Automated Highway System

Concept Summaries

May 1996

NAHSC

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WHAT IS AN AUTOMATED HIGHWAY SYSTEM?

The Automated Highway System (AHS) is a future component of our national highway system that will allow vehicles – automobiles, buses and trucks – to operate under automated control. When fully automated, the vehicle's steering, braking, and throttle are controlled by on-board and/or roadside systems, not the driver.

Billions of dollars a year are lost due to accidents on our roadways, with as much as ninety percent of all accidents caused by human error. By automating some driving functions, it should be possible to reduce the occurrence of some of these accidents. Also, by eliminating or reducing the variances of vehicle and traffic behavior, we can increase efficiency so that a single AHS lane can carry as much traffic as that in three manual lanes.

Making automobiles smarter is not a new idea. Global Positioning Systems (GPS) and cellular communications are now available for locating drivers in need of emergency assistance. Microprocessors provide "intelligence" to the ignition, transmission, suspension, braking, and other vehicle subsystems. Many buses and trucks are now equipped with sensors to detect obstacles all around the vehicle, especially at the blind spots, and are even capable of providing collision warning signals to the driver.

AHS aims to provide more uniform performance and safer operations by standardizing and streamlining basic driving functions. When all the vehicles in a lane are operating automatically and in a predictable fashion on our highways, more efficient highway operations, improved predictability, increased throughput, and improved safety levels will result. AHS also allows vehicles to operate at shorter headways, doubling or tripling throughput at congested freeway speed.

By providing more efficient vehicle operations, the accordion effect of accelerations and decelerations and weaving will be greatly reduced, resulting in greater fuel economy and reduced pollutant emissions. Furthermore, the deployment of AHS can be a step towards deploying roadway powered electric vehicles.

To achieve these objectives, AHS will need special capabilities. Systems will need to control spacing between vehicles and keep vehicles within the lane boundaries. The system/vehicles will have to prevent or sense and avoid threatening obstacles. Vehicles will need the ability to collect and interpret information about the highway and surrounding vehicles.

"What is the National Automated Highway System Consortium?"

The National Automated Highway System Consortium (NASHC) was formulated in response to a U.S. Department of Transportation Request for Applications to conduct a systems design feasibility, definition and prototyping of a safe, reliable, cost-effective automated highway system capable of substantially improving safety and efficiency on our highways. It is a private/public partnership which consists of nine core participants and the USDOT. The core participants are Bechtel, California Department of Transportation, Carnegie Mellon University, Delco Electronics, General Motors, Hughes, Lockheed Martin, Parsons Brinckerhoff, the University of California Partners for Advanced Transit and Highways (PATH) Program, and Freightliner (pending).

The NAHSC's mission is to specify, develop, and demonstrate a prototype automated highway system by the year 2002. The prototype will point the way to automated vehicle operation, leading to improved mobility of people and goods, increased productivity of surface transportation, and a better quality of life.

The specifications will provide for progressive, evolutionary deployment that can be tailored to meet regional and local transportation needs. The Consortium will encourage opportunities for spin-off vehicle and highway automation technologies to achieve early benefits for all users of the surface transportation system.

Important Open Issues

The Automated Highway System will grow out of technologies that are currently being developed and demonstrated. For example, adaptive cruise control is currently being developed that allows vehicles to maintain a safe following distance. This distance can be made extremely tight with the addition of electronic communications between vehicles, making virtually synchronized braking and acceleration possible. Also, in development are sensors that detect roadway striping or markers and allow automated lane following, even in situations that would challenge a good driver. These capabilities and others will be demonstrated by the Consortium in 1997.

The NAHSC is at the same time looking to the future when these capabilities will be applied in the real world, in which drivers become inattentive if they have nothing to do, debris falls on roadways, vehicles break down, drivers are often erratic, roadways have multiple lanes and interchanges, budgets are limited, and right of way for expansion is very costly. Selecting the best approach to the national AHS revolves around many issues, including the following.

