technology and can vary
- lane-changing
 - efficient due to full infrastructure control
- merging
 - efficient due to full infrastructure control

Flow Optimization:

- full system flow optimization

Others:

- full incident management flow control, if the infrastructure control system is fully operational
- the whole system is down if the infrastructure control system fails

Rating: #3 - 2 or 3, depending on technology. #3a - 2 or 3, depending on technology

4.1.5.10. Concepts #2, 2a

Concept Summary:

Slot, Infrastructure control, free-agent, continuous barriers, mixed classes

Similar to #3, except that this concept involves slots of variable length

Similar to #3a, except that this concept involves infrastructure control

Rating: 1 or 2, depending on technology

4.1.6 Reconcepting and Downselect Suggestions/Inclinations

The throughput team reached much consensus regarding reconcepting and downselect suggestions, which is documented in the first subsection. Although the team could not reach a unanimous consensus on a number of

issues, it identified the majority views on these issues, which are labeled as "inclinations" and documented in the second subsection. Some Inclinations are stated as such because the rationale was not primarily about throughput, which was the jurisdiction of the Team.

4.1.6.1. Reconcepting and Early Loser Suggestions from the Throughput Team:

On Mixing Of AHS And Non-AHS Vehicles:

(1) "Full Mixing" of AHS and non-AHS vehicles in a lane is not considered as AHS but something short of AHS. (This solution was motivated in part by applications of automation technologies to rural areas.) Therefore, it should be treated separately from the current concept development effort, which focuses on the target AHS (i.e. the end state of AHS).

On Distribution Of Intelligence:

(2) Create a new distribution called "Infrastructure Assisted". The Infrastructured Assisted solution provides more functionality than the Supported in that communication from the infrastructure to INDIVIDUAL vehicle or platoon and vice versa is allowed at merging locations, e.g. on-ramps, highway-to-highway interchanges and other merging locations.

(3) Eliminate Autonomous Concepts as target mature AHS concepts. (Although some variations of them could be good intermediate steps toward mature AHS.)

(4) Eliminate Infrastructure Controlled concepts. (This suggestion is made in the absence of a clear understanding of the Virginia Tech concept.)

On Obstacle Detection And Avoidance

(5) Leave Obstacle Detection and Avoidance in for further analysis. There does not exist sufficient evidence regarding the viability of the automated solutions. Treat this concept characteristic as an attribute that needs to be explored for each selected concept, instead of as a concept discriminator.

4.1.6.2. Some Throughput Team's Inclinations Regrading Early Loser etc.

On Mixing Of AHS And Non-AHS Vehicles

(6) Eliminate Concept 17, which supports platooning with virtual barriers, for primarily safety (and also throughput) reasons.

(7) Eliminate Concept 15, at least the version described in the Concept Description Document, for reason of attribute incompatibility. The current Concept description calls for Infrastructure Managed distribution of intelligence while allowing Full Mixing of automated vehicles and manual vehicles in a lane.

(The two Inclinations above were actually team consensus but were not provided as Suggestions because the rationale was not primarily about throughput, which was the jurisdiction of the Team.)

On Entry/Exit

(8) An inclination is to eliminate Entry/Exit attribute as a concept discriminator. However, realizing the fact that some concepts, e.g. the autonomous ones and a solicited concept involving mechanical linkage between two longitudinally adjacent vehicles) do not require special entry/exit facilities, the team thought that Entry/Exit should remain as a concept discriminator, at least until those concepts have been ruled out. Those concepts that do require either dedicated on-off ramps or transition lane but differ only in this concept characteristic can be combined for the following reason. Dedicated on- and off-ramps are a necessity for locations with heavy entry/exit demand. Without them, congestion on the manual portion will limit access to and egress from AHS lanes. A transition lane is needed for light-demand areas. Entry/exit configuration is likely to be site-specific, depending on the availability of land, demand volume, construction cost, etc. At this point, the solution set should perhaps be changed from the current two solutions (i.e. dedicated and transition lane) to a different set of two solutions (i.e. "dedicated/transition lane", and none).

On Mixing Of AHS And Non-AHS Vehicles

(9) Entry/Exit solutions are closely related to the attribute "Mixing of AHS vehicles with Non-AHS vehicles", particularly the solutions "Continuous Barriers", "Barriers with Gaps" and "Virtual Barriers". Consequently, it is better to use Physical Barriers (continuous for a long segment or with gaps) and Virtual Barriers (continuous for a long segment or with gaps) as two solutions for this concept discriminator.

On Mixing Of Vehicle Classes

(10) Another inclination is to eliminate "NO MIXING" of vehicle classes [throughout the AHS; not even transitory mixing] as a solution and hence eliminate the whole concept characteristic as a concept discriminator. However, some team members disagreed with this.

To support non-mixing of vehicle classes throughout the AHS would require a dedicated on-/off-ramp for each vehicle class at each interchange that entry/exit of the class of vehicle is to be supported. A set of 8 highway-to-highway connector ramps is required for each class of vehicles at each of such interchange. The structures are likely to be very complex and costly. Also, in a configuration where there is only one truck lane, blockage of the truck lane after an incident implies the blockage of all truck traffic until the clearance of the blockage. In addition, the current mix of vehicle classes on the highway shows a low truck and bus percentage, which casts doubt on the desirability of dedicating lanes to specific vehicles classes throughout the AHS. (Local authorities will have the option of dedicating lanes to specific vehicle classes.) Some member questions the "requirement" of supporting trucks on AHS and believe it may be dropped in the future after evidence against it accumulates. If it is indeed dropped, much effort will be wasted if the Consortium concentrates exclusively on the Mixed solution.

4.2 SYSTEM SAFETY

The material provided in this section briefly summarizes the results of the safety concept

evaluation team meeting held at the Richmond Field Station of UC Berkeley September 7 and 8, 1995. This meeting was called to allow the safety team to compare individual evaluations of the concepts for the AHS. Attendees at the meeting included P. Goddard (Hughes), R. Hettwer (Hughes), E. Page (Bechtel), L. Valavani (Volpe), J. Castro (CALTRANS), B. Michael (PATH), and S. Shladover (PATH). The meeting was successful in providing a clear consensus on several of the concept dimensions and on those concept dimensions which could not be resolved and would need to be carried forward into the next round of concept development (C2).

4.2.1 Baseline AHS System

For the purposes of evaluating the various concepts and concept dimensions, the team used a baseline of a mature AHS system. This was taken to mean that in at least some areas, the AHS would be multi-lane - having several adjacent automated lanes of traffic at one time. The approach of evaluating the effectiveness of a concept or concept dimension based on a mature AHS, operating under worst case conditions, was taken to ensure that concepts which did not have adequate growth potential would be penalized. For some of the concept dimensions, the difference between single lane and multi-lane AHS operation is of major consequence for safety.

4.2.2 Evaluation Approach

The evaluation approach used by the team during the meeting consisted of evaluation of the concept dimensions based on a combination of evaluation metrics provided by Bret Michael and some of the safety MOEs which had previously been developed. The specific evaluation measures the team used included:

1. Emergency and failure handling capability - This capability was considered to be the ability of the concept dimension to aid in handling or preventing rogue vehicles, including aberrant behavior caused by sudden failure of vehicle or infrastructure equipment. Sudden, safety critical

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failures of vehicles and/or the appearance of obstacles in very dense urban traffic in multi-lane AHS applications was given particular scrutiny.

2. Inclement weather - Did the concept dimension assist in inclement weather capability, hinder it, or was it indifferent?
3. Media event potential - Does the concept dimension have a potential for causing multi-vehicle crashes? These crashes were felt to have an impact on the acceptance of the safety of the AHS out of proportion to their rate of occurrence.
4. Complexity - How testable and verifiable was the system approach?
5. Coordination required - How much inter-vehicle and wayside-vehicle communications were required under both normal and emergency situations?
6. Data/Sensor fusion potential - How complex was the data from the sensors and the processing of that data needed to support system operation under normal and emergency operation?
7. Maintenance deferral problem potential - How subject was the approach to safety problems caused by maintenance deferral by either the vehicle owner or the roadway operator?
8. Average collision rate - How well was the concept or dimension expected to perform with respect to the average number of collisions?
9. Average collision speed and severity - How well did the concept or dimension perform with respect to average severity of any collisions?
10. Average number of vehicles per collision - What was the expected impact of the concept or dimension on the number of vehicles per accident? This was separate from the media event size multi-vehicle collisions.
11. Robustness - How well did the concept or concept dimension appear to handle failures in any part of the system? Could it reasonably be expected to survive multiple failures without compromising safety?

Each of the evaluation measures was evaluated qualitatively, not quantitatively. The team did not consider the design detail currently available able to support detailed measurements of any of these measures. Also, the team decided that measurement of each individual concept against these measures was without merit. Instead, the concept dimensions which underlie the concepts were evaluated. This resulted in a set of safety team evaluations which clearly indicate the team's recommendations and those areas where further work will be needed before the team can make a decision regarding the concept dimension. The needed work tended to be additional studies which need to be completed and documented so the team can compare the results with the concept dimensions.

4.2.3 Concept Dimension Evaluation Results

This section provides a brief overview of the results of the team's evaluation of the concept dimensions. Some of the major issues are presented where appropriate. However, most of the results are provided without detailed backup based on the conversations between team members during the meeting.

4.2.3.1 Entry/Exit

Two options are available for this dimension; dedicated entry and exit ramps or transition lanes. All members of the team agreed that dedicated entry and exit ramps are preferred for their ability to control rogue vehicles, allow controlled and more thorough check-in of vehicles if needed, and prevent gore point problems associated with impalement and/or rejection of entering vehicles in transition lanes due to local traffic surges. All of these are potential issues in very dense urban traffic during peak traffic hours. Overall, entry/exit was not considered a major discriminator between possible approaches. All team members felt that this was probably allowable as a roadway operator's decision. On a scale of one to five (five highest), entry/exit was considered to be of level one importance. The team recommends that entry/exit be considered an implementation

issue, best solved by local roadway operators and should not be used as a concept discriminator. The AHS should be designed to support both approaches.

4.2.3.2 Mixing of AHS and non-AHS traffic in the same lane

Separate automated lanes with barriers between the automated lanes and the non-automated lanes were considered safest by the team. Mixing of AHS and non-AHS traffic may be possible without major safety impact in a few, limited cases, in single, barriered lanes. However, in multi-lane implementations, mixing of automated and non-automated traffic creates a major compromise in system safety. The team rated this dimension a three (of five) in importance. One of the major issues with barriers for single lane concepts that the team felt deserved mention was the potential for blockage of the lane, due to jamming between the barriers of a vehicle in a collision. This could lead to a multi-vehicle collision when the first vehicle (e.g. articulated truck) suddenly blocks the lane. Vehicles are not generally expected to maintain 'brick wall' stopping distances during automated travel.

4.2.3.3 Mixing of vehicle classes

The safety team concluded that mixing of vehicle classes during active use of the roadway would compromise safety. Allowing different classes to use the automated roadway during different times would be acceptable if the roadway is checked for damage and debris after heavy vehicles have been allowed use of the roadway. The team considered this dimension to have an importance ranking of three on a scale of one to five (five highest).

4.2.3.4 Obstacle avoidance

The safety team was unable to provide a definitive recommendation with respect to obstacle detection and avoidance approaches. Some members of the team believe that any manual involvement in obstacle avoidance is unsafe, other members strongly disagree believing that driver

takeover may be safer than automated avoidance in some, low traffic conditions. Neither side of the ensuing discussion was able to cite any significant studies to support their beliefs. Thus, both manual and automatic obstacle detection and avoidance approaches need to be included in the C2 concept development. The current concepts include only one concept, 1A, with manual detection and avoidance. This indicates a strong predilection to discard manual obstacle detection and avoidance on the part of the concept developers. The team recommends that manual detection and avoidance not be discarded from consideration until definitive study of the possible options and their impact can be performed. In some cases, manual intervention may have the potential to be safer than automatic avoidance. Combined manual and automatic detection and avoidance techniques may have potential and should also be explored. This dimension was considered to have an importance ranking of 3 to 4.

4.2.3.5 Separation policy

Traditional slot concepts, being based on infrastructure control were considered unsafe by the safety team. This is primarily a robustness issue. After discussion, the team was unable to realistically distinguish between platoon and free agent concepts. A free agent equates well to a one vehicle platoon. The team consensus was that the AHS will have to be designed to allow both free agent and platoon concepts to be implemented. There is some preliminary evidence from precursor studies and from studies conducted at PATH that platoons may be safer at some traffic densities due to low inter-vehicle collision speeds within platoons. However, these studies make a number of simplifying assumptions, chiefly that all colliding vehicles remain in the same attitude during the collision (all rear end collisions, single lane or single file), that may invalidate the studies. Detailed simulation and analysis is needed, including detailed simulation of multiple automated lanes and the post initial collision vehicle vectoring, which is common in real world collisions. Both platoon and free agent separation policies need to be studied further

during the - C2 activity. The team recommended that slot concepts be dropped from further consideration. This dimension was considered to have an importance ranking of 4 to 5.

4.2.3.6 Distribution of intelligence.

The safety team consensus was that all infrastructure control concepts were too prone to catastrophic failure due to common cause or common mode failures. Major multi-vehicle collisions were considered to be too likely when failure occurred for infrastructure controlled options to deserve further consideration. The safety team considered the other four possible distribution of intelligence options to be, more correctly, layers in a well developed AHS system instead of separate concepts. The AHS must support operation as an infrastructure managed system. It must also support operation, albeit possibly at a lower throughput, as an infrastructure supported, as a cooperative, and as a autonomous (driver alertness is an issue here) system. The team felt that the difference in operation should be dependent on the infrastructure equipment which has been installed and on whether or not it is operational at a given time. The team found that the concept that should be explored is how to provide the needed layering of functionality to allow the AHS to respond to differences in local installations and to failures with appropriate spacing and speeds so that safety is not compromised. The different options, which are currently being cited, were not seen by the safety team as appropriate concept discriminators. The options with lesser infrastructure support seemed to be more appropriate for lower capability 'modes' of operation, to be appropriate for areas that do not need to support high throughput, or possibly to provide an evolutionary path to an infrastructure managed design. An infrastructure managed design with its ability to maintain visibility over a significant roadway area, and to recommend or command emergency response of vehicles when unexpected events occur, was considered to allow the maximum safety achievable without undue vulnerability to common mode or common cause failures.

Concepts that did not allow centralized emergency coordination of vehicle responses would need to maintain greater spacing and hence lower throughput to achieve operational safety equivalent to an infrastructure managed approach. This dimension was considered to have an importance ranking of 5.

4.2.4 **Current Conclusions**

The safety team concluded that the concepts as currently developed cannot serve as adequate safety discriminators for the concept selection currently in process. Safety evaluation of the individual dimensions was possible for some of the dimensions. Other dimensions will require further, more detailed study during the next concept selection phase (C2). The distribution of intelligence, with the exception of infrastructure controlled, was found by the team to be less a concept than an appropriate layering of functionality, all of which needs detailed exploration as the program progresses.

4.2.5 **Safety Ratings**

For the overall evaluation exercise (Section 4.6 below), it was necessary to generate numbers that captured the consortium's best guess as to a safety rating for the various concept. These were generated as follows.

The overall evaluation team reviewed the safety team report, and based on that report, assigned preliminary safety evaluation ratings to each concept. These numbers were given to the safety team for review. After some revision, they were used in the overall evaluation.

4.2.5.1. Safety Numbers

The concepts were rated by giving each characteristic a safety rating on 0-10, and each dimension a rating on how much it influences safety. These were the numbers reviewed with the safety team. They are discussed in Appendix C.

4.2.5.2. Final Safety Rating Results

Each Concept was given an overall safety score by a weighted adding of the safety

rating of each of its characteristics. This was normalized to a range of 0 to 100%, with higher scores being better. The safety

ratings that resulted from this process were. The safety scores are graphed below.

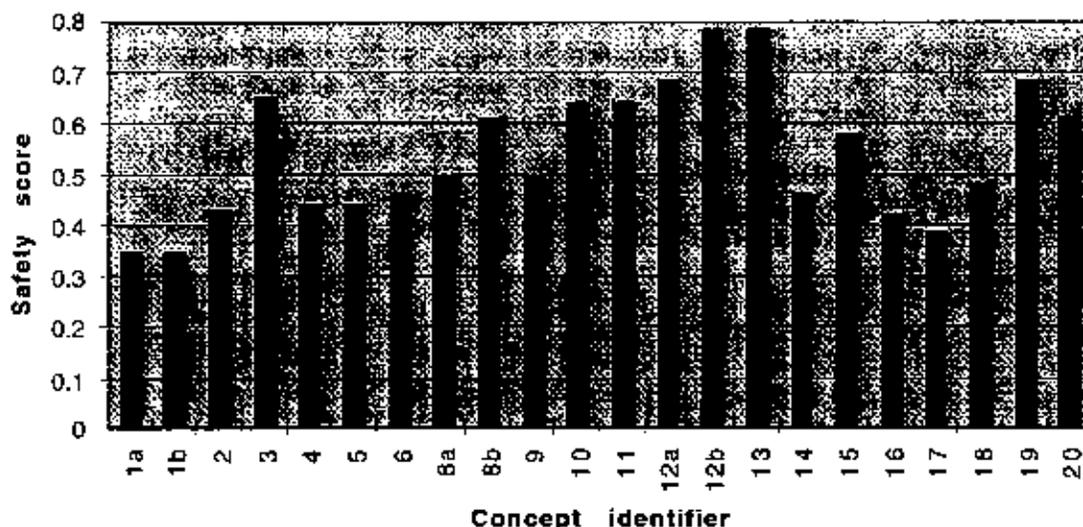


Figure 4.2.4-1. Overall Concept Safety Rating

4.3 COST EVALUATION

4.3.1 Introduction

This section concentrates on ranking the Concepts with regard to cost, from a purely qualitative perspective. The process requires quantitative judgments for comparison purposes only, but no functional cost estimates have been performed in this evaluation. The 22 Concepts have been considered as "end-state," with no accommodations for an evolutionary path. An average degree of complexity was also assumed for each Concept in an attempt to accommodate the various vehicle types and settings (rural, urban, and suburban) that currently exist.

The initial step in this evaluation process was to identify the potential cost contributors and define the key cost elements. Cost is attributable to a variety of factors, but it was imperative that the number of discriminators be limited to perform an effective assessment. The following list identifies these "key" cost elements.

1. Infrastructure and Support Capital Costs-Civil/Structural

2. Infrastructure and Support Capital Costs-Systems and Instrumentation
3. Vehicle-Based Capital Costs-Instrumentation
4. Operations and Maintenance

Cost Element 1 encompasses the costs associated with building or modifying the functional portion of the highway to meet the AHS service requirements. This includes the paved surface, plus entry or exit ramps and any elevated portions of the freeway. Cost Element 2 accounts for the cost of building the infrastructure network. This could involve the construction of a central control facility, as well as any remote communication stations. Cost Element 3 represents the vehicle costs attributed to AHS functions only. This cost element does not attempt to account for the total vehicle cost, but concentrates on those costs added purely to support AHS. Cost Element 4 accounts for the operation and maintenance expenses for the infrastructure and the vehicles.

These key cost elements attempt to encompass most of the cost issues required to construct and operate a transportation facility of this nature. Given the developmental stage of the AHS program, a

variety of cost issues were not considered in this evaluation. These issues apply generically to the AHS program and, for the most part, are not Concept dependent. Specifically, the following cost issues were not considered in this evaluation, but must be reviewed at a later stage of development to determine their impact on AHS:

1. Drivers Education
2. Insurance and Liability
3. Technological Developments
4. Operation Inefficiencies

With the cost elements and general assumptions defined, the next step of the evaluation was to clarify the cost sources associated with each cost element. This allowed a scoring system to be developed to identify those Concepts that had the potential for maximum cost in each cost element. Because the dimensional characteristics define each of the 22 Internal Concepts at a high level, pursuing the relative costs on an individual Concept basis was impractical. A more practical manner of addressing the cost issue was to isolate possible costs that relate to each dimensional characteristic.

For each cost element, the assumption was that two or three of the Dimensions envelop most of the related costs. As the applicable Dimensions were reviewed, scores were assigned to each dimensional characteristic to designate the potential for high cost versus low cost. A score of *10* for a specific dimensional option represented the potential for maximum cost, while *0* represented no cost impact. Weighting each Dimension acknowledged the fact that, for a particular cost element, one Dimension may affect cost more significantly than another. The weighting was designed so that scores of *10* for each applicable Dimension resulted in a combined score of *100* for that particular cost element. Thus, a Concept with a score of *100* for a given cost element represents the maximum possible cost associated with that cost element.

The Concept composite ranking was determined by assigning relative weights to each of the four cost elements and summing these weighted values. The weights for each cost element were assigned on a percentage

basis and reflect the relative contribution of each cost element toward the maximum cost possible for a given Concept. Marketability was a consideration when assigning a weight to Cost Element 3, since this element represents cost incurred directly by the consumer. The assumption was that the automotive market would not tolerate an extremely high cost associated with the AHS features, whereas the other capital cost elements could absorb a potentially higher cost, since funding would originate with state and federal governments, as well as private enterprises.

The 22 initial candidate concepts were ranked from high to low after calculating a composite score for each concept. This ranking reflected the data compiled for each cost element, but sensitivity analyses were performed to test for consistencies and to identify any reasonable conclusions.

4.3.2 Cost Element Summary

A relative scoring table, concept scoring matrix, and cost element rating graph have been prepared for each of the four cost elements. These results are presented in Appendix D and summarized below. The scoring table identifies the Dimensions that have been considered to encompass the cost for each cost element, plus the associated weighting. This table also assigns the relative scoring for the dimensional options and provides the assumptions and rationale for these values. The scoring matrix displays the scores and calculates an element rating for each Concept. The rating graph displays as a bar graph the results of rating each Concept.

The relative scoring tables reflect the range of costs associated with each of the applicable Dimensions. Given the high level at which the Concepts are currently defined, the manner of incorporating each of these dimensional options into AHS is unspecified.

To maintain consistency throughout the evaluation, the relative scores were based on the highest practical cost for each of the options. The term "practical" has been included in this description to emphasize the fact that informed judgments were applied

when scoring the Concepts and restraint has been applied when contemplating a worst-case cost scenario. The assumptions and rationale portion of the tables attempt to outline the extent to which the subteam considered the dimensional development. As the Concepts become more clearly defined, these scores and assumptions should be reviewed and adjusted accordingly.

A review of Cost Element 1 offers a prime example of the range of possibilities that exists for each option. A dedicated AHS facility with continuous barriers has been assigned a score of 10 based on the maximum level of complexity. However, this aspect of the system can be instituted several different ways, as dramatized in Appendix D.

The values applied in the scoring tables reflect potential cost and, as noted, should be reevaluated as the Concepts become more clearly defined. The preceding example is intended to identify alternatives for one specific dimensional option, as well as acknowledge the range of alternatives that exist for other dimensional options.

4.3.2.1. Cost Element 1

Cost element 1 addresses the costs associated with building or modifying the physical portion of the highway. Two Dimensions were considered to envelop the costs associated with this element. The Dimension entitled "AHS and Non-AHS Mixing" identifies the requirements for interconnecting an AHS freeway with a non-AHS freeway. This Dimension was regarded as the major civil/structural cost element due to direct association with the physical infrastructure, and is weighted accordingly. The Dimension entitled "Class Mixing" outlines the necessity for class-specific lanes on the AHS freeway. This Dimension was considered to affect selective portions of the infrastructure only and, as a result, was weighted much lower.

4.3.2.2. Cost Element 2

Cost Element 2 addresses the cost of instituting the systems and instrumentation network necessary to control the AHS

environment. Three Dimensions were considered to envelop this cost element. The Dimension entitled "Distribution of Intelligence" identifies the level of participation the infrastructure has in controlling the operation of the AHS facility. This Dimension outlines the basic system functions of the infrastructure and, as a result, was weighted heavily. The Dimensions entitled "Obstacle Detection" and "Separation Policy" were considered to define specific parameters that enhance the system. These Dimensions were weighted lower, since the impact on the system cost depends entirely on the role of the infrastructure. The complexity required to adequately detect roadway obstacles warranted a slightly heavier weighting between these two Dimensions.

4.3.2.3. Cost Element 3

Cost element 3 addresses the cost of adding AHS-related sensors and intelligence to a vehicle. Two Dimensions were considered to envelop this cost element. The Dimension entitled "Obstacle Detection" specifies the most sophisticated sensor requirements on an AHS vehicle. This was weighted heavily due to the wide field of view required on-board the vehicle to adequately detect obstacles, plus the extensive coordination required to support automated evasive action. The Dimension entitled "Distribution of Intelligence" defines a much broader range of sensor requirements, but none as complicated as avoiding and detecting obstacles; thus the lower weighting.

4.3.2.4. Cost Element 4

Cost element 4 addresses the relative costs attributed to infrastructure and vehicle O&M. By definition, these costs depend on the first three cost elements; therefore, three Dimensions were considered to envelop this cost element. The most dominant Dimension from each of Cost Elements 1, 2, and 3 was assumed to represent the O&M for that cost element. The dimensional scoring mirrors that applied to the Dimension in the previous ratings, for each respective cost element. The O&M for the infrastructure system was weighted the heaviest to reflect the relatively

short service life of an electronic-based system and the extensive network of personnel required to prevent extended down times. The O&M for the physical infrastructure was weighted marginal to reflect the resources required for snow removal and other maintenance tasks along the extensive highway system. The O&M of the vehicle was weighted low, since the AHS-specific maintenance required for the vehicle will be minimal.

4.3.3 Composite Cost Ranking

The relative weighting table, Table 4.3-I, identifies the weights applied in the composite analysis to each of the four cost elements. This table summarizes the make-up of the composite analysis and outlines the rationale used to determine these weightings. Cost Elements 1 and 2 have been considered equally heavy when calculating the composite ranking. As described in the introduction, this evaluation considered potential cost with an emphasis on practical applications. Therefore, most of the potential cost was assumed to be linked to the assembly of the infrastructure. Structural capital costs will be required at the beginning of the operation cycle, while the system capital costs will be cyclical and will hinge on the instrumentation service life. If a present value analysis were to be performed on these costs, the assumption would be that these costs would be fairly

equal and encompass most of the AHS costs included in this evaluation. Cost Elements 3 and 4 have also been considered equally in this composite ranking. The AHS-specific vehicle costs have been weighted lower than the infrastructure costs as a result of marketability considerations. These costs, for the most part, must be passed directly to the vehicle consumers and will become a sensitive issue when determining retail prices. Government subsidies may play a role, but competitive marketing will be an incentive to minimize these costs. The large volume of vehicles expected to use the AHS roadways constitutes a sizable cost, but the cost of the AHS-related options alone were considered to be less than either component of the infrastructure. When considered on an annualized basis, the O&M for a typical existing freeway is less costly than the capital expenses. Certain components of the AHS O&M are unpredictable, but a similar relationship was assumed in this evaluation.

The concept ranking matrix, Table 4.3-II, summarizes the cost element ratings and calculates the Concept composite ranking. Figure 4.3-1 displays the results of this ranking in bar graph format. The resulting values have been sorted from high to low and presented in Table 4.3-III to allow easier comparison of the Concepts. These scores are ratings and do not relate directly to dollars. Higher scores indicate more expensive.

**Table 4.3.3-I. Composite Ranking—All Cost Elements
(Impact Proportioned by Relative Weighting)**

Weight	Cost Element	Assumptions and Rationale
30%	<i>Cost Element No. 1</i> Infrastructure Capital Costs – Civil/Structural	<ul style="list-style-type: none"> • High cost of inserting/modifying existing well-developed infrastructure • Long useful life of physical infrastructure
30%	<i>Cost Element No. 2</i> Infrastructure Capital Costs – Systems and Instrumentation	<ul style="list-style-type: none"> • Relatively short service life for infrastructure instrumentation • Need to upgrade/update systems and equipment frequently to utilize advancing technology
20%	<i>Cost Element No. 3</i> Vehicle-Based Capital Costs	<ul style="list-style-type: none"> • Relatively short service life to utilize advancing technology • Limited to increased cost associated only with AHS "options" • Lower outlay required when comparing the contribution of each capital-based cost element towards the maximum possible cost
20%	<i>Cost Element No. 4</i> Operations and Maintenance	<ul style="list-style-type: none"> • High levels of maintenance standards for roadway instrumentation to assure reliable operation • Relatively high operating costs of infrastructure-assisted system • AHS vehicle maintenance costs will not be significantly higher than for non-AHS vehicle

Table 4.3.3-II. Summary of Cost Element Rating and Calculation of Concept Composite Reading

Concept No.	Cost Element Percentage				Total
	0.30	0.30	0.20	0.20	1.00
	Cost Element No. 1 Rating (Infrastructure & Support Capital Costs, Civil/Structural)	Cost Element No. 2 Rating (Infrastructure & support Capital Costs, Systems & Instrumentation)	Cost Element No. 3 Rating (Vehicle-Based Instrumentation Capital Costs)	Cost Element No. 4 Rating (Operations and Maintenance Costs)	Composite Ranking
1a	8	7	9	9	8
1b	8	7	100	19	28
2	80	90	38	95	78
3a	100	79	79	82	86
4	40	7	88	31	38
5	40	7	88	31	38
6	40	28	79	49	46
8a	80	28	79	64	61
8b	100	28	79	64	67
9	80	38	79	64	64
10	40	59	79	67	59
11	40	69	79	67	62
12a	80	59	79	82	74
12b	100	59	79	82	80
13	100	69	79	49	49
14	40	38	79	49	49
15	8	59	79	55	47
16	32	28	79	46	43
17	32	7	88	28	35
18	80	7	60	42	47
19	80	59	51	78	68
20	100	28	51	60	61
HIGH	100	90	100	95	86
AVERAGE	59	39	73	57	55
STANDARD DEVIATION	33	27	20	23	20
MEDIAN	60	33	79	62	60
LOW	8	7	9	9	8

**Table 4.3.3-III. Composite Ranking
(Sorted From Highest to Lowest Cost)**

Max of Composite Ranking	
Concept No.	Total
3a	86
13	83
12b	80
2	78
12a	74
19	68
8b	67
9	64
11	62
8a	61
20	61
10	59
14	48
15	47
18	47
6	46
16	43
5	38
4	38
17	35
1b	28
1a	8

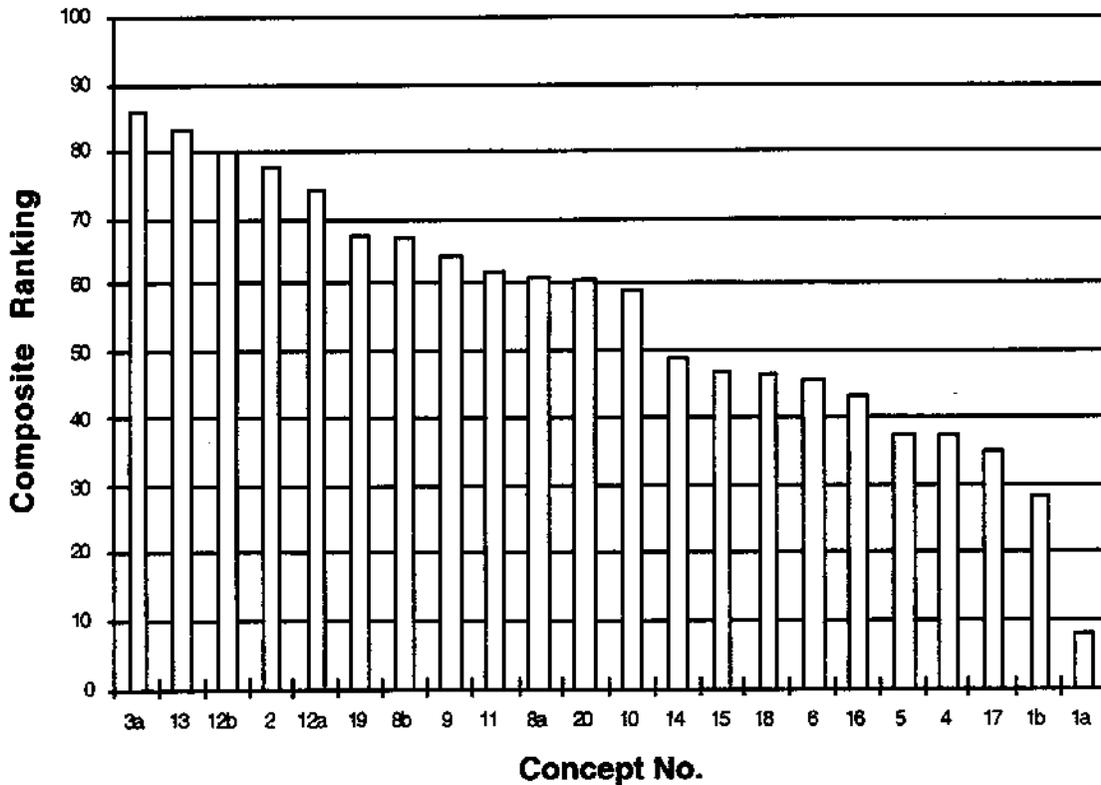


Figure 4.3.3-1. Composite Ranking (Highest to Lowest)

4.3.4 Sensitivity Analyses

The sensitivity analyses were considered essential in determining the consistency of the evaluation results. The weights applied when rating each of the cost elements, as well as when performing the composite ranking, were the focus of these analyses. Various composite percentages were applied to recalculate the rankings and these results were compared with the original data. A similar comparison was made with each of the four cost elements. The goal of these analyses was to identify common results that would support a reasonable conclusion.

