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.

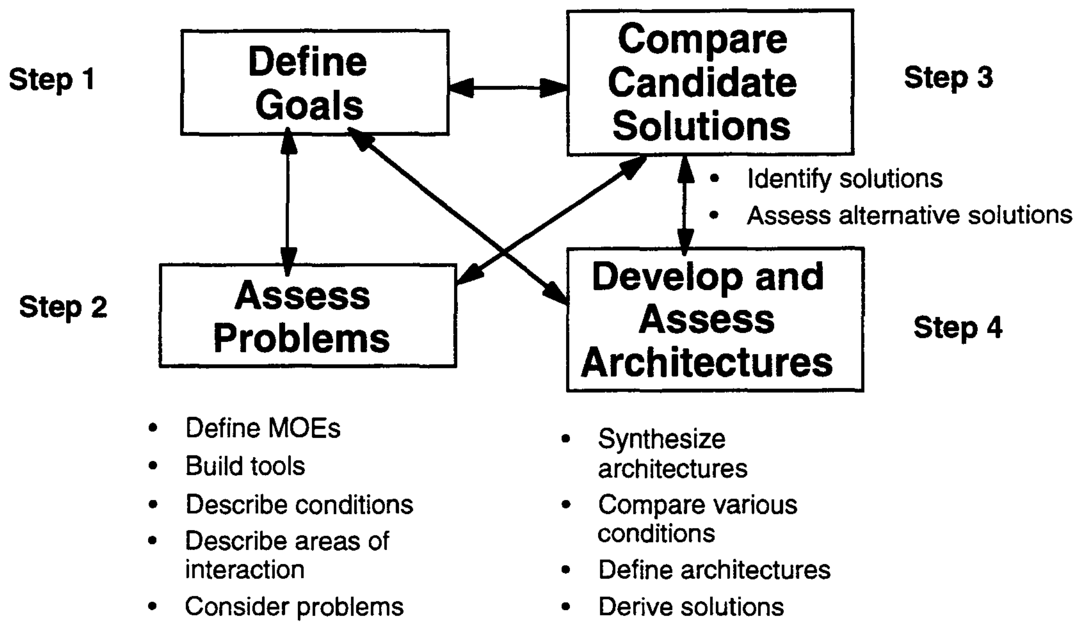

Figure 1.1-1. The classical four step process for concept development iteratively builds concepts that meet customer needs.

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 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.

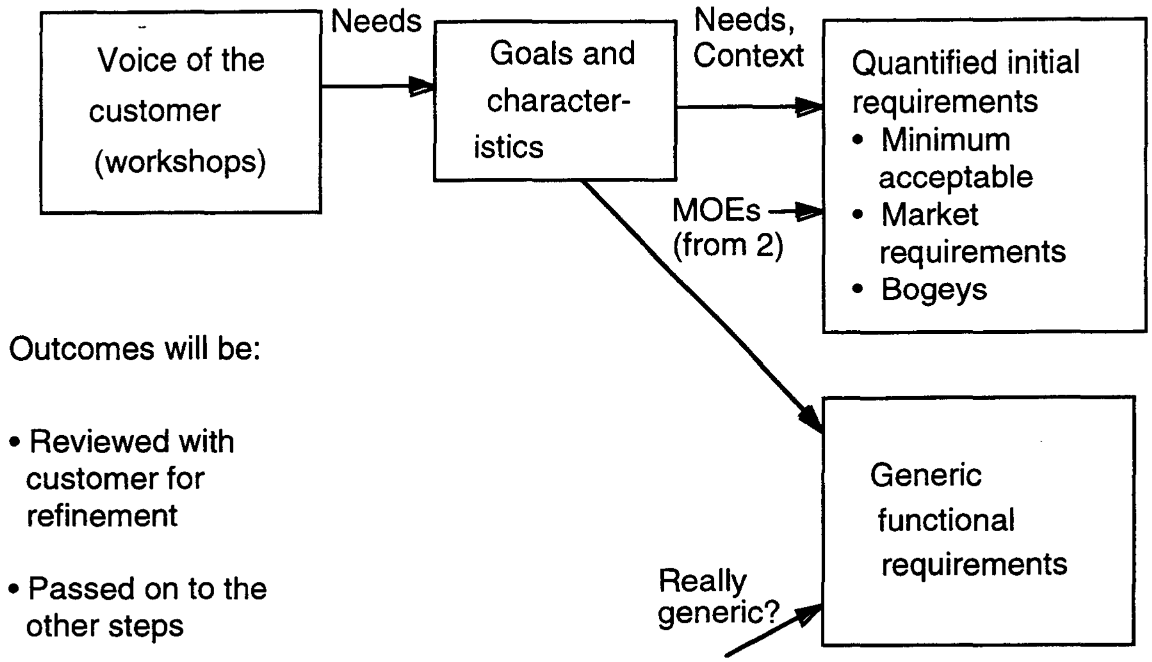

Figure 1.2-1. Define Goals. The goals that drive the concept development flow out of stakeholder inputs.