- Will AHS vehicles be able to drive automated when mixed in regular traffic on ordinary lanes, or only on specially designated highway lanes where manual traffic is not allowed?
- Will AHS designated lanes require fully barriered separation from regular traffic? How acceptable are physically isolated but interlinked manual and AHS networks?
- What are acceptable costs to vehicle owners and highway operators for AHS capability?
- How much throughput increase on congested urban lanes is necessary and feasible?
- How will AHS operate on inter-urban and rural highways?
- How much control should the vehicle have and how much the roadway electronics?
- Should platooning be supported as a means to increase capacity, and if so, how? Platoons are relatively separated communicating groups of vehicles acting in coordination.
- To what extent should the AHS, and highway operations work to keep obstacles out of the roadway? Greater effort costs more, but reduces disruption to traffic.
- What obstacle detection capabilities will be necessary and feasible?
- What societal and institutional issues must be resolved to get stakeholder acceptance and actual deployment?

AHS CONCEPT DEVELOPMENT

These open issues cannot simply be addressed one-by-one, because issues are linked to one another. To deal with these interactions, several AHS concepts, overall ideas for the design of an AHS, have been created. Each concept is a possible answer for all classes of vehicles and for the entire national AHS, with particular applications in different settings.

The concept development and selection process to a final concept involves several steps. Initially, in phase one (C1) there were 30 concepts. Evaluation methodology included investigations into the costs, flexibility, safety, and throughput of each concept. In November 1995, five concepts were synthesized from the original set. Currently, we are in the process of further downselecting to three concepts, which may be from our current list, or redefined concepts based on what we learn in this phase (C2). Those three concepts will be further examined in detail in the next phase which will result in the selection of one concept for specification and prototyping. (C3)

What Do the Concepts Have in Common?

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

- Each automated vehicle will be responsible for keeping itself in its lane and maintaining appropriate distance from the vehicle ahead.
- AHS will take full advantage of any deployed ITS services.
- Once in automated mode, the driver will be able to disengage himself/herself from ordinary driving tasks.
- The automated vehicles will have a manual mode, in which they will operate on any conventional road like any other vehicle but, perhaps, with enhanced capabilities.

Summary of the Five Concepts

The following is a brief summary of each of the five concepts.

Independent Vehicle Concept. This concept is built around the idea that evolutionary deployment requires vehicles that can be independently upgraded and that can operate automatically when mixed with manual traffic, which requires vehicles to do everything on-board. In-vehicle technology enables the vehicle to operate automatically using on-board sensors and computers.

While the vehicle is capable of using data from roadside systems, it does not depend on infrastructure support to operate.

Cooperative Concept. This concept is built around the belief that the vehicles must communicate with other AHS-equipped vehicles to achieve the best throughput and safety, and that with reasonable computation and communications, the vehicles can do everything on-board. This concept is similar to the Independent Vehicle Concept, however, in this case vehicles communicate with each other and coordinate automated driving operations in an area.

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

Infrastructure Assisted Concept. This concept goes beyond infrastructure support to a system where 2-way communication between an individual vehicle and the highway infrastructure allows the roadside system to assist inter-vehicle coordination during entry, exit, merging and emergencies.

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

The following table summarizes some of the differences among the concepts.

	Independent Vehicle	Cooperative	Infrastructure Supported (IS)	Infrastructure Assisted (IA)	Adaptable
CONCEPT STRUCTURE					
Decision Process	In-vehicle technology	In-vehicle technology exchanges information with technology in other vehicles	In-vehicle technology receives information from roadside controller	In-vehicle technology receives guidance from roadside controller	In-vehicle technology plus capability to select from cooperative, IA or IS systems
Decision-Maker	Vehicle	Vehicle	Vehicle	Vehicle/ Roadside controller	Vehicle or roadside controller in different application
Technology Location	Vehicle	Vehicle	Vehicle, roadside	Vehicle, roadside	Vehicle(s), roadside
FEATURES					
Allows Platoons	No	TBD	Yes	Yes	Yes
Requires Barriered Lanes	No	No	Yes	Yes	No
Allows User Disengaged, Mixed with Manual AHS Operations	Yes	Yes	No	No	Yes
Requires Infrastructure Intelligence	No	No	Yes	Yes	No
Requires Infrastructure Intelligence for Maximum Concept Capability	No	No	Yes	Yes	Yes
COMMUNICATIONS					
Vehicle to ITS	Yes	Yes	Yes	Yes	Yes
Vehicle to Vehicle	No	Yes	Yes	Yes	Optional
Broadcast Infrastructure to Vehicle	No	No*	Optional	Optional	Optional
Infrastructure to Individual Vehicle	No	No*	Limited**	Yes**	Optional