The ranking of individual Concepts from high to low with respect to cost was never intended to identify the single most-expensive Concept. It is impossible to accurately perform this task given the current high level of the Concepts. Instead, grouping the Concepts into high-, medium-, and low-cost groups would be possible if the results were consistent throughout these sensitivity analyses. This grouping could then be used to identify the AHS characteristics with the highest potential cost and possibly to support a cost-benefit analysis.

The first step in determining sensitivity involved modifying the percentages that were applied in the composite ranking. This process could be used to determine if one cost element is able to control the results. The specific results are in Appendix D.

Independently modifying the applied weights from each cost element formed the basis of the next step of the analysis. Adjusting the composite percentages did not significantly affect the results; therefore, the original percentages were considered to be acceptable or, as a minimum, representative. Changing the internal weights of a cost element without modifying any other parameters isolated the direct impact of this change and more clearly defined the significance of each cost element in the composite ranking. This also generated more

data to support the creation of cost-groups and help define their alignments.

4.3.5 Cost Conclusions

The original phase of this evaluation process attempted to rank the Concepts from high to low with regard to cost. While this effort was completed, it is not clear that the ranking alone is actually a useful tool. The second phase of this evaluation explored the weights applied in the composite ranking itself, as well as the internal weights applied to the cost elements. The additional data generated in this exercise verified that consistencies existed in the evaluation. Reviewing this data showed that cost groupings could be created to identify those Concepts consistently occurring at either the high or the low end of the cost scale. Three groupings were created as a result of this effort. The sensitivity data showed that seven Concepts consistently occur at the high end of the composite ranking, regardless of how the weights are modified. It also showed that six Concepts consistently appear at the low end of the composite ranking. The remaining nine Concepts fluctuate in their relative positions, but are uniformly found in the middle portion of the ranking. The following list, as displayed in Table 4.3.5-I, identifies the groupings, plus the common attributes shared in each group.

- *Group A: Toward the high end of the composite ranking scale*—Characterized by a fully dedicated AHS facility with considerable infrastructure support (Concepts 2, 3a, 8b, 12a, 12b, 13, and 19)
- *Group B: Mid-range of the composite ranking scale*—Characterized by dedicated AHS lanes with moderate infrastructure support (Concepts 6, 8a, 9, 10, 11, 14, 15, 18, and 20)
- *Group C: Toward the low end of the composite ranking scale*—Characterized by slightly modified existing roadway and an emphasis on vehicle-based intelligence (Concepts 1a, 1b, 4, 5, 16, and 17)

Table 4.3.5-I. AHS Internal System Concepts (Concept Groups)

Candidate Concept Identifiers	1a	1b	2	3a	4	5	6	8a	8b	9	10	11	12a	12b	13	14	15	16	17	18	19	20
Distribution of Intelligence																						
Autonomous	X	X																				
Cooperative					X	X													X	X		
Infrastructure Supported							X	X	X	X						X		X				X
Infrastructure Managed				X							X	X	X	X	X		X					X
Infrastructure Control			X																			
Separation Policy																						
Free Agent	X	X	X		X		X	X	X		X		X	X			X	X		X		X
Platooning						X				X		X				X	X			X		X
Slot				X																		
Mixing AHS & Non-AHS Vehicles in Same Lane																						
Dedicated lanes with continuous physical barriers			X	X				X	X	X			X	X	X					X	X	X
Dedicated lanes with some gaps in the physical barriers					X	X	X				X	X				X						
Dedicated lanes with virtual barriers																		X	X			
Full Mixing	X	X															X					
Mixing Vehicle Classes in Same Lane																						
Mixed	X	X	X		X	X	X	X		X	X	X	X			X	X	X	X	X	X	X
Not Mixed				X					X						X	X						X
Entry/Exit																						
Dedicated			X	X				X	X	X			X	X	X					X	X	X
Transition	X	X			X	X	X				X	X				X	X	X	X			
Obstacle																						
Manual sensing and avoidance of obstacles	X																					
Automatic sensing, stop or manually avoid																				X	X	X
Automatic sensing and automatic avoidance maneuver if possible	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			

Group "A" - High
 Group "B" - Mid-Range
 Group "C" - Low

These groupings highlight the cost issues associated with reshaping this country's highway network. It seems to indicate that costs could be controlled by making use of the existing resources. However, a cost-benefit analysis must be completed to adequately interpret these conclusions.

4.4 FLEXIBILITY/DEPLOYABILITY CONCEPT EVALUATION

This section summarizes the process and findings of the "Flexibility/Deployability" subgroup of the Automated Highway System Work Breakdown Structure C1 task, *Develop Initial Suite of Concepts*, one of five concept evaluations performed for the C1 task. The task was initiated 25 July 1995 and essentially concluded with the presentation at the Systems Requirements Review #1 on 22 September. The findings were summarized in a presentation at the AHS Workshop #2, 20 October.

4.4.1 Summary

The evaluation of the 23 concepts for Flexibility/Deployability was beneficial from five perspectives:

- 1) Assessment of the concept dimensions to the Flexibility/Deployability concerns,
- 2) Observation of design peculiar attributes to enhance Flexibility/Deployability,
- 3) Identification of requirement deficiencies,
- 4) Development and training in the use of decision analysis tools, and
- 5) Team building.

In regard to item 1), Assessment of the concept dimensions to the Flexibility/Deployability concerns:

The findings are tabulated as follows:

In regard to item 2), Observation of design peculiar attributes to enhance Flexibility and Deployability: Much of the discussion of design peculiar attributes was contingent upon application specific opportunities. These and other design centered issues will

be addressed in the continuing concept development phases of the program.

In regard to item 3), Identification of requirement deficiencies: The Objectives and Characteristics document has since been improved to eliminate some contentious statements, and requirements development is part of the spiral development process.

In regard to item 4), Development and training in the use of decision analysis tools: Many of the Consortium members learned what is planned to be a frequently applied decision analysis process.

In regard to item 5), Team building: The consortium is composed of people from different corporate, government and academic environments. This task helped to form better relationships within the consortium—professional and inter-personal.

4.4.2 The Objective

The Flexibility/Deployability subgroup, referred to henceforth simply as the Flexibility group, was challenged to assess the relationship between concept dimensions and eleven (11) of the AHS System Objectives and Characteristics (SOC) [Automated Highway System Objectives and Characteristics 2nd Draft; May 22, 1995.]. Figure 4.4.2-1 lists the SOC topics designated as "flexibility issues"—as compared to the other four evaluation groups: Throughput, Safety, Cost and Social Acceptability. The Concept Dimensions were created by the Concept development (C1) team and are defined in section 2 of the C1 Report. Twenty three concepts were developed to support this analysis and are defined in section 3 of the C1 Report.

4.4.3 The Process

The Flexibility group applied a structured decision analysis method. The process assured the findings are defensible and supported by the whole team. The process steps are defined as follows and described in the following paragraphs:

- Review Objectives and Characteristics for Discriminating Criteria

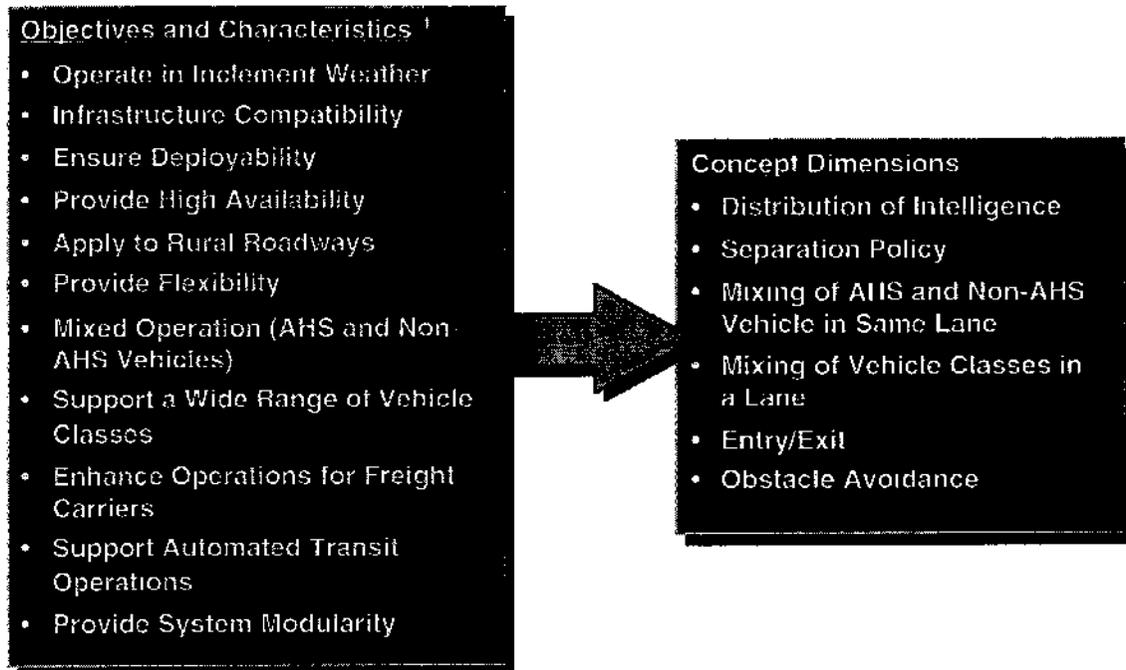


Figure 4.4.2-1 Flexibility Evaluation Objective

- Develop Criteria Definitions and Scoring Symbols
- Score Each Concept Based on Criteria, Completing the “Flexibility Assessment Table”
- Process and Analyze the Data
- Report Findings

4.4.3.1. Review Objectives and Characteristics for Discriminating Criteria

The “flexibility” paragraphs of the SOC document were scrutinized for salient discriminators. Specifically, the following sections (SOC page numbers in parentheses) prescribe the evaluation boundaries:

- Inclement Weather (pg. 23)
- Infrastructure Compatibility (pg. 26)
- Phased-in Implementation of Technology (pg. 27)
- Public Acceptance (pg. 27)
- High Availability--System Malfunction (pg. 28)
- Emergency Vehicles (pg. 28)
- Rural Roadways (pgs. 28 and 31)
- Support a Wide Range of Vehicle Classes (pg. 31)
- Enhance Operations for Freight Carriers (pg. 32)

- Enhance Operations for Transit Operations (pg. 32)
- Provide System Modularity (pg. 33)

4.4.3.2. Develop Criteria Definitions and Scoring Symbols

A coarse evaluation methodology to perform relative qualitative comparisons was ascribed to this task. To achieve robustness, symbols were selected as a scoring proxy in lieu of absolute values. The evaluation criterion were decomposed into five relative categories and specific definitions for each criteria were documented. One of the eleven criteria and discriminating evaluation definitions is shown below as an example. The complete set of criteria is provided in Appendix E.

Infrastructure Compatibility

- (&) This concept requires extensive modifications to the infrastructure, e.g. creation of new travel lanes or entry/exit lanes.
- (#) This concept requires some modifications to the infrastructure, e.g. installation of communication and control equipment.

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- (-) This concept requires minimal modifications to the infrastructure, e.g. lane markers, magnetic nails or tape.
- (0) This concept requires no modifications to the infrastructure.

Two other scores, "+" and "x", are also used in some criteria to indicate better than current.

4.4.3.3. Score Each Concept Based on Criteria. Completing the "Flexibility Assessment Table"

To facilitate the collection and manipulation of the data, a "Flexibility Assessment Table" was created. Each team member performed an assessment of each of the 23 concepts, based on the criteria discussed in section 2.2. A representation of the Table is shown in Figure 4.4.3-1.

	Inclement Weather	Infrastructure Compatibility	Public Acceptance	Phase-in Technology	High Availability - Malfunction	Emergency Vehicles	Mixed Type with non AHS	Vehicle Classes	Freight Carriers	Transit Operations
01a										
01b										
02										
03										
03a										
20										

Figure 4.4.3-1 Flexibility Assessment Table

4.4.3.4. Process and Analyze the Data

Numerical values were assigned to replace each of the symbols. The scale spanned 15 points from negative nine (-9) to positive six (+6). A summation for each of the concepts was performed and the original 22 concepts were then ranked--from 1 to 22--for each of the evaluators.

Note: A concept was created at meeting August 23rd, resulting in a total of 23 concepts. The evaluation process was repeated to incorporate the additional concept.

A cumulative ranking was prepared and the results were examined by the Flexibility group. Data entry errors were corrected. This analysis was shown to be insensitive to single and multiple scoring changes.

Each of the criteria were considered to be of equal importance for the initial evaluation. A weighted evaluation, whereby proportional factors were assigned based on

a survey of the Program Manager's Council, was also performed. This is a fairly coarse analysis and the findings were not affected by the assignment of the weighting factors.

A spreadsheet program (Microsoft Excel) was utilized to facilitate the data manipulation. Appendix E provides the converted data sheets, summary tables and graphs.

4.4.3.5. Report Findings

The methodology and findings of this process were presented and discussed at a C1 Concept Team meeting August 20th and also at the AHS SRR #1 September 21st. The findings were combined into the team report presented at the AHS Workshop #2, October 20th. The success of the process was dependent upon providing an objective, structured approach and assuring team validation of the methodology and the results.

4.4.4 The Team

Team membership of the Flexibility group included representatives from many of the AHS core participants. Jerry Sobetski performed the role of group leader.

<u>Personnel</u>	<u>Organization</u>
Michelle Bayouth	Carnegie Mellon
Albert Chen	Delco
Tom McKendree	Hughes
Bret Michael	PATH
Steve Schuster	Hughes
Asfand Yar Siddiqui	Caltrans
Jerry Sobetski	Lockheed Martin

The group membership was intentionally broad, presuming the task would be best accomplished by "systems thinking" persons representing dissimilar points of view. The size of the group proved to permit discussion of diverse opinions--and yet allow completion of approximately 80% of the task within one month.

4.4.5 The Results

4.4.5.1. Analysis

The scoring results are shown in Table 4.4.5-I and Figure 4.4.5-1. The conclusions drawn from the data and team discussion follows:

- a) The scoring results were reviewed for reasonableness and predictability. The data provided what the team felt were expected results; there were no surprises.
- b) Two outliers were identified. The common trait of the two concepts was *infrastructure control* distribution of intelligence.
- c) The group sought out concept dimensions common to the best ranked concepts. The two best scored concepts were based on a *vehicle autonomous* distribution of intelligence. Other dimensions common to the favorably scored concepts are: *free agent* separation policy, *full mixing*, *dedicated lanes*

with virtual barriers, mixed vehicle classes within a lane, and *transition lanes* for entry exit.

- d) At the opposite end of the spectrum, in addition to *infrastructure control* distribution of intelligence, *dedicated lanes, dedicated entry/exit*, and *not mixed vehicle classes* were identified as poor architecture solutions for deployment and flexibility.
- e) Two simple sensitivity analyses were performed. As mentioned earlier, the relative scoring was not affected by changing some of the individual scores. Also, weighting of the criteria (based on a survey of the PMC) did little more than change the relative position of some concepts by a couple of places.

4.4.5.2. Process Critique

The interpretation of the System Objectives and Characteristics document, and specifically how this analysis process linked the rural highway environment to the mixed traffic scenario was challenged. The mixing of AHS and non-AHS equipped vehicles is a significant flexibility and deployment issue; however, this issue is not unique to the rural highway environment. Therefore, the evaluation was performed correctly--providing for the scoring of the concepts relative to their ability to accommodate mixing of types of vehicles. The implication anticipated as concept development matures. For many of the concept development team members, this was their first experience with this form of decision analysis methodology. This task was valuable not only for the findings relative to the concept dimensions, but also as education and team building.

A note of caution. This is a coarse analysis intended to identify relative pros and cons of the concept dimensions. The evaluation team performed this analysis for an unspecified application. Specific design solutions and geographic application sites analysis could cause challenge of these findings. Also, the fidelity of the analysis does not support specific critique of any one concept versus another.

Table 4.4.5-I. Concepts in Rank Order from Most to Least Flexible/Deployable

Candidate Concept Identifiers	1b	1a	15	16	17	11	12a	12b	10	4	18	8a	9	8b	13	5	6	19	14	20	3a	3	2
Distribution of Intelligence																							
Autonomous	X	X																					
Cooperative				X					X	X					X								
Infrastructure Supported			X								X	X	X			X		X	X				
Infrastructure Managed		X			X	X	X	X							X		X			X			
Infrastructure Control																					X	X	
Separation Policy																							
Free Agent	X	X	X	X			X	X	X	X	X	X	X			X			X				X
Platooning				X	X								X		X	X		X	X				
Slot																				X	X		
Mixing AHS & Non-AHS Vehicles in Same Lane																							
Dedicated lanes with continuous physical barriers						X	X			X	X	X	X	X			X		X	X	X	X	X
Dedicated lanes with some gaps in the physical barriers					X			X	X						X	X		X					
Dedicated lanes with virtual barriers			X	X																			
Full Mixing	X	X	X																				
Mixing Vehicle Classes in Same Lane																							
Mixed	X	X	X	X	X	X	X		X	X	X	X	X		X	X	X	X					X
Not Mixed							X							X	X					X	X	X	
Entry/Exit																							
Dedicated						X	X			X	X	X	X	X			X		X	X			X
Transition	X	X	X	X	X			X	X						X	X		X					
Obstacle																							
Manual sensing and avoidance of obstacles		X																					
Automatic sensing, stop or manually avoid										X							X		X				
Automatic sensing and automatic avoidance maneuver if possible	X		X	X	X	X	X	X	X	X		X	X	X	X	X		X		X			X
RANK	4.1	5.6	7.0	7.3	7.7	8.8	8.8	10.3	10.7	11.2	11.2	11.3	11.8	12.0	12.5	13.3	13.7	13.8	14.5	14.8	16.8	21.3	21.6

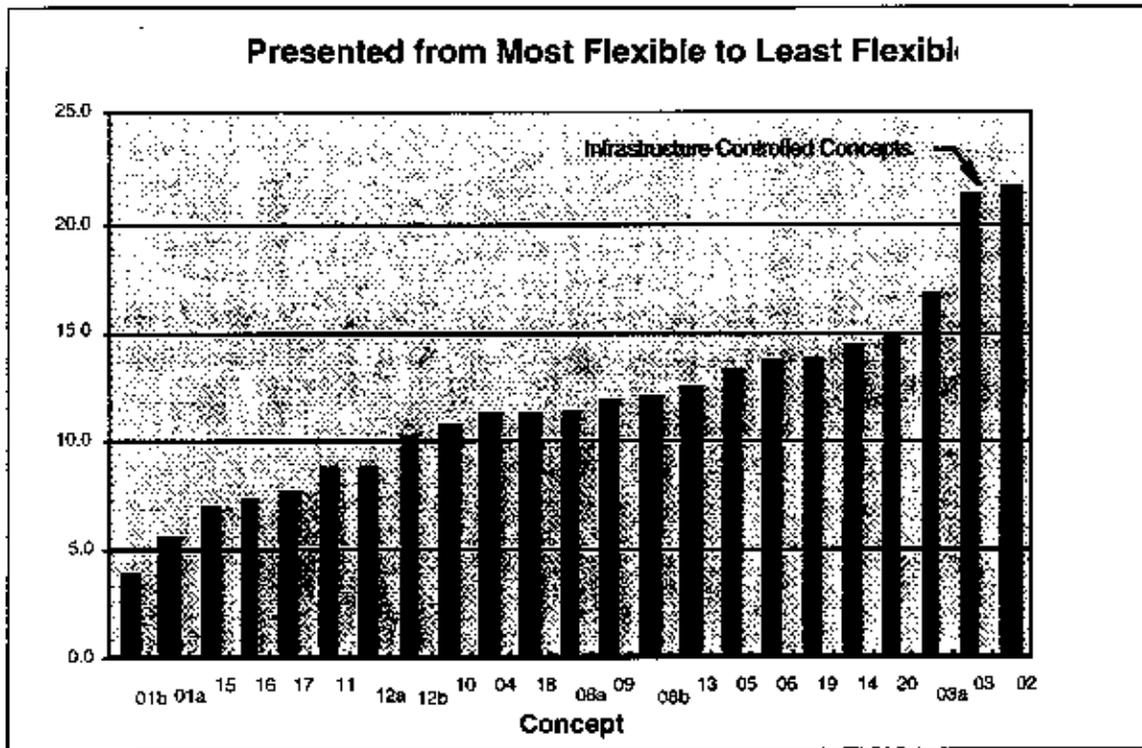


Figure 4.4.5-1. Rank order of concepts for Flexibility/Deployability

4.4.5.3. Flexibility and Deployment Findings

The findings of the evaluation are summarized in Table 4.4.5-II and Table 4.4.5-III.

Table 4.4.5-II. Observations relative to the Objectives and Characteristics

Objectives and Characteristics	Observations
Operate in Inclement Weather	⇒ Technology Dependent ⇒ Not Well Supported by Autonomous Architecture (assuming no vehicle supported communications)
Infrastructure Compatibility	⇒ Movable Physical Barriers Preferred
Ensure Deployability	⇒ Emergency Vehicle Support Facilitated by Communication to AHS Traffic
Provide High Availability	⇒ Availability is a Function of Reliability
Support a Wide Range of Vehicle Classes	⇒ Possible for All Architectures
Enhance Operations for Freight Carriers	⇒ Consider Priority Use, Not Just Access
Support Automated Transit Operations	⇒ Consider Priority Use, Not Just Access
Provide System Modularity	⇒ Possible for All Architectures

Table 4.4.5-III. Findings: Concept dimensions vs. Flexibility/Deployability

Architecture	Favored Dimension	Indifferent to the Flexibility Evaluation	Discouraged Dimension
Distribution of Intelligence	Autonomous	Cooperative Infrastructure Supported Infrastructure Managed	Infrastructure Control
Separation Policy	Free Agent	Platooning Slot	
Mixing of AHS and Non-AHS Vehicles in Same Lane	Dedicated Lanes with Virtual Barriers Full Mixing		Dedicated Lanes with Continuous Physical Barriers Dedicated Lanes with some Gaps in the Physical Barriers
Mixing of Vehicle Classes In a Lane	Mixed		Not mixed
Entry / Exit	Transition		Dedicated

4.5- Acceptability

This section of the C1 Final Report consists of that portion of the evaluation of the twenty-two original consortium-generated concepts relative to the overall category of acceptability issues.

4.5.1 Introduction

This report documents the work performed within the Acceptability component of the overall Concept Development Task of WBS C1. It covers the work performed since the Technical Interchange Meeting (TIM) in Denver the last week of July 1995. The work that is documented in this report consists of the following areas:

- Formation of the Acceptability Team
- Development of the set of evaluation criteria
- Methodology for performing the evaluations
- Methodology for derivation of the aggregated concept evaluation results
- Depiction of the overall concept rankings based on the Acceptability Team's analysis
- Discussion of the findings, including interpretation, conclusions, and recommendations

4.5.2 Formation Of Team

The Acceptability Team was assigned the task of considering a particular subset of the AHS performance objectives and characteristics contained within *Automated Highway System (AHS) System Objectives and Characteristics 2nd Draft (May 22, 1995)*. These issues were related to the social, user, and political acceptability of AHS and was generally referred to as the acceptability issues. The formation of the Acceptability Team was a very easy and natural task since built within the framework of the AHS Consortium's overall program is the Societal and Institutional (S&I) group that is looking at numerous related issues. The other advantage of having the Acceptability team be comprised of Societal & Institutional group staff, is that the people making up the S&I group are well distributed among the consortium organizational

core members, though not all core organizational members, however, they truly reflect the views of the core organizations from an S&I perspective. The Acceptability Team was comprised of the following people:

- Mark Miller (California PATH), Team Leader
- Janie Blanchard (Bechtel)
- Matt Hanson (Caltrans)
- Avraham Horowitz (GM)
- Haris Koutsopoulos (CMU)
- Alan Lubliner (PB)
- Edith Page (Bechtel)
- Habib Shamskhov (PB)

4.5.3 Evaluation Criteria

The final list of evaluation criteria was formed from an iterative process based on input from the entire C1 Team at the in-progress concept evaluation team meeting held at PATH in August as well as subsequent meetings among a subset of the Acceptability Team. There was a very substantial list of potential criteria that was pared down to reach this final list (See next section on Section 4.5.4 OMITTED CRITERIA). Suggestions made at the August meeting were, for the most part, incorporated into the decision-making process to develop the final list with some final modifications, however, made by the Acceptability Team. The final list consisted of the following twelve criteria, grouped into four major categories:

MOBILITY/ACCESS

- Trip Time Predictability
- Trip Time
- Accessibility
- Intermodal Transportation Operations

USER ISSUES

- Adaptability/Training
- Driver Participation (level of engagement in non-driving activities)
- Driver Participation (level of engagement, ability to monitor the goings-on of the system and ability to communicate with the system)

ENVIRONMENT

- Vehicle Emissions
- Fuel Consumption

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- Travel - Demand Management/ Transportation Systems Management Policies (TDM/TSM)

OTHER

- Ease of Construction and Maintenance
- Ease of Traffic Operations

The original set of eight attributes for the Acceptability category from the Objectives and Characteristics document is as follows:

1. Enhance mobility
2. More convenient & comfortable traveling
3. Reduce environmental impact
4. Easy to use
5. Facilitate intermodal & multimodal transport
6. Disengage driver from driving
7. Support TDM policies
8. Support sustainable transportation policies

The set of criteria used in the evaluation is as follows:

- A. Trip time predictability
- B. Trip time
- C. Accessibility -
- D. Intermodal
- E. Adaptability/training
- F. Driver participation (I) [driver disengagement]
- G. Driver participation (II) [ability to communicate with system]
- H. Vehicle emissions
- I. Fuel consumption
- J. TDM/TSM
- K. Ease of construction & maintenance
- L. Ease of traffic operations

An exact and complete correspondence between these two sets cannot be made since the Acceptability team modified the list in their review of the original 8 attributes in conjunction with suggestions made by the C1 team at the August meeting.

The correspondence is given in Table 4.5.3-I.

4.5.4 Omitted Criteria

Numerous topics were brought up for consideration during both the August meet-

Table 4.5.3-I. Correspondence between original set of attributes and final evaluation criteria selected.

ORIGINAL SET OF ATTRIBUTES\ FINAL EVALUATION CRITERIA	
1.	A. and B.
2. & 4.	E.
3.	H. & I.
5.	D,
6.	F. and G.
7.	J.
8.	No correspondence as team felt this was a non-discriminator among the concepts at least in their present form Criteria C., K., & L. have no counterparts in the original list of eight as these criteria were added by the team, and original criteria #8 was not used in the evaluation.

ing and subsequent discussions within the Acceptability Team regarding potential evaluation criteria. These issues, which are listed below, were felt to be significant yet were omitted from further consideration for the evaluation because (1) there was likely to be insufficient information with which to evaluate the concepts relative to such issues, (2) such criteria were really not concept discriminators, considering the current stage in the concept development, that is, their very high level of description, even at a qualitative assessment, (3) such criteria were already addressed in other criteria, or (4) such criteria were already addressed by other teams.

Even with the twelve criteria that the team eventually selected there was some doubt as to whether or not they were concept discriminators. This suspicion was proved out, as several team members chose for several of the criteria the "U" score.j The Acceptability category was especially prone to this occurrence as at least some of its topic areas were less quantitative than the throughput, cost, and safety categories. The omitted criteria are listed below. These issues are important, and as the concepts get substantially more developed, may more easily submit to investigation.

- Ride smoothness
- Acoustic noise
- Visual impact
- Electromagnetic fields
- Driving characteristics (local increases in emissions)
- Incentives for efficient use of available resources (sustainable transportation policies): modal vehicles
- Incentives for efficient use of available resources (sustainable transportation policies): infrastructure
- Community goals (neighborhood growth/development and infrastructure construction)
- Land use patterns
- Market demands (different user needs [commercial, transit, private], price, rollout plan)
- Progressive phased deployment
- Equity
- Privacy
- Sustainable transportation policies

4.5.5 Evaluation Criteria And Ranking Levels

Appendix F lists each of the twelve evaluation criteria accompanied by the complete set of gradation levels and descriptions. Where possible, the middle ranking level designated by "0" was associated with a neutral or no impact grade. This was not, however, feasible for all twelve criteria (See for example, the following criteria and associated description for their "0" grade: Intermodal, Adaptability/Training, Driver Participation (I), Driver Participation (II), and TDM/TSM).

4.5.5.1. Mobility/Access

- Trip time predictability
- Trip time
- Accessibility
- Intermodal

4.5.5.2. User Issues

- Adaptability/training
- Driver Participation (I) (Disengaged if desired)
- Driver Participation (II) (Engaged if desired)

4.5.5.3. Environment

- Vehicle Emissions
- Fuel Consumption
- Transportation Demand, Management (TDM)/Transportation, System Management (TSM) Policies

4.5.5.4. Other

- Ease of construction & maintenance
- Ease of traffic operations

4.5.6 Methodology For Performance Of The Evaluation

The process of evaluating the concepts was by nature a very qualitative endeavor, based on best professional judgment as well as any research results known to each team member in his or her knowledge base of information. Of course, each team member had the full set of write-ups for each concept to aid them in the evaluation. These write-ups, however, did not always prove to be the best source of information to execute the evaluation, because of the variability in the write-ups, from writing style, depth of knowledge of each concept developer, and level of detail contained within each document. An additional method sometimes used to assist in the evaluation was to concentrate on the six dimensions (distribution of intelligence, separation policy, mixing of AHS and non-AHS vehicles in same lane, mixing of vehicle classes in same lane, entry/exit, and obstacle detection/avoidance) and investigate the dimension(s) which was(were) the true determinant(s) of the impacts of each of the concepts relative to each of the evaluation criteria.

4.5.7 Methodology For Derivation Of Results

For each of the twelve evaluation criteria, each team member had a choice of the following five ranking levels or grades from which to choose: "++", "+", "0", "-", "--", and "U". Obviously, the "++" represented the most attractive score while "--" represented the least attractive score. The "U" score was used to allow the team members to express their inability to assign a grade, however qualitative, for any of the

twelve criteria. The fact that the team members were not forced to make a selection was done because it was thought that the criteria within the Acceptability category might more readily associate itself with some uncertainty. Even the criteria that were eventually chosen from a substantially larger set of potential evaluation criteria, a lot of which were thought to be either non-concept discriminators or insufficient information about them, would be shown to require evaluators to answer with "U". The category labeled "U" generally stated that "unable to determine x due to lack of sufficient information". It was felt that such a category to capture the uncertainty sentiment was important to include in the evaluation.

A numerical score was assigned for each of the five grading options for each criteria, i.e. for "++", "+", "0", "-", and "--" as 4, 2, 0, -2, and -4, respectively. The raw data from the individual team members was first aggregated by giving equal weight to each team member who actually made a selection for each concept and evaluation criteria. As a result of having the choice to select this "U" option, not all 7 team members "voted" for each concept/evaluation criteria pair. The summary score used for each cell of the Acceptability assessment matrix (Table 4.5.7-D) was an average or normalized score for each cell, i.e. the total score for that cell divided by the number of team members who actually selected a score, and not "U". It was important to factor out the differences in the number of scorers, otherwise, a concept could be penalized simply because not every one voted for one of the 5 scores. The aggregated Acceptability assessment matrix consisted of twenty-two columns (concepts) and twelve rows (criteria).

Of the 264 cells in the 12 x 22 assessment matrix, approximately 16% of them contained raw scores (excluding the "U" vote) that had major differences among them, i.e. a spread of either three or four gradation levels. The team was unable to meet either in person or via a conference call to reconcile the differences. It was possible, however, to discuss with some individual team members some of the major differences where their vote was the outlier

to better understand where the major differences arose from, whether it was a difference in assumptions, in their knowledge/information base or in their best professional judgment.

There were two areas where variability was allowed due to uncertainty. The first area was whether to keep or omit one of the evaluation criteria, namely, Driver participation (II). Four of the seven team members voted "U", and thus any representation of the results including that criteria would necessarily represent only a minority view. Instead of eliminating this criteria from further consideration, it was suggested by the team to include both cases in the sensitivity analyses to investigate the impact of this criteria. The second area was in the set of weights assigned to the twelve (or as just indicated, in some cases eleven) criteria. The default set of weights was equal weight for all criteria. Opinion from team members was solicited on different sets of weights to test out to perform sensitivity analyses to address the uncertainty in knowing which set of weights to use. Different sets of weights were used in conjunction with the original set of evaluation criteria as well as the slightly modified set of criteria (Driver participation (II) omitted).

The following sets of weights were used in the sensitivity analyses run:

1. Default set of weights: equal weights among the criteria
2. Trip time predictability, Accessibility, Vehicle emissions, Ease of construction & maintenance had equal weight and three times the weight of all other criteria, which were weighed equally among themselves.
3. Vehicle emissions, Fuel consumption, Ease of construction & maintenance, and Ease of traffic operations had equal weight and three times the weight of all other criteria, which were weighed equally among themselves.

