Use of System Characteristics to Define Concepts for Automated Highway Systems

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The automated highway system (AHS) is a surface transportation system program that uses modern electronics to instrument highways and vehicles to provide "hands-off" and "feet-off" vehicle operation. Research to date shows that AHS has the potential to double or triple the nation's highway efficiency and to dramatically increase highway safety. The impact of AHS on the nation's highways would be comparable to the impact the jet engine had on aviation 40 years ago. FHWA has established an AHS program that will (*a*) identify and analyze alternative AHS concepts; (*b*) demonstrate the potential feasibility of AHS in 1997; and (*c*) if feasible, select and document the evolutionary AHS concept to be operationally tested beyond 1997. An operational test, with public participation, would then be conducted. Analysis, modeling, simulation, and testing will be used in comparing and evaluating the concepts. To assist FHWA in defining the AHS program, an initial definition and assessment of alternative AHS concepts has been made. The process by which AHS concepts were defined using the primary system characteristics of an AHS, specifically the functional and physical characteristics of an AHS, are described, and those characteristics that may vary from one concept to another are identified. From this, those distinguishing factors, termed concept definition factors, are used to postulate the initial set of AHS concepts.

In response to the Intermodal Surface Transportation Efficiency Act (ISTEA) (*1*), FHWA has established a program to determine the feasibility of automated highway systems (AHS). An AHS uses modern electronics, sensors, and communications on highways and vehicles to provide "fully automated" vehicle operation; this means that as an AHS vehicle pulls onto the AHS lane of an expressway, control of the vehicle's steering, braking, and acceleration is assumed by the AHS to provide lateral and longitudinal control until the vehicle exits and the driver again assumes control of the vehicle.

Substantial research to date shows that AHS has the potential to double or triple the nation's highway efficiency (*2*) and to dramatically increase highway safety (*3,4*). This impact of AHS on the nation's highways would be comparable to the impact the jet engine had on aviation 40 years ago. The long-range goal of the program, then, is to significantly improve the safety and efficiency of the nation's surface transportation system through a national effort that best ensures the early, successful deployment of automated vehicle highway systems.

It is recognized that first and foremost, the AHS is a highway vehicle system; therefore, its design must be based on solid, state-of-the-art engineering of both the highways and the vehicles that operate on them. This paper focuses on just those aspects of the highway and vehicles that might pertain to AHS. Also, it is recognized that resolution of AHS institutional issues, such as tort liability, may have a significant impact on how an AHS is designed, implemented, and operated. This paper does not address these impacts.

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The near-term objective of the AHS program is to test AHS feasibility and, if positive, select an AHS concept that would be used for follow-on operational test and evaluation. It is believed that a feasible AHS will be a robust, affordable, user-friendly fully automated vehicle highway system that evolves from today's road system and has significantly better safety, efficiency of operation, and comfort than today's highways. Specific activities of the current program include a 1997 proof-of-feasibility demonstration, in response to the congressional direction in ISTEA; selection and documentation of the preferred AHS concept for further test and evaluation; and development of a plan for evolution from today's highways to AHS, possibly using products that incorporate partial vehicle control, such as collision avoidance.

Work has begun. An effort to develop human factor guidelines for the program is under way (5), and 15 contracts have been awarded to identify and analyze key AHS requirements, risks, and issues dealing with design, deployment, and operation (*6,7*). FHWA has issued a Request for Applications for a consortium to work in partnership with FHWA to (*a*) implement the 1997 demonstration and (*b*) select the AHS concept that will benefit the public and industry as it evolves from today's highway system, and is preferred for operational testing.

PURPOSE AND APPROACH

To assist FHWA in defining the AHS program, an initial definition and assessment of alternative AHS concepts has been made. This paper defines the process by which the AHS concepts were defined and describes an initial set of AHS concepts. In taking the first step toward defining AHS concepts, assumptions were made about potential approaches for AHS implementation. These assumptions were made with the intent of not excluding any AHS concepts that might conceivably be considered legitimate. As AHS research continues and full sets of alternative AHS concepts are defined, the material in this paper will need to be revised. An AHS must be designed to meet the overall goals established for the system. Table 1 provides an overall summary of some strawman AHS deployment and operations goals.

The AHS goals will not vary from one AHS concept or design approach to another (*8*). What varies are the design characteristics of the various system concepts or design approaches, or both, postulated to meet the goals. Accordingly, this paper describes the system characteristics that would be used to meet the AHS goals and identifies the AHS characteristics that may be used to distinguish one AHS concept from another, termed concept definition factors (CDFs). Then using the CDFs, an initial set of AHS concepts is defined and discussed.

