Automated Highway System (AHS)

WBS C1 Final Report

Develop Initial Suite of Concepts & Workshop #2

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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.

<u>Autonomous</u>

Autonomous is equated to automated vehicle. The infrastructure provides <u>at most</u> 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 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.

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 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	• 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	• 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	• 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

Dedicated Lanes - Continuous Physical Barriers	• 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.
Dedicated Lanes - Some Gaps in Physical Barriers	• Occasional gaps in physical barrier allows transition from adjacent lane(s). • Can permit adjacent lane to be a transition lane.
Dedicated Lanes - Virtual Barriers	• 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.
Full Mixed Lanes	• 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	• 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.

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	• 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	• 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	• 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	• 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	• 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	
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			

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 applcation.

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 theirrelative 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: Dedicated - continuous barriers 10* - gaps in barriers 5 - virtual barriers 4 Full mixing 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)

- 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

Mobility/Access	User Issues	Environment	Other
• Trip Time Predictability • Trip Time • Accessibility • Intermodal Transportation Operations	• 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)	• Vehicle Emissions • Fuel Consumption • Travel Demand Management /Transportation Systems Management Policies (TDM/TSM)	• 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

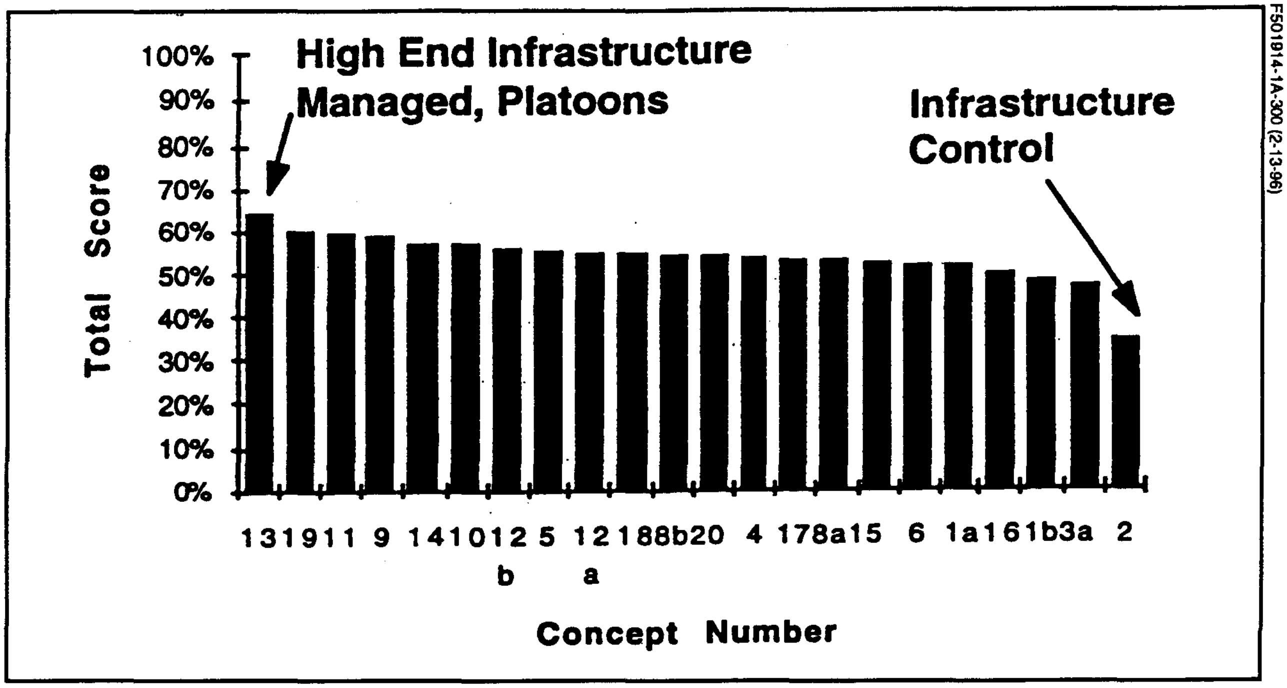
0.7 OVERALL EVALUATION

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).