TABLE 4.5.7-I. ACCEPTABILITY ASSESSMENT

EVALUATION CRITERIA:	CONCEPT #										
	1a	1b	2	3a	4	5	6	8a	8b	9	10
MOBILITY/ACCESS:											
Trip time predictability	0.8	0.8	1.86	2.67	2.14	2.29	2.43	1.86	2	2.57	2.43
Trip time	0	0.4	0.83	1	1	1.33	1.5	1.83	2.33	3	1.5
Accessibility	1	1.33	0.8	0.8	0	-0.67	0.8	0.8	0.4	0.33	0.4
Intermodal	-0.2	0.2	1	0.33	0.33	0	1	1.67	0.33	1.33	1

USER ISSUES:											
Adaptability/training	1.67	1.67	0.67	0	0.67	-0.67	0.67	1	1	0	0.33
Driver participation (I)	-2.29	1	3.33	3.33	3.33	3	3	3.67	3.33	3.33	3
Driver participation (II)	4	0.67	-1.33	-0.67	0	-1.33	-1.33	-0.67	0.67	-0.5	1.5

ENVIRONMENT:											
Vehicle emissions	1.2	1.67	2.71	2.33	1.57	2.57	1.86	2.14	2.29	2.86	1.86
Fuel consumption	1.2	1.2	2.83	2.4	2.4	3	2.6	2.17	2.33	3.33	2.6
TDM/TSM policies	-2	-2	0.5	0	-1.5	-1.5	-0.25	0.25	-0.25	0.25	0.5

OTHER:											
Ease of construction & maint.	0	-0.29	-3.14	-3.14	-1.43	-1.43	-2	-2.57	-2.29	-2.57	-2.43
Ease of traffic operations	0.29	0.86	-0.29	0.29	-0.33	0	0.57	0.57	0.29	0.29	0.57

EVALUATION CRITERIA:	CONCEPT #										
	11	12a	12b	13	14	15	16	17	18	19	20
MOBILITY/ACCESS:											
Trip time predictability	2.43	1.86	2.57	2.29	2.57	1.2	1.86	2	1.29	1.57	1.71
Trip time	1.57	1.5	2.67	3	2	1.6	1.83	2	0.83	2.17	1.5
Accessibility	0	0.8	0.8	0.8	0.33	0.8	0.8	0	0	0	0.4
Intermodal	1	1.33	0.33	0.33	1	1	1	0.33	0	1	-0.33

TABLE 4.5.7-I. ACCEPTABILITY ASSESSMENT (CONTINUED)

EVALUATION CRITERIA:	CONCEPT #										
	11	12a	12b	13	14	15	16	17	18	19	20
USER ISSUES:											
Adaptability/training	0	1	0.67	-0.33	0	0.8	1	0	0	-1.33	-0.33
Driver participation (I)	3.33	3.67	3.33	3	3	2.67	3.33	2.67	0	0.57	0.57
Driver participation (II)	1	1	0.5	0.5	-1	0.67	0.67	2.67	2	0	0.67
ENVIRONMENT:											
Vehicle emissions	2.71	2.14	2.29	3.14	2.71	2.4	1.86	2.57	2	2.43	1.86
Fuel consumption	3.17	2.17	2.33	3.33	3.17	2.4	2.6	3	2	3.17	1.83
TDM/TSM policies	0	0.5	0.5	1	0.25	1	0.75	-0.5	-1	1	-0.25
OTHER:											
Ease of construction & maint.	-2.71	-2.71	-3.29	-2.71	-2.29	-1.5	-0.67	-0.67	-1.71	-3.29	-2.57
Ease of traffic operations	0.29	0	0	0.29	0.29	-0.33	0.33	-0.33	-0.29	0	0.29

Each of these sets of weights were used with and without the inclusion of the Driver Participation (II) criteria.

4.5.8 Evaluation Results

The results of the evaluation are depicted in the Figures 4.5.8-1. Similar figures in the appendices, which depict all the alternative sensitivity analyses, are ordered both by concept number as well as by evaluation score. The former method readily shows results corresponding to the original ordering of the concepts which were clustered by certain of the six dimensions. The latter method of illustrating the results clearly indicates where changes in scores occur as well as extent of such changes, i.e. steepness of changes in heights of bars corresponding to each concept score:

Labels used in the above figures are described as follows:

- Driver Participation (II) DP (II)
- Trip time predictability TTP

- Accessibility A
- Vehicle emissions VE
- Ease of construction & maintenance ECM
- Fuel consumption FC
- Ease of traffic operations ETO

4.5.9 Findings: Interpretation, Conclusions, And Recommendations

Even though numerical scores were assigned and calculations were made from which a single summary score was derived for each of the twenty-two concepts, the objective was not to pick out the top six concepts. There was definite clustering of concepts in the top tier of concept scores from which it would be inappropriate to say much about the absolute top six scores. It would be important to make statements about such clustering. It is, however, relatively easy in some cases to confidently say, "eliminate concepts X, Y, and Z". The general objective is to recognize features or dimensions that the more successful

CONCEPT RANKINGS: ACCEPTABILITY
12 CRITERIA, EQUAL WEIGHTS

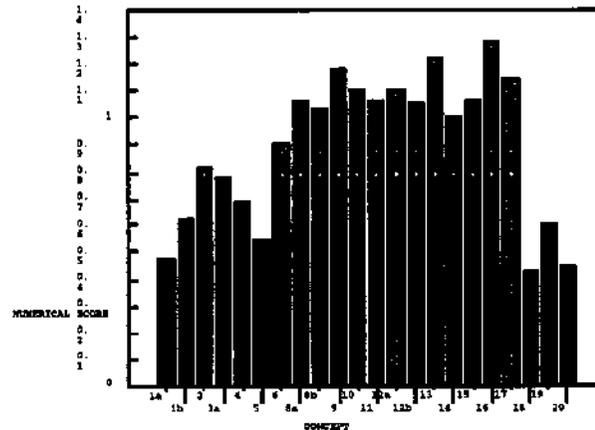


Figure 4.5.8-I. Acceptability Evaluation Results

concepts, relative to this evaluation, have in common. There may, for example, be multiple tiers or levels in the concept rankings, and, of course, differences among the concept scores within the same tier are too close to be able to say that such differences were statistically significant. Moreover, there is insufficient data to make such claims.

Raw data indicated a high level of clustering around the three middle range grading levels (+,0,-) for almost all criteria (exception: Driver Participation (I)). Approximately 16% of the assessment matrix cells of disaggregate raw data contained scores (excluding "U" vote) with major differences, i.e. a spread of three or four gradation levels. Some criteria were sometimes difficult to evaluate either because such criteria were not deemed by the evaluator to be a concept discriminator or there was insufficient information, especially Driver Participation (II) and TDM/TSM. Generally, though not without exception, concepts 6-17 scored higher than either 1-5 or 18-20 across sensitivity analyses with and without the inclusion of Driver Participation (II). The following three conclusions may confidently be made about the findings of this analysis:

- automated obstacle detection *and* avoidance is *very* important
- some form of infrastructure involvement is important (support or manage)
- platoons generally looked on positively, not exclusively though

These three findings remained fairly consistent even allowing for the sensitivity analyses, not exclusively though or without exception, (See the two sets of figures 1, 5, and 9 [all 12 criteria] and 3, 7, and 11 [Driver participation (II) thrown out]). The one notable consistency throughout the evaluation analysis is that automated obstacle detection and avoidance is very important and so confidently it may be said that concepts 18 through 20 should be deleted from further consideration, or rather, the dimension of manual control of obstacle avoidance should be deleted from further consideration.

It is suggested that variation should be maintained in following original dimensions: separation policy, mixing of AHS/non-AHS, mixing of vehicle classes, entry/exit.

4.6 COMPOSITE SCORING

An attempt was made to combine the various evaluations into an overall evaluation. The process illustrated to the participants how difficult it is to combine multiple, often conflicting, attributes into a single, overall rating, without making badly mistaken implicit assumptions.

4.6.1 Developing the Composite Weightings

As expected when alternatives are evaluated from different viewpoints, the ratings of the five teams varied considerably. For example, the minimal alternatives (such as 1a) were given good ratings in cost and flexibility, but

low in safety and throughput. The Program Management Council agreed that a resolution of these differences requires relative weighting of the various factors. To this end, the results of the five evaluation teams were turned into numerical ratings. In many cases, the team gave multiple ratings, which were combined using weighting factors provided by the teams themselves. The throughput team assigned a range of ratings, so both high and low are shown. The following Table 4.6.1-I summarizes those ratings. Except for cost, higher is better. Since these are ratings and not actual measures the values are not linear, e.g., a score of 20 is not necessarily twice as good as a score of 10.

Table 4.6.1-I. Evaluation Ratings of the Candidate Concepts

Concept Number	Safety Composite	Cost Composite	Thruput Low	Thruput High	Flexibility	Acceptability
1a	70	8.10	1	2	16.00	0.44
1b	70	28.30	1	2	15.40	0.70
2	85	78.60	1	2	-11.40	0.79
3a	129	85.90	2	3	1.50	0.75
4	87	37.30	2	3	10.10	0.66
5	87	40.30	3	3	7.90	0.70
6	92	45.40	2	3	5.60	0.93
8a	100	61.00	3	3	7.60	0.96
8b	121	67.00	3	3	7.90	0.92
9	100	64.00	4	4	7.90	1.14
10	127	58.30	3	3	8.40	0.94
11	127	61.30	3	4	10.90	0.96
12a	135	73.90	3	3	10.40	0.90
12b	156	79.90	3	3	9.40	0.89
13	156	82.90	4	5	7.90	1.15
14	92	48.40	3	4	4.40	1.03
15	115	46.90	2	2	10.50	0.97
16	83	42.40	2	2	11.40	1.21
17	78	37.30	2	3	11.60	1.07
18	95	46.90	3	3	8.60	0.39
19	135	67.90	4	4	4.90	0.55
20	121	61.00	3	3	3.90	0.41

Each of these ratings was based on an independent scoring scheme, and so direct comparisons are not possible. The levels of the scores vary by one or two orders of magnitude. Hence the next step was to normalize them, with 0 being the lowest achievable score and 1 being the highest. A single throughput score came from averaging high and low. Again, except for cost, high is good. The results of the normalization are shown below in Table 4.6.1-II.

There was a two-stage process to determine the proper weightings. In both cases the Expert Choice tool was used to merge the inputs of the Program Managers, Council. In the first round, the members were asked to rate the relative importance of each of the 24 Objectives and Characteristics from the stakeholders' viewpoint. This was done in the form of a questionnaire generated by the tool, which asked whether each criterion was equally important or moderately, strongly,

very strongly or extremely more important than each of the others. Expert Choice then applied the widely used Analytical Hierarchy Process to compute weightings from these responses and identify areas of inconsistencies within the answers for each individual and across the group. The inconsistency levels were found to be acceptable for this high-level analysis. These weightings were used within some of the evaluation areas to weight the various issue areas to produce the single value in the table above. Flexibility in particular did this, since that area addresses a very large number of criteria. The next stage repeated the process with the five evaluation areas. Again, the inconsistency levels were acceptable. The resulting weights are:

- Throughput 24%
- Safety 25%

Table 4.6.1-II. Normalized Evaluation rating

Concept Number	Safety Score	Cost Score	Thruput Score	Flexibility Score	Acceptability Score
1a	35%	8%	13%	77%	56%
1b	35%	28%	13%	79%	59%
2	43%	79%	13%	46%	60%
3a	65%	86%	38%	65%	59%
4	44%	37%	38%	76%	58%
5	44%	40%	50%	72%	59%
6	46%	45%	38%	68%	62%
8a	50%	61%	50%	72%	62%
8b	61%	67%	50%	73%	61%
9	50%	64%	75%	74%	64%
10	64%	58%	50%	72%	62%
11	64%	61%	63%	77%	62%
12a	68%	74%	50%	77%	61%
12b	78%	80%	50%	74%	61%
13	78%	83%	88%	73%	64%
14	46%	48%	63%	67%	63%
15	58%	47%	25%	77%	62%
16	42%	42%	25%	76%	65%
17	39%	37%	38%	75%	63%
18	48%	47%	50%	75%	55%
19	68%	68%	75%	70%	57%
20	61%	61%	50%	67%	55%

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- Cost - 22%
- Flexibility 13%
- Acceptability 16%

The following Figure 4.6.1-1 shows the results of using the weightings to merge the five evaluations. The one that was the best, number 13, is the very high end approach, with platoons, infrastructure management, dedicated lanes, and even segregation by classes. In other words, everything possible that might increase performance has been included, and this is rated the best even when cost is taken into account. On the other end is the infrastructure controlled solution, which is cumbersome, inflexible and expensive. Considerably better, but still low, is the modified slotting concept, 3a. In between, the more powerful solutions rated high, while more rudimentary solutions were low, even considering cost and flexibility. In general, those concepts with the most layers of control, especially when coupled with physical controls such as barriers, scored best.

However, no concept was excellent across the board. They all scored less than 70%, which means that they all have some drawbacks. This indicates that there are trade-offs in these selections, and a deeper analysis might change the relative ratings. On the other hand, the results were only somewhat sensitive to the weightings selected within the range of values that the PMC members generated. The AHS goals of supporting flexibility and deployability suggests another way of looking at these results, and that is to look for a range of price-performance options. The above results might suggest that Concept 13 is the best solution everywhere, when it is clearly over-kill in areas that do not have major congestion problems. A rural area, for example, may have sparse traffic on long roads, which would suggest a simple system with minimal additional infrastructure, possibly even autonomous.

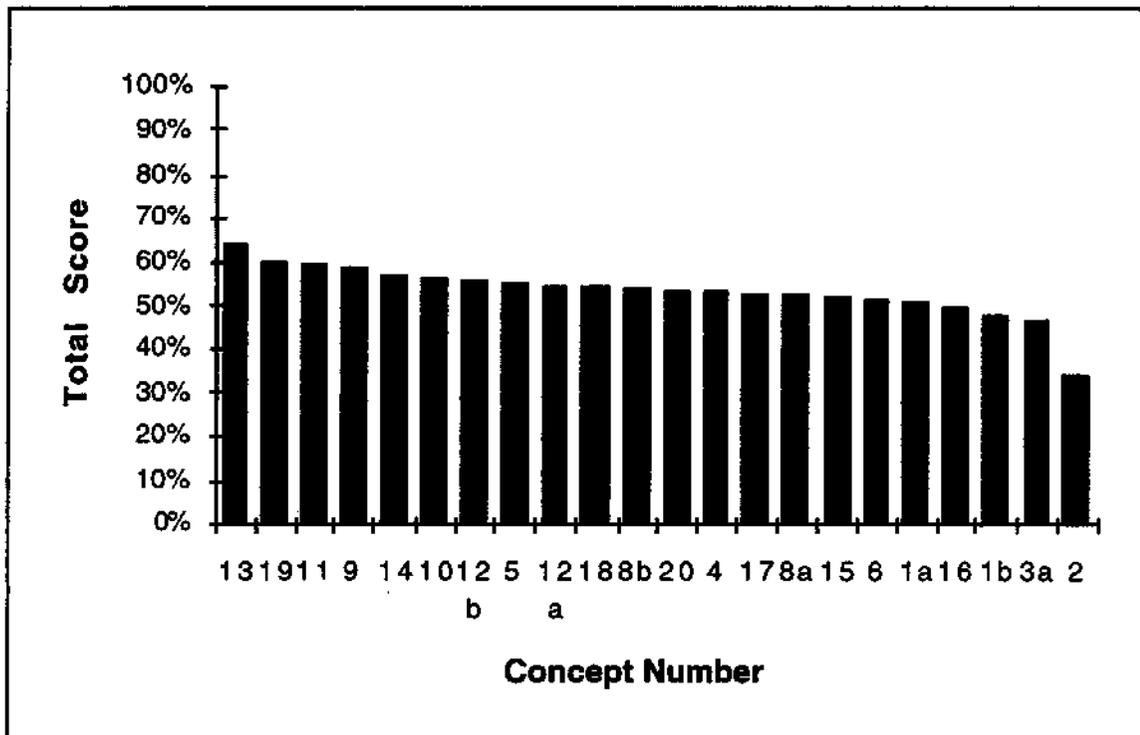


Figure 4.6.1-1. Overall Ratings of the Candidate Concepts

Figure 4.6.1-2 below plots performance against price. The cost score on the horizontal axis is directly based on the cost ratings discussed in Section 4.3. Recall that this is a relative rating, not an actual cost, and so is not necessarily linear. The vertical axis is a weighting to the four scores other than cost, and then normalizing the answer. Thus the points on the top edge of the group of points price range by choosing those that are merit score, computed by applying the are rated better than those directly below them, which are of comparable cost. This allows the selection of the best choice within any at the upper edge of the envelope. Now the autonomous choice looks good as a low-cost option, since its merit score is not much less than others that cost considerably more. But slots and infrastructure control are

clearly overpriced for their performance. Analysis of the specific points on this graph also showed that Infrastructure Managed is more cost-effective in general than Infrastructure Supported concepts, especially in high end designs.

The following Figures 4.6.1-3 through 4.6.1-8 indicate the impact of the various concept characteristics on cost and performance. These charts were based on previous weightings roughly estimated from the weightings for the objectives and characteristics, so the positions of the points do not match the previous figure exactly. Here the merit score is the horizontal axis and cost is vertical, so the best choices lie on the lower edge.

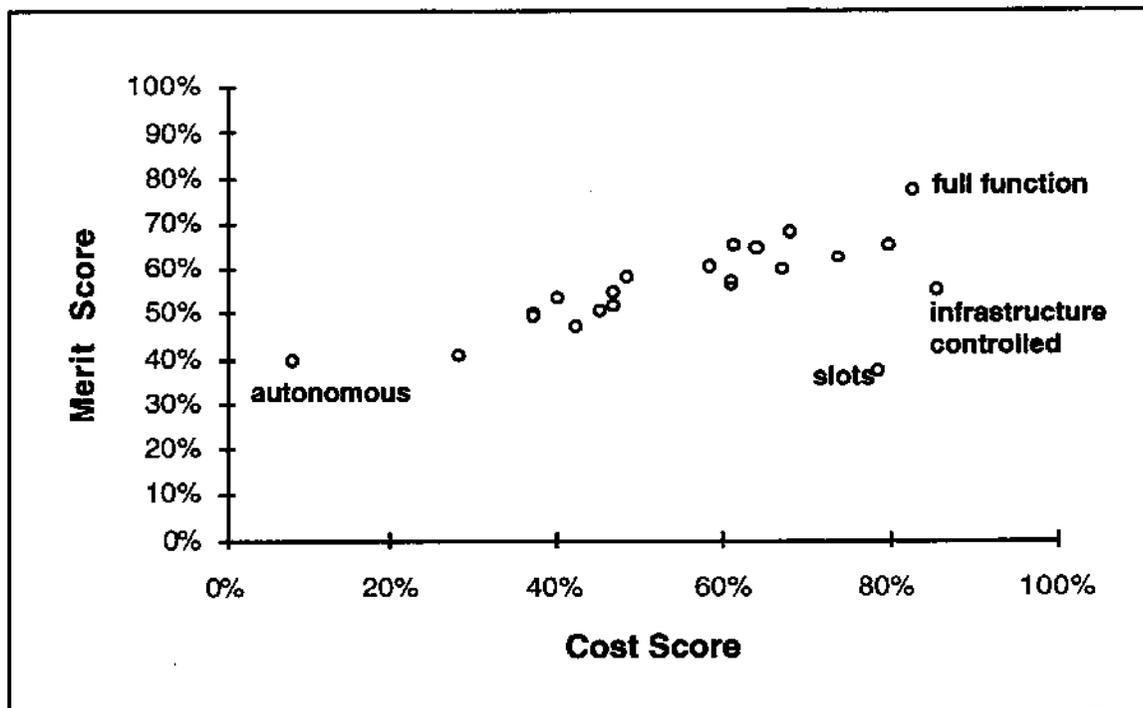


Figure 4.6.1-2. Comparison of Overall Performance vs. Cost for the Candidate Concepts

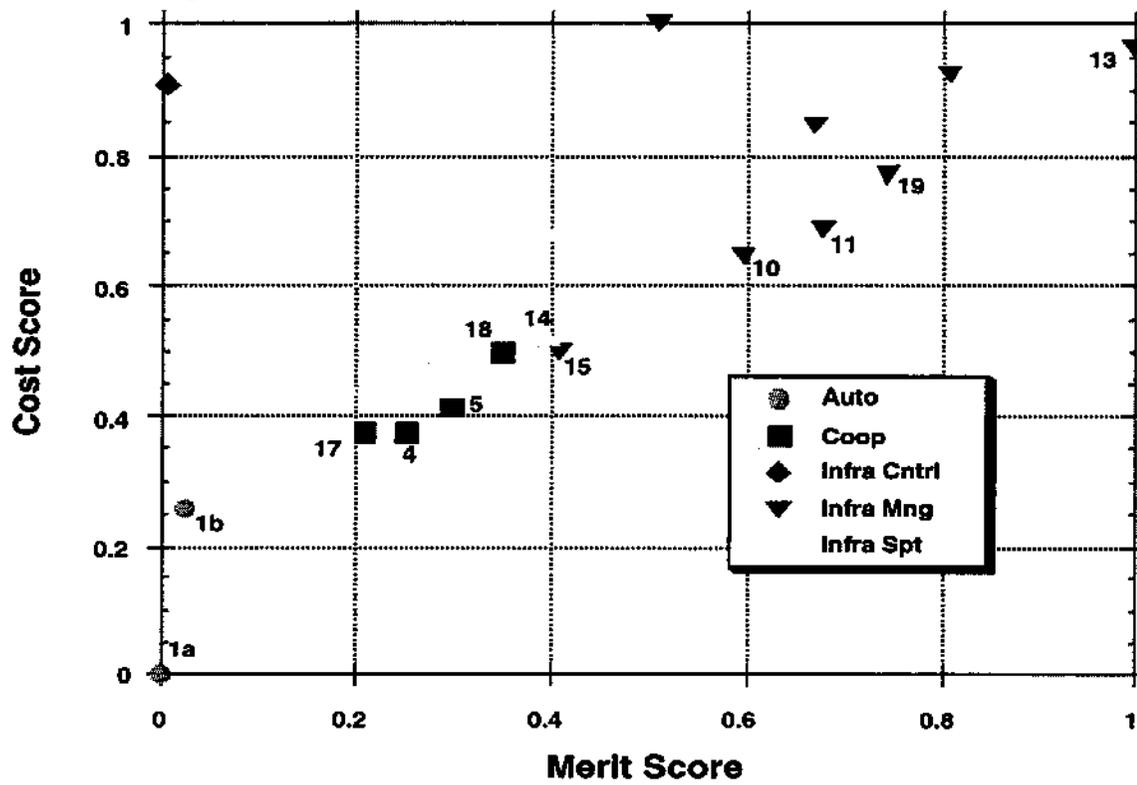


Figure 4.6.1-3. Cost and Performance Per Allocation of Intelligence

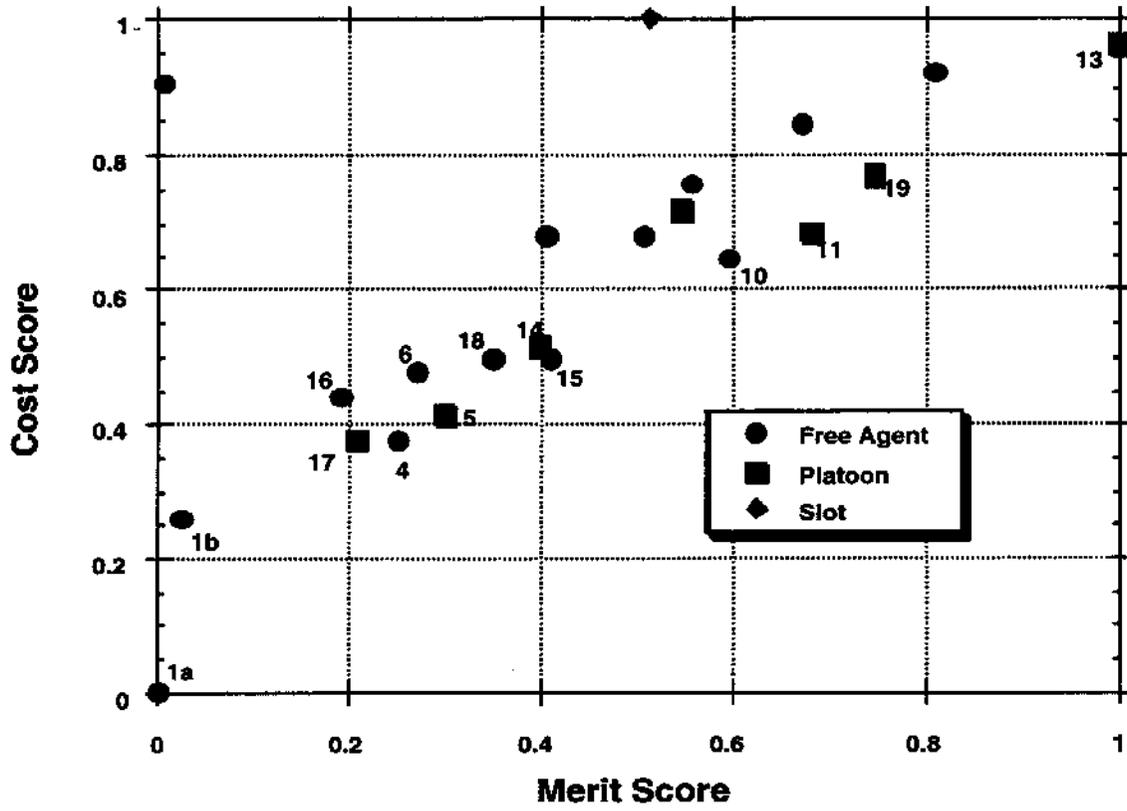


Figure 4.6.1-4. Cost and Performance Per Separation Policy

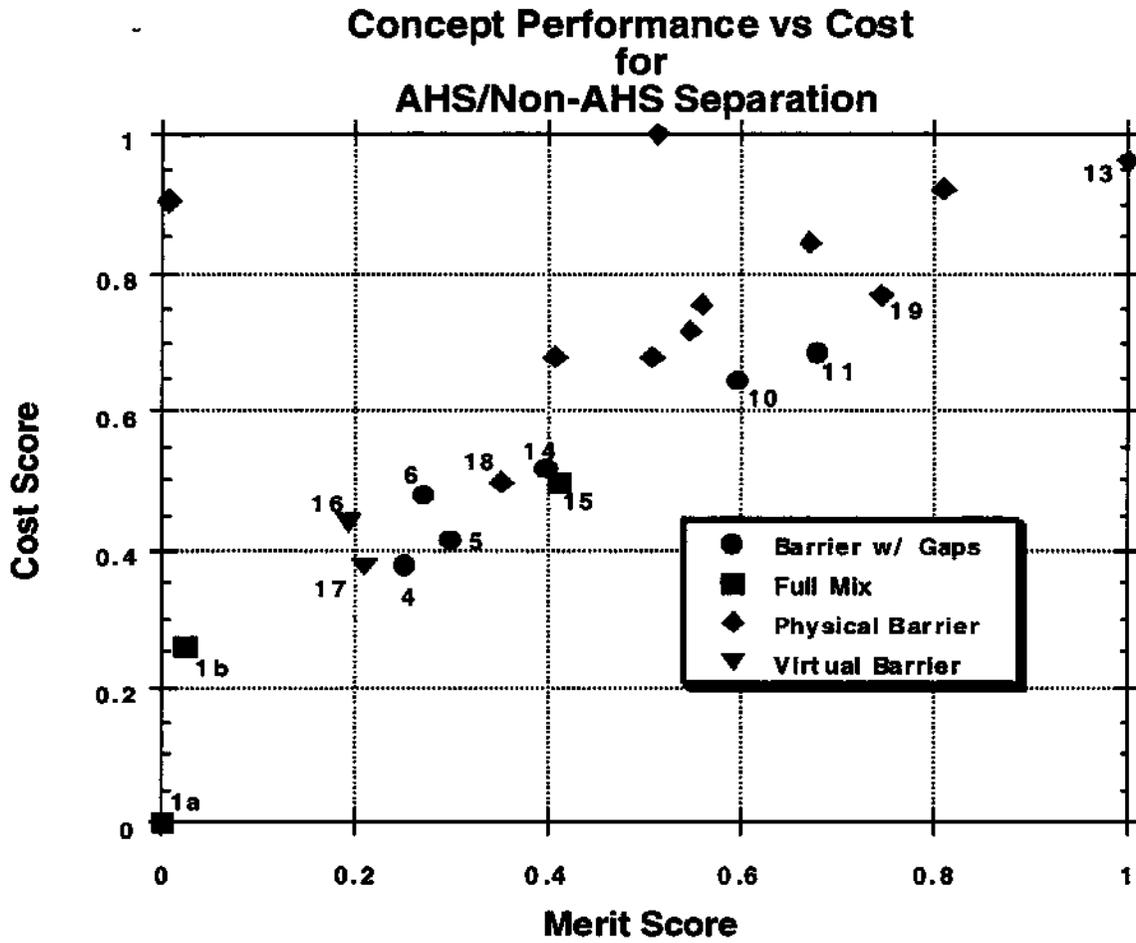


Figure 4.6.1-5. Cost and Performance per Mixed Traffic Approach

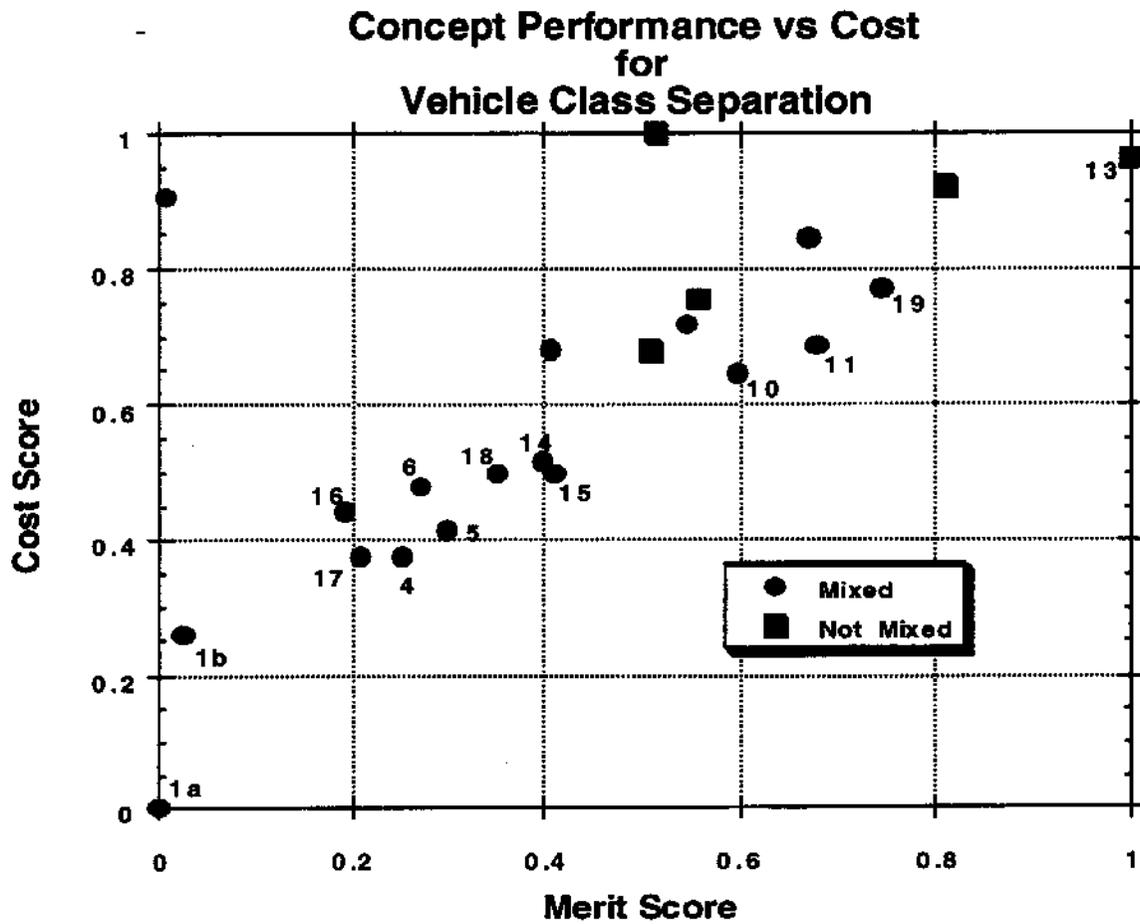


Figure 4.6.1-6. Cost and Performance Per Class Mixing Approach

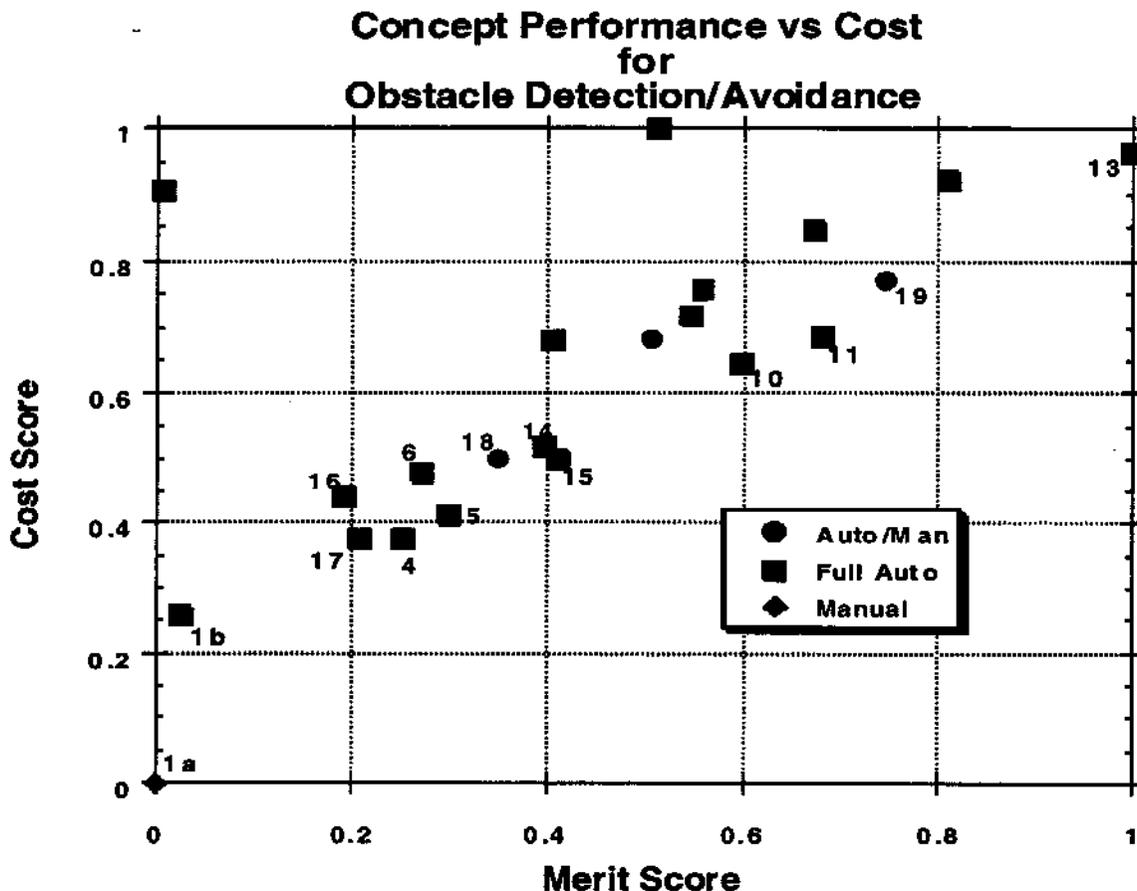


Figure 4.6.1-7. Cost and Performance Per Obstacle Detection and Avoidance Approach

This analysis needs to be caveated. Strong statements at this point about many of the dimensional choices must not be made, since the ratings are qualitative and non-linear. There is a temptation in this type of situation to compute cost-benefit ratios, but with this rating data the result would be meaningless.