TABLE 1 Overview of Major Deployment and Operations of AHS Goals

- **Improve Operating Effectiveness** — Increase throughput of people, goods, and vehicles, and improve operation in adverse weather.
- **Improve Transportation Service** — Provide a full range of services, reduce travel time, and improve travel reliability.
- **Improve User Desirability** — Improve safety, enhance personal mobility, increase comfort of highway travel, provide user-friendly service, reduce insurance costs, and ensure affordable cost.
- **Improve Community Desirability** — Reduce land use, property impact; reduce need for emergency support; reduce construction disruption.
- **Improve State Transportation Agency Desirability** — Provide a basis for long-term upgrade to major highways, enable smooth transition, enable smooth installation, enable practical operation, provide better cost/benefit ratio, and integrate with and support transit operations.
- **Provide Societal Benefits** — Strengthen the nation's economy, nurture the U.S. AHS industry, support national emergencies, reduce fossil fuel consumption, and reduce pollutants from vehicles.

DEFINITION OF AHS CONCEPT

For purposes of this preliminary investigation, an AHS concept is defined as a conceptual-level system configuration that is defined by a set of characteristics and is fundamentally different from other conceptual-level AHS system configurations. A fundamental difference is when both instrumented vehicles and roadways differ from other configurations to the extent that changing to another configuration would cause a major redesign of the system. An example of a fundamental difference would be an approach in which only specially designed narrow vehicles are allowed on narrower-than-normal AHS lanes. To change such an AHS system to a different approach using normal widths would mean (*a*) widening the AHS lanes or reconfiguring the roadways and (*b*) evolving away from the narrow vehicles.

AHS COMPONENTS

AHS goals can be met by a variety of conceptual-level system configurations or concepts. Both functional and physical characteristics may distinguish among AHS concepts.

For purposes of this paper, it is assumed that the functional and physical characteristics of an AHS can be described in the context of these major components. (There may be many different approaches for segmenting the AHS into major components; the segmentation in this paper is suitable for initial analysis; however, as the program progresses, adjustments will need to be made as more accurate or varied definitions or both, are developed.) The various segments are as follows:

- Vehicle,
- Roadway infrastructure,
- Command and control,
- Entry and exit infrastructure,
- Communications (could be included with command and control), and
- Operations and maintenance.

This paper considers only the major characteristics that distinguish among AHS concepts. The first three AHS components—vehicle, roadway infrastructure, and command and control—all have these major characteristics. The analysis upon which this paper is based shows that the variations in the communications component and operations and maintenance component, although interesting, will not distinguish one overall AHS concept from another. The entry and exit infrastructure component has some interesting characteristics and variables, but they do not seem to be fundamental differences; that is, changes in approaches will not change the way in which either the vehicle or roadway is designed, and the entry and exit strategies could be changed without changing the rest of the system. Following are some of the major entry and exit infrastructure variables:

- Time of check-in: On-the-fly check-in in buffer lanes versus slow/stop at check-in stations (such as toll booths); all concepts will have on-the-fly check-in as a goal, if technically possible. It is assumed that noninstrumented vehicles may be part of the check-in traffic stream.
- Queue for check-in: Intermixed vehicles versus separate lanes for certain types of vehicles (e.g., trucks); this variant would be decided by assessment of which is more efficient at a particular entry plaza; in fact a given system could employ both options. Either approach could be used by most concepts.
- Queue for merging: All vehicles enter sequentially intermixed into the same AHS lane versus vehicles separated by type or entering by platoon, or both, possibly into specialized lanes; this variant also would be decided by assessing which is more efficient at a particular entry plaza; in fact a given system could employ all of the options, and the approaches could all be used by most concepts.

On the basis of this analysis, it was concluded that the entry and exit infrastructure component did not have major characteristics that could distinguish one concept from another, and that most if not all fundamental differences among AHS concepts will be defined in the vehicle, roadway infrastructure, and command and control components.

VEHICLE CHARACTERISTICS

Primary Functional Characteristics

The primary function of the AHS vehicle is to carry the driver, passengers, and goods as they are moved through an AHS system. The AHS vehicle must (*a*) provide for controlled vehicle movement while in the AHS; (*b*) interact with the AHS roadway infrastructure component to obtain traction and support for operation while in the system, and to obtain lane boundary indications; (*c*) interact with the entry and exit infrastructure component to provide smooth and rapid entry and exit to AHS; (*d*) provide accurate control responses to directions received from the command and control component regarding vehicle braking, steering, throttle, and lights; (*e*) detect and maintain the status of critical vehicle functions; (*f*) support access to and from the command and control and communication components; and (*g*) interact with the driver, on a user-friendly basis, with respect to AHS status and driver directions.

Primary Physical Characteristics

For any vehicle to operate as part of an AHS, regardless of the concept, it must have certain physical characteristics.

AHS Capability Rating

Any vehicle produced for the U.S. market after a to-be-determined date will have one of three AHS capability ratings. Only the AHS-capable and upgraded AHS-compatible vehicles will be allowed on AHS roadways.