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 infrastructure 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:

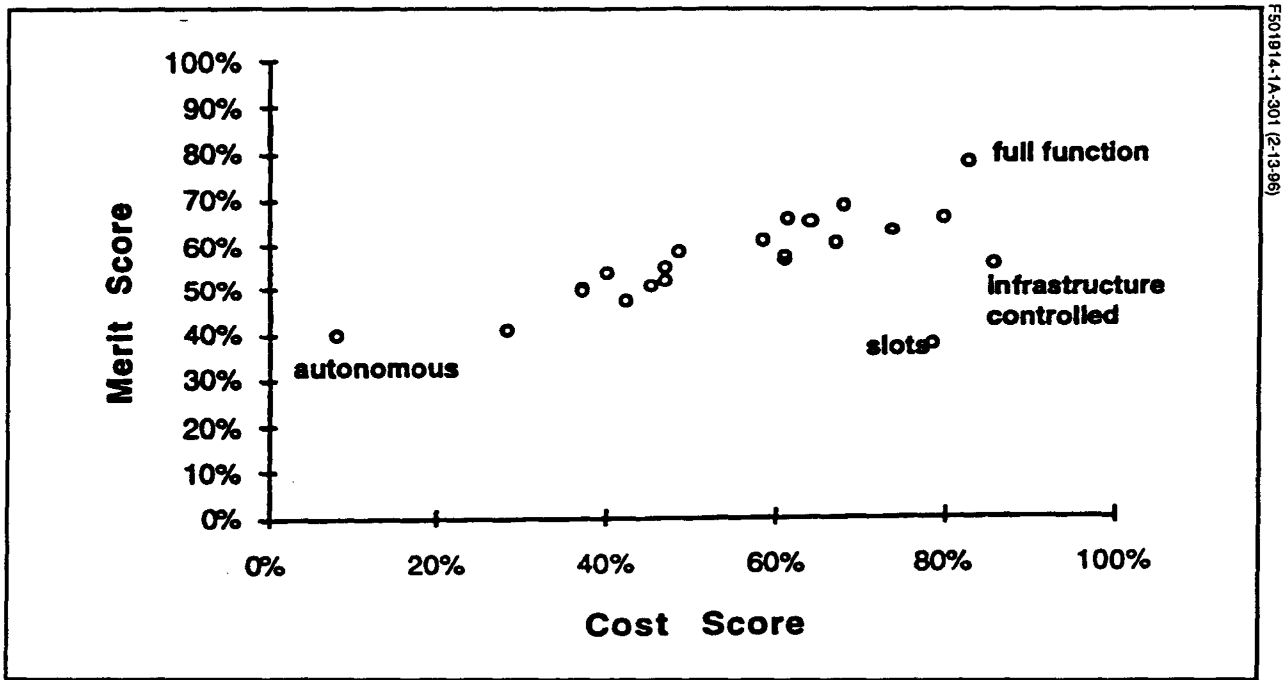
- Infrastructure involvement
- Role of the driver
- Amount of layering (options)
- Separation policy
- Manual and automatic vehicle mixing