The major conclusion of this analysis is that there is a range of reasonable price-performance options between the simple lane and headway keeping concept and the

concept that pushes control and throughput to the maximum. This suggests building families of related concepts by choosing good options within each price range and developing a smooth deployment path through these options. An example is shown below. The growth path starts at the left with a low-cost low-performance option. As you move to the right, further capability is added, allowing the system to grow progressively to whatever level is appropriate for the local needs and budget.

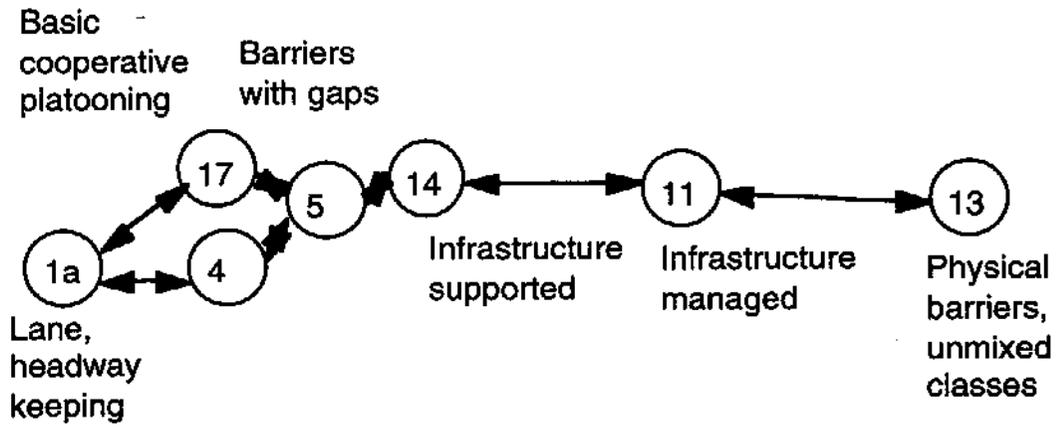


Figure 4.6.1-8. An Example Growth Path of Options with Good Performance for Price

5. CONCLUSIONS AND ISSUES

The results of the evaluation teams were approached from both a quantitative and a qualitative view. The contracted concepts provided important insights that greatly influenced the selection of the six concept families. The quantitative analysis is discussed in Section 4.6.

5.1. OBSERVATIONS ON CONCEPTS AND THEIR CHARACTERISTICS

5.1.1 Allocation of Intelligence

The Infrastructure Controlled approach, in which the infrastructure controls the vehicle at a micro level (brakes, steering and throttle) should not be continued in its present form. The ratings across all criteria were poor. The reasons for this are that this approach lacks robustness in that it risks single point failure in either the infrastructure or the communications links. In such a failure, the essentially dumb vehicles have no backup, and so the entire system is prone to catastrophic failure. There are also concerns about technical feasibility. The communication requirements are probably excessive, and the reliability requirements may not be achievable. On the other hand, alternative forms that do not have these drawbacks will be considered. In particular, contracted concepts will be carefully considered for means to achieve high infrastructure control while limiting these risks. Also, as concept designs are further refined, an infrastructure controlled module may find use in specific situations, such as backup for a failed vehicle.

The functional descriptions of the concepts indicate that some sort of centralized control is necessary for flow control and merge management in very dense traffic. Merging is a major issue area, especially as traffic density increases. The individual vehicle may not have a broad enough picture of the situation in the local area to coordinate a merge, even with communication with

neighbors. For example, an entering vehicle cannot necessarily sense and track the approaching gaps as it comes up to an on-ramp. This indicates the need for some way of maintaining a broader picture of flow, gaps and obstacles. This may be done in the infrastructure via sensors or communication with the vehicles, or a sophisticated system of data fusion that would allow it to be distributed among the vehicles. Thus, the purely Autonomous approach is not viable as a mature option; however, it may provide an early stepping stone to multiple concepts, especially one that emphasizes the individual vehicle. Similarly, a purely Cooperative approach is only reasonable where there are long merge areas or low traffic rates, unless the vehicles have distributed intelligence to form a "virtual TOC."

The descriptions for those concepts based on Infrastructure Supported and Infrastructure Managed indicated that the right answer is somewhere between the two. The Infrastructure Managed descriptions did not use the continuous tracking of the vehicles, whereas the Infrastructure Supported descriptions were forced to add some vehicle-specific communications under some circumstances. This suggests a new dimensional choice, which we call Infrastructure Assisted or Coordinated. It does global general system monitoring and flow control, and coordinates individual vehicles within a local area, such as at a merge point or an incident. These points may be defined dynamically, for example, when and where an obstacle is detected. Individual vehicles are not tracked over long distances or handed off zone-to-zone. This type of concept characteristic development is consistent with the "re-concepting" approach, in which improvements to the concepts based on lessons learned are more important than selecting the best of the given options.

This also suggests a continuum of infrastructure control. There is probably no single optimum level of centralized

involvement, and in fact it may vary from region to region. However, these variations are compatible within a conceptual framework, so a vehicle will be able to travel seamlessly through communities with different policies. The various levels of control will overlay on top of the vehicle-centered capabilities.

The best concepts are layered; each includes the ones below. This conclusion was especially strong from the Safety team. Multiple layers of control allow safe operation during failure. Figure 5.1.1-1 below shows the layers from Autonomous to Infrastructure Managed. The basic vehicle self-control of Autonomous underlies all of these options. Cooperative adds vehicle-to-vehicle communications and coordination. Infrastructure Supported adds infrastructure broadcasts to the vehicles and control by

location. Infrastructure Assisted adds selective control by the infrastructure of individual vehicles and Infrastructure Managed extends it to control of all vehicles at a macro level. The Safety team concluded that all of these layers are necessary, so that in a failure, the AHS will degrade gracefully to a less capable, but still safe, system. Note that these layers are all active at all times, performing different tasks, so there is no need for a risky mode change in a failure.

Figure 5.1.1-1 shows other advantages of this approach. One is a smooth evolutionary path from the initial systems, which will be less complex, less capable and less expensive, to the later, full-functioned systems. Finally, this affords a range of local options, tailored to each community's budget and transportation needs, while allowing seamless travel among regions.

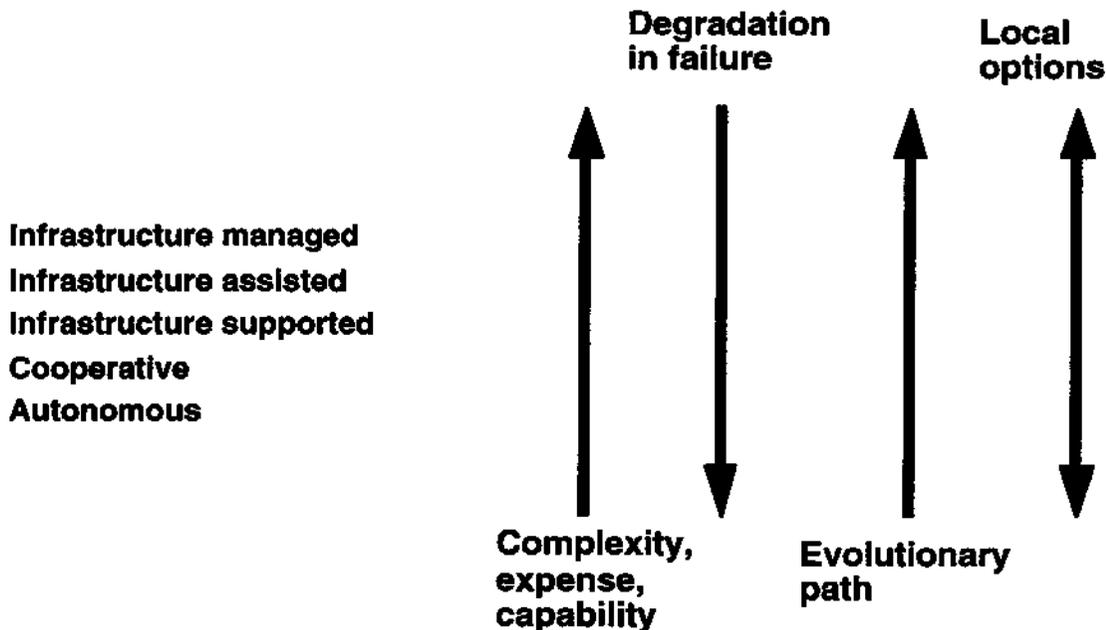


Figure 5.1.1-1. A Concept with multiple layers of functionality supports graceful degradation, a smooth evolutionary path and a range of local options

This conclusion indicates that there should be at least one concept family built around this approach. This will allow the team to compare the costs of providing the greatest amounts of layering with other more structured approaches.

5.1.2 Separation Policy

The Concept team cannot yet decide on the question of platooning vs. free agent. There is analysis to support either approach, and the results are very dependent on assumptions, such as braking speeds. This is especially true in the mixed classes of vehicles situation that the AHS must handle, in which heavy trucks and small sports cars coexist. The relative acceleration and, especially, braking capabilities greatly impact the achievable spacings. Central to all of this is the safety policy. Can minor accidents be tolerated? What constitutes "minor"? Must the number of vehicles involved in an incident be limited? To what? With what certainty? The team recommends that this issue be a significant area of study in Task C2.

It is possible that the Automated Highway needs to be able to support both platooning and free agent approaches. The above analysis will determine in what regions and under what circumstances one approach or the other will be used.

The slotting approach scored poorly relative to the other alternatives, so it will not be included in the six concept families. On the other hand, if results emerge from the contracted concept or other analysis that indicate approaches to slotting that alleviate the drawbacks, the approach will be reconsidered. In fact, as the design gets refined, slotting may be used in particular situations, such as at a merge point.

5.1.3 Mixing of AHS and non-AHS Vehicles in the Same Lane

The fully functioned AHS uses dedicated lanes. This is actually a much simpler problem than designing an AHS to allow manually-driven vehicles on the same lanes, since those vehicles are neither predictable nor controllable. There are safety risks due

to this mix, and requisite conservative spacings would likely negate any throughput advantage of the AHS.

Surprisingly, one of the concepts that allowed mixing scored well on the evaluations. Although not all vehicles were instrumented, they were all tracked, so there was a complete centralized status picture.

Feedback from the Workshops has indicated that many areas cannot dedicate a lane to AHS, since they have neither lanes to spare nor funding for the construction of new lanes. An example is rural areas with long stretches of two-lane roads. The second lane is needed for passing, and so cannot be dedicated to AHS, yet the length of the road makes it unacceptably expensive to build a third lane, and in some mountainous areas, it may be next to impossible. This indicates that many roadways may never support a dedicated AHS lane.

The contracted concepts in many cases started their evolutionary schemes with mixed traffic. This gives further validation to the need to consider mixing with manual traffic at least as an early or regional option.

Of course, to get the real throughput and disengagement benefits of AHS requires dedicated lanes. All of the most highly ranked concepts used dedicated lanes.

The other aspect of this dimension is the means for separating the automated and the manual traffic when dedicated lanes are used. The evaluation of this aspect involved many questions of topography, building costs and traffic patterns, all local considerations. The team concluded that such concrete configuration should be a local decision. But virtual barriers such as yellow lines may not be safe, especially in tight platooning. Hence, the team recommended that the concept families not use virtual barriers in high-end concepts.

5.1.4 Mixing of Vehicle Classes in a Lane

The highest rated of the concepts segregates vehicle classes, such as heavy trucks and cars. This allows tighter spacing, more control and increased safety. The drawback is the expense of building separate ramps, lanes and interchanges for the various

classes. This will make class separation unacceptable for most localities. AHS must serve all users, so the only other option is to mix the classes in each lane. The AHS must accept mixed classes in general, though some localities may find dedicated lanes worth the expense. Concurrent class mixing has major safety and throughput implications that need to be well understood. A local option that needs to be accommodated is to accept all classes, but avoid concurrent mixing, such as by restricting the AHS to passenger cars and small buses during rush hour, and to large trucks and buses at other times. This assumes a parallel manual highway or lane is available.

5.1.5 Entry/Exit

The comparison of dedicated and transition lanes revolved around the same kinds of local considerations--topography, building costs, traffic patterns--that drove the closely related barrier comparisons. As in that case, the team decided that this is a local decision, and that the AHS should allow localities to choose either approach.

5.1.6 Obstacle Detection and Avoidance

The Acceptability Team rejected those concepts that did not perform fully automated obstacle detection and avoidance as not being full AHS, nor providing fully disengaged driving under all conditions that the public expects from an AHS. But there is a major technical question here, as to whether or not it is possible to detect and avoid all dangerous obstacles. The Concepts Team recommended a study of this issue by the Technology Team, and this is ongoing.

The role of the human is a major issue. The Safety Team was fiercely divided on this issue. One group thought that allowing the human to take over under any circumstances introduced unpredictability, lack of control, slow reaction time and unsafe actions due to panic, greatly reducing safety. Furthermore, any system that relies on the driver prevents safe disengagement, and hence, is not AHS. Another group was concerned about the ability of technology to ever be able to make the sophisticated judgments that are second

nature for humans, such as pattern recognition and inferencing. Examples are natural driver reactions to seeing a deer about to enter the roadway, or swerving cars several vehicles ahead. To be acceptable, the system must work at least as well as a human at these and other tasks. The drivers may insist on keeping some level of control, such as a panic button.

This is another major issue area. The Team recommends significant study in this area during C2.

5.2 INSIGHTS FROM EVALUATIONS

5.2.1 National and Local Decisions

The team found that many of the characteristics that were originally defined as concept differentiators are actually local decisions that must be accommodated by the national AHS system. These include all of the physical infrastructure issues, such as whether to use a dedicated ramp or a transition lane, and the layout of ramps, barriers and other concrete configurations. Vehicle class mixing should also be a local option since it is tied to physical configuration.

More generally, the stakeholders have expressed a range of needs that indicate that the level of AHS functionality within a broad range must be a local decision. Perhaps platooning or free agency should be a local option; these alternatives will be further studied in C2.

The national decisions center around the vehicle as the common element. Any equipped vehicle needs to be able to travel seamlessly across the country, even as physical configurations, level of functionality and level of control change.

5.2.2 The Layered Approach

This need to support a range of local options suggests an open architecture and a flexible architecture that allows adding on capabilities. This flexibility is approached in terms of adding on, rather than in terms of selecting building blocks, for the simple

reason that large scale systems tend to evolve over time. We visualize this as a series of layers, each of which overlays and adds functionality to the ones below.

This idea first surfaced from the Safety Team analysis. They recommended layers for robustness relative to failure. In fact, they essentially rejected any option that did not use Infrastructure Managed, the richest approach and one which includes all the underlying intelligence approaches. It soon became clear to the Concept Team that this approach had other key benefits. The layered approach is shown in the Figure 5.2.2-1. It allows a smooth evolution

without throwing away anything from the original system. It also provides a range of compatible local options.

The quantitative results, described previously in Section 4.6, pointed to potential growth paths by taking the best-rated concept within each cost category. It turns out that this suggests families of concepts with the additive characteristic of a layered architecture. These families have several desirable characteristics.

- There is a wide range of price-performance choices, affording local flexibility

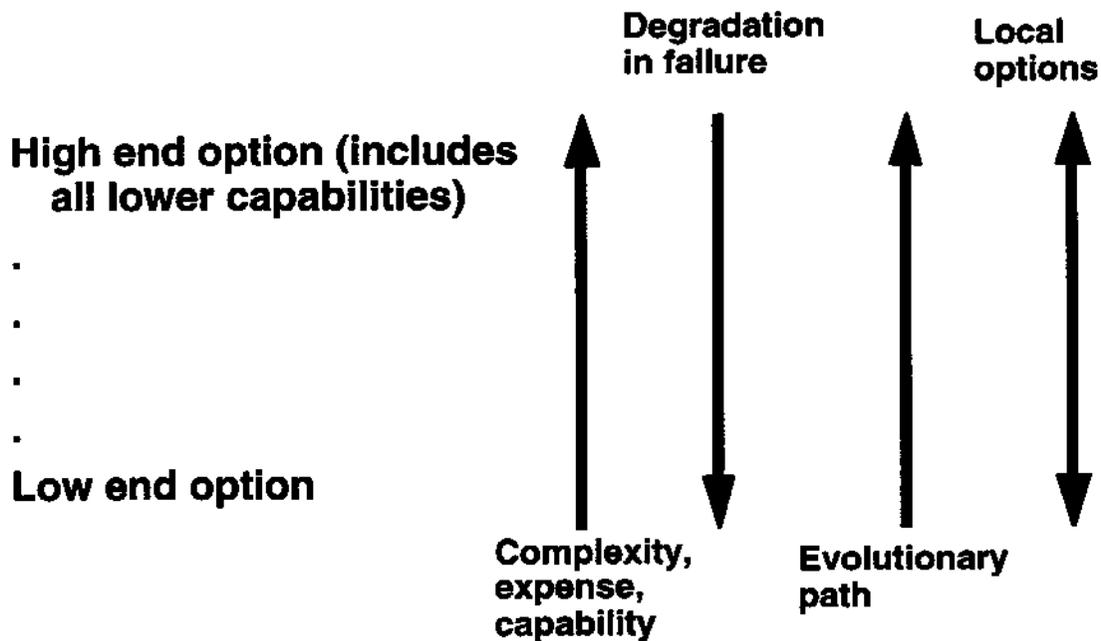


Figure 5.2.2-1. The layered approach to concept architecture

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- Options are available for rural, inter-urban, suburban and urban areas
- The early steps were rated highest in flexibility
- The later steps were rated highest in performance
- In every case, the initial step has a good cost-benefit ratio, so individuals and agencies will be motivated to initiate the system
- Each successive step has a good cost-benefit ratio, so there is incentive to expand
- The system can be built up gradually, lowering risks and supporting acceptability
- The development is robust relative to funding changes and other risks to continuation

One of the key items at the System Requirements Review was the definition of a "concept family." There was agreement that the outcome of Task C2 should be six concept families, but there was no initial agreement on what constituted a family. The attendees broke into working groups to decide this question, as well as to make recommendations for the six concept families. Three alternatives were presented. The "downselect" approach picks six specific single concepts. The "issues" approach builds the families around key issues. The "options" approach defines families of compatible concepts each with a smooth growth path.

The "options" approach was selected by the working groups. The motivation for this approach is that it supports evolutionary deployment and local tailoring, each of which is called for in the NAHSC Mission Statement. Further, it allows safe degradation in a failure if the family is built in layers. This allows the level of complexity of the AHS at any time and at any locale to be based on the need of the situation. For example, light traffic areas have no infrastructure support, moderate traffic areas use some infrastructure support, and heavy use areas have infrastructure

management. Different options are allowable for different conditions. For example, a basically autonomous system advances to infrastructure assisted as traffic requires, and platooning may be used in urban areas, while free agents are used in rural.

5.3 ISSUES AND CONCLUSIONS

The goals of Task C1 were to identify the most important unresolved issues, the most important new issues, and a viable range of options for each, and to develop six new system concept families to serve as a framework to address these issues. These results are to be based on the conclusions, lack of conclusions, and recommendations of the synthesis and evaluation of 23 concepts.

The 23 concepts originally developed and evaluated for C1 were not "downselected." The reasons for this are:

- Some of the dimensions were determined to be local options rather than discriminators
- The AHS solution will not be a single concept, but a range of options to satisfy a variety of regional needs, as well as a feasible growth path
- The 23 concepts were not a complete set of alternatives, but were chosen as representative of the range and intended to suggest improvements.

C1 resolved some issues and highlighted others. The decisions that were made:

- Infrastructure control (the infrastructure gives brake and throttle commands to the vehicles) was eliminated as a candidate
- The slot concept was eliminated
- Physical configuration (ramps, transition lanes, barriers), as long as it is safe, is a local option. For example, virtual barriers (painted lines) are not safe between platoons and manual roadways.

- Concept families will be defined as families of compatible options with a growth path, and hence, are not necessarily mutually exclusive.

5.3.1 Major Issues and Dimensions

There were several key issues that were either unresolved in C1 or were newly raised in C1.

5.3.1.1. Infrastructure Involvement

The options that survived the analysis are Autonomous, Cooperative, and Infrastructure Supported. A new option was developed, namely Infrastructure Assisted. Further analysis and definition will determine exactly how much infrastructure management is necessary in this option, so it is referred to as Infrastructure Assisted/Managed.

This issue of allocation of intelligence, the level of involvement of some intelligence outside the vehicle making decisions based on more global knowledge, is generally seen as the key discriminator of concepts. The working groups at the System Requirements Review as well as the stakeholders at the Workshop suggested this as the framework for defining the six concept families, which is essentially what was done.

5.3.1.2. The role of the driver

Ideally, the driver should be disengaged at all times, but there may be situations in which he is asked to take over, or situations in which he demands to take over. Some early implementations may require a totally engaged driver. There are many issues here. Should he be totally engaged always in some implementations, and if so, how do we ensure that he stays engaged? Should he have the option of taking control? Should he be a backup obstacle sensor? Should he ever be required to take control? Can the technology do the whole job no matter what happens?

The options here are engaged, partially (conditionally) engaged and totally disengaged. Partially engaged, if it is appropriate, will need to be defined based on determining

situations in which the driver will demand or require control.

5.3.1.3. The optimal amount of layering (options)

The above section discussed the benefits of layering information and control. However, there is certainly a limit to this. Additional layers add cost and complexity. There is a trade-off with compatibility. The evolution may take place by spreading geographically, rather than building on previous systems. In other words, wherever the AHS is deployed, it is essentially fully functioned, and the growth occurs by extending the road network that constitutes the AHS.

The team recommends that the six concept families include families that include narrow ranges of options as well as wide ranges.

5.3.1.4. Separation policy

There are now two options here, platoon and free agent. As discussed before, the issue revolves around assumptions on safety policy and performance characteristics (especially braking) for the target vehicle mix. It is likely that both options will be accommodated, but further analysis needs to be done to understand when and where each should be applied.

5.3.1.5. Manual and Automatic Vehicle Mixing

There are two choices here, to support a mixed option or not. Certainly the fully functioned AHS will use dedicated lanes. The issue is whether this should be a requirement on all AHS lanes. Feedback from stakeholders and the use of early mixed implementations in many of the contracted concepts indicate the need to reopen this issue.

Table 5.3.1.5-I summarizes the conclusions and issues.

5.3.2 The Issues and the Selected Concept Families

All of the alternative solutions to the major issues discussed above are represented in the concept families selected, which are

described in Section 7. There are two vehicle-oriented options, Vehicle Centered (based on Autonomous) and Cooperative Plus (based on Cooperative). The other four combine the vehicle and infrastructure. Driver Involvement is based on the premise that the driver must be involved, either because the technology cannot do everything or because human nature demands it. Infrastructure Supported Platoons and Infrastructure Assisted Platoons address high-end systems with varying levels of infrastructure involvement. Maximally Layered is designed to maximize the options available.

The main issue defining alternatives is and always has been the allocation of intelligence. The four options listed are the main definers for the concept families. However, autonomous and cooperative, as originally defined are too limited to be full AHS systems, so they are represented as starting points for more complex concepts.

With the elimination of slots, the remaining choices are platooning and free agent.

Further analysis with realistic and broad assumptions must be undertaken to resolve this issue. However, if platooning is feasible, free agent may be considered a special case and hence, an option.

The driver role ranges from fully engaged to fully disengaged, with intermediate roles as a backup sensor or responding to emergencies. A related issue is whether or not the AHS vehicles can operate in AHS mode in the same lane as manual vehicles. There is one concept specifically developed around a partially engaged driver, while others never allow a disengaged driver, even early in the evolution.

The amount of layering determines both the complexity and the flexibility of the AHS. The alternatives range from Maximally Layered, with full layering through all allocations of intelligence to Assisted Platooning, which may have only one underlying layer. The Vehicle Centered family ranges from very rudimentary to fully functioned in only three steps.

Table 5.3.1.5-I. Conclusions and Issues

Major conclusions	Local decisions	Major issues for C2
<ul style="list-style-type: none"> • Infrastructure Controlled should not be continued in its present form. • The most robust, powerful and flexible concepts are layered. • Slotting should not be continued as an overall approach. • High end implementations for dense traffic must have dedicated lanes with physical barriers and some sort of unified control of vehicles within an area. • Concept families each are to be defined as collections of compatible concepts through which there is a smooth evolutionary path. 	<ul style="list-style-type: none"> • Platooning or free agent (if both are viable) • Ramp configuration, use of transition lanes, types of barriers, and other physical characteristics, within safety guidelines • Class mixing 	<ul style="list-style-type: none"> • Separation policy, and its implications for throughput and safety • Mixing of automated and manual vehicles in the same lanes • Obstacle detection and avoidance • The role of the driver • The level of infrastructure involvement • The optimal amount of "layering"

6. SOLICITED CONCEPTS

In counter point to the Consortium's internal efforts to define, develop, and evaluate a set of initial concepts, the NAHSC conducted a national solicitation for AHS concepts. As a result of this solicitation, seven concept development contracts were awarded and completed during this task.

The goals of this solicitation were many, not the least of which was to satisfy the clearly stated requirement in the Request for Application for a "national solicitation for" "identification and description of multiple, feasible AHS concepts". In addition, the NAHSC desired to capitalize on the work done during the Precursor Systems Analysis phase where many organizations had studied a wide variety of AHS issues and in the process developed well founded ideas on the necessary and desirable features of an AHS concept. In fact, many of our contracts were let to organizations involved in the PSA effort and strong and surprisingly consistent concept themes came from this source. Even beyond the NAHSC and PSA work, the Consortium expected, and found, that other organizations had looked at the problems afflicting highway transportation and had developed conceptual solutions involving automation.

Solicitation for Proposals

Following April 1995 Workshop #1 in Fort Lauderdale, Florida, the NAHSC released through the Commerce Business Daily (CBD) a solicitation for concepts. The solicitation asked for proposals of complete AHS concepts rather than proposals of a specific technology. The solicitation asked for proposals on AHS concepts which had the following major characteristics:

- provide fully automated driving of motor vehicles on limited access highways
- provide significantly increased throughput and safety over conventional highways
- operate with automobiles, buses, and trucks
- incorporate a non-contacting, electronic guidance system

- be feasible and affordable
- allow AHS equipped vehicles to be operated manually on non-AHS equipped highways
- contain an aggregation of technologies sufficiently mature today to be integrated into a fully functional prototype ready for field testing in the year 2001

The solicitation also asked for an initial description of the concept and an initial evaluation of the concept against the requirements of the AHS System Objectives and Characteristics document prepared under Task B1A and provided to each interested organization.

In addition to the CBD announcement and the AHS System Objective and Characteristics document, each interested organization was given a Statement of Work (SOW) for the concept development effort. This SOW was based on the SOW for the Consortium's own concept development work and was so designed to focus the work of the contractor towards a concept description and evaluation which was roughly equivalent to the Consortium's internal efforts. This would maximize the Consortium's later ability to compare internally and externally generated concepts on an approximately equal and fair basis. The SOW established a time frame for the studies (approximately 3 months) and the products of the study including briefings and a final report.

Evaluation of Proposals and Award of Contracts

In response to the CBD solicitation, the Consortium received twenty-seven responses. One was a duplicate copy, and two were not considered to be responsive under the terms of the solicitation. The remaining 24 were initially evaluated to determine whether or not they were proposals for development of a full AHS concept, for a partial concept, for concept evaluation, or for a specific technology. Twelve of the 24 were determined to be proposals for full AHS concept development. These twelve proposals were from:

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Battelle / Ohio State
Calspan
Convergent Technologies
George Washington University
Haugen Associates
Honeywell
Penn State (2 proposals)
SRI International
Toyota
Unduluda Associates
Virginia Polytechnic University

To further evaluate these twelve concepts, and to make the final selections and awards, the Consortium established an evaluation board. The board in turn, established a set of evaluation criteria and a process for ranking each of the 12 proposals against each other. The four categories of evaluation criteria were:

- Overall scientific and/or technical merits of the proposal. Is the concept being proposed unique, reasonable, technically credible, and does it meet the characteristics listed in the solicitation?
- Offeror's responsiveness to the technical requirements of the solicitation and demonstration of technical competence as reflected in the proposed approach and supporting technical description. This was evaluated on:
 - Whether the proposed research plan is complete, systematic, logical, practical and clear
 - Sufficient detail to assess the reasonableness of the proposed methodology
 - Demonstrated knowledge of the critical issues concerning AHS concepts
 - Identification of potential problem areas and means for overcoming them
 - Awareness of the practical considerations and constraints
- Ability to perform technical work. Offeror's resources to complete the contract requirements satisfactorily and on schedule, including
 - Education, experience and competence of research team in the areas of AHS, concept devel-

- opment, system architecture, and oral and written communications
- Education, experience and competence of the principal investigator or project manager
- Adequacy of the management plan, including organization, manpower allocation, work schedule, and monitoring to insure success. Adequacy of the proposed allotment of time, overall and on a task-by-task basis.
- Adequacy of facilities, equipment, and support to conduct this study.
- Past performance. Offeror's relevant and successful experience.

In the final evaluation process, the uniqueness of the proposal was considered separately in order to assure ourselves that unique and feasible solutions were not being rejected just because their uniqueness made them appear too risky.

The evaluation board members first evaluated each proposal separately, then met, discussed both the criteria and the proposals, and developed a composite ranking for each proposal for each criterion. The result of this evaluation was that the proposals divided into two distinct groups, a group of seven with generally high rankings and a group of five with generally lower rankings. A decision was made to award contracts for the seven proposal with the highest rankings. The board then assigned each of the seven selected contractors to one Consortium Participant for management of the contract. The proposals selected and awarded were:

- Battelle / Ohio State, assigned to Lockheed Martin
- Calspan, assigned to Hughes
- Haugen Associates, assigned to General Motors
- SRI International, assigned to PATH
- Toyota, assigned to Carnegie Mellon University
- Virginia Polytechnic University, assigned to Lockheed Martin

Brief Description of the Concepts

Each of the seven concepts is described, in the words of each contractor, following:

6.1 AN INTEGRATED AUTOMATED HIGHWAY SYSTEM (AHS) CONCEPT WITH SPECIAL FEATURES FOR BUSES AND TRUCKS

BATTELLE/OSU

The Integrated System Concept (ISC), being developed and evaluated by the Battelle/ OSU Team with its subcontractors TRC and BRW, is a concept which includes a multi-tude of operating procedures and infra-structures, and a special emphasis on trucks and buses. The different operating proce-dures and infrastructures issue is especially relevant to providing the level of flexibility needed to accommodate differing Urban, Rural, and Fringe situations even in a fully deployed AHS implementation. This flex-ibility also helps in both local and partial implementability of AHS technologies, and multi-stage deployment.