TBD = Still to be determined for this concept

Optional = Optional for Stakeholders to Choose, may be required for maximum throughput performance

** = Exists as a capability, but not being used as concept is defined*

*** = Degree of Communication is locally tailorable*

Section A

Independent Vehicle Concept

CONCEPT VISION

The Independent Vehicle Concept is based on a vision of fully automated vehicles operating within, and evolving out of, the existing manual system (See Figure A–1). Autonomous vehicles are immediately deployable on all freeways as soon as the technology is available. Deployment will not be limited by building new or converting existing infrastructure, nor by market penetration issues.

Four key and highly desirable features are the motivating factors behind this concept:

- The use of existing infrastructure almost exclusively
- No central control and no loss of privacy
- Incremental deployment through its ability to operate in mixed traffic
- Automation features to provide enhanced safety when used off the highways

The infrastructure has no access to vehicle-specific origin/destination information and no knowledge of who is driving on the roadway. This concept does not currently provide for vehicle-to-vehicle nor vehicle-to-infrastructure communication, however it does support incoming roadway and congestion information based on ITS services. Vehicle-to-vehicle communication may prove to be a requirement for emergency situations, and will be added to this concept as required.

FEATURES AND ATTRIBUTES

The Independent Vehicle Concept is characterized by on-vehicle equipment that is used for lane-determination and lane-keeping, velocity and acceleration control, obstacle avoidance, and route determination. These fully autonomous vehicles are capable of driving in and around manually driven vehicles on all freeways, and use limited capabilities such as obstacle- and lane departure-warning on arterials and local streets.

Existing infrastructure is used to the greatest extent possible without additional sensors, infrastructure-based communications systems, or new civil infrastructure needed.

Independent Vehicle Concept

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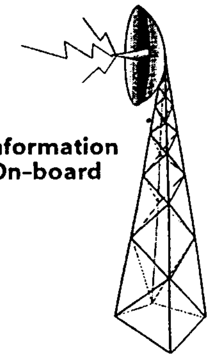
Goals

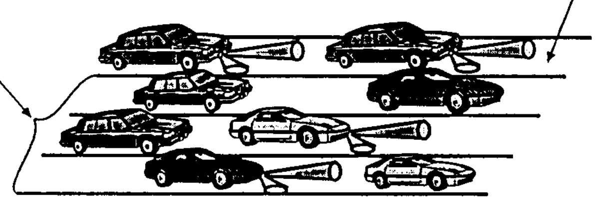
- Use Existing Infrastructure Almost Exclusively
- Sensor-based System with No Communications
- No Centralized Control, No Loss of Privacy
- Incremental Deployment through Mixed Traffic Capability
- Automation Features Usable of Freeways for Enhanced Safety

ITS Broadcast Information Is Available for On-board Route Guidance



On Freeways with 3+ Lanes, a Lane May Be Dedicated If:
- Market Penetration Warrants
- There is no Impact to the Other Lanes

Fully Automated Vehicles Operate within Existing Manual Traffic



On the Side Streets, Driver Warning Systems Will Be Used
- Obstacle Warning
- Lane Departure Warning
- Adaptive Cruise Control

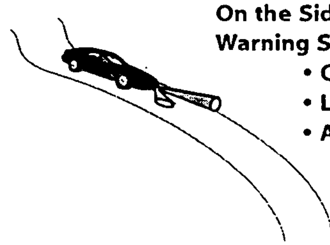


Figure A-1 Independent Vehicle Concept

DEPLOYMENT STAGES AND TIME FRAMES

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

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

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

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

End State. As more manual vehicles are retired from service, an increase in automation will be seen throughout the nation's freeways. Eventually, this will lead to a fully autonomous system which can continue to handle manually driven vehicles. This last phase is known as the ***End State AHS***. Automation capabilities will continue to evolve and expand to the side-streets and arterials as the technologies and on-board algorithms progress to handle these types of traffic situations.