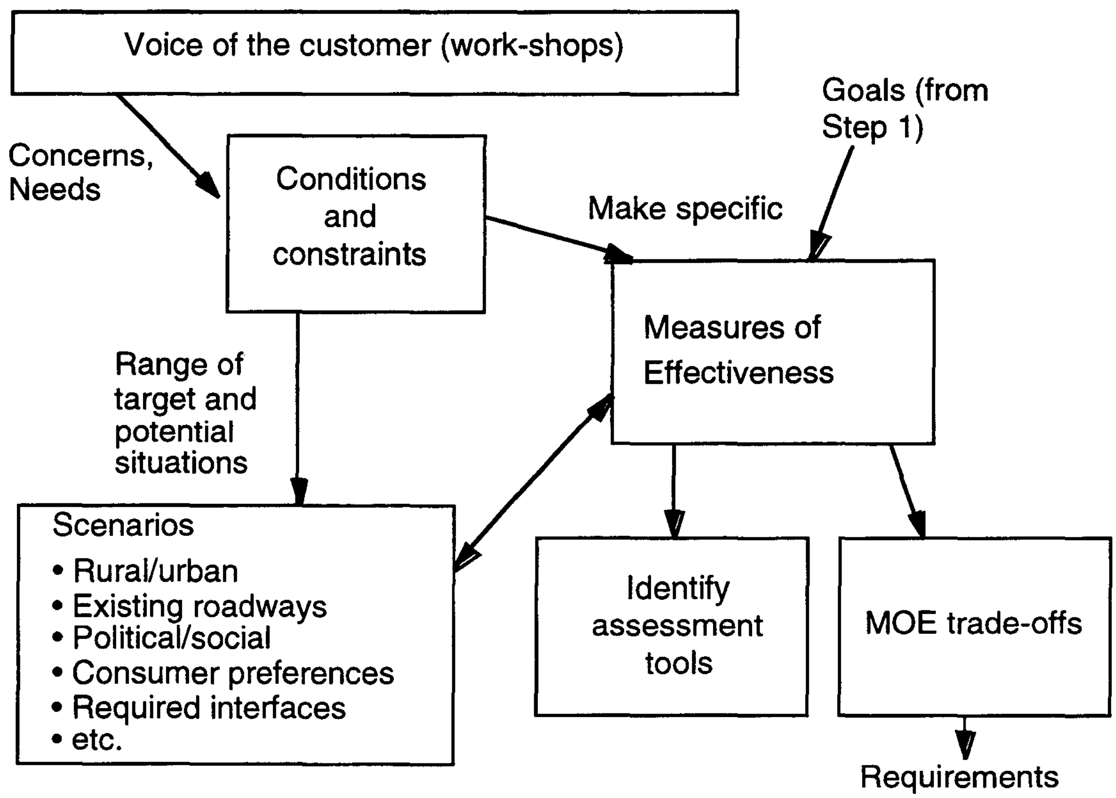

Figure 1.3-1. Assess Problems. The voice of the customer is translated into conditions, constraints, and specific measures of effectiveness. These then drive the application scenarios and the tool development.