The ISC is based on a vehicle heavy distribution of intelligence. The ISC concept involves a "smart" vehicle and a minimally instrumented infrastructure in Rural areas, and increased levels of sensing and communication to provide additional functionality in the Fringe and Urbanenvironments. This Concept is being developed assuming the availability of passive roadway-based markers and passive vehicle-based indicators. Currently, the concept features (1) OSU's radar reflective stripe as the roadway marker which facilitates lateral (and other) vehicle control functions, and (2) OSU's Radar Reflective Patch as the vehicle-based type of indicator which facilitates follow-the-leader or convoy operation of heavy duty vehicles. One key aspect of these technologies is the ability to function well in a variety of situations - i.e., in inclement weather, in tunnels, on metal bridges, etc. Additionally, the Radar Reflective Stripe technology can provide a "look ahead capability".

The ISC specifically considers truck convoys in Rural areas and bus convoys in Urban areas. These special applications are woven into the main Concept and evaluated as a whole. Special attention is being given to allowing the owners/operators of AHS capable vehicles to derive the maximum benefit of the vehicle heavy distribution of AHS intelligence in all driving scenarios - e.g., various evolutionary stages of AHS deployment, mixed traffic, and even on non-AHS roadways.

6.2 CALSPAN AHS CONCEPT FAMILY: MIXED FLOW THROUGH DEDICATED FLOW

CALSPAN

Three concepts are grouped together to cover the range of participation from near zero to near one hundred percent. Thus, they can cover the evolution from first deployment to some future mature nationwide network. These also cover the range of application scenarios from high-capacity urban freeways to four-lane intercity freeways. All three concepts move vehicles as individual free agents rather than groups. When a lane is dedicated to automated mode use only, the vehicle class description would include a mass ratio specification (heaviest allowed to lightest allowed) and a maximum width specification. Vehicles outside the class would have the opportunity to use the automated mode in the other lanes mixed with vehicles operating in the manual or partially automated mode.

The three concepts can be termed mixed flow, mixed transition lane and dedicated flow. The mixed flow concept applies with few physical modifications to all freeways including four-lane freeways. The mixed transition lane concept applies to the range of freeways six-lanes wide and wider. The dedicated flow concept applies to maximum throughput applications on freeways with generous rights of way.

6.2.1 Concept 1 - Mixed Flow

In the mixed flow concept, the automated mode can be used in any lane. Modest driver comfort, convenience and safety benefits can be predicted for this concept, if the automated vehicles operate in the same lane, pairing up if the opportunity arises. The concept applies to all freeways at all participation levels but does not significantly increase the throughput capability of a given roadbed width. It applies, even in the long term, to four-lane freeways because it allows manual vehicles the opportunity to pass. Automated heavier vehicles would normally operate in the right lane. The infrastructure would monitor and advise. The driver would, in early deployment, be particularly alert for foreign objects and the behavior of manual vehicles. However, the driving experience would be much improved because of the automated gap regulation and lane following.

6.2.2 Concept 2 - Mixed Transition Lane

The mixed transition lane concept evolves from the mixed flow concept on six-lane and wider freeways when participation¹ grows to the point where only a few vehicles are displaced by dedicating a cruise lane to automated use. The cruise lane should be wide enough to be able to park a disabled vehicle to one side of it and still safely pass on the other side. This extra width is necessary to manage malfunctions and would also be helpful in maintenance. The mixed lane adjacent to the cruise lane becomes the lane selected by automated vehicles when desiring to access the dedicated lane - a transition lane. To maximize the throughput of vehicles of all sizes, automated heavier vehicles would cruise in the rightmost lane mixed with manual traffic, using the transition lane to pass if necessary. As participation builds over time and the flow in the dedicated automated lane increases, a physical barrier would be used to protect the automated cruise lane from the other traffic and foreign objects. The barrier would move to the right by one

¹Participation is the percentage using and seeking to use the automated mode in a specific section of freeway.

lane width at sections where the access and egress lane changes actually occur. The vehicle itself would be responsible for:

- lane regulation
- gap regulation
- vehicle malfunction management
- driver malfunction management
- surface condition
- obstacle management.

and through a limited-range, random access communications link to other vehicles:

- access/egress execution
- emergency braking
- obstacle management
- surface condition
- space regularization² (optional)
- incident detection.

Infrastructure remote control stations through sector broadcasts would be responsible for

- speed gap commands by sector
- regularization by sector
- traffic sensing
- obstacle detection (shared with vehicle and driver)
- weather sensing (including surface condition), and
- management of driver malfunction.

The Freeway Traffic Operation Center (TOC) would be responsible for:

- normal cruise flow management
- access/egress flow management
- entry/exit flow management (in conjunction with regional TOC)
- incident management
- weather factor integration.

It would operate the remote control stations and receive information from them using a two-way data link. The freeway TOC also communicates with the regional TOC to the extent dictated by freeway entry/exit flow increases that eventually would be the result of higher cruise lane flows.

The driver would have much more opportunity to divert attention since no manual vehicles would travel in the cruise lane. However, the driver would be required to remain alert and "on-call" to manage malfunctions that require some driver role. Examples are: change of exit selection, selection of the breakdown side of the lane and vehicle stoppage due to vehicle fire, control roughness, shut down of a failed nonessential subsystem, monitor vehicle automatic management of a malfunction, etc. The driver should assist in detecting and avoiding obstacles by causing a bias in the lane tracking position using a slow drift rate on/off controller with lane position override at the edge of the lane.

6.2.3 Concept 3 - Dedicated Flow

The dedicated flow concept removes manual vehicles from the transition lane. With a dedicated transition lane and sufficient participation to justify the cost of substantial midway modification, large access and egress flows can be managed. This would include demerging and merging of high flows at the intersection of two AHS's. It also would include connecting the transition lane

²Space regularization is the automatic arrangement of space available in the lane to add more vehicles efficiently.

with a manual freeway entry/exit so that the entire process becomes automated. In this concept, a mature AHS might allow the driver even more freedom of activity.

6.2.4 Concept Relationships

All three concepts regard the interfaces between an AHS and the existing manual system to be the freeway entries and exits. Since flows must balance, these points are the important coordination hand-offs between the freeway TOC and regional TOC. Concepts such as dynamic route assignment and demand management become highly important to realize the full benefits of AHS in a high-demand urban region. Also the placement of new dedicated entry/exit involve highly important regional social, economic and environmental issues which are not AHS-specific and truly belong at the interface of AHS concept development.

The deployment plans follow market developments. As the market and participation builds, Concept 2 and eventually Concept 3 are deployed. Concept 1 might be used for intercity travel, even in the mature network. Some site-specific requirements might drive the deployment of Concept 3 earlier.

Lane throughput capacity is tied to safety through an analytical approach that proceeds from a Safety Policy to vehicle density at given conditions and speed range. The existing roadbed construction and the existing right of way are exploited using automation, communication, and software rather than use concepts requiring extensive infrastructure modification. This strategy should minimize cost while obtaining marketable benefits.

6.3 PAC-ITS

Packet Autopiloted Cruiseway-Intelligent Transportation System

HAUGEN ASSOCIATES

6.3.1 What Is PAC-ITS?

- A packet train is a mix of 15 or 20 vehicles - personal cars, low profile buses and freight units - mechanically coupled together for intercity travel
- A professional "pilot" controls each packet train from a special lead vehicle
- All vehicles in the packet train are guided by a high-tech lateral guidance system controlling them to keep precisely the same path
- The power trains and brakes of all vehicles are interconnected so they accelerate and brake as one unit
- PAC-ITS trains might initially operate on the Interstate; eventual operation on new high speed guideway using reserved time slots with high safety margins

6.3.2 Why the PAC-ITS Concept?

1. Personal car users can have the confidence of mechanical links and a trained human pilot, rather than relying on complex electronic sensors and logic.
2. Drivers and passengers use their personal vehicles but have zero driving responsibilities while part of the packet train; can relax, sleep, watch movies, etc., with personal privacy.
3. PAC-ITS simplicity minimizes personal car modifications and driver adaptation; no airplane cockpit equivalent needed for AHS operations.
4. The aerodynamics of PAC-ITS trains can achieve a factor of 5 or 10 reduction in aerodynamic drag, with major reductions in energy use and emissions.
5. PAC-ITS trains will permit faster travel between cities - with speeds raised by 5 mps every 2 or 3 years as safety and energy savings goals are met.
6. The overall simplicity of PAC-ITS should allow its deployment in mixed traffic to begin within the next decade.
7. Mechanically linked packet trains can achieve the highest possible roadway capacity with greatly enhanced safety.
8. PAC-ITS can raise productivity sharply; a pilot can control a train of 20 specialized freight vehicles, thereby creating a new class of high paying jobs.
9. Intercity bus economics, and thus, bus service, can be greatly improved with the PAC-ITS pilot controlling several buses as well as a profitable mix of freight and personal vehicles.
10. High-speed PAC-ITS links can take pressure off airports by reducing the need for short haul flights; increase remote airport feasibility.

6.4 THE HONEYWELL-BRW-UNIVERSITY OF MINNESOTA CONCEPT

HONEYWELL

This section uses the definitions of the various dimensions from Section 2.13.2.

6.4.1 Distribution of Intelligence

This concept is a hybrid of infrastructure-supported and infrastructure managed intelligence. Whereas lane changes are requested from and managed by the roadside system, it has no authority to reroute vehicles--vehicle navigation is controlled by each individual vehicle, based in part on information supplied by the roadside system (e.g., about accidents).

6.4.2 Separation Policy

Vehicles travel as platoons in the urban setting. Vehicles in the rural setting are free agents.

6.4.3 Mixing of AHS and Non-AHS Vehicles in the Same Lane

In the urban setting, there are dedicated lanes with continuous physical barriers to separate the automated lane from the manual lanes. In the rural setting, full mixing of automated and unautomated vehicles is allowed.

6.4.4 Mixing of Vehicle Classes in a Lane

In both settings, the various vehicle classes are mixed in all lanes. However, in the urban setting, special lanes and/or large-scale bypasses are provided for poor performance vehicles where there are (1) significant grades in the roadway, and (2) areas of consistently high density traffic.

6.4.5 Entry/Exit

In the urban setting, dedicated on- and of-ramps are used, with an inspection site at each on-ramp. In the rural setting, there are non dedicated on-ramps with inspection sites; there are no dedicated off-ramps.

6.4.6 Obstacle Detection and Avoidance

In both settings, automatic sensing and automatic avoidance maneuver (if possible) are used.

6.5 EVOLUTIONARY AHS CONCEPT BASED ON PRECISE POSITIONING, IMAGE RECOGNITION, AND INTELLIGENT AUTONOMOUS CONTROL

SRI INTERNATIONAL

SRI, under contract to NAHSC through UC Berkeley and PATH has developed an evolutionary approach to AHS that, with minimal infrastructure requirements, provides selected interim capabilities and utility to ensure a viable and mature system upon completion of a phased development effort. The evolutionary stages include: (1) A follow-the-leader capability in which the lead vehicle is manually driven and multiple automated vehicles follow in a platoon. The primary beneficiaries of this phase may be long haul freight operations. (2) An advanced cruise control system that allows properly equipped vehicles to stay within surveyed highway lanes, maintain safe separation distances, and avoid collisions with obstructions and other vehicles. Vehicle drivers on long trips may be the beneficiaries of this phase which should dramatically reduce the number of single vehicle road departure accidents. (3) A completely automated system with autonomous vehicles operating on, eventually, dedicated AHS highways.

There are four key aspects to the concept: (1) The ability of each vehicle to measure its absolute position on the road to within a centimeter or two. When combined with vehicle sensor data and road database information, this high-precision location capability provides the information required for safe and reliable control and maneuvering, especially in emergencies. (2) The integration of data from multiple active and passive sensors to ensure reliability and form a dynamic model of the environment around the vehicle for situation awareness. (3) A supervisory control system for each vehicle that can recognize and efficiently act to critical events. (4) The majority of the sensors and system control resides in the vehicles so the infrastructure changes are minimal. The dominant technologies chosen to provide the required capabilities are: The Global Positioning System (GPS) for position location, image recognition using multi-spectral sensors (optical, infrared, radar and LIDAR) for situation awareness and guidance redundancy, and artificial intelligence and intelligent controllers for sensor fusion and supervisory control.

The absolute precise positioning supplied by this concept is a major step in the development of practical Roadway Powered Electric Vehicles (RPEV). Precise positioning allows the power to be transferred to the vehicles at very limited distribution points. The ultracapacitor, currently being developed, allows the vehicle to take on a large amount of electrical energy in a small fraction of a second.

6.6 LIGHT AHS CONCEPT SUMMARY

TOYOTA

This is a summary of the concept of a LIGHT CAR that, together with a LIGHT INFRASTRUCTURE, forms a LIGHT AHS. The LIGHT AHS arises both from the vehicle orientation of an auto manufacturer and from the need for AHS to be fundamentally market-driven to succeed. Through an evolutionary development approach, the LIGHT AHS is intended to be light in terms of the cost of modifications to the existing infrastructure, light in the complexity of the vehicle, light on the wallet of the car-buying and road-building taxpayer, and light in the effect of implementation on society. It features the use of light (Photonics) technologies where appropriate to sense, communicate, and control.

The LIGHT CAR uses precise measurements made by onboard optical sensors to guide the vehicle. The LIGHT AHS Concept also includes a magnetic marker lane reference and a roadway-to-vehicle communications system, which are essential parts of the LIGHT INFRASTRUCTURE. The LIGHT AHS Concept extends the LIGHT CAR to include an onboard map database for coarse road geometry information and roadway features. The combination of these technologies makes possible a near-term, realizable, robust, redundant, fullfeatured vehicle that can be used on any AHS segment in the US.

The LIGHT AHS Concept maximizes the use of currently existing highway infrastructure over the course of the AHS evolution. Infrastructure modifications may be limited to a roadside communications transmitter and receiver for road geometry updates, climate, and traffic information dispersal and acquisition. In areas of frequent poor weather, more frequent periodic passive markers on the roadway will be installed for fine motion control. Passive reflective or magnetic markers have been selected for the LIGHT AHS Concept but other technologies may also be applicable. Deployment is done in phases to "think and learn while running" in an attempt to focus investment on high return areas of AHS' promise. Putting as much of the technology on the vehicle as possible will continually renew AHS with each succeeding car model. As technology progresses, the LIGHT AHS will become lighter, particularly in the infrastructure.

- **Allocation of Intelligence**

The allocation of intelligence evolves with the deployment of the LIGHT AHS. Initially, as components of the LIGHT AHS are deployed for mixed traffic, the vehicle will be fairly independent of the infrastructure, relying on passive elements. As more AHS features are deployed, the vehicle and the infrastructure become more interdependent, with a balance of intelligence. Ultimately, the LIGHT AHS is an "Infrastructure Supported" concept. The control decision making is left primarily in the vehicle. The infrastructure supports this decision making by providing additional information that is difficult to obtain with onboard sensors.

- **Separation Policy**

Both "Free Agents" and "Platoon Operation" are permitted in the LIGHT AHS Concept to give the driver an element of control and freedom of choice.

Mixing of AHS and non-AHS Vehicles Some features of the LIGHT AHS will be available in mixed traffic on all conventional highways throughout the evolution of the AHS which will improve the safety and performance of conventional highways.

- **Mixing of Vehicle Classes in a Lane**

The LIGHT AHS Concept will accommodate any vehicle which meets the minimum performance and equipment standards.

- **Entry/Exit**

Dedicated entry and exit ramps are preferred, but shared on-ramps and off-ramps with transition lanes are feasible for the LIGHT AHS Concept, causing a slight degradation in

the overall system performance. A retractable, soft barrier at the entry can discourage non-AHS vehicles from entering without causing a traffic delay or hazard.

- **Obstacle Detection and Avoidance**

Obstacle detection is primarily automatic using both onboard and infrastructure-based sensors. Initially, infrastructure-based sensors will be needed since current sensor technology does not cover all possible road conditions. As the technology advances, the LIGHT AHS will be less dependent on infrastructure elements. The driver interface will provide the driver with a limited ability to alert the system of obstacles not detected by the AHS. However, control actuation will still be automatically controlled by braking and/or steering.

6.7 COOPERATIVE INFRASTRUCTURE MANAGED SYSTEM (CIMS)

VIRGINIA POLYTECHNIC

The Virginia Tech Center for Transportation Research Concept is a cooperative infrastructure/vehicle based automated management approach referred to as a "Cooperative Infrastructure Managed System (CIMS)". There are many possible AHS concepts and each has its individual strengths and weaknesses. The "Cooperative Infrastructure Managed System (CIMS)" builds on the various strengths of several systems in a cooperative fashion. The CIMS system is neither a totally vehicle-based system nor a totally infrastructure-based system. It relies on cooperation between processors on the roadside and on the vehicle and shares command decisions between the vehicle and the infrastructure. The concept uses communications to integrate the vehicle with the roadside. In addition, this system does not need complex roadside sensors to detect and manage the vehicles. Instead, it uses cooperation between the vehicle and roadside infrastructure to determine the best path for each vehicle on the road based on a global knowledge of location of all the vehicles in an area. Through this cooperation, the tasks best suited for the vehicle are performed on the vehicle and the tasks best suited for the infrastructure are performed at the roadside.

The system fuses together the multiple sources of sensory data from both the vehicles and infrastructure into a layered management algorithm designed to optimize the safety of the system while maintaining designed throughput potential. A new solid state ultra-wideband communications system is used for precise vehicle and roadside waypoint location and simultaneous information sharing. The location from this sensor can be fused with on-board sensors to provide an accurate picture of the surroundings in which to develop an integrated control strategy.

This design approach attempts to fully exploit the opportunity of cooperation between the roadway and the vehicles to simplify the sensors and processing required for autonomous vehicle operation. By taking some of the bulk of the processing and sensing load off the vehicle and distributing it throughout the infrastructure, added vehicle costs are minimized with little added infrastructure. All sensory input the vehicle has to offer can be communicated to the infrastructure and integrated with the global information set.

6.8 EVALUATION OF THE SOLICITED CONCEPTS

By design, the Contractors were given a broader task in defining their concepts than was attempted with our internally defined concepts. Internally, we specifically focused our study on a limited number of architectural and operational questions, as described in detail elsewhere in this report. Although our concept teams did identify specific technologies as part of their concept definition work, we did not press a detailed analysis of implications of those technology selections on the resulting concept. Further, the selected technologies played almost no role in the subsequent evaluation of the concepts.

The contractors, in their analysis, were asked to use the same evaluation criteria, and were asked to describe their concepts in terms of our architectural and operational questions. But beyond that, they were given freedom to raise and address any other architectural, operational, or technology questions. And they did.

Technical Issues

This resulted in a spectrum of useful work which will be valuable to the Consortium over a much broader period of time than just this initial concept development effort. Several of the contractors analyzed and evaluated specific technologies as part of their concepts. Battelle and Ohio State University featured the use of radar reflective stripes to define the roadway and radar reflective patches to identify other vehicles. Haugen Associates based their concept on mechanical links between vehicles and trained professional drivers rather than relying on complex electronic sensors and software logic. SRI included in their concept carrier phase GPS to provide vehicle position information to within a centimeter or two. Toyota emphasized the use of on-board optical sensors. Virginia Tech included in this concept an ultrawideband communications which can provide both communications and precise vehicle and roadside waypoint locations. Most of this effort will be extremely useful in the near future when the Consortium

integrates our concepts with specific technologies to build a working prototype. Some of the contractor's proposals already have spawned work under our Enabling Technologies task.

Architecture Issues

With respect to the architecture question we raised internally, the contractors were relatively consistent in their own conclusions. Almost all the contractors considered a combined vehicle/infrastructure architecture, but with variation in the relative degree of intelligence allocated to each component. Still, almost all felt that some AHS infrastructure was necessary to achieve maximum capacity and safety. The Battelle concept is based on a vehicle-heavy distribution of intelligence, with a "smart" vehicle and a minimally instrumented infrastructure in rural areas and increasing levels of sensing and communications to provide additional functionality in the fringe and urban environments. Calspan likewise advocated a vehicle/infrastructure architecture with infrastructure remote control stations and a Traffic Operation Center. Honeywell suggested a hybrid between our infrastructure-supported and our infrastructure managed architectures. SRI formulated a vehicle intensive architecture with a minimal control infrastructure. Toyota's concept included an interesting approach of evolving first from a mode where the vehicle is fairly independent of the infrastructure to one where the vehicle and the infrastructure became more interdependent, to an ultimate architecture where again the vehicle becomes more capable and less dependent on the infrastructure. Virginia Tech proposed a more infrastructure dependent architecture relying heavily on wide band communications with the vehicles.

Operational Issues

It was in the area of operational issues that the contractors provided the most useful help for this phase of concept development. Indeed, their conclusions had a very strong impact on the selection of the concepts for the next phase of our investigations. The most enlightening aspect of the contractor's effort was their consistent, and strong, emphasis on deployment scenarios and regional

application scenarios. All of them felt that a viable AHS concept must satisfy an incremental deployment scenario where there is a gradual introduction of increasingly capable AHS functions. They also felt that a successful AHS would have to be adaptable in a variety of urban, intercity, and rural applications.

In this specific area of deployment scenarios and regional adaptations:

- Battelle described a concept with different operating procedures for rural and urban areas. For rural areas they proposed mixed traffic operation, on non-dedicated AHS lanes, with a minimum of infrastructure, possibly none at all. They viewed this system as an advanced version of adaptive cruise control, possibly with GPS based speed alerts for hazards. They also felt that simple, leader-follower truck convoys would be a viable addition. For urban areas where the system has to start dealing with increasing and eventually stifling demand, Battelle proposed dedicated lanes (link HOV lanes) and bus convoys, supported by a more complex infrastructure.
- Calspan proposed three levels of capabilities, which could be applied either as deployment stages or as regional adaptations. The first stage provided the capability for some automation in mixed traffic lanes. Modest gains in driver comfort, convenience and safety would be experienced. The second stage provides dedicated cruise lanes with access via mixed transition lanes. Barriers would be introduced to protect vehicles in the automated cruise lane. In the final stage, dedicated entry/exit ramps are introduced to further smooth the flow of increased traffic.
- Haugen focused on intercity applications. This was a natural consequence of their design, since the mechanical coupling approach involves considerable entry and exit delays (when compared to electronically coupled designs) and these longer delays only make sense if time then spent on the

AHS is longer. That is, the benefits of this concept are more apparent with longer distance intercity routes than with shorter commute routes.

- Honeywell likewise foresaw mixed traffic rural applications and dedicated lane urban operations. They also shifted functions from the infrastructure to the vehicle as they contrasted their urban and rural assumptions. They proposed that vehicles on a rural AHS highway would operate as individuals but that on an urban AHS they would operate in platoons.
- SRI International proposed a more vehicle centered approach where the vehicles had primary responsibility of maintaining a spatio-temporal situational awareness based on communications with other vehicles and suite of on-board sensors. They felt that three evolutionary steps would be required. The first provided follow-the-leader concept where instrumented vehicles would be able to lock on to and follow manually driven lead vehicles. In the second stage, individual vehicles would have advanced cruise control with automatic lane keeping. Both of these phases involved mixed traffic operations. In the third and final stage, they added an infrastructure control system and operation on dedicated AHS lanes.
- Toyota also talked of three phases but in a context of pre-AHS, AHS, and beyond AHS evolution. Their first phase is a driver assisting, vehicle based system with adaptive cruise control, collision warning and control, and lane departure warning and control. The second phase is a full AHS system and incorporated vehicle and infrastructure elements. Their third phase looks at a time when all automobile travel is entirely automated and intriguingly predicts that the system will evolve back into the vehicle with no infrastructure component.
- Virginia Tech developed a concept which also starts with mixed traffic operations then evolves into dedicated lane deployments. This, they feel, would provide safety and convenience

benefits early with throughput enhancements coming at the later stage. Further, they see intercity uses as the most natural early deployment venue. They differed however, with some of the other contractors, as seeing a global control infrastructure being required from the beginning.

On the issue of separation policy, most of the contractors felt that a free agent, independent vehicle policy would be appropriate in their light duty, rural, mixed mode operations and that a platooning capability would be necessary to achieve high capacity in congested urban areas. Many felt that both of these capabilities should be incorporated in the AHS design. Most felt that if platoons were supported that they should be limited to platoons of a single vehicle class. One contractor, Calspan, offered a different solution. Their analysis caused them to reject platooning as less safe than maintaining a constant minimum spacing between vehicles, and as not necessary to achieve the same high gains in throughput (up to 4 times today's highway throughput).

On the issue of mixing different classes of vehicles, that is, on building an AHS which can support different classes of vehicles operating in the same lane at the same time, all the contractors felt that it would be unreasonable to build an AHS without this capability. Some (Calspan and Battelle) warned against mixing of vehicle classes within a platoon. These two also recommend incorporating an ability to operate with segregated classes to allow localities to address specific performance goals. One, SRI, went even further and felt that although the capability was necessary it should be rarely used. Toyota felt that all vehicles would have to meet certain minimum performance and equipment requirements.

On the issue of the two types of entry/exit configurations (transition lanes or dedicated on/off ramps) there was a little more variation between the contractors. Calspan, Battelle, and Toyota felt that both types would be necessary, either because of right-of-way considerations or to meet different throughput needs. They concluded that transition lanes would be more appropriate

in rural or lower demand applications and dedicated ramps would be more appropriate in urban or higher demand applications. Honeywell felt that dedicated on-ramps, which would allow for vehicle inspection, would be necessary but that dedicated off-ramps would not be required. SRI and Virginia Tech opted for transition lanes.

On the final issue of obstacle detection and avoidance, most contractors, with the exception of Haugen, wanted to see automatic obstacle detection and avoidance. Haugen's concept used trained professional drivers. Two contractors, Calspan and Toyota, felt that the drivers should be allowed to intervene if they saw an obstacle, and Calspan commented on the issue of ensuring the driver stayed attentive to this role.

Conclusions

The effort and thought that the contractors gave to this work, and the ideas, concepts, and recommendations they provided us have strongly influenced the concluding effort of this task, that is, selection of the issues on which the 6 concept families would be based. Further, they have given us their insight on various other technical approaches to AHS which have broadened the range of enabling technologies we will consider. A few of the more important recommendations we got from these contractors are:

- We should consider using a suite of different types of sensors, both on the vehicle and along the infrastructure, along with sensor fusion algorithms to increase the probability of maintaining a true situational awareness.
- We should have a flexible design to address a wide variety of market opportunities in addition to the congested urban application. Indeed, there was a healthy difference of opinion as to which application would be the first the market would embrace.
- We should include introductory systems to stimulate the market for more advanced and higher performance fully Automated Highway Systems.
- We should design the system to operate with a minimum of infrastructure

in areas where maximum throughput performance was not needed.

- We would need an infrastructure component to achieve maximum throughput performance.

In final conclusion, this effort achieved its goals. We solicited for strong, helpful concepts and we got them.

Rejected Concept Suggestions

Although the majority of the ideas for concept coming to us in the solicited concepts were evaluated and accepted by NAHSC, either for incorporation or for further consideration, a few ideas were evaluated and rejected. In some cases, the rejected ideas were contrary to conclusions we had drawn from our own concept development and the arguments were not sufficient to warrant reconsideration. In other cases, the rejected ideas, although novel, were not of sufficient merit to warrant further investment of NAHSC resources. Of the rejected concept ideas which were central to a solicited concept, two stand out.

Infrastructure Control -- As documented in Section 5 of this report, the NAHSC came to the conclusion that infrastructure control, as we defined it for our internal concepts, was not viable because it made the infrastructure-to-vehicle communications link safety critical. Although they didn't push the concept as far as we did, Virginia Tech seemed to place too much reliance in the infrastructure-to-vehicle communications link in their proposed concept. As a result, they did not include any discussion of what the concept would do if this link was not available. In our opinion, a viable concept must include a clear description of its capabilities when communications fails. Degradation when communications fails should be gradual, minimal, and safe. When considering this, the concept developer may have cause to reconsider the allocation of functions between the vehicle and the infrastructure. A different allocation may result than that which had looked attractive when communications were not allowed to fail.

Mechanical Coupling of Vehicles -- The concept advanced by Haugen and Associates had, as its most noticeable technical feature, and as the feature around which its salient operational characteristics were developed, the idea of mechanically linking platoons of vehicles. Their rationale for selecting this approach, along with the use of professional platoon drivers, was to minimize the complexity of sensor and system electronics and to minimize the technical problems and risks of a AHS. On this basis, Haugen developed the operational aspects of their concept to take full advantage of these assumptions about technology. After evaluation of this concept, as described in the contractor's Final Report (an appendix to this document), the NAHSC decided that it would not pursue research on mechanically coupled vehicles for the following reasons:

- In part, Haugen proposed using mechanical linked vehicles based on the risk that the technology to implement an electronic link is not presently viable and presents too much risk to the Program. The NAHSC does not share this view, nor did it find any public support for this view among AHS stakeholders.
- Mechanical linking requires off-line platoon coupling and uncoupling with attendant delay. This delay becomes more noticeable when trip times are shorter, as would be the case for commuting trips. Any concept the NAHSC can accept must be flexible enough to address urban congestion.
- The cost of providing paid professional drivers to lead each platoon is a serious drawback, and becomes more of a drawback with shorter trips times (commuter trips).
- The inconvenience and time delay incurred when a vehicle, and the platoon of which it is a part, traveling in an intercity trip (say from Chicago to St. Louis) needs to stop for an unexpected reason (traveler becomes sick, young children need to use a rest room, etc.).

7. CONCEPT FAMILIES

7.1 RECONCEPTING PROCESS

The development of the concepts was based on an early recognition that the 6 concept families selected in C1 would not simply be down selected from the 23 concepts in chapter 3. Instead, the lessons from the evaluation were synthesized (chapter 5), and a set of six new concept families incorporating those lessons were generated.

There were four steps in the development of these concept families. The first step, discussed in Section 7.2, took place at the System Requirements Review of September 19-21, at which the evaluation results and the solicited concepts were presented, and working groups discussed recommendations for the concept families. The next step (7.3) was to form candidate concept families from these discussions. The third step (7.4) was to fuse these alternatives into a smaller number of concept families. The final step (7.5) was the selection and definition of the six families. Section 7.6 describes the concept families.

7.1.1 Requirements for the Set of Six Reconcepted Concept Families

Before actually selecting the six concept families, an attempt was made to set requirements the set of concept families would meet. Suggested requirements are discussed below.

- Must consist of six concept families. (This was followed, and drove selections.)
- Must be available for presentation to the AHS System Concepts Workshop October 18-20. (This set a schedule to fully decide on the six concept families, which slipped somewhat. That slip left insufficient time to fully educate the consortium members on the six selected concept families, resulting in some confusion at the Workshop.)
- Must include concepts families with platooning, and concept families without platooning. (The C1 analysis was insufficient to make a final decision on platooning vs. free-agent, and thus both

must be represented in the set of concept families. This was followed.)

- There must be concept families with layered levels of control. (A key issue was determining features on which different concept families with layered control could vary.)
- There must be a concept family with only one layer of control. (This was not followed (all concept families included concepts with multiple layers of control), but some concept families included concepts which have only one layer of control.)
- Some felt there was some requirement in terms of how much the concept families are defined in full deployment and in operational test. Despite that, no such requirement was made or followed in the reconcepting, largely due to time limitations.
- Concepts may be technology-specific, if the technology is central to the concept. This was followed, but the concept families were not initially defined in technology-specific terms.
- Each concept family may be described within it's own point of view of what defines a concept family. In other words, the different concept families do not have to be defined using the same schema. This was followed, most notably in Driver Involvement (7.4).

7.1.2 Concepting decisions made generating the set

- Infrastructure control (the infrastructure gives brake and throttle commands to the vehicles) was eliminated as a candidate
- The slot concept was eliminated
- Physical configuration (ramps, transition lanes, barriers) is a local option
- Class mixing is a local option (but impact needs to be better understood)
- A layered approach has merit and should be considered further, although it is not the only approach
- Concept families will be defined as families of compatible options with a growth

path (and hence are not mutually exclusive).

7.1.3 Issues areas to be addressed in this reconcepting set

- Platoon vs. free agent
- The role of the driver (Should he be totally engaged always? Should he have the option of taking control? Should he be a backup obstacle sensor? etc.)
- The optimal amount of layering
- The level of infrastructure involvement
- Mixing with manual

7.2 EVALUATION RESULTS AND RECOMMENDATIONS

The System Requirements Review, held September 19 -21, 1995 in McLean, Virginia, was in large part a forum for concepts and concept evaluations. Specifically, September 20th included presentations on the solicited concepts, which were discussed in Section 6, and the evaluations of the candidate concepts relative to throughput, safety and cost (Section 4). The evaluation results continued the next morning with flexibility and acceptability. Most of the day was a working session. The attendees, which included core team members, solicited concept teams and associates, broke up into working groups to discuss dimensional decisions, new dimensional correlations, additional dimensions, clustering within an evaluation factor and comparisons across evaluation factors. The groups were then asked to make recommendations in terms of the meaning of concept family and the specific concept families to pursue. The groups reconvened and presented their conclusions to the others. Many of the conclusions emphasized the need to address various stakeholder groups and highway scenarios. The associates, especially, as stakeholder representatives provided insight into the range of situations the concepts must address. There were also general recommendations for concept families. The group agreed that concept families will be defined as compatible sets of concepts with a smooth evolutionary path among them, but the group did not make specific recommendations for the six concept families.