- AHS-capable Vehicle: The vehicle is capable, as it is produced, of fully automated operation on a standard U.S. AHS roadway.
- AHS-compatible Vehicle: The vehicle is capable of being upgraded for full operation on an AHS roadway. The vehicle must include those items that are most economically included at the factory; and the design must readily accommodate the AHS upgrade components (sensors, processors, etc.).
- Non-AHS-compatible Vehicle: The vehicle is not capable of being upgraded for full AHS operation on a reasonable basis.

Mode of Operation

AHS vehicles must be able to operate in a fully automated manner on AHS roadways and under manual control on nonautomated roadways. Instrumentation for other services on non-AHS roadways, such as autonomous intelligent cruise control, may be used to provide part of the AHS control; these other services may act as evolutionary steps toward AHS.

Vehicle Status

Vehicles must have, or be upgradable to include, sensors and diagnostics to detect (*a*) malfunctions in engine, cooling, electrical, and braking systems; (*b*) performance degradation, including but not limited to power train performance, tire inflation, and loss of traction; (*c*) status of the on-board AHS system components and their interfaces; (*d*) ability of the driver to resume control; and (*e*) low fluid levels for fuel, engine, transmission oil, coolant, and brake fluid. Additional/different sensors would be needed for electric vehicles.

AHS Instrumentation

An AHS vehicle must include the AHS instrumentation, which may encompass

- Longitudinal sensors: Provide warning for spacing (position keeping), collision avoidance, and obstacle detection;
- Lateral sensors: Provide sensing of other vehicles laterally for passing, lane changing, merging, and collision avoidance; and
- Lane boundary sensors: Provide sensing of the lane boundaries by interacting with the roadway infrastructure to provide for lane keeping.

Mounting for Communication, Command, and Control

The vehicle must provide for mounting communications and command and control components.

- AHS communications: Provide for mounting of, and interactions with, communications components for interacting with wayside and vehicles; mounting provisions must include electronics packages and antennae.
- AHS command and control processor(s): Provide for mounting of, and interactions with, command and control component electronics; interface provisions include interactions with sensors, the driver, actuators, the communications component, and other IVHS services.

Chassis Design

Special AHS chassis designs may include dimension restrictions, special crash protection such as special side, front, or rear crash protectors, or emergency towing or removal connectors, or both of the latter two. As the community moves toward AHS deployment, performance specifications for these sensors, actuators, and chassis provisions will be developed so that AHS-compatible vehicles can be produced and marketed.

Vehicle Variables

Some of the vehicle characteristics that distinguish one AHS concept from another are summarized next.

Vehicle Class

Vehicle class describes dimension and performance traits of the vehicles that can be accommodated by an AHS lane. The classes are defined on the basis of (*a*) maximum width of the vehicles that can be accommodated by an AHS lane; (*b*) minimum rate of acceleration to access the lane; and (*c*) minimum top speed in the lane. These variations are considered fundamental; for example, changing lane width or buffer lane length to accommodate vehicles that are wider or slower, respectively, could result in a major change to the AHS design. Other factors such as stopping distance, weight, or height also should be considered eventually.

Roadway Infrastructure Interaction

The roadway infrastructure interaction variable defines the physical vehicle-to-roadway interaction. Most (but not all) AHS approaches assume a rubber-tired vehicle riding on freeway-quality road surfaces. However, the interaction between the vehicle and the roadway infrastructure could be significantly different. Two variations are addressed in this paper. One variation would be the use of pallets (i.e., specialized trucks) with AHS instrumentation that would hold noninstrumented vehicles (*9,10*). The second (albeit unconventional) variation could be a specialized pallet that would use another form of roadway interaction that includes magnetic levitation and air cushion. This alternative is highly speculative but is theoretically possible; it is included for the sake of completeness. A pallet is assumed because vehicles may not be designed for this kind of operation.

Vehicle Power Source

Most AHS concepts assume that the vehicles have an on-board power source, such as fuel for internal combustion engines or batteries for electric motors. However, there is a variation in the way electric power is provided to electric vehicles while they are on the roadway (*9*). The vehicle would need to be designed to accommodate this power transfer. The straightforward way of providing the power would be through electric contacts with power rails along the roadway; however, there are concerns that this is not a viable technology to evolve through the twenty-first century. Other noncontact approaches for transferring electric power include microwave or induction; the viability of these approaches needs to be examined.

Vehicle Lateral Control Strategy

Lateral control strategy refers to the method by which the vehicle interacts with the roadway infrastructure to determine its lateral position in the AHS lane. There are at least three alternatives: (*a*) passive center lane markers such as magnets; (*b*) passive barriers or markers on the side of each lane, or both, or (*c*) active lane markers such as an activated embedded wire in the roadway or, in theory, radio frequency triangulation. The vehicle's lateral position sensors would need to be designed to accommodate these significantly different kinds of markers.