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

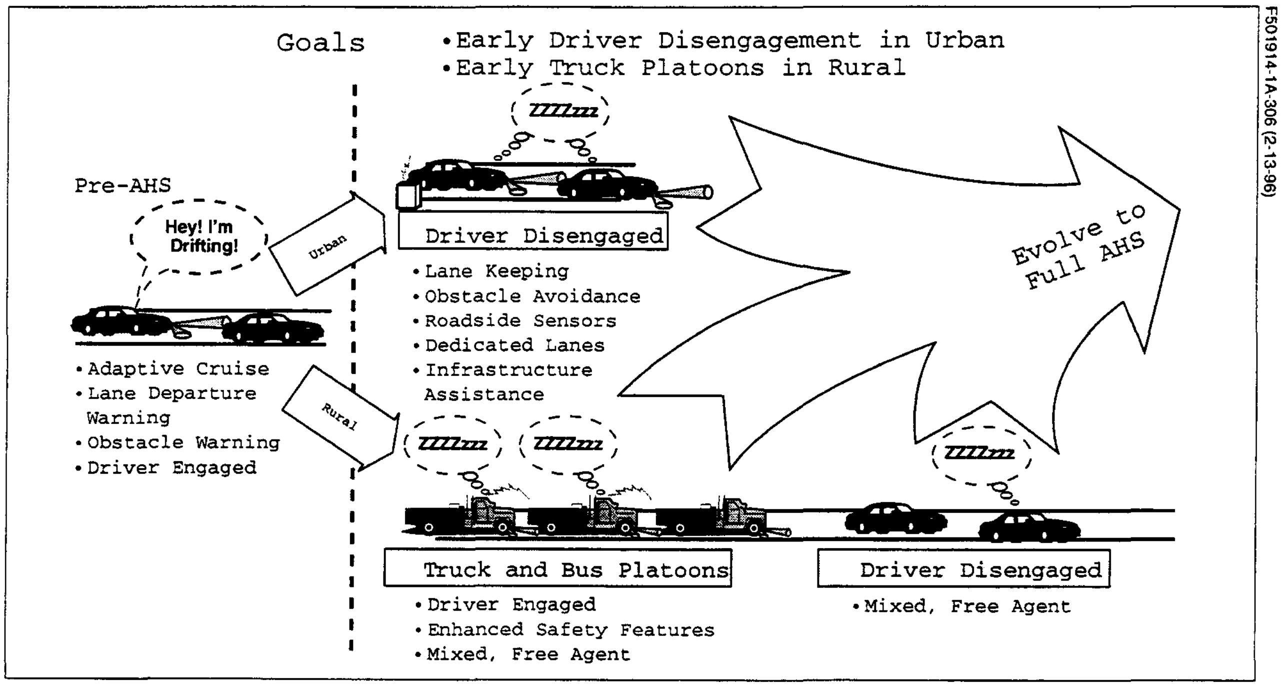
Concept Families	Architectural Focus
Vehicle Centered	Maximizes the performance that can be obtained from lone vehicles, while at the same time holds down cost by eliminating the cooperative layer. May be minimally supplemented with infrastructure assistance to improve throughput. Provides an early benefit 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.

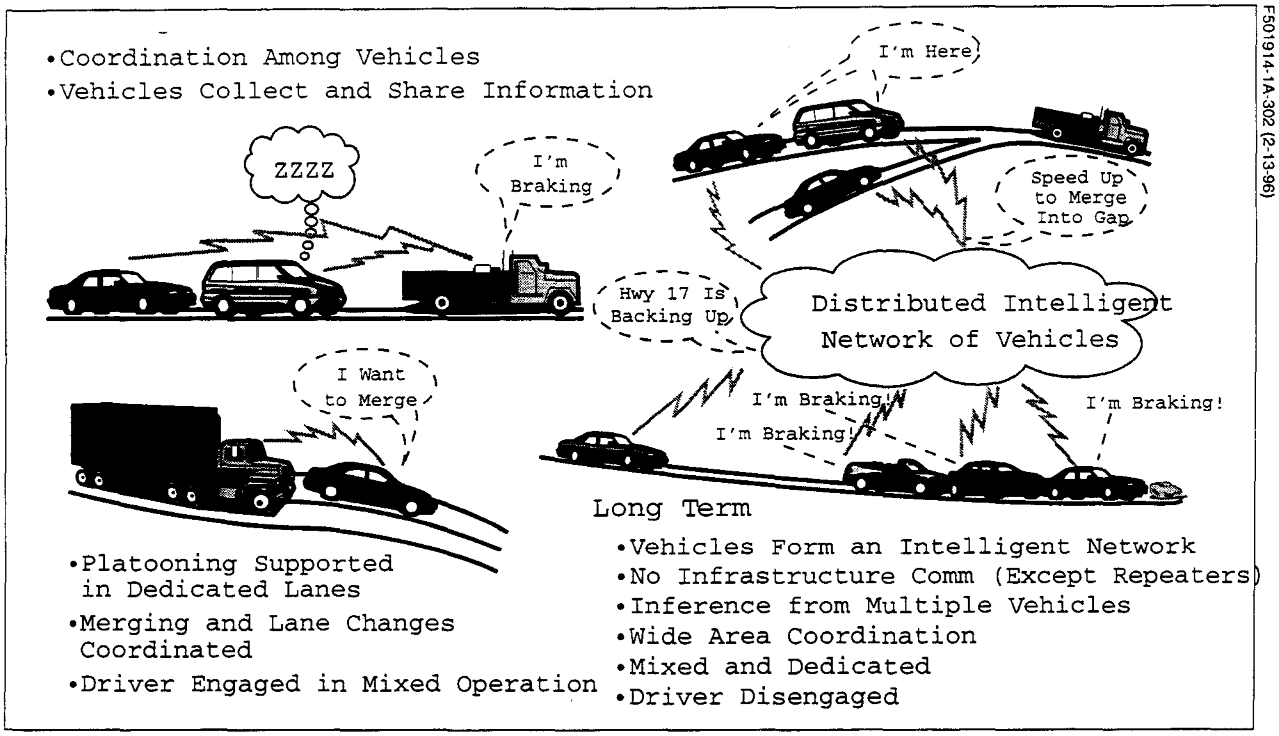
0.10 STAKEHOLDER FEEDBACK

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:

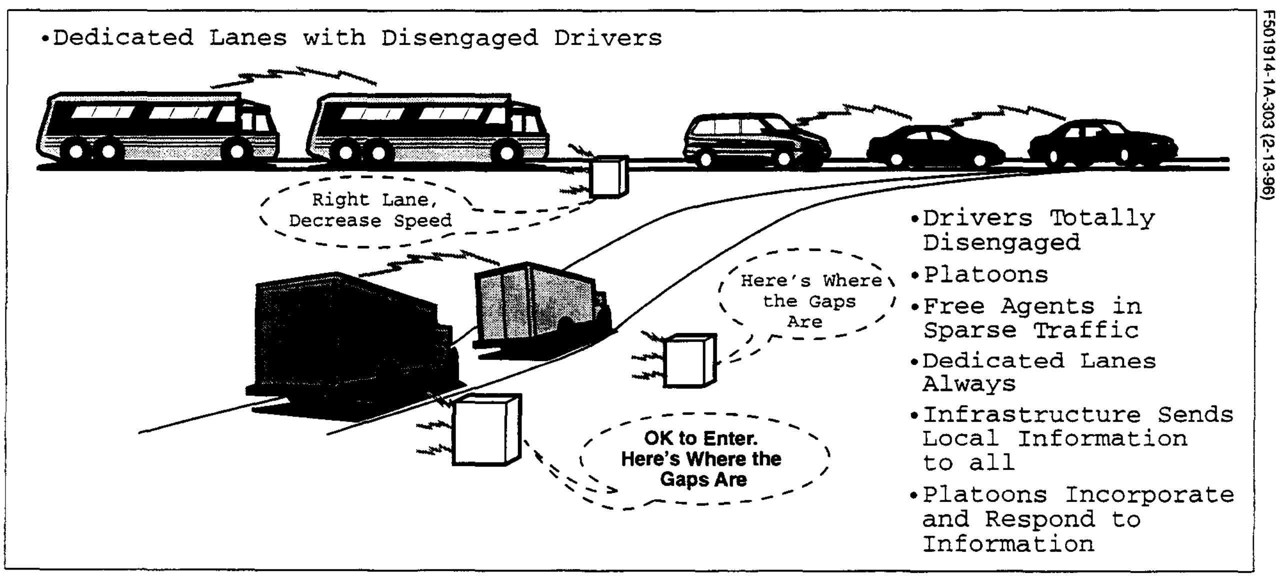
- Independent Vehicle (formerly Vehicle Centered)
- Cooperative Vehicle (formerly Cooperative Plus)
- Infrastructure Supported (formerly Infrastructure Supported Platoons)
- Infrastructure Assisted (formerly Infrastructure Assisted Platoons)
- Adaptable (formerly Maximally Layered)