7.3 STRAWMAN PARTIAL SETS OF RECONCEPTED CONCEPT FAMILIES

The next step was to fuse the results of the meeting into a set of recommended concept families, from which would come the six families. Various team members developed lists of candidates from their notes and recollections of the various recommendations from the meeting. In particular, a set of six concept families was built on the prevalent recommendations that the concepts be defined by the allocations of intelligence. Also, it was clear to the concepts team that to achieve the diversity of candidate concepts that was recommended there should be at least one free agent concept.

7.3.1. The Allocation of Intelligence Set

The matrix in Figure 7.3.1-1 identifies the six concept families built on the key allocations of intelligence. There had been general agreement at the meeting that allocation of intelligence is a major concept discriminator. Each number in the matrix represents a distinct concept. The check marks indicate an option for the concepts in the same row. So, for example, number 1 is autonomous free agents that can operate in mixed (or segregated) traffic with manual vehicles, and the driver has partial control (or possibly less). Concepts 3, 4 and 5 are all infrastructure supported, but they differ in the level of driver involvement, the ability to operate mixed with manual and whether or not they support platoons.

One weakness of this set of concept families is that it excludes any concept families that are driving disengaged mixed in manual traffic. Nor were there any platooning concept families that do not require infrastructure electronics. Nonetheless, the broad sweep of the concepts captured a reasonable sense of how the different concept factors may correlate, and several of the selected concepts fit within this broad sweep.

Figure 7.3.1-1. Six Candidate Concept Families

	Platoons		Manual and Automated Traffic		Driver Roles			
	Platoons	Free Agents	Mixed	Segre-gated	Partial Control	Malfunc-tion Manage-ment	Routine Obstacle Detection	Panic Button
AUTONOMOUS (No communications other than ITS)		1	1	√	1	√	√	√
COOPERATIVE (vehicle-vehicle communications added)		2	2	√	2	√	√	√
INFRASTRUCTURE SUPPORTED (VRC [Vehicle to Roadside Communications] added, broadcast both ways)	5	3, 4	3	4, 5		3	4	5
INFRASTRUCTURE ASSISTED/ MANAGED (2-way VRC added, comm. to individual vehicles on dedicated channel)	6	√		6				6

*Each number refers to a concept

7.3.2 The Free Agent Set

This consisted of three concept families, which were also three stages of an evolutionary path, and one alternative concept family requiring dedicated lanes for all operations that was isolated in the development flow.

Figure 7.3.2-1 diagrams these concepts and their evolutionary relationship. The first three concept families (labeled 1, 3, 2 in deployment sequence) are shown below:

In selecting the six concepts, it was ultimately decided to merge these concepts 1, 2 & 3 into a single concept family with an evolutionary path, with the focus on the middle point of the evolution as the evaluatory "full deployment." (The final phase is simply indicative of a future growth path.)

Also suggested was an alternative concept, the "Insta-Platoon" on Dedicated Lanes

Urban and Interurban Goal: Platoon on dedicated lanes. Full infra-

structure involvement in forming of platoons, merging of vehicles, directing & managing of traffic.

Rural Goal: None, unless capable of having dedicated lanes.

Evolutionary Path: None. Instant drop of capability.

- No AHS capabilities until dedicated lanes are available
- Platoons, heavy infrastructure involvement in forming of platoons, merging/ demerging of vehicles, traffic management
- Vehicles do not have autonomous capability except for degraded modes

7.3.3 The Issues - Oriented Set

This set developed only 5 concept families. They were:

7.3.3.1 Preferred Platooning

The intent of this concept family was to capture the best system concept, given that it

Concept 1 - Autonomous

Urban Goal: Free Agent autonomous vehicles on dedicated lanes with complete driver disengagement

Interurban Goal: Same as urban

Rural Goal: Vehicles with greatly enhanced safety features/stress relievers. Driver is engaged. Responsible for vehicle. Trucking platoons are in place (lead vehicle driven, following vehicles are driver disengaged).

Concept 3 - Autonomous to the Limit

Urban Goal: Further throughput gains achieved by enhancing infrastructure capability. Infrastructure processes data, transmits recommended speeds, routing preferences, entry/exit limitations

Interurban Goal: Same as urban

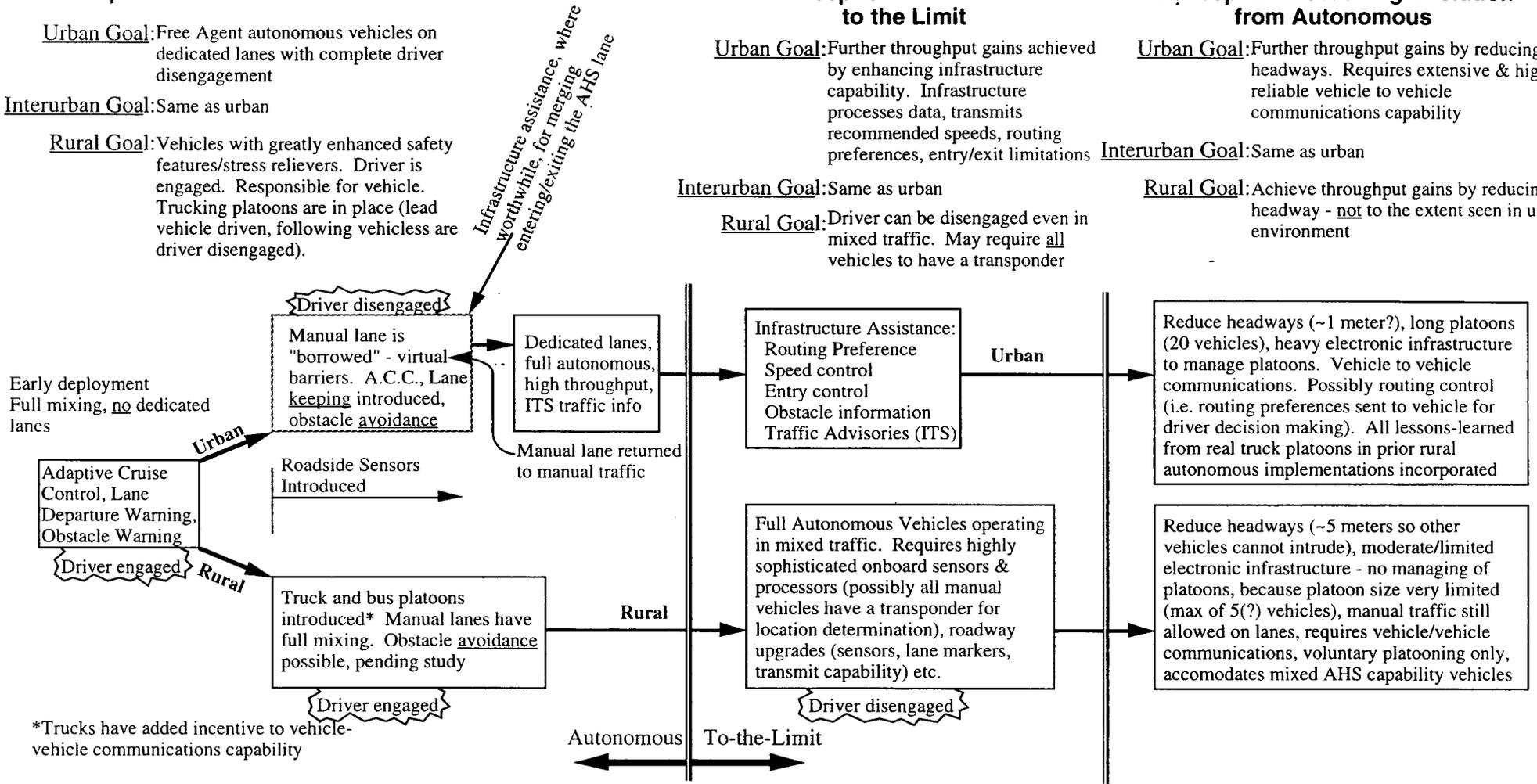
Rural Goal: Driver can be disengaged even in mixed traffic. May require all vehicles to have a transponder

Concept 2 - Platooning-Evolution from Autonomous

Urban Goal: Further throughput gains by reducing headways. Requires extensive & highly reliable vehicle to vehicle communications capability

Interurban Goal: Same as urban

Rural Goal: Achieve throughput gains by reducing headway - not to the extent seen in urban environment



operates only on fully dedicated lanes, and strongly supports platooning. It was thought that concepts 9 or 14 from Appendix H might best represent this option. The purpose of this concept family, however, was to allow the advocates of limited systems optimized for high throughput through platooning, designed to operate brain-off only on dedicated, physically isolated lanes, to select their preferred system.

7.3.3.2 Preferred Free Agent

The idea for this concept was to select the free agent concept that seemed most promising. It was not clear what the selection would be, but the advocates of free agency would be the ones to decide.

7.3.3.3 Fully layered

This concept was intended to support every level of intelligence, from autonomous through infrastructure managed, as well as platooning, mixing of vehicle classes, and the physical layout of the roadway and entry/exit, as local options. The vehicles would be capable of operating autonomously, but if there were multiple vehicles around, their cooperative layer would naturally emerge. The purpose of this concept is to leave nearly everything possible as a local option.

7.3.3.4 Brain-Off mixed with manual

All the other proposed concept families seemed to require fully dedicated lanes, or driver involvement. This concept family starts by saying that the driver may fully disengage on the highway when mixed with manual traffic. It is expected that would be the driving requirement on the system, and thus significantly different from the others.

While technically very challenging, this is dramatically preferred from a flexibility and deployability standpoint. It would still be able to operate on dedicated lanes, and might accrue significant advantages (such as the ability to platoon for high throughput) when doing so.

It was suspected that the preferred member of this family would also be nearly identical to "fully layered" in those cases where it was operating on dedicated AHS lanes.

7.3.3.5 Full physical isolation from check-in to check-out

In this concept family, the driving characteristic was that the vehicles were restricted to dedicated roadways that physically bar intruders for their entire length. It might also provide substantial roadway markings, such as radar-reflective markers along the walls. This provides a very coddled environment for the vehicle, which should allow substantial off-loading of cost and complexity.

7.3.4. The Representative Set

The final set of recommended concept families was designed to cover the range of alternatives that looked viable following the evaluations.

- Platoon, no mixing with manual ever, range of intelligence from cooperative to infrastructure assisted, supports free agent, various barrier configurations (but not virtual barriers.)
- Free agent (as exemplified, for example, by ongoing work at CMU)
- Some human involvement at all times. Ranges from lane keeping, headway keeping to high end with human as in Calspan
- Supervehicle. Cooperative pushed to the limit. The SRI concept seemed to fit here.
- Single layer (infrastructure assisted). Just stops in failure or goes to autonomous. Revolutionary, not evolutionary.
- Assisted mixing. Allows mixing of AHS vehicles with less-than-AHS vehicles (may include concepts for partial automation with a diversity of automation capability in different vehicles)

7.4 THE MERGED RECONCEPTING SET

This set was developed by merging the various reconcepting sets. It was circulated among various members of the C1 team, and the six concept families selected were derived from this set.

These nine candidate concept families were defined based on the decisions and key issue areas from the Concepts meeting at the SRR. Suggestions for concept families that came out of the break-out sessions were also included. These families are summarized in Table 7.4-I.

Table 7.4-I. Summary of the Merged Reconcepting Set

	Layered	Vehicle Options	Autonomous Free Agent	Driver Involvement
Allocation of intelligence	autonomous, cooperative, infrastructure supported, infrastructure assisted, infrastructure managed	autonomous, cooperative, infrastructure supported, infrastructure assisted, infrastructure managed	autonomous, infrastructure supported (without vehicle-vehicle comm)	autonomous, cooperative, infrastructure supported, infrastructure assisted, infrastructure managed
Separation policy	platoon, free agent	platoon, free agent	free agent	platoon, free agent
Mixing with non-AHS	Yes, no	yes, no	Yes, no	Yes, no
Mixing of classes	Yes, no	Yes, no	Yes, no	Yes, no
Entry/exit and barriers	Transition lane, dedicated ramp, full, partial or virtual barriers	Transition lane, dedicated ramp, full, partial or virtual barriers	Transition lane, dedicated ramp, full, partial or virtual barriers	Transition lane, dedicated ramp, full, partial or virtual barriers
Obstacle detection	Manual or automated detect, manual or automated avoid	Manual or automated detect, manual or automated avoid	Manual or automated detect, manual or vehicle avoid	Manual detect and avoid in conjunction with optional automated detect or avoid
Role of the driver	Completely or partially engaged or disengaged	Completely or partially engaged or disengaged	Completely or partially engaged or disengaged	Completely or partially engaged; bears responsibility

	Super Vehicle	Dedicated Platoon	Mixed with Manual	Fully Isolated
Allocation of intelligence	Autonomous, cooperative	Infrastructure assisted	Autonomous, cooperative, infrastructure managed	Autonomous, cooperative, infrastructure supported, assisted or managed
Separation policy	Platoon, free agent	Platoon	Free agent	Platoon, free agent
Mixing with non-AHS	Yes, no	No	Yes	No
Mixing of classes	Yes, no	Yes, no	Yes	Yes, no
Entry/exit and barriers	Transition lane, dedicated ramp, full, partial or virtual barriers	Dedicated ramp, full barriers	Transition lane, virtual barriers	Dedicated ramp, full barriers
Obstacle detection	Vehicle or manual detect, vehicle or manual avoid	Automated detect and avoid	Automated or manual detect, automated or manual avoid	Automated or manual detect, automated or manual avoid
Role of the driver	Completely or partially engaged or disengaged	Disengaged	Completely or partially engaged or disengaged	Completely or partially engaged or disengaged

	Dual Layer
Allocation of intelligence	Infrastructure assisted
Separation policy	Free agent
Mixing with non-AHS	No
Mixing of classes	Yes, no
Entry/exit and barriers	Transition lane, partial or virtual barriers
Obstacle detection	Vehicle or manual detect, vehicle or manual avoid
Role of the driver	Completely or partially engaged or disengaged

7.4.1 Layered

This concept family supports the wide range of promising options, including free agent as a special case. In fact, it includes any concept developed by defining combinations of the acceptable options for the dimensions. Specifically, it includes the range of intelligence from autonomous to infrastructure assisted (or managed if needed), supports free agent or platoon, and various barrier configurations and mixing options. This family appears to include elements of all of the solicited concepts. It is layered to support a phased deployment and multiple local options. In fact, there are multiple growth paths, which are themselves local options. There are two questions that this family is addressing: (1) What are the costs and benefits of a layered approach? (2) What are the costs (financial, standards, complexity, compatibility, etc.) of maintaining a wide range of options?

One approach: Fully Layered, Infrastructure Options, Designed from the Bottom Up.

This concept is influenced by a vehicle design philosophy; the architecture is grown out of the vehicle. First, a fully functional autonomous vehicle is designed and debugged. Then vehicle-to-vehicle communications (with margin) are designed so that the vehicles can share a common traffic picture and coordinate their actions. Then, infrastructure support messages are defined, along with the architecture for how vehicles respond

to this information. Finally, infrastructure management commands can also be detected and followed. Particular members of this concept family are distinguished by a roadway-vehicle specification (possibly specifying, for example, a particular pattern of magnetic nails or radar reflective strip), a logical architecture, and a communications specification, and implicitly by the vehicle architecture. The vehicles drive in a [driver] brain-off manner, autonomously when alone, cooperatively when there are other vehicles around. They also can receive and use infrastructure support information, and receive and follow infrastructure management commands. Vehicle platoons are formed when directed by the highest available decision level.

Another approach: Fully Layered, Infrastructure Options, Designed from the Top Down

This concept is influenced by the system design philosophy; the architecture is defined outward from the vehicle-infrastructure interface. First, a vehicle-infrastructure interface is designed, which, when supported on both sides by the vehicles and the infrastructure, allows the vehicles to drive in the system. Then, the vehicles are given additional functions so they can operate where there is only infrastructure support. After that, cooperative and autonomous modes are added. Particular members of this concept family are also distinguished by a roadway-vehicle specification, a logical architecture and a communications specification. The highway can operate at any level, from infrastructure managed to autonomous, letting vehicles run in brain-off mode. The infrastructure manages the vehicles, which are robust enough to operate with only infrastructure support. With no infrastructure support the vehicles devolve to cooperative, or even autonomous, mode. Vehicle platoons are formed when directed by the highest available decision level.

7.4.2 Vehicle Options

This is an expansion on Layered, with a range of vehicle options as well. This double layered concept family supports automated driving on the highway, with the location able to decide on any level from cooperative through infrastructure managed. Vehicle platoons are

formed when directed by the highest available decision level. Buyers have the option of purchasing vehicles with limited options (for example, a vehicle which cannot platoon, and thus is not allowed on the platooning lanes). An open question to be determined by further work is "what is the set of option packages for AHS from which buyers may select?" A particular issue is "what is the least expensive AHS option one may select?" Another open question is what vehicle options, if any, are there in which the driver is in the automated driving loop (for example, possibly performing as a hazard spotter). Another issue is whether capability mixing is allowed on a lane or whether all admitted vehicles must be equipped to operate at the level of the lane or higher.

7.4.3 Autonomous free agent

In this concept family, vehicles are autonomous, with no transmit capability, but able to receive ITS features such as real-time traffic information. Thus, they can operate at the infrastructure supported level without cooperative capability. Early implementation on non-dedicated lanes provides some automated vehicle functions while traveling mixed with manual traffic, but requiring the driver to remain in control. Where dedicated AHS lanes are provided, AHS vehicles travel in Free-Agent mode with high throughput. In some locations the infrastructure may establish roadside sensors, particularly for obstacle detection, and broadcast that information in the immediate area. This concept is based on PSA analysis that indicates that free agent has throughput comparable to that of platooning. The question here is (1) the comparison between the platooning and free agent under various vehicle mixes, infrastructure configurations, assumptions and safety policies and (2) whether there are requirements for intensive infrastructure involvement.

7.4.4 Driver involvement

This family includes the full range of options in Layered, with a major exception. Each of the concepts in this family have some human involvement at all times. Examples range from lane keeping and headway keeping with the

driver fully responsible to high end concepts with the human acting as a backup sensor, as in the Calspan concept. This also includes Battelle's concept of a lead truck. The basic premise behind this approach is that no automated system will in the near future match the pattern recognition and inferencing capabilities of the human. In the very long term, such concepts may evolve to fully automated systems as the obstacle detection technology matures. The question being addressed is the cost, risk, safety and benefit comparisons of relying on, allowing or forbidding driver intervention.

7.4.5 Supervehicle.

This concept family is heavily vehicle-oriented, with very little infrastructure. Specifically, the infrastructure includes at most sensor-readable lane markers, digital ITS traffic information and GPS. In the high end variation, the oversight and management activities that might otherwise be carried out by the infrastructure are distributed among the vehicles, so that the vehicles in an area together become a virtual local processor. This may involve extensive message passing over large areas and sophisticated data fusion and inferencing. This family includes autonomous and cooperative pushed to the limit. It also includes the SRI concept. This family is based on the issue of vehicle versus infrastructure, with the maximum possible in the vehicle.

7.4.6 Dedicated platoon

This is a single element concept family with some local options within it. The motivation here is to pick the best solution and avoid the expense of the underlying layers and of a gradual upgrading. This is a revolutionary, not evolutionary, approach. The thought behind this is that the AHS will be put in place in finished form, one area at a time, and that the evolution will be geographic only. The choice of free agent or platooning as well as class mixing may be set locally or dynamically. Physical configuration (ramps, transition lanes, etc.) is a local decision. There is one level of vehicle automation; any vehicle not so equipped may not use the AHS. The design will determine whether there are underlying layers for failure. All options in this family have a completely disengaged driver, based on

the assumption that any manual activities on the AHS are dangerous. The comparisons to be made here are between the benefits, risks and costs of an evolutionary and layered approach and a revolutionary approach and between the benefits and risks of keeping the driver out of the loop.

7.4.7 Mixed with manual

This concept family allows automated vehicles to drive in a brain-off mode when mixed with manual traffic. Particular members of this concept family are primarily distinguished by the level of infrastructure and vehicle activity allowed when mixed with manual traffic, and the range of allowed operational modes when automated traffic is in dedicated lanes. Note: This may not be a concept family or even a concept in its own right, but a possible enhancement to concepts that allow mixing with manual traffic.

Assisted mixing is a variant on this concept; it allows mixing of AHS vehicles with less-than-AHS vehicles. For example, the less-than-AHS vehicles may be equipped with reflectors and/or communications. They are not automated, but may share the AHS roadways if they are equipped to support the automated vehicles. The question here is the cost, risk and benefit of mixing with traffic that is not fully automated.

7.4.8 Full Physical Isolation

This concept family requires that the Automated roadway be fully physically isolated from manual traffic and other preventable hazards from check-in through check-out. It guarantees vehicles this restricted environment, which the vehicles exploit to simplify the automated driving problem. To make the down-select from 6 to 3 might require a technical case to be made within this concept family, showing a particular member which achieves some major advantage (e.g., low user costs) from exploiting the simplified environment that the AHS Vehicles operate in. Particular members of this concept family are largely distinguished by the vehicle-roadway interface (specified down to the level of the particular implementation of the particular technologies used).

7.4.9 Infrastructure-Assisted Free Agent

This is a single element concept family with some local options. This is an infrastructure-assisted system where the vehicles operate autonomously except at merge points; here they receive directions from the infrastructure. The autonomous layer also serves as a failure mode, a geographic option, and an evolutionary stepping-stone to the full concept. Infrastructure-to-individual vehicle communications is supported, but there is no vehicle-to-vehicle communications, and vehicle-to-infrastructure communications is limited to driver alerts for obstacles and emergencies. There is no mixing with manual traffic; the choice of class mixing may be set locally or dynamically. Barrier options are limited to virtual barriers and barriers with gaps. Obstacle detection and avoidance could be either manual, automatic, or a combination of the two. This concept offers a compromise between the expense of a fully-layered system, and the inflexibility of a single layer approach.

7.5 FINDING THE RECONCEPTING SET

The nine candidate concepts were sent to the core team members for review. The Hughes and PATH teams then convened a meeting at PATH to select the six concepts, based on all candidates and all feedback and suggestions. In selecting the six concepts, Layered turned into Maximally Layered. It was decided that Vehicle Options, was a design option to be worked out within the development in C2 of Maximally Layered. Autonomous Free Agent was incorporated within the Vehicle Centered concept family. Driver involvement continued as a selected concept family. Supervehicle was essentially captured within Cooperative Plus.

Dedicated Platoon was carried forward as two separate concept families, Infrastructure Supported Platoons, and Infrastructure Assisted Platoons. This allowed a continued extensive comparison of these answers to distribution of intelligence within the context of a concept of platooning on dedicated lanes. Mixed with Manual was dropped, although the rural implementation of Vehicle Centered

includes the same capabilities. Cooperative Plus may develop into a concept with brain off driving mixed with manual traffic, and Driver Involvement should also look at mixing with manual traffic. Full Physical Isolation was dropped as a concept, but may be partially embraced by Infrastructure Supported Platoons and Infrastructure Assisted Platoons.

Finally, Infrastructure Assisted Free Agent was dropped, although it remains a local option within Maximally Layered.

7.6 THE SELECTED SIX CONCEPT FAMILIES

7.6.1 Overview of the Six Concept Families

In summary, the six concept families selected were as follows.

7.6.1.1 Vehicle Centered

This architecture focuses on maximizing the performance that can be obtained from lone vehicles, while at the same time holding down cost by eliminating the cooperative layer. It may be minimally supplemented with infrastructure assistance to improve throughput. It also provides an early benefit for urban users in the form of driver disengagement, and for rural and intercity users in the form of driver-assisted truck and bus platoons.

7.6.1.2 Cooperative Plus

This concept family focuses on obtaining the maximum performance achievable without requiring infrastructure electronics. This is done by using extensive vehicle-to-vehicle communication to pass messages over extended ranges, and by providing the vehicle with substantial on-board processing.

7.6.1.3 Driver Involvement

All members of this concept family make use of man-in-the-loop operations. The exact areas of human involvement are design options, and may include obstacle detection, obstacle avoidance, and handling catastrophic hardware/software failures or other un

expected problems. This range of design options will be refined later, based on technology studies which reduce the uncertainty regarding man vs. machine performance.

7.6.1.4 Infrastructure Supported Platoons

This concept family focuses on the throughput and safety implications of driver disengaged platooning, in the framework of an infrastructure-supported system where the infrastructure does not communicate with individual vehicles. Since the Infrastructure Assisted concept family is similar but has an Infrastructure-Assisted architecture, this concept family pair will also provide an excellent comparison of the benefits and cost of infrastructure-supported vs. infrastructure-assisted.

7.6.1.5 Infrastructure Assisted Platoons

This concept family focuses on the throughput and safety implications of driver disengaged platooning, in the framework of an infrastructure-assisted system where the infrastructure communicates with individual vehicles when appropriate (for example, merge points). Since the Infrastructure Supported concept family is similar but has an infrastructure-supported architecture, this concept family pair will also provide an excellent comparison of the benefits and cost of infrastructure-supported vs. infrastructure-assisted.

7.6.1.6 Maximally Layered

This concept family focuses on providing a family of choices, with full layering for geographic, deployment, and failure options, and numerous alternatives in the other dimensions. This architecture has the flexibility to evolve as experience is gained from early deployments, and has robustness in the case of failure, but it may be costly to implement and maintain, and it raises issues of the transfer of control from one layer to the next.

7.6.2 Summary Table

The concepts, in their deployment phases, are summarized in Table 7.6.2-I.

Table 7.6.2-I. Summary of Six Concept Families

Concept	Deploy Phase/ Geogr. Option	Distrib of Intelligence	Mixing with Manual	Driver Engagement	Separation Policy	Comments
Vehicle Centered	1	Autonomous	Rural only	Rural only	Lead driver-engaged truck and bus platoons in rural	Truck and bus platoons in rural
	2	Infrastr. Assisted with Autonomous backup	Rural only	Disengaged	Autonomous truck and bus platoons in rural	Disengaged driver
Cooperative Plus	Early	Cooperative (autonomous backup)	Begins with engaged driver in mixed traffic, and progresses...		Platooning where dedicated lanes are available	Option for early benefits
	Late	Cooperative (autonomous backup)	...toward disengaged driver on dedicated lanes		Platooning where dedicated lanes are available	Maximize perf. of totally vehicle based architecture; Disengaged driver; mixed with manual and platooning are local options
Driver Involvement	1	Autonomous to Infrastructure Supported inclusive	Yes	Engaged	Free agent	Explores role of engaged driver
	2	Autonomous to Infrastructure Supported inclusive	No	Engaged	Free agent	Dedicated lanes for performance gains
Infrastructure Supported Platoons	1	Autonomous to Infrastructure Supported inclusive	No	Disengaged	Platoons	Explores platooning with infrastr. support in dedicated lanes; use all techniques possible to improve perf.
Infrastructure assisted platoons	1	Autonomous to Infrastructure Assisted inclusive	No	Disengaged	Platoons	Explores platooning with infrastr. assistance in dedicated lanes
Maximally Layered	Early	Autonomous	Yes	Engaged	Free agent	Explores early benefits with evolution path
	Intermed. example	Cooperative with underlying autonomous	No	Disengaged	Geographic option	Platooning option
	Late example	Infrastructure managed with underlying infra-structure support, cooperative and autonomous	No	Disengaged	Platoons	Maximum flexibility and degradation options; explores interaction of layers

Each of these families is defined by the characteristics which the members of each particular family share. There remain a host of important issues that are undecided within each family. The different possible answers define the different members of each family. Some important issues may not yet be identified.

There are two sorts of variability within each concept family. The first is "stakeholder options." These are choices that people will have if a particular concept is chosen and deployed. For example, local officials may have a choice between having platooning traffic on a lane or free agent traffic on that lane. The choices provided to individuals, such as between different packages of AHS capabilities to buy, are also "stakeholder options."

The second sort of variability is "design options." These are choices that still need to be made by the consortium about exactly what concept will be implemented. For example, AHS may be designed so that it allows platooning, or so that it does not allow platooning. As the individual concepts are discussed below in detail, the distinction between stakeholder options and design options will be emphasized. Note, it may be a design option to offer a stakeholder option.

Finally, these six concept families are merely the point of departure for future work. If it is later found that the best refinement to one of the six is to make a choice that is outside the formal definition of that concept family, a refinement that makes sense will still be selected.

7.6.3 Descriptions of the Concept Families

7.6.3.1 Vehicle Centered

This concept family is based on a particular vision of AHS evolution. This is also the only concept family which has already developed explicit and distinct goals for urban and rural areas. It is expected that before AHS is deployed, the fielded capabilities will be as follows: driving with adaptive cruise control, lane departure warning, and obstacle warning, but with the driver engaged. Lower end vehicles may not have all these features. It

will be technically possible to combine adaptive cruise control and lane keeping in the same vehicle, but this will not be done, because drivers would then in fact disengage, which would be unsafe when obstacles and emergencies come up.

The first AHS phase thus focuses on safely, providing driver disengagement in the urban areas when dedicated AHS lanes are established by reducing hazards and providing automatic obstacle avoidance. The goal in the rural areas is to continue and enhance driver engaged free agent driving, mixed with manual traffic on non-dedicated lanes. Vehicle Centered offers a stakeholder option in this phase for truck platoons on mixed rural roads, where only the lead driver needs to be engaged.

In the first phase of Vehicle Centered in urban areas, vehicles travel on dedicated lanes with the driver disengaged. The vehicles include lane keeping and obstacle avoidance. There is some infrastructure assistance and infrastructure support, as appropriate to support the goal of driver disengagement. The exact details are design options, but infrastructure assistance to support vehicle merging at entry is expected. As a stakeholder option, there may be roadside sensors supplementing system performance. One use would be to look into the "blind-spots" to warn of hazards, keeping vehicles from having to slow down.

The second phase of this AHS is most clearly distinct in the rural areas. While autonomous vehicles may already travel mixed with manual traffic on non-dedicated lanes, in Phase 2 of Vehicle Centered the goal is to disengage the driver. This is safely accomplished with improved sensor and processing capability on the vehicle. As a design option, it may also be necessary to require all vehicles (not just AHS vehicles) to carry simple transponders. This is the primary concept family for examining driver disengaged vehicles mixed with manual traffic, and the only one where this is a firm concept goal rather than a possible design option.

The second phase of Vehicle Centered is less distinct in urban areas. There, infrastructure is

progressively added, increasing the safety and throughput capabilities of the system.

There is a well-defined follow-on evolutionary path in this concept family. That third phase would add vehicle-to-vehicle communications and supports platooning.

7.6.3.2 Cooperative Plus

This concept family focuses on obtaining the maximum performance from a totally vehicle-based architecture. The mature vision is of platooning AHS vehicles on high-throughput dedicated lanes, coordinating their short and long-term maneuvers using vehicle-to-vehicle data links, with longer-range data being passed up and down the traffic stream by on-board data reduction and message rebroadcasts. This scheme could, for example, allow vehicles throughout a large metropolitan area to all have on-board maps with real time traffic information, which is fine-grained near the vehicle and increasingly coarse-grained for areas further away.

The details of the vehicle-to-vehicle communications are design options. Particular questions include "Is it non-line-of sight?"; "What is the communication range or ranges?"; "What is the bandwidth?"; "What is the basic network protocol?"; and "What spectrum is used?"

A major conceptual task in developing this concept family is to take the specific infrastructure functions, as they are developed for the Infrastructure Supported and Infrastructure Assisted concepts, and try to determine how to implement equivalent functions using only on-board processors and vehicle-to-vehicle communications.

Cooperative Plus spreads across a continuum of capabilities that will be available for deployment sooner versus later, and is represented in the summary chart in Table 7.6.2-I by two distinct phases. Early capabilities include platooning, coordinated merging and lane changes, and some extended message passing. Capabilities which may take longer to field include creating a more intelligent extended network, inference from multiple vehicles, and wide area coordination. Uncertainties in technical development rates make this continuum somewhat fuzzy. The

sequencing of capabilities over deployment are design options.

Design options include the possibility of providing driver-engaged operation mixed with manual traffic as an early capability, and the possibility of providing brain-off driving mixed with manual traffic later. Providing repeater stations to connect vehicle-to-vehicle communications in sparse traffic, as either a requirement or a stakeholder option, are design options. Another design option would be to provide some stakeholder options for electronic infrastructure involvement.

7.6.3.3 Driver Involvement

The fundamental assumption for this concept family is that the driver will be required to perform some functions.