ROADWAY INFRASTRUCTURE CHARACTERISTICS

Primary Functional Characteristics

The function of the AHS roadway infrastructure is to (*a*) provide traction and support for vehicle operation, including vehicles operating properly and those that are malfunctioning; (*b*) enable safe vehicle operation by ensuring vehicle separation in case of severe system malfunction (e.g., separators and barriers); (*c*) provide connectivity for entering and exiting vehicles and connectivity to other AHS systems; (*d*) provide passive or active indication of lane boundaries; (*e*) provide sensing of environment or obstacles, or both; (*f*) support/enable command and control and communications access to AHS vehicles and to roadway conditions; and (*g*) support access to roadway by emergency and maintenance vehicles.

Primary Physical Characteristics

It is assumed that most AHS concepts will require a freeway type of AHS roadway (as defined by AASHTO), with the difference that the AHS lanes may be significantly narrower. The narrower lanes are possible because lateral position in the AHS roadway lane will be controlled automatically; therefore, lateral position can be held to much closer tolerances than they could with human operators. Because of this, more AHS lanes can be built on existing roadway surfaces.

The roadway infrastructure design as a whole must be tailored so that AHS roadway lanes are sufficient to respond to the traffic flow needs. The specifics of how the roadway may be constructed are not addressed in this paper. For example, the decision of where to add AHS lanes (median of existing roadway, shoulder of existing roadway, elevated over existing roadway, or separate from existing roadway) should depend on the existing roadway configuration, surrounding environment, and relative cost/benefits. Also not addressed are the design and placement of barriers and the type of roadway surface. These implementation options do not define alternative AHS concepts, although the AHS design must obviously consider them.

The AHS entry and exit plazas are defined as part of the entry and exit infrastructure component; however, buffer lanes are needed as part of the roadway infrastructure to accommodate vehicles that are accelerating and decelerating as they enter and exit the system. Provisions also have to be made to accommodate vehicles with malfunctions (flat tires, overheating, etc.). The roadway surface condition will be monitored as part of the command and control component. Conditioning of the roadway surface is required for all AHS installations. The only option is the extent to which the conditioning is automatic, such as heated surfaces on selected key bridges. Depending on the extent to which lane changing is allowed and the strategy for accomplishing that, some buffering may be needed between AHS roadway lanes.

The roadway infrastructure must have provisions for accommodating command and control sensors, processors, and communications links that may be located at roadside. Also, the infrastructure must be designed to accommodate the special AHS operations and maintenance systems and any specially designed emergency vehicles.

Roadway Infrastructure Variables

The variable roadway infrastructure component characteristics correlate directly to the variable vehicle component characteristics; the roadway infrastructure view of these variables is given below.

Lane Width

Lane width is defined by the maximum width of the vehicles that will operate on a given AHS roadway lane, and the expected performance tolerances of their automatic lateral control. Lane width correlates with vehicle class and implies that AHS systems can be designed so that different classes of vehicles are separated, either in different lanes, in separate platoons, or even by areas of access. For example, a congested urban area could restrict inner-city access by trucks to only "narrow" ones; or high-performance intercity lanes could be offered as an added service. The vehicle performance would affect the length of entry/exit buffer lanes and would affect the ability of one platoon to pass another in a restricted space.

Vehicle Interaction

Vehicle interaction is the variable that defines the physical vehicle-to-roadway interaction. As with the vehicles, this interaction can vary depending on the kind of vehicle to roadway interaction assumed for an AHS approach—either freeway road surface (primarily), pallet, or specialized roadway interaction. The pallet may not require any special roadway design but would require the entry and exit component to have provisions for pallet loading, unloading, recirculating, storage, and maintenance.

Roadway Power Source

If the roadway infrastructure component provides full or partial electrical power to some or all of the vehicles, its design would be significantly different from that of infrastructures in which no power is provided.

Roadway Lateral Control Strategy

Infrastructure design will differ significantly depending on whether the lateral control strategy is to use (*a*) passive lane markers that are magnets in the centers of lanes; (*b*) passive barriers or markers or both, on the side of each lane; or (*c*) active lane markers such as an activated embedded wire in the roadway or radio frequency triangulation.

COMMAND AND CONTROL CHARACTERISTICS

Primary Functional Characteristics

The primary control of AHS is provided by the command and control component. The approach for accomplishing the command and control functions will significantly affect how the system is to be implemented. The five major functions of AHS command and control are described.