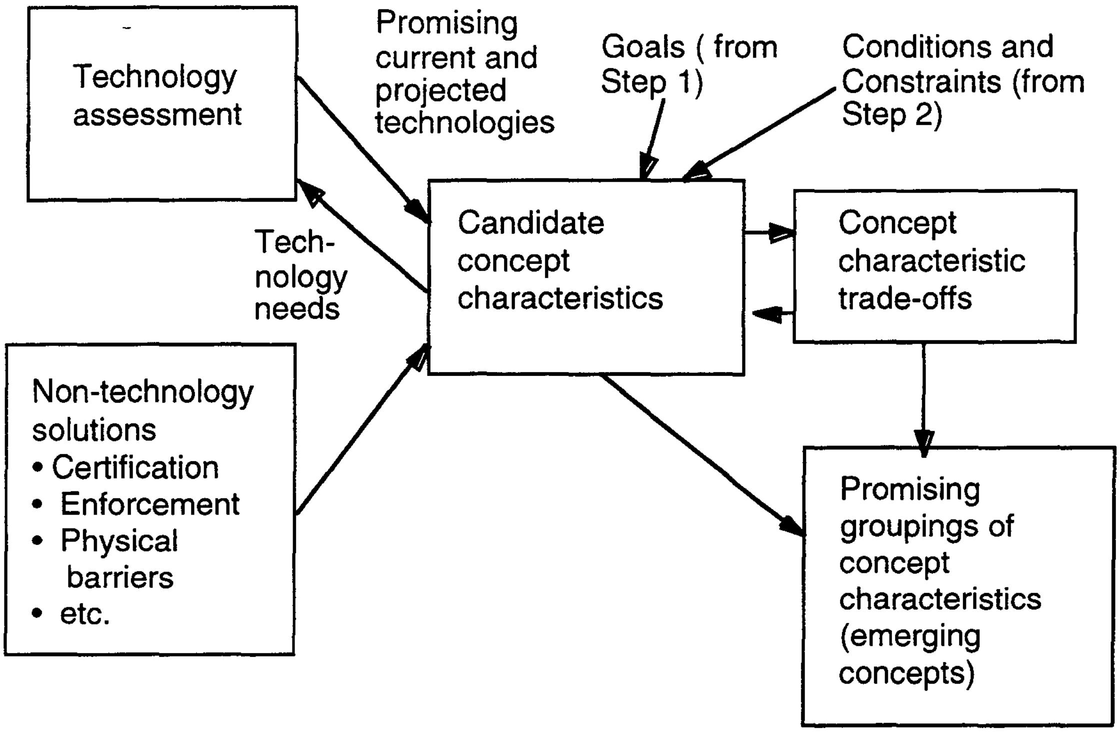

Figure 1.4-1. Compare Candidate Solutions. The alternatives for each of the concept characteristics are compared, suggesting promising characteristics and compatible groupings, leading to the development of full candidate concepts.

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

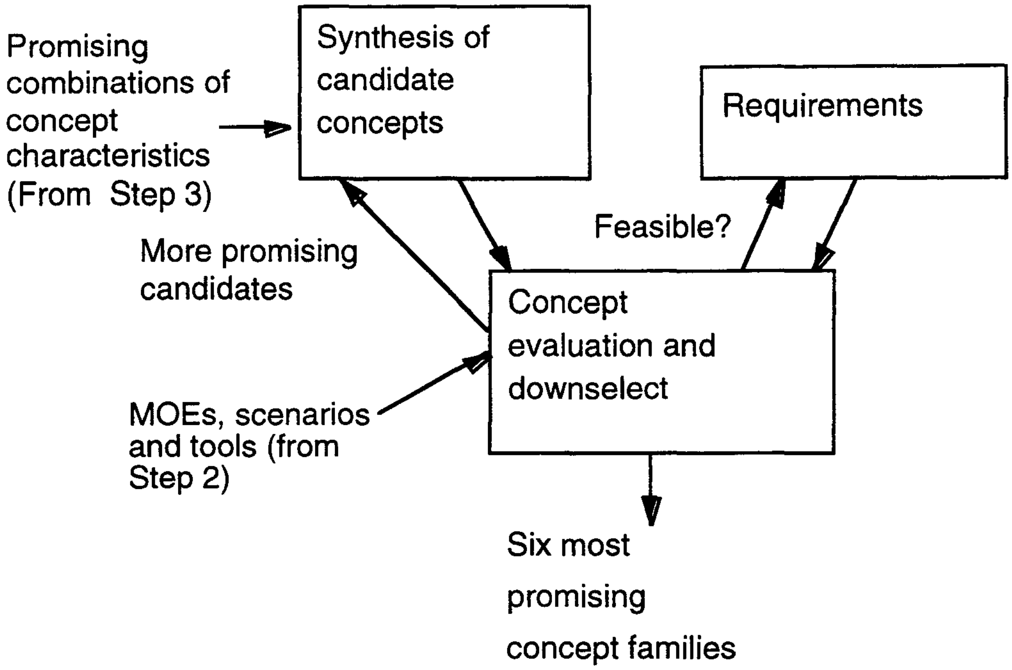

Figure 1.5-1 Develop and Assess Architecture. The concept characteristics are synthesized into candidate concepts. These are then evaluated against the key measures of effectiveness and requirements identified so far.

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 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. Stnd. 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. Stnd 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 be 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 platooning 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