The exact nature of the driver involvement remains a design option, but the driver is always more involved than simply having a panic button. Choices vary along two related dimensions. One dimension is the degree of driver engagement in the driving process. A second dimension is the degree of driver control over the automated driving process.

A clear breakpoint in the first dimension is whether or not the driver ever can fully disengage. In one case, the driver is continuously engaging with the driving task, at least to the point of knowing without warning when certain actions are required. Examples of such driver involvement include being responsible for seeing and recognizing approaching obstacles, continuously monitoring for something else like system failures or other problems, and performing a major continuous task, like lateral or longitudinal control.

In the other case, the driver may fully disengage from driving until notified otherwise. Options here include automatic obstacle detection and avoidance approaches, which ask the driver to examine and decide on uncertain obstacles, and vehicles, which come to a halt when obstacles are encountered and ask the driver to then manually circumvent the obstacles. A major issue with this category is the ability of drivers to reorient and respond quickly enough when they are concentrating on something other than driving.

Vehicle versus driver control is a distinct dimension of driver involvement. For example, one design option might let the driver take control of the vehicle at any time, but still allow the driver to usually disengage. Another design option may require the driver to be continuously engaged in routine obstacle detection, but may maintain automated control of the vehicle even when obstacles are detected.

In Driver Involvement, vehicles will be able to travel automated both on dedicated lanes, and when mixed with manual traffic (i.e., this is a stakeholder option). Many design options, such as the exact driver involvement tasks, may vary between dedicated and mixed lanes. Platooning is not a design option.

The distribution of intelligence option for this concept family is autonomous, cooperative, and infrastructure supported layers, but that may be changed if further analysis were to show that a different distribution of intelligence is necessary for driver involvement to make sense. Infrastructure support is a stakeholder option in rural deployments. It is the involvement of the driver to some extent which is not subject to change in this concept family.

7.6.3.4 Supported Platooning

In this concept family the vehicles travel in platoons on dedicated lanes, with the driver disengaged. The infrastructure provides general support, such as speed directives and data distilled from roadside sensors, but no assistance directed to particular vehicles. The vehicles will have capabilities to operate in a degraded mode.

Platooning is for increased throughput. When traffic is sparse, the vehicles would operate as free agents. The platooning details, such as platoon size, intra- and inter-platoon spacing, and speed, are design options.

This is the first of the concept families that definitely does not evolve from engaged drivers in mixed traffic, but starts with disengaged drivers in dedicated lanes. This concept does not support operations on mixed lanes with manual vehicles.

7.6.3.5 Assisted Platooning

The focus of this concept is safely maximizing throughput, using every compatible method available, and standardizing all implementations of AHS on a single national scheme, with minimal concept level stakeholder options.

In this concept family the vehicles travel in platoons on dedicated lanes with the driver disengaged. The infrastructure provides support, and provides assistance directed to particular vehicles, such as vehicle-by-vehicle instructions for merging two streams of traffic. The vehicles will be capable of operating in a degraded mode, for example autonomously if vehicle-to-vehicle communications is lost.

The platooning details are design options, and may vary from the platooning details in Infrastructure Supported. Many lower level design options for safely maximizing throughput are probable. When traffic is sparse, the vehicles would operate as free agents.

This concept does not support operations on mixed lanes with manual vehicles.

7.6.3.6 Maximally Layered

The focus of this concept family is in providing the largest compatible and useful set of stakeholder options possible. The single national standard for AHS vehicles and infrastructure set in this concept family would have tremendous local flexibility built in.

The concept is expected to include an early deployment option of autonomous vehicles on non-dedicated lanes, with the driver engaged. In early deployment there is a risk of accidentally creating and locking in a standard that is inappropriate in the long run. The evolutionary path and sequence of standards is an important issue in evolving concept families like this one.

In the standard version of Maximally Layered, vehicles will be able to drive autonomously. On dedicated lanes they will be able to travel with the driver disengaged. Where there are multiple vehicles they will automatically cooperate. Local traffic authorities will have

the option of deploying infrastructure support processors and communications, and infrastructure assistance processors and communications, along with optional infrastructure sensors. Local traffic authorities will be able to set AHS roadway policies, including speed levels, whether or not platooning is allowed, platooning parameters, and minimum vehicle standards for roadway sections and lanes.

There is a design option of giving customers the stakeholder option to buy less capable AHS vehicle packages, foregoing the corresponding AHS vehicle opportunities. For example, a vehicle might not have the equipment to perform infrastructure assisted platooning, and would not then be allowed onto an infrastructure assisted platooning lane. A high-end vehicle would be able to drive on every AHS lane.

Vehicles will be able to drive mixed with manual traffic, but only in a driver engaged state.

An important design option is setting the minimum standard for roadways on which

disengaged driving is allowed. Another design option is deciding on how many different standard packages of capabilities for AHS vehicles customers may choose between, and what they will be. An important design issue is trying to develop a passive layering protocol, so vehicles and the infrastructure are not responsible for recognizing and actively switching between different layering states.

There is an implicit expectation that actual deployment will evolve, starting with autonomous vehicles operating with the driver engaged and mixed with manual traffic, and progressing to dedicated lanes, higher levels of distribution of intelligence, and higher throughput. Thus, the deployment phases for this concept family shown in the summary table are notional examples of local implementations, not required sequences. The prior levels continue to exist as degraded modes and as options for less crowded parts of the National Highway System. The rural areas are expected (but not required) to generally stay behind the urban areas in terms of deployed infrastructure.

8. CONCEPTS WORKSHOP

The AHS System Concept Workshop, October 18-20, 1995, in San Diego, afforded an opportunity for interested stakeholders outside of the Consortium to review the state of Consortium AHS thinking near the end of the C1 task, and to provide feedback.

To elicit and collect that feedback, this workshop included three breakout sessions, one on system requirements, one on concept development and evaluation, and one on the six concept families. In each case the format was a plenary session reviewing the subject, and then six parallel breakout sessions, divided by stakeholder group and led by a moderator, who discussed the subject.

The stakeholders brought well-informed and diverse outside opinions into this process. Their feedback in these breakout sessions is discussed below.

8.1 SYSTEM REQUIREMENTS BREAKOUT SESSIONS

This breakout session was driven by a desire to capture from the stakeholders the "proper" AHS weightings desired in the effort described in section 4.6. The charts for this session consisted of a large number of pairwise comparisons, asking the workshop members, "Goal A is _____ as important as Goal B," where Goals A and B could be Safety, Enhancing Mobility and Access, Providing More Convenient and Comfortable Highway Travelling, Reducing Environmental Impact, or Increasing Throughput, and the blank could be filled in with "Extremely," "Very Strongly," "Strongly," "Moderately," or "Equally" (in either direction). Also, there were questions asking for percentage improvements in vehicle accidents, fatalities and major injuries, driver stress, fuel economy, emissions, cost/benefit ratios, and competitive AHS benefits (compared to other transportation alternatives).

Some stakeholder groups did work through all the comparisons and were able to present their summary conclusions. Others ad-

ressed only a few comparisons, but attempted to clarify the meaning of the terms, in light of their own stakeholder interests and needs.

The feedback from these breakout sessions are summarized below.

8.1.1 Vehicle Industry and Electronics Industry

- Safety vs. Throughput:
 - Without safety, AHS is not saleable
 - Public cannot perceive throughput
 - Vote showed that safety is more important
- Safety vs. Mobility and Access:
 - If AHS safety is at least as good, with higher efficiency for the driver, the public will accept AHS
 - If trip times were somewhat longer, but more predictable, some driver would find that acceptable
 - Vote showed that safety is deemed more important
- Safety vs. Convenient and Comfortable:
 - Safety sells -- up to a point
 - People willingly use cellular phones and navigation systems (to say nothing of eating in their cars) even though these activities compromise safety
- Safety vs. Reducing Environmental Impact:
 - No widely accepted comments on this issue
 - Vote showed a belief that safety is more important
- Throughput vs. Mobility and Access:
 - No widely accepted comments on this issue
 - Vote showed no bias
- Throughput vs. Convenient and Comfortable:
 - People will but AHS because of convenience and comfort, not because of throughput
 - Vote showed bias towards convenient and comfortable

- Throughput vs. Convenient and Comfortable:
 - No widely accepted comments on this issue
 - Vote did not show bias
- Mobility and Access vs. Convenient and Comfortable:
 - Mobility and access is a societal issue
 - Vote showed no bias
- Mobility and Access vs. Reducing Environmental Impact:
 - No widely accepted comments on this issue
 - Vote showed no bias
- Convenient and Comfortable vs. Reducing Environmental Impact:
 - No widely accepted comments on this issue
 - Vote seemed to show a slight bias in favor of convenient and comfortable

8.1.2 Commercial Operations and Trucking

The commercial vehicle operations stakeholder community is driven very strongly by economic considerations, and all AHS objectives and characteristics are therefore translated into cost and benefit terms by them. Their overwhelming priority for AHS is productivity improvement, which combines the safety, throughput and mobility/access objectives. This group believed that those are so intimately intertwined with each other that it does not make sense to try to separate them. Environmental issues took second priority in their ranking, followed by comfort and convenience, which they believed should be treated separately rather than being lumped together. Since their vehicle drivers are paid employees, these latter issues did not carry much weight by themselves except inasmuch as they could be translated into trade-offs against the salaries they must pay or into reductions in employee turnover.

This group believed that relief of urban congestion would be beneficial to them by improving their productivity, but they thought the benefits would be very hard to quantify and to factor into an economic

justification for equipping their vehicles with AHS capabilities. They did not think that throughput in vehicles per hour was a relevant consideration for them because it is rare to find a roadway where the present-day truck volume exceeds the capacity of the system. They were more interested in the rural long-haul operations. Here, they were very conscious of the competition that AHS might offer to intermodal TOFC/COFC operations, which are already well established and cost-competitive for hauls exceeding about 400 miles. They cautioned against "reinventing the wheel" by trying to duplicate the railroads' TOFC/COFC or RoadRailer types of service or over-emphasizing the very long-haul operations. They believe that the primary advantage that trucks enjoy today is their higher trip-time reliability, and want to make sure that this is preserved. At the same time, they do not gain that much by further increasing that reliability, since that is already their competitive advantage relative to the railroads and they have already captured the business that is sensitive to this.

There was considerable interest in the concept of the truck convoy, with automated trucks following a manually-driven leader, if they would be able to operate long enough convoys to significantly increase productivity. However, this interest was tempered by the reality that the tractor unit is the most costly element in their consist, and that this still does not let them reduce the number of tractors to nearly the extent that TOFC does. They were interested in energy and emissions savings from the drag reduction in closely-spaced convoys, as well as the possibility of lower pay rates or longer duty time limits for the inactive drivers of the automated follower units. They were concerned about the political and labor sensitivities associated with such a new service, as well as the perceptions of automobile drivers who are likely to feel intimidated by a long convoy of large trucks next to them on the highway.

This group was able to indicate what their quantitative goals were for AHS, in many cases without significant controversy. The most controversial goal was associated with reduction in number of crashes, and this

eventually arrived at selection of the 50-75% reduction range, which was what they thought would be needed to warrant the investment in AHS. For serious/fatal crashes, the same range was also chosen, but it was agreed that the goal here was to be toward the upper end of that range rather than the lower end (and therefore higher than for total number of crashes). They insisted that throughput be converted to productivity or travel time and then be evaluated in cost/benefit terms since these were more meaningful to them as vehicle operators rather than system operators. They chose a 0-25% improvement goal for trip time predictability, since they do not believe that the highway is the source of their predictability problem but the local streets they use for access are the real problem here. They would like to see stress reduction in the 25-50% range, assuming that this can be translated into relaxed regulations on driver duty time. They would like to see fuel economy and emissions improvements in the 25-50% range. Overall, they would expect to see a benefit/cost improvement of 25% and a payback period for any investment within two years.

8.1.3 Transit Operations

The planned agenda for this series of breakout sessions was to conduct a simple survey to compare the relative importance of various pairs of benefits, such as safety, throughput, mobility and access, convenience and comfort, and environmental impact. This group could only address a very few of the pairs due to the need to extensively expand on each benefit in order to have a common and reasonable basis of evaluation.

- **Safety vs. Throughput**
The group quickly understood that they were being asked to compare the importance of an *increase* of safety to the importance of an *increase* of throughput. The transit operators present quickly pointed out that theirs was a relatively safe operation to begin with, primarily because of the size of a bus compared to passenger vehicles

and because of their use of trained professional drivers. The largest safety problem in the transit industry is in the stop-and-go areas with a city. The express routes are by far the safest portions of their operations now. Although they expect AHS lanes to be much safer than today's freeway lanes, the difference to transit operations may not be noticeable.

Increasing throughput, or the capacity, of highways, on the other hand, might be considered a negative from a transit view point. The public might be more inclined to see the increased capacity as an incentive to switch back to the convenience of a private auto.

At this point, the side issue of driverless buses was brought up. Although the cost savings potential is attractive, the public reaction may be negative because the driver (or any on-board transit system employee) is seen as a deterrent to the dangerous actions of other passengers.

- **Safety vs. Mobility and Access**
The use of AHS to increase mobility and access, from a transit perspective, proved to be very attractive. The discussion centered around using electronically coupled platoons of buses (smaller buses) which could split apart to better service suburban and central city neighborhoods.
- **Convenience and Comfort vs. Environmental Impact**
Environmental impact is very important when planning a transit system but when a customer considers using the transit system, over some other alternative, comfort and convenience is paramount.
- As a final note, transit operators reminded the Consortium that near-term spin-offs were necessary to keep their interest in AHS alive.

8.1.4 Highway Design and Environmental

- The group responded principally as highway design stakeholders due to the individuals present at the session, although selected comments were offered on various environmental

issues. In this context a third stakeholder group was suggested for future outreach and workshop activity: highway operators, including both public and private (i.e. toll road operators) operators.

- The group expectation was that a fully deployed AHS would carry with it the perception of being "extremely safe"; any evidence to the contrary, however small, would create a disproportionate negative public reaction. Safety was judged as strongly more important than throughput. Operational efficiency was seen to be a key evaluation metric in the nearer-term.
- Throughput ranked second only to safety. There is a perceived environmental concern regarding throughput as it relates to induced demand. The group judged it to be quite difficult to link throughput to mobility and/or access. The group advised that NAHSC pay special attention to assessment of total network carrying capacity limitations where an AHS segment is only part of a larger network of arterials and other secondary roads.
- The group indicated that the general criteria of "mobility/access" was not clearly enough defined yet to be usefully evaluated. In general, "convenience/comfort" was given a lower ranking since the current perceived level of these factors was considered generally acceptable. More delineation is needed for the "rural/urban" criteria before it can be properly evaluated.
- The group advised caution when specifying explicit safety-related metrics since there is considerable disagreement over which metrics are the best. For example, the raw number of safety incidents tabulated is a much different metric than a metric of relative severity of incidents. Existing bodies of knowledge related to safety codes in current design practice can provide guidance for the cost/safety trade-off.
- Regarding a comparison of AHS with other transportation alternatives, the

group felt that such comparisons are best done in the context of relative benefit/cost. The decision-making focus should be at the MPO level. AHS can be classified for comparison purposes as a major "operational highway improvement." Public expectations are such that AHS benefits will need to be well understood and obvious to prospective users.

8.1.5 Transportation Users and Insurance Industry

SAFETY

- If AHS is at least as safe as today's highway system, the user gives more weight to enhancing mobility, comfort and convenience, and reducing environmental impact.
- Use caution in promoting a fail-safe system because the user may assume that it is a sure attribute of the system.

THROUGHPUT:

- Throughput is perceived as a concern for transportation planners and highway providers, not for the users.
- Users care more about mobility and accessibility.

MOBILITY/COMFORT AND CONVENIENCE:

- Both are rated as highest priority of the system objectives from the user's perspective.

ENVIRONMENTAL IMPACT:

- Participants have doubt about AHS's ability to reduce overall environmental impact.
- Reducing environmental impact is more important than enhancing highway safety and throughput.

OTHER ISSUES:

- The AHS design and deployment should be "widely embraced" by users.
- Stakeholders' input is crucial and outreach is the key to solicitation.
- Success of the 1997 demo is crucial to future AHS research and development; any failure during the demo will be devastating.
- The Consortium must develop evolutionary deployment strategies.

- Deployment must be embedded in TIPs (MPO); seed funding is important.
- Do not overlook the liability issues.
- Emphasize the concept of "contract with the driver": driver relinquishes vehicle control in exchange of user benefits.
- Cost must be a major consideration during AHS R&D.

Measures of Acceptance (MOA's) for the technology, either available or being developed, should be assessed and used as a major input to the design and evaluation process.

8.1.6 Governmental Agencies and Other Institutional Organizations

The group of representatives from government agencies and other institutional organizations discussed the AHS objectives and characteristics. The group used the materials provided describing the AHS objectives and characteristics as a point of discussion. The following were discussed as areas of issues and needs:

- AHS must support intermodal transportation.
- AHS must foster partnerships between the different agencies (i.e., federal, state, local and international)
- Agencies have the need to balance transportation systems (i.e., AHS, transit, rail, etc.) to provide overall service to users.
- We need to ensure flexibility and adaptability of the AHS due to the different environments, applications and agencies involved in its implementation.
- The Consortium will need to show the benefits of an AHS as an alternative to other transportation options.
- AHS must be deployed incrementally.
- We should not overlook the law enforcement regulations and other societal/institutional issues.
- How to ensure the safety of the system?
- Owner-operators expressed the concern for operations, maintenance,

and resources required for something as high-tech as AHS.

- The relationship between ITS and AHS?
- How to get from test track to deployment in a financial sense.
- Compatibility with other ITS developments.

In discussing the level of importance or priorities between the system objectives, the following overall points were made:

- We need to separate the "musts" versus the "wants"
- The priorities of objectives will depend on the application. For example in an urban setting the priority may be on throughput while in the rural setting the priority may be on safety.
- AHS will be sold on its benefits

The discussion regarding the safety objectives included the following points:

- Safety is to be considered a "must" - we assume that the system will be safe. Improved safety is a want.
- The AHS should be designed for zero accidents.

In discussing the throughput objectives the following points were made:

- Throughput benefits are dependent on location - benefits will be lower in a rural area
- AHS needs to be equal or better than HOV alternatives in throughput improvement.
- We need to remember that we are interested in the throughput of people and goods, not vehicles.

In discussing the reliability and trip predictability objectives the following points were made:

- AHS must be market driven. The users must see the need and trust the safety of the system.
- AHS needs to be integrated into the total transportation system.
- Need to consider the comfort of the public.

In general, the group thought that the objectives and characteristics captured in the

AHS System Objectives and Characteristics document was a good set and definition of the top-level needs.

8.2 CONCEPT DEVELOPMENT AND EVALUATION BREAKOUT SESSIONS

The Plenary before this breakout session reviewed the process the Consortium went through to select the initial set of concept characteristics, to define the range of options within each, to develop the 23 concepts from these characteristics, to evaluate each concept, the results from the seven solicited concepts developed by outside contractors, and the general conclusions drawn from the internally and externally developed concepts.

The feedback from these breakout sessions are summarized below:

8.2.1 Vehicle Industry and Electronics Industry

Objective: Determine viable dimensions from industry viewpoint

Results:

- Agreed on (1) distribution of intelligence, and (2) mixing with manual vehicles as dimensions.
- Separation policy is not a dimension, but an open cross-cutting issue.
- Group believes that a knife-edge cutover from mixed lanes to dedicated lanes is necessary. A policy decision will govern the changeover. This decision will require extraordinary cooperation between industry and government.

8.2.2 Commercial Operations and Trucking

Distribution of Intelligence

They would prefer more vehicle-oriented concepts for intercity uses and more infrastructure-oriented for urban use. They would expect to see progress over time toward more infrastructure management functions as this becomes economically justified (but not as far as infrastructure

control). Those who had experience with existing truck inspection and weigh-in-motion stations raised important questions about whether these large and costly facilities would be needed at every AHS entry location. This is a valid issue to be considered as part of the check-in function evaluation.

Separation Policy

This group is interested in truck convoys or platoons and believe that these would require at least the cooperative level of intelligence. They would like to see both free agents and platoons considered, depending on the level of demand and variability in performance among vehicles. The aerodynamic drag reductions in platoons were seen as a potentially significant advantage. The major concern about platoons was the large variability in performance among different trucks (especially braking), particularly considering the contrast between empty and full-loaded trucks. There was a strong preference for platooning "on the fly" in order to avoid queuing and delays associated with formation of platoons before access to the AHS. Truck convoys mixed with manual traffic were seen to be a desirable early application if these could be found feasible.

Mixing with manual traffic

Separate automated lanes were seen to be very desirable, but the key question for this group was when they would become economically justifiable based on the volume of automated traffic. They thought that physical barriers between them and the manual traffic would help gain public acceptance because of higher perceived safety. There was uncertainty about whether the automated lanes should be the inner or outer lanes, because there are problems with both alternatives. If the AHS is in the innermost lanes, the trucks would then need to cross multiple lanes to enter or exit the AHS, which increases stress, vulnerability to problems with the rest of the traffic, and potential for crashes. If the AHS is in the outer lanes, the trucks would need to coexist with all the complications of entering and exiting manual vehicles. They would like to consider truck platoons in mixed traffic,

with specially trained drivers for the lead vehicles.

Mixing of automated vehicle classes

The commercial vehicle group urged the NAHSC to find ways of safely mixing the vehicle classes within the same automated lanes. They saw themselves as likely early adopters of AHS because of the economic (productivity) incentives and their corps of specially trained drivers. However, they thought there would be very few locations with sufficient truck traffic to justify a separate lane for truck use. The one special case where they thought separation would be needed was for operations on steep grades, where the limited performance of trucks would be a significant impediment to the rest of the traffic stream otherwise.

Entry and Exit

The choice of transition lanes or separate ramps would need to depend on local conditions. The truck operators were comfortable with having truck access limited to certain locations because of the cost and space implications of the longer ramps they would need for acceleration and deceleration and the cost of flyover ramps that could accommodate their vehicles.

Obstacle Sensing

Automatic obstacle detection was considered to be very desirable if it is feasible. Truck drivers are more skilled than the general driving population, so they may be better equipped to override an automatic system when needed, but it was not clear how much override capability would be desirable. This group was intrigued with the idea of premium pay for specially trained drivers of the lead vehicle of a platoon, who would have full obstacle sensing responsibility, with lower pay for the sleeping "drivers" of the following vehicles, who would not have any obstacle sensing responsibilities. In neither case would the vehicles have any obstacle sensing.

Other issues

A number of other issues arose in the discussion, which did not fit into the pre-defined categories. The most important of these is the observation that everything is

driven by the economics of obtaining competitive advantage for this stakeholder group, so they can be very "objective" and dispassionate decision makers, looking closely at the "bottom line." Other specific issues that are worth citing are:

- the automated lanes will need to provide access for incident and emergency response functions, which could be challenging with barriers separating them from the rest of the roadway;
- what, if any, special training or licensing would be required for drivers, especially at the earlier stages of development of the system?
- need to ensure close integration of the AHS work with the ITS-CVO services, which are becoming widely accepted because of their economic benefits;
- there are likely to be special check-in condition monitoring issues for trucks associated with the condition of the couplings and the loads they carry (especially if there are open loads);
- truck convoys may need special terminal facilities unless they can be assembled entirely "on the fly."

8.2.3 Transit Operations

This breakout session focused on uncovering features or capabilities that could be included in AHS which would be uniquely useful for transit operators and might not otherwise be a part of the system if only automobile applications are considered.

- The first feature addressed was the need for aids in lateral positioning of buses for level platform loading. Transit operators are looking at the use of level platform loading to speed loading, especially in station areas, and as a way to facilitate loading of disabled passengers. Low platform buses are another approach which can be used where high level platforms are not practical. The desire is to find a way to help the driver close to within an inch or so of a platform without ever hitting it. Although not a major problem, the group did see this as an application where an early spin-off of

AHS lateral control technologies could be used to solve a present problem.

- The next topic was the relationships between roadway powered electric vehicles and AHS. Roadway Powered Electric Vehicles, or RPEV, proved to be a very interesting topic to transit operators. The San Diego Association of Governments recently studied the application of RPEV, both to transit operations in San Diego and to long haul truck operations from the Mexican border north to a rail intermodal facility near San Bernardino. In both cases they found an number of attractive features in RPEV. In transit operations, it would cost far less than light rail, could share its right-of-way with other vehicles, and could go places (inside buildings) where internal combustion vehicles cannot. For long haul operations (as well as transit operations) they found that only 6 to 10% of the lane miles need to be powered to provide unlimited range. They felt that a combination of RPEV and AHS technologies could be a very strong combination. AHS would allow them to maximize the capacity, and therefore the payback, on their investment in an RPEV lane. As an after thought, it was pointed out that automated control of electric vehicles is simpler than automated control of internal combustion vehicles.
- As a final topic in this series, the use of AHS in line haul applications was discussed. Line haul refers to the long distance part of a trip. In any trip, the longer the AHS segment, the larger the benefits. Since the AHS segment will also be the highest speed segment of a trip, the importance of a long distance AHS segment is magnified. Ron Fisher proposed the application of AHS technology to beltways (the beltways around Washington, DC being a good example) as a way to service long distance travelers. The I-15 truck corridor that San Diego is looking at is another good example. A third good example is the HOV lane transit operations of Houston Metro.

8.2.4 Highway Design and Environmental

- Regarding the "Distribution of Intelligence" criterion, the group felt that the "Infrastructure Supported" option might satisfy most performance expectations for maximizing throughput, and at much less cost by comparison to other options such as "Infrastructure Managed." The "Infrastructure Controlled" option was judged to be too revolutionary for early deployment -- evolutionary approaches to deployment were felt to be much more appropriate. Close coordination across political jurisdictions was emphasized as critical regarding this criterion.
- Regarding the "Separation Policy" criterion, the group expressed a clear preference for intermediate and gradual steps to evolve the optimum platoon formation characteristics. In this regard, liability concerns were emphasized. The so-called "brick wall" standard for guiding safety policy and stopping distances was seen to be a crucial constraint by some of the group.
- Regarding the "Mixing with Manual Vehicles" criterion, the group wanted to alert the Consortium that near-term technical innovations may modify some of our basic design assumptions. A specific example cited was the continuing evolution in physical barrier design and fabrication. Mixing was not seen to be completely undesirable, especially if it was selectively tested in an evolutionary deployment strategy with clear understanding of its implications.
- Regarding the "Mixing Vehicle Classes" criterion, the group felt that the trucking industry may be the first to use AHS extensively and thus their concerns were critical. Whether or not we allow mixing within a platoon needs to be studied further before a final decision is made. The notion of time-based segregation of truck platoons should also be studied.

Dedicated AHS truck lanes would have infrastructure cost implications that must be studied.

- Regarding the "Entry/Exit Alternatives" criterion, the group was concerned that multiple transition lanes might substantially reduce throughput; this issue needs careful study. Another key study area is whether dedicated transition lanes could have their own less conservative geometry by comparison to conventional lanes.
- The group suggested renaming the "Obstacle Sensing" criterion to "Obstacle Sensing and Avoidance." There may be hybrid alternatives we can develop for partial driver control under certain conditions.
- As an additional feature for further study, the group offered the possibility of using AHS to assist in dynamic lane changing for purposes of peak traffic counterflow and emergency use.

8.2.5 Transportation Users and Insurance Industry

- The inputs to the process seem to be from a requirements standpoint rather than a user standpoint. We need to address the end user needs and problems. For example, the end user doesn't care about throughput; he is interested mainly in his own trip time. The driver doesn't care about distribution of intelligence; he only cares about his own role. All of the technical terms need to be translated into terms that the general public can understand. This is necessary to get any meaningful feedback from the ultimate user, the driving public. A town hall meeting is highly recommended. The driving population also needs to be considered in the design. AHS must be designed for the full range of drivers, not just the most expert or technically knowledgeable.
- An open architecture is recommended to allow "plug and play" capability for various options. There are a range of needs, and so it needs to be flexible. ITS will be in place before AHS, and so AHS needs to be defined to be compatible with ITS and to take advantage of its capabilities.
- From the user's viewpoint, the only issues on separation policy are those that affects his role. Specifically, spacing comfort is an issue. Tests (Iowa simulator) show that a spacing of 1.88 m is not comfortable. Other issues are entry/exit ease, who controls the spacing (driver or system? Can the driver ask for more spacing from surrounding vehicles if he is uncomfortable?) and privacy from the prying eyes of nearby motorists.
- It was felt that the system will need a high degree of adaptability to user preferences to be acceptable. Specifically, the driver should not be forced to endure tight separations that make him uncomfortable. The trick is to prevent such driver choice from destroying throughput. One option may be to allow selections based on driver familiarity, so that new AHS drivers may be given bigger spaces until they become more comfortable. Another possibility is to give the driver some acceptable options; he can't select the size of the gap, but could be asked whether or not he would accept a gap.
- It was not clear to the group what the users would want in the way of barriers. Initially, they would probably want the protection of a solid barrier, but might change their minds if they understood the high costs, or the fact that this would mean large distances between access points. A major issue in dedicated lanes is getting the incremental acceptance of something not used by all; there is an elitism concern. The only issue for the driver in entry/exit is the procedure he has to use.
- The public is resistant to mixing with trucks, so acceptance needs to be built gradually. Automated buses in the HOV lane may be a start. Dedicated lanes are not an option everywhere; you have to mix classes wherever there are few lanes.
- There should be options to do any of the alternatives for obstacle sensing and avoidance. It must be totally

automated in tight spaces since can't react fast enough manually. But there first will need to be a big sales job to convince the driver that "the system can do this better than you can." If the system knows about an impending problem, it should warn the driver well in advance so that he knows what to expect. The big deal is getting the users to trust the system and to believe that it will take the proper action to prevent mishaps. To build this trust, the demo should show the system responding to hazards. False targets need to be considered as well, since they will erode user confidence.

- The hardest part is getting the initial users. One option is to use regular HOV users. The first in-vehicle equipment may need to be provided free to the users. There may even need to be a monetary incentive. In the long term, however, things will actually get easier. Barriers and other design issues will go away as the highway system and the vehicles become completely automated.
- Another issue area is routing. Is it automated? How are platoons handled in routing? The eventual system will include interchanges; how is freeway-to-freeway platooning done?

8.2.6 Governmental Agencies and Other Institutional Organizations

The group explored the different dimensions used to define the concepts.

Distribution of intelligence

- The question was raised, does the vehicle orientation have less liability on the infrastructure?
- A concern was expressed as to the maintenance of the infrastructure for the concepts that require infrastructure control. An example is the heavy infrastructure requirements for the FAA system.
- It was mentioned that deploying AHS in an incremental fashion may result in different solutions along the way. For example, you may start with a vehicle

orientation initially but eventually may have more infrastructure.

- They recommended that "one size won't fit all."

Separation Policy

- The free agency scenario should be considered a fall back to platoons in graceful degradation sense. Currently our concepts come across as you have either free agency or platoons but not both. They recommends both.
- The group expressed a concern about the difficulty of exiting around long platoons that might be blocking the exit.

Mixing with Manual Vehicles

- The group felt that this was an evolutionary deployment issue. That initially you need to have vehicles mixed.
- The use of physical barriers to separate manual and automated traffic is a hot political issue in some parts of the country dealing with separating HOV traffic.
- We need to do a better job of defining what AHS vehicles can do with regards to improved performance on normal, non-automated highways.

Mixing Vehicle Classes

- This was seen as a user acceptance issue. Most people feel uneasy being stuck in a platoon with close headways with buses and trucks.
- There is of course the safety issues with having different vehicles with such different dynamics.

Entry/Exit Alternatives

- The key recommendation of the group was to minimize the infrastructure required, for example, flyover ramps. Local DOTs can't maintain the current inventory of bridges.

The group made the following conclusions following the discussions of the concept dimensions:

- The conclusions made by the consortium are reasonable.
- Incremental development is a must. All of the concepts need to reflect a growth path versus a point solution.

- With an incremental development we need to consider:
 - That there will be benefits along the way. Our concepts need to recognize/advertise these.
 - We need to identify the early winners to help create market demand.
 - The concepts need to emphasize the spin-off technology.

8.3 BREAKOUT SESSIONS ON THE SIX CONCEPT FAMILIES

The plenary before this final set of breakout sessions discussed the important and unresolved issues that existed at the end of this task and a description of the 6 concept families that were developed to address these issues.

The feedback from these breakout sessions are summarized below:

8.3.1 Vehicle Industry and Electronics Industry

Objective: Determine appropriateness of concepts to industry

Results:

- Given the 6 concepts, it was decided that “Infrastructure Supported” and “Infrastructure Assisted” concepts were on an evolutionary path. It also appeared that “Cooperative Plus” is an evolutionary step from “Vehicle Centered”.
- It was not clear how “Driver Involvement” and “Maximally Layered” fit on any evolutionary path.
- There was much debate over what “Driver Involvement” actually is. Is it a concept family, or is it an attribute? No conclusion was reached.
- Platoons vs. Free Agents was seen to be a cross-cutting issue that appears with every concept family. There should be a framework for considering this issue within each concept family. Family designations that have the work “platoon” in them should be reworded to “formation”.
- “Cooperative Plus” was seen to be troublesome if vehicles are not “fully-

equipped”. For instance, a vehicle with Intelligent Cruise Control and lane-keeping might raise driver expectations beyond its capabilities.