Traffic Flow Management

Traffic flow management senses conditions that affect traffic flow, determines changes required in that overall traffic flow, and provides overall guidance to AHS traffic through "traffic flow parameters." It is assumed that this function manages traffic after it has entered an AHS; the regulation of traffic entering and exiting the AHS is assumed to be a function of the entry/exit infrastructure component, which is not addressed in this paper.

Sensing of conditions will occur within a fixed geographic area of operation called a region. The size of a region is not defined, but it is assumed to be a reasonably large traffic management segment (e.g., a 100-mi^2 section of an urban area). It is assumed that a region can be segmented into many smaller local areas called zones so that local problems such as construction can be managed locally.

Sensing may be accomplished with organic sensors or through interaction with other IVHS systems or other AHS regions, or both. Conditions to be sensed could include the following:

- System condition: Malfunctions of the region's AHS, including communications and infrastructure malfunctions, must be detected; malfunctions of individual vehicles should also be detected.
- Environment: The roadway conditions, including wetness, temperature, and wind, will need to be monitored; monitoring could include the region's AHS roadway and connecting roadways (AHS and non-AHS); this could include both existing and projected conditions.
- Traffic conditions: Conditions sensed could include rate of flow in AHS lanes in the region and on connecting roadways (AHS and non-AHS), check-in and check-out plaza congestion, abnormalities, and projected traffic in the near term.
- Roadway impediments: AHS roadway impediments may include those that are planned, such as construction, or those that are unplanned, such as accidents; impediments on connecting roadways should also be sensed.

On the basis of the information received from condition sensing, the "traffic flow parameters" for the region as a whole and for specific zones will be constantly adjusted. Traffic flow parameters may include speed per lane segment or zone, spacing between vehicles and platoons, lane restrictions, passing/merging restrictions, and check-in and check-out restrictions (e.g., this plaza is closed). For some malfunctions, the traffic flow parameters may bring the traffic movement in a zone to a temporary halt, or divert it to non-AHS roadways, or both. For some weather conditions, the traffic flow parameters may lower the speed, increase the spacing between vehicles, and actuate special roadway conditioners.

Connectivity within and among the command and control component layers and with other AHS components will be provided by the communications component. It will consist of a variety of regional, wayside, or on-board (or all of these) communications systems. In this paper, it is assumed that the necessary communications links will be established and that the kinds of communications links will not be influential in defining AHS concepts.

Intervehicle Coordination

Intervehicle coordination provides management among vehicles in a vehicle cluster to ensure that crashes do not occur and that the overall flow of the vehicles is smooth. A vehicle cluster could be as small as one vehicle and all the vehicles within its sensing range or as large as sets of platoons of vehicles on multiple AHS lanes within a zone. The control must (*a*) operate within the constraints of the traffic flow parameters determined by the traffic flow management function (i.e., speed and spacing); (*b*) detect and track the relative positions of the vehicles in the cluster and maintain their status; (*c*) detect and be responsive to the needs of each of the vehicles in the vehicle cluster for merging, exiting, and lane changing; (*d*) determine potential openings in the traffic for merging, exiting, or lane changing, or all of these, and plan the maneuver including development of "control profiles" for each of the vehicles involved in the planned maneuver; and (*e*) transmit those control profiles to the vehicle control functions of the respective vehicles and track the vehicles to ensure that they follow the profiles. In theory, the intervehicle coordination function could be accomplished among autonomous, communicating vehicles if the proper cooperative algorithms were developed.

Incident Management

Incident management is, in effect, an extension of the intervehicle coordination function. It will (*a*) detect impending potential incidents, such as a vehicle not maintaining its position (e.g., not staying in its lane); (*b*) determine and calculate necessary controlling and evasive actions, and transmit these actions as incident management profiles to the vehicle control function of all affected vehicles; and (*c*) notify adjacent zones and the regional control center about the problem and the action being taken.

Vehicle Control

Vehicle control for each vehicle provides precise, millisecond-level (*a*) sensing of the vehicle's longitudinal and lateral position and (*b*) direction to the vehicle's actuators so that the vehicle either maintains its longitudinal and lateral position or tracks its control profile for merging, lane changing, or incident management. Depending on the concept, the on-board sensing of position may be a part of the intervehicle coordination function or may supplement that function. The latter case might provide added safety assurance but could lead to conflicts between the two functions that would need to be resolved.

Vehicle Management

For each vehicle, vehicle management maintains overall status and control awareness. It (*a*) monitors all vehicle status such as temperature and fuel supply; (*b*) maintains driver requests such as desired exit; (*c*) calculates and assesses overall management factors, such as destination versus fuel supply or on-board problem indicators, such as loss of traction versus current speed; (*d*) within the context of the overall traffic flow parameters, communicates with the vehicle control function if immediate actions are needed; and (*e*) interacts with the intervehicle coordination function for merge, lane change, entry/exit, or emergency stop requests/demands. Strategies for handling each of these requests will be handled by the intervehicle coordination function because other vehicles may be affected by the requesting vehicle's action.