BENEFITS AND LIMITATIONS

This concept is devised to be immediately deployable and marketable through integration with mixed traffic. It is also designed to be highly flexible to accommodate local needs. The benefits relating to deployment and market penetration are listed below.

- Because dedicated lanes are not promoted, the paradigm of building dedicated lanes without vehicle market penetration is eliminated. Likewise, users need not wait for new, dedicated lanes to be built before buying automated vehicles. State and local operators are also not faced with having to convert *existing* manual lanes for dedicated AHS use prior to a significant market penetration. This eliminates the concern that user groups will not be tolerant of congestion on manual lanes while the automated lanes go unused.
- Local and state highway operators can decide when and if to convert lanes based on local needs, impacts, and benefits.
- The trucking industry and passenger vehicles which heavily utilize the rural interstate system will not be limited in their access to the AHS system.
- Emergency vehicles will have fast response due to several factors. First, this concept does not add physical complexity to the freeway system. Second, AHS vehicles will help facilitate the response by automatically making way.
- Benefits in throughput and safety will be noticeable even with a small market penetration. All will profit from these improvements.
- Transit vehicles will benefit from automated capabilities early in the deployment process.
- The vehicle performs self-system checks. Elaborate "check-in" and "check-out" procedures associated new dedicated on- and off-ramps will not be required.

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

- The Independent Vehicle Concept's flexibility will be appealing to state and local governments, who will see improvements in congestion and safety due to automation, but will have the choice to build or convert lanes based on their own local priorities.
- Users will experience benefits early in the deployment process. The gradual introduction of automation will foster perception changes that alleviate user fear and lead to wider market acceptance.
- The emphasis on the maintenance of individual privacy will be appealing to many users and advocacy groups.
- The system will be convenient and readily available to all, regardless of geographical location. Rural users will enjoy AHS, as will urban users that travel routes where dedicated lanes are not practical.
- Emissions and energy saving benefits can be accrued early in the deployment process due to more uniform driving cycles.
- There are few issues associated with land use and environmental impact of building new roads in this concept. Additionally, there is no encouragement of new development around new entry/exit points.
- This concept, being relatively inexpensive, makes financing less of an issue.
- No additional liability is incurred by state and local governments, as the vehicle is responsible for all maneuvers. Liability remains similar to today, with the vehicle industry responsible for the product, and users responsible for using the product in the appropriate manner.
- Significant safety and throughput enhancements are achievable over the current manual system, especially as market penetration increases.

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

- The Independent Vehicle concept will require more thorough inspections of vehicle than is currently standard.
- This concept is based on the premise that it is technically feasible for automated vehicles to operate within mixed traffic.

Section B

Cooperative Concept

CONCEPT VISION

In the Cooperative Concept, vehicles use on-board sensors and computers to drive, and share information among other AHS-equipped vehicles so they can coordinate their motion for safety and high throughput (See Figure B–1).

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

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

The concept expects the final AHS Standards will not dictate what vehicles look like inside, but will define how vehicles act towards each other. Those actions are primarily defined in the communications protocol. To define how vehicles talk and listen, and what messages are passed, which is the focus of the Cooperative Concept, is largely to define the AHS.

FEATURES AND ATTRIBUTES

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

- The Design-For-Cost target is AHS as a new vehicle option available after 2010 for under $1000.
- Vehicles will have several on-board sensors (e.g., radar and vision sensors) to "see" the road and what is going on around them.
- Vehicles can use ITS services where available, for example, to obtain real time traffic information about the roadway ahead.
- Vehicles continuously communicate with each other about what they are doing and what is going on around them.