- Safety sells now; will “green” sell later?

8.3.2 Commercial Operations and Trucking

The group used the review of the concept families as a starting point for discussion of more general AHS issues, and gave limited attention to the differing attributes of the alternative concept families. Some of the families did not receive sufficient attention to produce any recorded comments.

Cooperative Plus

The group thought that in general vehicle-oriented concepts would be better for the trucking industry than concepts that would be reliant on public infrastructure improvements. They already have significant communication capabilities to support intermodal linkages, and this communication-intensive concept family led them to point out that we need to be clear that all of our concepts assume the baseline availability of ITS information and communication services. This is important to this stakeholder group because of the extent to which they have come to rely on the ITS-CVO services.

There were concerns about the viability of a concept as communication-intensive as this, based on questions of cost, technical feasibility and spectrum availability.

Driver Involvement

This was seen as a cross-cutting issue rather than a distinct concept family. There are also deployment issues here associated with the level of training and experience that drivers will need to have in order to develop confidence in the AHS system. The driver involvement question was seen to affect the formation of truck convoys or platoons. If these were formed while parked at a queuing station it would not be necessary to have a driver in each cab, but if they were formed “on the fly” it would require a driver in each cab.

Infrastructure Supported and Assisted Platoons

The group had problems with the jargon used to name these, not being able to make clear distinctions among “assisted,” “supported” and “managed.”

Maximally Layered

The group struggled with the purpose of this family and there was substantial sentiment for eliminating it as a distinct concept family. It was alternately perceived as having great value for regional tailoring or being technological overkill (or a “high-tech industry panacea”). It also elicited the concern that it would take too long to achieve, and that it was necessary to get some winning concepts available for use quickly.

General Cross-Cutting Issues

Much of the time was devoted to more generic AHS issues that cut across the different concept families. These included:

- The AHS must be economically competitive with railroad intermodal services in order to be adopted by the trucking industry. If the truck convoys still need a substantial ratio of power units to trailers it may be harder to be cost competitive. On the other hand, if AHS enables the truckers to extend from triples to combinations of four to seven trailers, their productivity could be greatly enhanced.
- The AHS does not need to be truly “national” in order to be viable. It may only be needed to link multimodal transfer points within specific corridor applications in order to be worth implementing for trucks.
- Highway designs may need to be modified to accommodate increased wear from truck tires consistently following the same track lines, or else the vehicle control systems may need to deliberately vary the tracking of the vehicles within the lanes to distribute the wear more evenly.
- Trucks are likely to need dedicated lanes for entry ramps and locations with significant grades because of their substantially limited acceleration capabilities. This may mean that

grades should be limited on AHS roadways if such extra lanes are not provided. It may be acceptable to impose minimum performance standards for AHS trucks, but the efficacy of this will be driven by cost/benefit considerations.

8.3.3 Transit Operations

- The session started with a description, by Loyd Smith, of Houston Metro’s transit operations and how they might use AHS features. A prominent, and AHS like, feature of their operation is use of 68 miles of HOV lanes to link the CBD with park-and-ride facilities. This has proved so successful they plan to expand it to more than 100 miles in the near future. The HOV lanes are single, reversible lanes. At the park-and-ride stations they have a dedicated on/off ramp which feeds directly into the HOV lane and is used both by passenger vehicles and the buses. Houston uses the HOV lanes today primarily as a high speed link between various suburbs and the CBD. They would like to extend the operations to connect suburbs but the radial structure of the highway and HOV network is a limiting factor. AHS technology is seen as a way to handle increasing congestion on the HOV/bus lanes, congestion which today does occur and is handled by instituting more restrictive HOV policies.
- The next topic was the cross-cutting issue of driver involvement. The normal concerns of safety and the safety implications of relying on the driver (which today is the biggest safety problem in driving) were raised. It was noted that there is hardly a system now in existence where, in emergencies, a person has no capability to intervene (even though that capability is rarely used). The group also felt that some level of driver training, specifically oriented to the AHS driving tasks, may well be required and would not differ from today’s situation where drivers are

specifically taught freeway driving techniques. The discussion then turned to the interface problems between AHS and arterial/freeway highways. The problem is of radical different capacities. However, it was again pointed out that the problems are not insurmountable, that such situations exist to day in freeway planning and are being handled by highway designers.

- When the group considered the question of operating in mixed traffic (automatic and manual controlled cars on the same highway, the reaction was that such a capability was obviously required for any reasonable deployment scenario. Perhaps, the group thought, transit and CVO could become the catalyst in starting an AHS deployment.
- Similar thoughts occurred when discussion a platooning capability, that perhaps platoons of trucks or buses would be where to start.
- Two thoughts occurred when discussing the last issue, flexibility and the "Maximally Layered" concept family: that we should consider transit and CVO evolution paths as well, and that the Consortium must keep their proposals in sync with other ITS developments as they occur.

8.3.4 Highway Design and Environmental

- The group suggested the following generic deployment scenario as a starting point and common basis for all future analysis of concepts: first, vehicles are equipped with individual AHS hardware features; second, AHS deployment begins with dedicated but mixed lanes; third, restricted lanes are marked as volume grows. The group identified several precedents to guide AHS in evolutionary deployment, in whatever form it may take, including precedents related to HOV deployment and TOC development. Finances and budgets make force deployment to be evolutionary, with clear and continuing documentation of benefits.

- Regarding AHS "cross-cutting" issues, as they pertain to this stakeholder group, it was felt that physical infrastructure capital cost assessment was a critical task that needed special care. A large part of these costs might lie with entry/exit area design and construction. The nature of separation between automated and conventional lanes was also seen to be a critical factor. Properly understanding the burden induced on arterial roads from an operating AHS segment was again emphasized.
- In critiquing the six concept families, the group did not have a clear understanding of the "vehicle centered" concept, and how it different from the "cooperative plus" concept. More explanation is needed, and in general this was true with regards to all the concepts, especially as they related to the prospective impact on bus and truck platoons. Obstacle avoidance also was not clearly enough defined. Driver involvement as a generic design issue should resolved outside of the mainstream of the concept down-select process. The group needed further clarification of how much intelligence would be contained in the vehicles under the "supported platoon" concept. The group again emphasized the need to carefully study evolutionary deployment strategies for all surviving concepts.
- Summary group feedback during this session focused on the following concerns: a more explicit description of the process by the Consortium of how we downselect from six to three concept families; an emphasis on eliminating undesirable features verses simply eliminating entire concept families; explicit rationales, clearly explained, regarding why certain concept groups were being dropped; and explicit addition of evolutionary deployment scenarios for all surveying concepts.
- Finally the group could not reach an internal consensus on whether NAHSC

should spend roughly equal resources studying all six concepts families prior to making its downselect decision.

8.3.5 Transportation Users and Insurance Industry

- The concept descriptions and distinctions were not clear to the group. In particular, it was difficult to take a given concept (such as one of the contracted concepts) and see where it fit in.
- The group saw two cross-cutting issues: What is the driver involvement? How do you use the infrastructure. The group recommended a concept development starting from the end goals of AHS, and then determine how to get there. It appears that the concepts chosen were stepping stones. From the user's viewpoint, there are really only two themes that separate the concepts from each other: What is the level of control relinquished? How close are the spacings? Education of the driver must be an integral part of each concept. So must outreach. To succeed, the system needs to give the users a perception of simplicity, and the confidence to use. Any additional certification is a negative, since it gives an impression of complexity.
- Remember the "ilities" (reliability, maintainability, availability). They drive cost, availability of service to the user and ease of use. The public is used to the reliability levels of current cars, and will not see the AHS vehicle as an improvement if it offers less reliability, no matter what else it does.
- Driver involvement was seen as a cross-cutting issue rather than a concept. There were strong, differing views on this issue among the group. On the one hand, some said that if the driver is involved, this is ITS, not AHS, and that the system is unsafe if he can take over. On the other hand, it was stated that drivers see, think and act, and that it is impossible to let them see and think but not act; they need to be able to override to save their own life. There were differences of opinion

on what the driver should be allowed to do in a "panic button" situation.

- In any case, the cost and evolutionary impacts of disengagement need to be weighed. The driver role may be different in different regions, especially depending on traffic density. The answer might be to give the driver a perception of a role, rather than a real role. The important thing is that he needs to be convinced that it's safe. We need to be able ultimately to tell him that the system can do it better. (Is this always true?) Let him do something and have an effect, but restrict it so that whatever he does cannot mess up the system.
- The next concept families discussed were Vehicle Centered and Cooperative Plus, with the emphasis on the latter. Cooperative Plus would benefit from taking advantage of the ITS infrastructure communications that will be out there anyway. There were technology and communications concerns about this concept. The group was not convinced that data aggregation would cut the communications load down to a manageable level. One advantage is that the technology will update faster since it is all vehicle-based, and vehicles are replaced more often than is infrastructure.
- There was a major concern with Cooperative Plus in that it operated without benefit of a traffic operations center (beyond what will be there for ITS). The public will not trust other cars to be properly maintained to perform the cooperation. There will be fear of "automotive anarchy" and the public would actually prefer a more familiar "big brother." It comes down to an issue of who you trust, and the public is more likely to trust a transportation agency than that jerk next to them in the old pickup truck.
- Supported and Assisted Platoons may be two steps in an evolution. The choice will probably come down to cost. Supported platoons have been used successfully in a marine environment. During the Gulf War,

GPS was used to get ships quickly through the Strait of Hormuz. The ships communicated via satellite, giving location and warning of obstacles. This allowed a spacing of 2 ship lengths, as opposed to the usual 7-ship spacing (brick wall stopping distance).

- Maximally Layered was said to be "what we want." The high end of this evolution is what we mean by AHS. There was concern that this looked like 1 through 5; the others seem to be just evolutionary steps in this family.
- There was some discussion about free agent vs. platooning. People will prefer free agent to start, until they get comfortable with it and start to see the benefits. Platooning was thought to be inherently more uncomfortable (psychologically) for the driver, and so it should not be used when it isn't needed. But this causes a problem if a driver who is not comfortable with platooning unexpectedly finds that the system is suddenly changing from free agent to platooning. The motorist wants predictability.
- The other main issue discussed was the user's desire for simplicity. He does not want to be burdened with any more administrative requirements. He already has to worry about registration, smog checks, etc., and does not want to add to this. The AHS should make life easier, not harder. The group voted on the six concepts and whether they are good choices. The results are:

Concept Number	Yes	No	No Opinion
1	4	3	5
2	1	7	4
3	3	7	4
4	9	0	3
5	9	0	3
6	10	0	2

8.3.6 Governmental Agencies and Other Institutional Organizations

Overall Comments regarding the six concepts:

- The concept families seem to represent attributes not concepts. For example, the driver involvement concept is an attribute that is applicable to all of the concepts. Recommend that the Consortium further refine/re-concept the families.
- Incremental deployment is captured by the concept families but it is not effectively communicated. We need to do a better job for each of the concepts to show the incremental development/deployment path. Need to include the phasing, timeline, incremental deployment critical components. The concepts need to reflect anticipated improvements that will be in the market place in the future.
- The concepts look too stand-alone. We need to integrate in ideas associated with ITS, ATMS and spin-off technologies.
- The group felt that the concept families would be more effectively communicated as representation of the distribution of intelligence. At this time, it seems to be the only discriminator between concepts. The other dimensions are still attributes and options available for any concept.
- Driver education and training will be critical. How do the education and training requirements change for each concept?

Specific comments included:

Concept #1

- It appears that it will be market driven, which is critical for deployment.
- There are some concerns about the technical issues associated with platooning in this concept.
- It seems to lack a global, well integrated transportation system view.
- Provides the best near term option.
- Best option suited for rural.

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Concept #2 -

- This concept does not provide an opportunity to take advantage of infrastructure related technologies that are likely to be in place. Lacks ITS emphasis to get information from the infrastructure to the driver.

- This looks like a deployment step in an incremental process versus a stand-alone concept.

Concept #3

- Driver training will be critical
- This is not a family of concepts but a feature applicable to all.

9. THE NEXT STEPS

The end of the C1 effort is not the end of concept development for AHS. After incorporating the stakeholder comments to create a revised set of concept families, the Consortium will continue with a C2 effort that takes those concept families as inputs, studies and evaluates the underlying issues in more detail, and creates three preferred concept families.

9.1 REVISED CONCEPT FAMILIES

9.1.1 Response to Stakeholder Feedback

The Workshop elicited much valuable and insightful feedback from the stakeholders. It gave the Consortium further insight into the needs and priorities of the stakeholders, and will greatly help shape the continuing AHS development. This section highlights specific feedback received on the six concept families and on the five underlying issues which the six concept families were structured to address. The Consortium has incorporated these ideas into the revised concept families. In many cases, there were conflicting and incomplete suggestions from the stakeholders. This is not surprising in light of the diverse nature of the stakeholder community, but it meant that the Consortium needed to thoughtfully and carefully consider each major concern to strike a balance across the feedback; it was not possible to provide a simple reaction to all comments.

Following are the major comments received on the six concept families:

9.1.1.1. Eliminate the driver involvement concept family, and address this as a cross-cutting issue across several concept families

This was probably the most prevalent comment received. The general feedback was that it was more fruitful to study this issue across several concept families than to devise a concept family specifically to study it. The Consortium accepted this comment in full. The concept family was eliminated,

and an engaged driver role will be one of the identified cross-cutting analyses. Furthermore, this issue will be studied in concept families 1, 2 and 6, each of which has an engaged or partially engaged driver in an early phase.

9.1.1.2. Combine concept families 4 and 5 (infrastructure supported/assisted platoons) since they are very similar, and 4 may be a precursor to 5

While this was a strong suggestion from several groups, it was offset by even stronger stakeholder feedback that the concept families should be distinguished by and developed around allocation of intelligence. These families will be kept separate as representatives of infrastructure supported and infrastructure assisted respectively. Further, the Consortium is not yet convinced that 4 (infrastructure supported) is a precursor to 5 (infrastructure assisted), and to combine them now would close off further inquiry.

9.1.1.3. Eliminate concept family 6 (maximally layered) since it is just the combination of all the others

Some of the stakeholders saw this as a redundant concept family, which would be constructed at the end by putting together all of the others. They felt that it was included only as a test of the interoperability of the others. While it may seem that way from the cursory overview, that was never the intent. This concept family is actually a single unified approach that provides beneficial functionality at every level of deployment and regional use. Thus, it may be significantly different from the other five independently developed concept families. The Consortium agrees that interoperability is a cross-cutting issue for all of the concept families, and that any concept selected only as a test of interoperability is not worth considering.

Many of the stakeholder groups rated this as the most promising concept family in

informal polls. There was also feedback that Concept #6 agreed with stakeholder ideas of what the AHS should be like. The Consortium felt that this feedback more than offset the suggestion to eliminate the concept.

9.1.1.4. Eliminate all the concepts and start over based on allocation of intelligence

One focus group suggested that all of the concept families be eliminated. Their suggestion was that everything except allocation of intelligence should be a parameter within the concept family (e.g. platooning, free agent, etc.). While not stated so strongly, other groups also felt that the concept families should include more degrees of freedom. There was general agreement that allocation of intelligence should be kept as the key concept distinguisher.

The Consortium is following this suggestion. Each of the remaining five concept families has been recast in terms of allocation of intelligence. These concept families were originally developed around the allocation of intelligence, so it is not really necessary to start over. Specifically, Vehicle Centered is Autonomous pushed to the limit, Cooperative Plus is Cooperative pushed to the limit, and Infrastructure Supported and Infrastructure Assisted are self-evident. Maximally Layered includes all allocations of intelligence. Aspects that were formerly concept differentiators are now cross-cutting issues, specifically platooning vs. free agent, and the role of the driver.

9.1.1.5. Eliminate Concept #2 (Cooperative) as it appears to require too much communication, promote anarchy and pose technical risks

The Consortium received considerable valuable feedback on the technical and social risks involved in this approach. Many important issues were raised, but no definitive evidence of infeasibility has yet been assembled. The Consortium agrees that this approach is risky, but has not yet done the analysis to see if the risk can be

contained. Hence, this concept will be retained so that the necessary analysis can be done, emphasizing and focusing on the issues raised by the stakeholders.

9.1.1.6. Combine Concept Families 1 and 2 as steps on an evolutionary path

This was a natural comment based on the high level presentation of the concept families. Had the concept families been conveyed more fully, the audience would have seen that the two concept families are inherently different, and in fact have no common evolutionary steps. This and other stakeholder comments made it very clear to the Consortium that not enough time had been used to present the concept families, and that the moderators should have been given more extensive background in the concept families. These are lessons learned that will be carried forward to the next Workshop. The confusion about the difference between these two concept families also pointed out problems with concept names. The names often led listeners to make unwarranted assumptions, which were very difficult to erase. This is a general problem with names of ideas, not specific to AHS, but it underscores the need for thoughtful naming. Hence, the Consortium renamed the concept families to reflect their key attributes, as well as to incorporate the changes in the concept families themselves, as discussed above.

The new names for the five concept families are:

- Independent Vehicle (formerly Vehicle Centered)
- Cooperative Vehicle (formerly Cooperative Plus)
- Infrastructure Supported (formerly Supported Platoons or Infrastructure Supported Platoons)
- Infrastructure Assisted (formerly Assisted Platoons or Infrastructure Assisted Platoons)
- Adaptable (formerly Maximally Layered)

Note that Driver Involvement, formerly the third concept family, has been eliminated.

9.1.1.7. Accept mixing of classes in a lane in all concepts

The AHS must be available to all stakeholders. But limitations in right-of-way are severe, so all concept families must permit the sharing of lanes by various types of vehicles if the local transportation agency so desires. All of the five concept families now include this capability in all evolutionary stages.

9.1.1.8. All concept families will assume the existence of and the use of ITS capabilities

Many of the stakeholders present at our workshop are involved in the Intelligent Transportation System Architecture and other ITS activities. They stressed the importance and benefits of our close involvement with these related activities. They also informed us about the ITS services that will be in place by the time the AHS is fielded. The Consortium will increase their involvement in ITS activities, build on the ties established with this community, and build the concepts around these services.

9.1.2 The Revised Concept Families

The Workshop comments led to the five revised concept families, based on the original six, as described in Section 7. The first task of the second phase of concept development (C2) must be a thorough documentation of these concept families. The authors will take into account all of the stakeholder feedback as they are refining these approaches, so it is expected that these concepts will change further. In fact, changes have already been seen in initial C2 task concept descriptions.

9.1.2.1. Independent Vehicle

The only real change here has been in the name. The new name was chosen to suggest that the vehicle is making its own decisions, though it may be supported by information from other vehicles or from the roadway.

9.1.2.2. Cooperative Vehicle

This new name was chosen to distinguish it from the Independent Vehicle concept, while still emphasizing that it is a vehicle-based concept. The concept itself is relatively firm. The challenge now is to provide enough design detail to demonstrate feasibility.

9.1.2.3. Infrastructure Supported

The key difference here is that this concept is no longer centered on platoons. Platoons are part of a cross-cutting issue. The challenge here is in filling out details starting with little more than the allocation of intelligence.

9.1.2.4. Infrastructure assisted

Here, too, the emphasis on platoons has been removed. This represents a high-end system, but otherwise there is still much to be defined. Even the allocation of intelligence is not determined at this point. The team developing this concept will need to decide exactly where and how infrastructure management is used.

9.1.2.5. Adaptable

The name has been changed to emphasize the tailorability to a range of needs. The term "layered" meant too many different things. This concept has not changed, but requires descriptions of what exactly these layers are.

9.2 THE NEXT PHASE

The report documents the AHS C1 effort. It is to be followed by the AHS C2 effort, which will expand upon the five concept families and ultimately select three preferred concepts. At the end of C1, the plan for C2 was as follows.

9.2.1 Flesh Out Five Concept Families

Develop "best" conceptual designs for each family, to achieve goals and objectives and

perform required functions while optimizing MOE value. Define end state system for each, together with realizable intermediate steps, local deployment options and potential degraded modes of operation. Describe each in about 20 pages of text (largely qualitative, rather than quantitative).

9.2.2 Define Applications Scenarios

Select real-world reference sites to serve as bases for concept evaluations, coordinating with Outreach, Societal and Institutional, and Tools teams. Collect data needed to characterize each site sufficiently for purposes of the concept down select evaluation, which is assumed to be at a highly aggregate, rather than detailed, level.

9.2.3 Cross-Cutting Studies

The major concentration of activity should be here, in analyses of cross-cutting issues that will determine the strengths and weaknesses of the alternative concepts. The concepts may be revised along the way, based on the knowledge that is gained from these cross-cutting studies. The working groups that conduct the initial generic studies may later work on the evaluations of the concepts (in the Task described in 9.2.6).

9.2.3.1. Human Factors/Driver Roles

The role of the driver is an important discriminator among the concept families, as well as among the intermediate deployment stages. It is essential that the constraints imposed by driver capabilities be understood as early as possible so that these can influence the concept development and selection:

- driver attentiveness under partial automation
- driver ability to detect obstacles at long range
- driver ability to resume control in emergency
- transfer of control to and from driver

- driver acceptance of close vehicle following

9.2.3.2. Separation Policy Implications For Throughput And Safety

Define the spacings that should be required between consecutive vehicles, based on whether they are operating autonomously, cooperatively or in platoons (both inter-platoon spacings). These must be based on analyses of safety, using supportable assumptions about vehicle performance and probabilities of occurrence and possible consequences of various failures. This work will require collection of data on real vehicle and roadway conditions, analyses of crash severities, and evaluations of acceptability of different frequencies and severities of crashes.

9.2.3.3. Cost Assessment

Make a first attempt to define a supply curve for AHS, including vehicle and infrastructure unit cost estimates as a function of quantity (or production volume) for a variety of assumed technical solutions within the six concept families. This would be the first step toward defining the cost effectiveness of AHS.

9.2.3.4. Market Elasticity Evaluation

Make a first attempt to define the demand curves for AHS services, identifying how much people would be willing to pay for the different levels of AHS functionality. This would be the second step toward the cost-effectiveness evaluation. It should be based on focus groups of representative stakeholders (primarily private vehicle purchasers, but also some trucking and transit representative), and can gain some synergy with the Task 7 (see 9.2.7) activities.

9.2.3.5. Technology Capabilities Relative To Concept Needs

Conduct a first-level assessment of the feasibility of delivering the capabilities required by each of the AHS concepts, based on technology to be available at the

"affordable" price in future years. Consider this in five year increments from 2005 forward to evaluate realism of implementation of each concept in each year. Link this activity to Technology Team work (Task B3).

9.2.4 Define Concept Evaluation Framework, Requirements And MOEs

Select a systematic approach to evaluate and compare alternative concepts for use throughout the C2 activities. Refine the definition of requirements and MOEs, based on the overall AHS objectives and characteristics so the concepts can be distinguished from each other.

9.2.5 Canvass For Stakeholder Representatives

Authentic and truly representative stakeholder representatives will be needed to provide input to the selection of weighing factors for the various MOEs and requirements and for more general feedback about the strengths and weaknesses of the alternative concepts (contributing to Tasks 3d [see 9.2.3.4] and 7 [9.2.7]). No resources are allocated here, based on the assumption that these will be provided as a byproduct of the Outreach and S&I activities. This must start early enough to have representatives available by March 1996.

9.2.6 Evaluate Concepts

Based on what has been learned in the cross-cutting studies of the Task described in 9.2.3, as well as use of the tools that are available by Spring 1996 and inputs from the S&I studies, evaluate the strengths and weaknesses of the alternative concepts. This

is the heart of the C2 activity, but it must build on much of the work that has been done before in C1 as well as other parts of the AHS workplan. The evaluations will cut across the concepts, following the general outlines already defined in the Task 3 (see 9.2.3) breakdown.

9.2.7 Solicit Stakeholder Reviews, And Develop MOE Weightings

Using the stakeholder representatives identified in the Task described in 9.2.5, conduct focus groups to obtain feedback on the alternative concepts and the importance to them of the various MOEs. Use the weighting factors derived in the chosen evaluation framework to identify the preferences of each stakeholder group for the concept. Seek to identify a supply-demand equilibrium point for each stakeholder group for each concept, based on the supply and demand curves derived earlier.

9.2.8 Workshop #3 (July/August 1996)

Extensive participation by people throughout NAHSC, especially those working on C2. This includes advance preparation of documentation, briefing materials and breakout facilitation materials.

9.2.9. Documentation Of Three Concepts And Process

Characterize the three selected concepts in approximately 50 pages each, to serve as the basis for advancing to the C3 concept development work. Document the results of the evaluations, with the reasons for selection and rejection of the concepts that were considered.

10.0 LESSONS LEARNED

This C1 task, called "Develop Initial Suite of Concepts and Workshop #2", was the first of a series of three concept development tasks that will take place during the first 4 years of the AHS Program. The "lessons learned" during this first phase are of great importance and will help in all future work, both in concept development and in other tasks. The lessons are grouped into two categories: lessons related to conduct of the workshop, and lessons related to the scope of the work on the task itself.

10.1 CONDUCT OF THE WORKSHOP

- Preparation for Workshops

Prepare those who will brief the stakeholders. In Workshop 2, this was particularly a problem in the stakeholder breakout sessions where the moderators were not given sufficient time to become familiar with the six selected concepts. Because of the short time between the definition of the concept families and the Workshop, the moderators were not sufficiently familiar with the concepts to give the stakeholders the information that they needed in order to give meaningful feedback. While there was much good general feedback that allowed an understanding of the various views of the stakeholders, the value of the feedback sometimes was degraded by the misconceptions of the moderator. For the concept related breakout sessions in the next Workshop, perhaps people who are more familiar with the concepts and the underlying issues would be a better choice for briefing these sessions than the designated stakeholder moderator, even if they brief nothing else. One thing that was done right for this Workshop, and which needs to be repeated for all future Workshops and Forums, is preparation of complete book of briefing charts which is distributed to attendees at the start of the meeting. This is just a matter of a little self discipline but adds an important and obvious note of professionalism.

- Content of the Stakeholder Breakout Sessions

More thought needs to be given to the agenda for the stakeholder breakout sessions. The moderators need to prepare specific agendas for each session, either based on the preceding plenary briefing sessions or on the specific needs of this stakeholder group. Either way, the agenda cannot be Ad Hoc. The moderators need to ensure that the stakeholders will be given the information they need to respond with useful and informed feedback. The moderators have very little time to spend with the stakeholders. They must be sure this time is used wisely.

- Involving Stakeholders in Selection Process

Workshop 2 was conducted at the very end of the task. The stakeholders at the Workshop felt they were receiving a debriefing on the results of the initial concept selection task instead of feeling they were being made a part of the decision making process. Even though the Concept Team made significant changes to the concepts after the Workshop (reducing from 5 to 6, for instance), this feeling persisted. As a result, the plan for Workshop 3 is different. Workshop 3 will be held before the three new concepts are established and will present the results of the Team's evaluations rather than their decisions on new concepts. If stakeholder buy-in can be obtained for the conclusions stemming from these evaluations, then formulation of the new concepts should be much more understandable and acceptable.

- Reporting the Results of the Workshop

Thoroughly capture and disseminate all stakeholder inputs. At the conclusion of Workshop 2, there was confusion about who was responsible for writing up the minutes from each section (the moderator or secretary) and who was collecting them. Because of this, some of these were delayed, which

meant that they were not available to the teams in a timely manner and, possibly, some of the comments or the thoughts behind the comments were lost. In the future, there should be a clear procedure with a tight schedule so that the comments are captured immediately after the meeting. Even comments that seem off-base or things that the stakeholders say they do not understand need to be captured, since the Concept Team need to understand what's behind the misunderstandings.

10.2 THE TASK WORKSCOPE

- **Managing the Work**

The Concept team had 23 concepts to compare across five general evaluation categories. The Team considered assigning teams to an overall evaluation of a few concepts each, but for consistency assigned teams to evaluate all concepts relative to a single evaluation category (throughput, safety, cost, flexibility, acceptability). This worked well, allowing the teams to focus on the issues for the assessed characteristic and produce directly comparable evaluations. These evaluation were not done to the depth desired, but that is in the nature of the first iteration of the spiral approach. The process worked well and should be continued.

Large groups hamper, rather than support, decision-making. The Concept Team was most productive when small (3 to 5 people or so) subteams, with a clearly identified leader, were given a particular, clear assignment and a date to report their findings to the group (both written and oral). This focused the subteam between meetings, kept the meetings on target, and provided written documentation of the decisions made.

Telephone conferences are an effective way to supplement meetings once the members know each other well enough to recognize voices and picture the person speaking. There must be regular face-to-face meetings so that the team members get to know each other to this level, but once a month or so seems to be sufficient. The telecon needs to have an agenda and any materials to be discussed sent out ahead of time. E-mail has also proven to be a very good way to com-

municate, although this medium is still hampered by garbled enclosures in some cases.

- **Seeing Concepts as Stakeholders See Them**

Some stakeholders repeatedly said that what the Concept Team was presenting were not concepts. It took a while to understand this, but different stakeholder groups view "concept" to mean something relevant to their problems and concerns. Most often, these stakeholder groups were looking for operational concepts rather than technology or architectural concepts. Specifically, stakeholders were looking for an application to a particular situation, such as a dedicated truck lane concept, or a transit concept, or an urban concept, or a rural concept. The Concept Team, on the other hand, was viewing these as applications of their architectural concepts. This hampered communication. For example, in Workshop 2, when discussing the six candidate concepts, the stakeholders repeatedly asked for a trucking concept, a transit concept, and so on, when what the Team was presenting were six system alternatives, any one of which could be configured for a trucking application, a transit application, and so on. It is probably too late to change our terminology, but we need to be aware of this in any communications with the stakeholders.

This points out the general problem with stakeholder communications. The NAHSC needs to realize we do not yet speak their language. There are unfamiliar words or approaches in documents on transit or trucking, even those that advocate AHS. All of us need to get inside the stakeholder's heads, to learn to speak their language.

- **Concepts vs. Issues**

The concept development plan, as described in the Proposal, was based on a down selection process of going from many, to 6, to 3, to finally one concept. This original plan proved far too simplistic as we came to understand the complexity of an AHS system. In this complexity, all of the aspects of an AHS, including technology, architecture, functionality, and operations each have a staggering variety of conceptual

possibilities. In the beginning, a concept can only address a little bit of this complexity and in only a limited set of aspects. Therefore, concepts at any level of development, only deal with a subset of the aspects of a complete system. For those aspects which a concept does address, the concept makes a very good framework within which the issues of a particular aspect can be addressed, and can lead to a decision on that issue. This resolved issue can now become part of the given requirements for a new set of concepts aimed at resolving a new set of issues. This periodic formation of new concepts, rather than a downselect of existing concepts, is the way the concept development process must work. This has disappointed some stakeholders who have seen a favored concept disappear as concepts evolve even through all the resolved issues of that concept were carried forward. The Concept Team needs to make this facet of the process clear to the stakeholders to avoid these types of misunderstanding. The term "re-concepting" was coined to describe the process and it fits very well.

- Value of Outside help

In this first round of concept development, the NAHSC let seven contracts to outside organizations for development of concept ideas. The concept ideas provided by these contractors was of tremendous help in focusing the Concept Team on issues which must be addressed in the next round of concept development. In addition, several of the contractors demonstrated a depth of understanding that the Concept Team clearly should plan to tap in the future, especially in the areas of operations and functional requirements.

- Links between Concept Development and Concept Evaluation

Starting with essentially a clean slate, the Concept Team attempted to evaluate all alternative approaches to an AHS. But there was a dimensional explosion from 14 choices for allocation of intelligence, platoons, free agents or slots, various kinds of barriers and entry/exit configurations, and so on. Each dimension was assessed

individually, but that could only be carried so far because of the interrelationships; full concepts need to be evaluated. The Team selected 23 representative concepts that spanned the alternatives. Descriptions of each of these were written and used in the evaluations. The descriptions of the 23 candidate concepts were not worth the effort, at least not to the depth that they were done. It was time-consuming to write these documents, and the effort produced about 200 pages that were difficult to read and sometimes redundant. The evaluation teams, overwhelmed and short on time, in general based their evaluations on the dimensions rather than these descriptions. It would have been better to concentrate our energy on a few representative concepts with a discussion of what the impacts of changing the various alternatives would be.

More review was needed between the evaluators and the concept developers. Because of the short schedule, the evaluation teams did not have time to validate their conclusions with the concept developers. This was also due to the fact that there were 23 concepts to be evaluated. Hence some of the evaluations were based on misunderstandings of the concepts or lack of relevant information that was known by the concept developer. Future evaluations should schedule time for the concept developers to do at least a sanity check on the evaluations, or, better yet, contribute to them.

- The Magnitude of the Problem

For many on the Concept Development Team, this first round of concept definition and evaluation was an enormous learning experience, both of the range and complexity of the challenges posed by a safe automated vehicle/highway, and the breadth of possible solutions which are attractive to stakeholders. And the various stakeholders have conflicting demands, the requirements of which can only be stated in broad and general form. In addition, there are the constraints of evolving technology, and the demand for a realistic (whatever that might be) deployment plan. Originally it was thought that the right answer would bubble up through consensus building. But it has

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been very difficult to resolve the issues and reach consensus. The Concept Team needs to continue its efforts to define and justify the requirements of the AHS.