Primary Physical Characteristics

The AHS command and control component consists of processors and the software that operates on those processors to perform command and control functions. The AHS command and control is viewed as a single entity so that the necessary integration among the various functions can be more easily envisioned; however, its physical design will consist of processing capabilities (processors with backup and environmental support) at a minimum of three different kinds of locations: on-vehicle, zone roadside, and regional control center. The actual location of the software to perform the functions described above may be influenced by the variations possible in the command and control component, as described below.

On-Board Characteristics

The on-board (i.e., vehicle-mounted) processors will have interfaces with the vehicle's actuators and sensors, the on-board communications equipment, and any other on-board IVHS equipment. Because of the critical nature of the AHS processing, redundant sensing and processing may be necessary to provide the necessary levels of reliability and availability; this, too, may translate into space needs. The algorithms, response times, and reliability of the software must be specified to ensure proper, safe operation while in the system.

Zone Roadside Characteristics

It is assumed that the roadside zone sensor and processing capabilities would provide coverage over a relatively small roadway segment (e.g., a few hundred feet in length). For fully autonomous intervehicle coordination, the "zone" would move with the vehicles. It is assumed that the capability is (*a*) able to operate in all weather conditions; (*b*) very reliable and includes self-diagnostic capabilities, and (*c*) unmanned other than for maintenance. These locations must provide protection against the environment, connectivity to required communications channels, enclosures with adequate space for maintenance access, and space for future growth. Because of the critical nature of the AHS processing, redundant sensing and processing may be necessary to provide the necessary levels of reliability and availability; this, too, may translate into space needs.

The in-zone sensing capability may include sensing of (*a*) vehicles entering the zone; (*b*) vehicle position within the zone; and (*c*) roadway condition within the zone. Communications component instrumentation within the zone may include beacons, receivers, and transmitters for communicating with vehicles in zone; networks for communication among zones; networks for communicating with regional traffic management; and communication links with sensors.

Region Characteristics

It is assumed that regional centers will be needed to provide the broad view and control of AHS traffic. A regional AHS center will be able to interact with other AHS regions and other IVHS systems to provide overall, integrated network control. A regional center probably will be manned. It must have provisions for regional command and control processors, command and control center display capability, and communication links to zones, and other regions for network connectivity.

Command and Control Variables

The basic variations in command and control are (*a*) the extent to which the functions are performed on an automated basis and (*b*) the location at which processing occurs; that is how the "intelligence" is distributed (on board the vehicle, zone roadside, or regional) (*11*). It is assumed that all AHS command and control functions are automated (i.e., performed with software or with software assistance to humans). It is also assumed that the command and control component will have total control at all times, with the exception of extreme malfunctions; thus, only in extreme situations would the driver be allowed to take control while in the system. The primary variations at which command and control component functions can be performed are shown in Table 2.

There are practical constraints that help limit the location at which the functional software is performed (Table 2). For example, vehicle management should be performed on the vehicle because the data sensed are mostly on board, and the use of the information is mostly on board. Similarly, many traffic flow management functions should be performed primarily at the regional level. It appears that the primary command and control variables are the location of the intervehicle coordination and incident management functions and, to a lesser extent, some of the vehicle control function.

The following variables can be characterized as types of strategies for accomplishing the vehicle control functions: roadway centered, vehicle-centered, and combined.

Roadway-Centered Control Strategy

When the intervehicle control function is performed at the zone roadside, this strategy is termed roadway centered; that is, the command and control component located at the fixed zone will be aware of and track the multiple vehicles and their interactions in its area of coverage; it will control and relate the movements of those vehicles in accordance with the traffic flow parameters by giving pre-

TABLE 2 Variable Locations for Command and Control Functions

Command and Control Functional Characteristics	Most Likely Location		
	Regional	Zone	On-Board
Traffic Flow Management	✗		
Inter-Vehicle Control			
— Subordinate		✗	
— Autonomous			✗
— Combined		✗ — *Both*	— ✗
Incident Management			
— Subordinate	✗ — *Both*	— ✗	
— Autonomous			✗
— Combined		✗ — *Both*	— ✗
Vehicle Control			
— Subordinate (Combined)		✗ — *Both*	— ✗
— Autonomous			✗
Vehicle Management			✗

cise commands to the vehicle control function of those vehicles. A variation of the roadway-centered control strategy, which is not explored in this paper, is the synchronous control strategy. This strategy, also termed "point following," assumes that moving slots are electronically predefined in the lane, and a vehicle moves into a slot, moves along the lane in its designated slot, and moves out of the slot when it exits the system (12). This strategy implies significant roadside sensing and on-board vehicle sensing; it also implies a reliable, higher-bandwidth communications capability from the zone roadside to the vehicles.