Cooperative Vehicle

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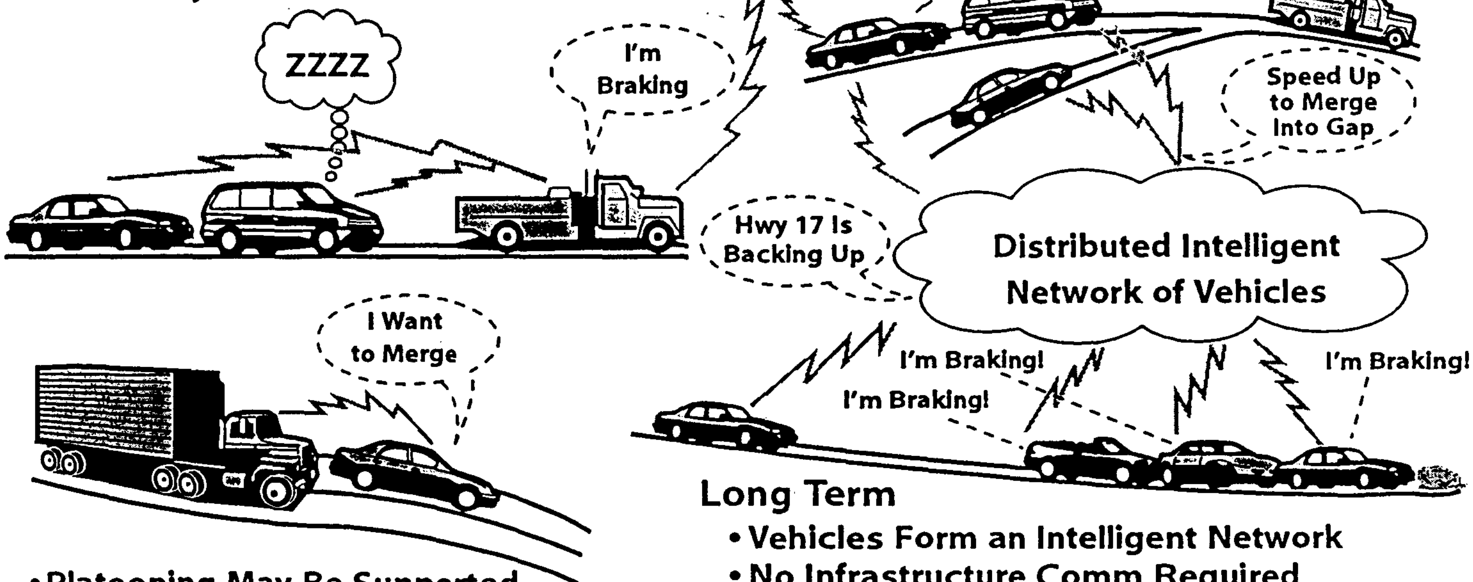
- Coordination Among Vehicles
- Vehicles Collect and Share Information Without any Electronic Infrastructure



- Platooning May Be Supported in Dedicated Lanes
- Merging and Lane Changes Coordinated

Long Term

- Vehicles Form an Intelligent Network
- No Infrastructure Comm Required
- Inference from Multiple Vehicles
- Wide Area Coordination
- Mixed and Dedicated
- Driver Disengaged

Figure B-1 Cooperative Concept

  - Vehicles pass information up and down traffic lanes, summarizing as it moves along.
  - Vehicles do not repeat information which has already been passed on.
- Each vehicle keeps track of what is going on around it, with lots of detail about the immediate area, and decreasing detail further away.
- The national AHS standard specifies how vehicles behave, while leaving internal designs to be decided and improved in the market.
- Operating rules are established to ensure vehicles are coordinated smoothly. For example, if a vehicle asks for a lane change, the rules tell vehicles in the adjacent lane to yield as appropriate.
- The concept facilitates adherence to operating rules, since many vehicles can see what an individual vehicle is doing.
  - For example, if a vehicle is supposed to yield and does not, nearby vehicles will notice that the vehicle is not following the rules, and is possibly malfunctioning. Communication among surrounding vehicles will identify this vehicle so they can stay clear. That identification will also allow traffic enforcement to pull the vehicle over and give it a "fix it" ticket.
- Operating rules lead vehicles to rapidly agree on a joint response to problems, such as failed vehicles or obstacles on the roadway.
- Vehicles can drive automatically on regular lanes, safely with regular traffic.
  - When technology has advanced enough to do this, possibly after 2010.
  - Obstacle detection looks like the critical technology.
- On special AHS-only lanes, cooperative vehicles can drive closely with little wasted space, thereby increasing throughput on lanes.
- The use of platooning is an option for the Cooperative Concept, contingent on further investigation showing it is necessary for maximum throughpout, and is safe.