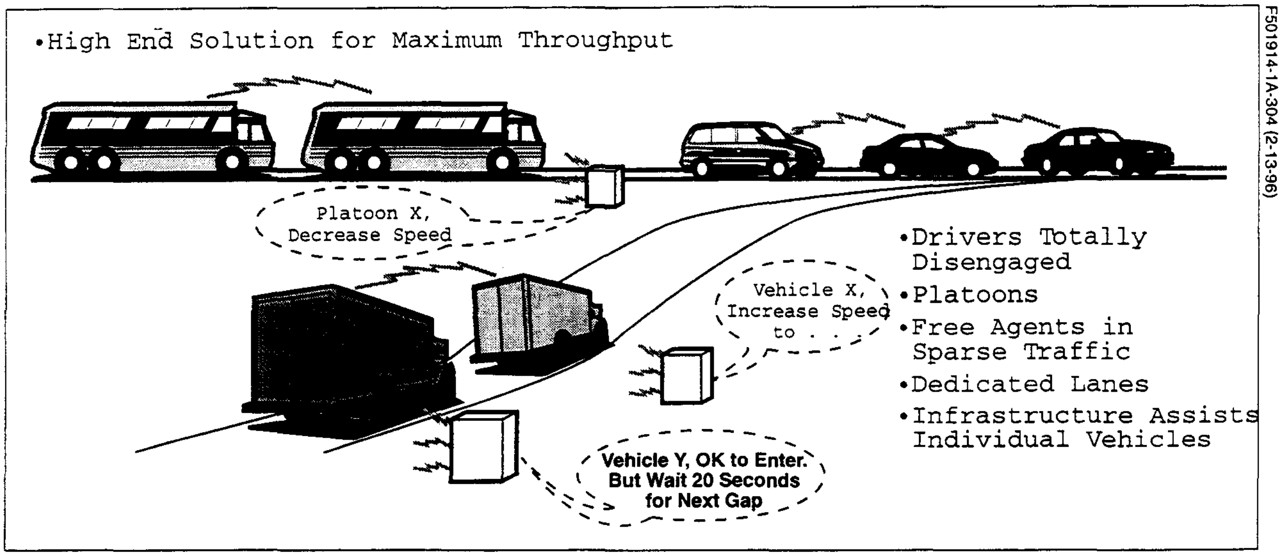
Independent Vehicle



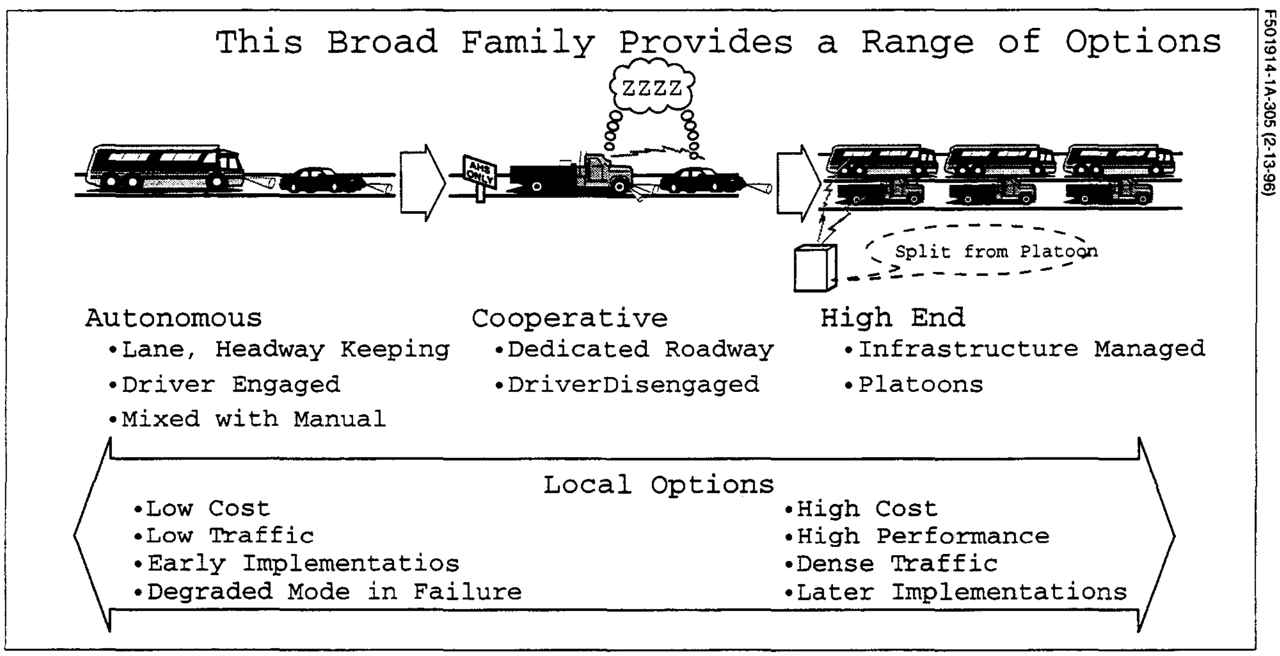
Cooperative Vehicle



Infrastructure Supported



Infrastructrure 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.