Vehicle-Centered Control Strategy

The intervehicle coordination and vehicle control functions could be performed exclusively among cooperative command and control component processors on board a cluster of vehicles. The roadway infrastructure component role would provide information (probably passive) on lane boundaries and other roadway characteristics. The command and control component located at the zone roadside would provide active information to vehicles on roadway conditions; it might also detect overall traffic flow rates and assess levels of congestion.

This strategy implies a higher level of sensing and computation on board the vehicle and probably significantly higher communications capabilities among vehicles in a cluster. Further investigation is needed of the approach for handling incident management and its relative safety and effectiveness.

Combined Strategy

A combination of the roadway-centered and vehicle-centered control strategies is quite feasible; many variations could be defined. Because these variations are not addressed in this paper, they are all grouped together as one strategy. This is an area in which a focused analysis might prove to be fruitful.

CDFs

The variables identified earlier constitute the characteristics, termed CDFs, that distinguish concepts from each other. Specifically, there were four variables among the vehicle and roadway infrastructure components and one variable in the command and control component, for a total of five CDFs, as follows:

- Vehicle class (size and performance);
- Roadway infrastructure interaction (type of interaction between the roadway and vehicle);
- Power source (on-board vehicle or roadway-provided electric vehicles);
- Lateral control strategy (passive embedded markers, passive physical side lane boundary markers, or active embedded markers);
- Vehicle control strategy (i.e., vehicle control and intervehicle coordination; three alternatives are roadway-centered, vehicle-centered, or combined approaches)

A major variable within an AHS is the longitudinal spacing between vehicles; however, vehicle spacing is considered a concept variation rather than a CDF. This is because the vehicle spacing of most concepts can and will be varied, and this will be done without any major changes to the vehicle or the roadway. Specifically, the AHS spacing at any given time will be determined by (*a*) the operating tolerances of the command and control component design; (*b*) acceptability to the drivers and passengers; and (*c*) the changing traffic flow parameters calculated by the traffic flow management algorithms. A given AHS command and control component design will have limits on the tolerances of spacing that it can safely allow. Over time, these limits may evolve to closer tolerances as electronic components and sensors are produced that are more responsive; however, this evolution should not cause major redesign of the vehicles or the infrastructure—electronic component replacement is not considered a "fundamental difference."

INITIAL CONCEPTS DEFINITION

Alternative AHS Concepts

The CDFs were used to define an initial set of AHS concepts. This was done by examining the various combination of the factors that could be made without regard to whether the combinations are practical. A total of 147 combinations is possible. Theoretically, each of these combinations could be considered an alternative AHS concept. However, the design or implementation or both, of many of these combinations is either highly unlikely or nearly impossible; for example, a pallet system may not be able to accommodate heavy interstate trucks. The concepts are identified by eliminating these unlikely combinations; the resulting number of concepts is 37.

In Table 3, the various potential combinations and concepts are grouped into eight different categories. Six of the categories are created using the vehicle class and lateral control strategy CDFs; the other two categories are special cases—roadway powered and special pallet. The selection of these categories was somewhat arbitrary; different groupings are certainly possible but would result in the same overall number of combinations and concepts. The assumptions made in assessing whether a given combination of CDFs was unlikely or unfeasible are described as follows.

- Wide truck use: Assumes a freeway type of roadway; no pallets would be used; energy provided from on board the vehicle.
- Passive lateral control strategy: The vehicle control will not be pure roadway centered; it will be primarily vehicle-centered control.
- Active lateral control strategy: The vehicle control strategy will not be purely vehicle centered; it will contain some control from the roadside.
- Roadway-provided electric power: All vehicles will be specially designed and will be narrow; the control strategy will not be purely vehicle-centered; and the lateral control strategy will be active, not passive.

Potential Combined Concepts

The 37 alternatives are simplistic; that is, there is no implied mixing of ideas from one alternative to another. For example, it is assumed that a roadway used by large trucks cannot be a pallet system because a pallet system would be all pallets.

The eventual AHS implementation will probably be a combination of a few of the alternatives. For example, pallets could be in-

TABLE 3 Categories and Number of Alternatives in Each Category

Category	Combinations	Concepts
• Wide trucks or smaller, passive lateral control	36	6
• Wide trucks or smaller, active lateral control	3	2
• Normal passenger vehicle or smaller, passive lateral control	36	8
• Normal passenger vehicle or smaller, active lateral control	18	4
• Narrow vehicle only, passive lateral control	12	8
• Narrow vehicle only, active lateral control	6	4
• Narrow vehicle only, roadway-powered	18	4
• Narrow vehicle only, special pallet	18	1
Total combinations	147	37

termixed with nonpallet traffic, including wide trucks. The AHS concept modeling and simulation capability must be able to accommodate these combinations. A few of the potential combinations of these concepts are defined and discussed as examples.