DEPLOYMENT STAGES AND TIME FRAME

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

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

Δ National AHS Rollout

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

Second Phase. Operational Tests are conducted, and the results used to finalize the national AHS Standard in support of a national AHS rollout. Meanwhile, the commercial automated precursors will become increasingly sophisticated and robust. A car company might surprise the market by successfully offering an option for fully automated driving on ordinary highways. The earlier release of a draft national AHS standard will help make vehicle automation upwardly compatible with AHS.

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

The Cooperative Concept recognizes that follow-on evolution is desirable, and explicitly makes provisions to support subsequent phases to be designed and developed after full AHS deployment.

BENEFITS AND LIMITATIONS

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

- Allows AHS operations without the cost, delay and difficulty of legally and physically dedicating a separate AHS-only lane
  - Drivers can use Cooperative vehicles for automated driving on any highway
- Supports the local option of dense traffic on dedicated lanes for very high throughput
- Provides extreme flexibility in local deployment options, without the confusion or difficulty of multiple communications systems
  - Some options, such as having roadside computers that tell every vehicle what to do at a merge, could be offered, but are not now included because they appear unnecessary
- Vehicles talk to each other, giving them a very good idea of the nearby traffic they cannot directly see
  - Allows detailed maneuver coordination
  - Maintains situational awareness in the vehicles at all times
  - Helps when driving in manual traffic when another Cooperative vehicle is nearby

Potentially unique disadvantages of Cooperative are:

- May impose some slightly higher standard (e.g., striping with radar reflective tape) on all highways, not just dedicated AHS only lanes
- May require that vehicles guarantee smaller uncertainty in their braking capabilities

Section C

Infrastructure Supported Concept

CONCEPT VISION

The Infrastructure Supported concept envisions automated vehicles on dedicated lanes which can use infrastructure intelligence and global information to optimize AHS user services (See Figure C–1). In its mature deployment, the Infrastructure Assisted AHS concept is designed to support *fully automated vehicles on dedicated lanes* to safely and effectively increase throughput. The concept has special options for congested urban, inter-urban, and rural highways.

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

The Infrastructure Supported Concept is designed to:

- Minimize costs of automated vehicles by using relatively mature technologies and carefully controlling the environment in which they operate to make the environment as predictable as possible
- Obtain safety, congestion reduction, comfort and convenience of fully automated travel quickly by identifying limited-scale early deployment applications where automated vehicles can be operated in well-structured environments
- Maximize the safety of AHS travel by isolating automated vehicles from non-automated vehicles and obstacles, thereby eliminating accidents due to manually driven vehicles
- Seek maximum impact on reducing congestion problems in heavily-traveled urban and intercity corridors by aiming for high throughput while maintaining safety
- Place more emphasis on eliminating the high-delta-velocity crashes that produce fatalities and serious injuries
- Seek a distribution of intelligence that makes the system fault tolerant and economical
- Optimize travel time and reliability, using roadside support to speed and flow fluctuations in addition to entry and exit rates