Separate Lanes for Various Vehicle Classes

In this combined approach, all vehicles would be accommodated in the system, but on different lanes where justified. Wide AHS lanes would be provided to accommodate wide trucks and transit vehicles. Smaller vehicles could also use these lanes; this would be the case where traffic density did not justify the separate lanes.

Transition Pallets

Pallets owned by the roadway operator could be intermixed with the other AHS traffic to allow noninstrumented vehicles to use the AHS roadway. The pallet is viewed as a fully instrumented, four-wheeled chassis upon which a noninstrumented vehicle could park—as on a trailer—and be transported through the AHS system; power would be provided by the pallet or conceivably by the vehicle placed on the pallet. Pallet loading and unloading facilities would be needed at entry and exit points.

Intermixed Roadway-Provided Electric Vehicles

In this approach, a special narrow AHS roadway lane would be constructed to provide partial or full power to electric vehicles as they operate on the roadway or to allow operation by narrow vehicles that have on-board fuel. Because the roadway-powered vehicles would need to be specially designed the number of them in a given AHS area may be low initially. This intermixing would allow the lanes to have higher utilization as the number of roadway-powered vehicles slowly increases.

Evolution from Vehicle-Centered to Combined Vehicle Control

Some AHS instrumentation may be available on some vehicles before the AHS actually becomes operational. For example, AHS instrumentation, if properly designed, could conceivably be used for collision avoidance on noninstrumented highways. Options could include autonomous intelligent cruise control; frontal collision warning and avoidance; lane keeping; and lateral collision warning and avoidance. Assuming that standards and specifications had been established in advance for these collision-avoidance features, then these vehicles could possibly operate on an early AHS roadway with little if any added instrumentation.

CONCLUSIONS

On the basis of the study effort summarized in this paper, the following conclusions are drawn:

1. A process can be developed to identify AHS concepts in a structured manner. The structured process developed and used in this paper seems to allow most, if not all, concepts to be identified.
2. There is at least one approach for structuring an AHS into its major components. An initial definition of each component's functional and physical characteristics can be made, and the major variations from one concept to another can be identified. These major variations are termed the concept definition factors; they can be used to identify a set of AHS concepts.
3. By eliminating the unlikely combinations of the concept definition factors, the number of AHS concepts defined in this paper is 37. Eventual AHS deployments probably will be combinations of two or more of these concepts.
4. The 37 concepts are not necessarily a complete and definitive set of AHS concepts; that complete set will be defined as the AHS program proceeds. However, they do provide an adequate basis for scoping and defining the AHS program in this early planning phase.

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REFERENCES

1. Public Law 102–240, December 18, 1991, *Intermodal Surface Transportation Efficiency Act* of 1991 (ISTEA).
2. Rao, B., et al. Investigations into Achievable Capacities and Stream Stability with Coordinated Intelligent Vehicles. Presented at 70th Annual Meeting of the Transportation Research Board, Washington, D.C., 1993.
3. *Our Nation's Highways—Selected Facts and Figures,* FHWA-PL-92-004. FHWA, U.S. Department of Transportation, 1992.
4. *The Status of the Nation's Highways and Bridges: Conditions and Performance*. FHWA, U.S. Department of Transportation, 1992.
5. *Human Factors Design of Automated Highway Systems (AHS).* MITRE Corporation, McLean, Va., Sept. 1992.
6. Stevens, W. *Precursor Systems Analyses for the AHS Program.* Working Paper WP 92W0000382. The MITRE Corporation, McLean, Va., 1992.
7. *Broad Agency Announcement for Precursor Systems Analyses for the Automated Highway System (AHS) Program.* U.S. Department of Transportation, Nov. 1992.
8. Stevens, W. *Automated Highway Systems Concepts Analysis.* Technical Report MTR 93W0000123. The MITRE Corporation, McLean, Va., Aug. 1993.
9. Bender, J. An Overview of Systems Studies of Automated Highway Systems. *IEEE Transactions on Vehicular Technology,* Vol. 40, No. 1, IEEE Vehicular Technology Society, New York, Feb. 1991.
10. Wilson, D. G. et al. *Quadramode Transport: A Class of Controlled Systems.* Industrial Liaison Symposium on Urban Transportation, May 1971.
11. Shladover, S. E. et al. Automatic Vehicle Control Developments in the PATH Program. *IEEE Transactions on Vehicular Technology,* Vol. 40, No. 1, IEEE Vehicular Technology Society, New York, Feb. 1991.
12. Fenton, R. E. et al. Automated Highway Studies at The Ohio State University. *IEEE Transactions on Vehicular Technology,* Vol. 40, No. 1, IEEE Vehicular Technology Society, New York, Feb. 1991.

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