Infrastructure Supported

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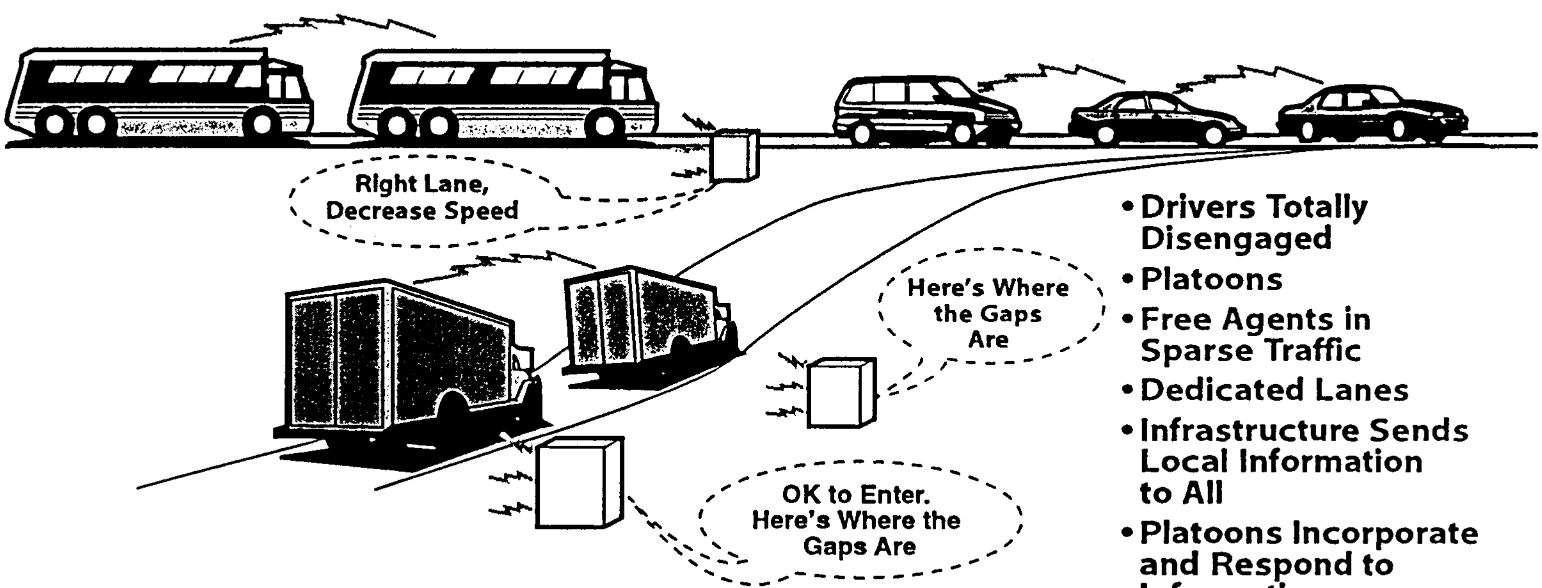
• Dedicated Lanes with Disengaged Drivers



• Drivers Totally Disengaged
• Platoons
• Free Agents in Sparse Traffic
• Dedicated Lanes
• Infrastructure Sends Local Information to All
• Platoons Incorporate and Respond to Information

Figure C-1 Infrastructure Supported Concept

FEATURES AND ATTRIBUTES

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

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

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

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

DEPLOYMENT STAGES AND TIME FRAME

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

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

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

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

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

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

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

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

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

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

Stage 4: Segregated and infrastructure supported platooning vehicles.

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

BENEFITS AND LIMITATIONS

Some primary benefits from the Infrastructure Supported Concept are:

- Better local control of system demand and congestion patterns
- Greater system-wide reliability
- Reduced emissions by smoother acceleration and deceleration patterns
- Efficient response to system failures to minimize system-wide delays

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

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

- Platooning or free agent
- Single or multiple lanes
- Dedicated or transition lane entry and exit.
- Global infrastructure supported signs for flow control or static control

Section D

Infrastructure Assisted Concept

CONCEPT VISION

The Infrastructure Assisted Concept has all the features that the Infrastructure Supported (I/S) Concept offers. It is designed to support fully automated vehicles on dedicated lanes to safely and effectively increase throughput. Similar to the Infrastructure Supported Concept, vehicles would receive communications from roadside infrastructure. However, the Infrastructure Assisted Concept envisions direct communication and control of individualized vehicles by the infrastructure control system at entry/exit, highway interchange, and other critical flow points (See Figure D–1).

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

FEATURES AND ATTRIBUTES

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

DEPLOYMENT STAGES AND TIME FRAMES

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

BENEFITS AND LIMITATIONS

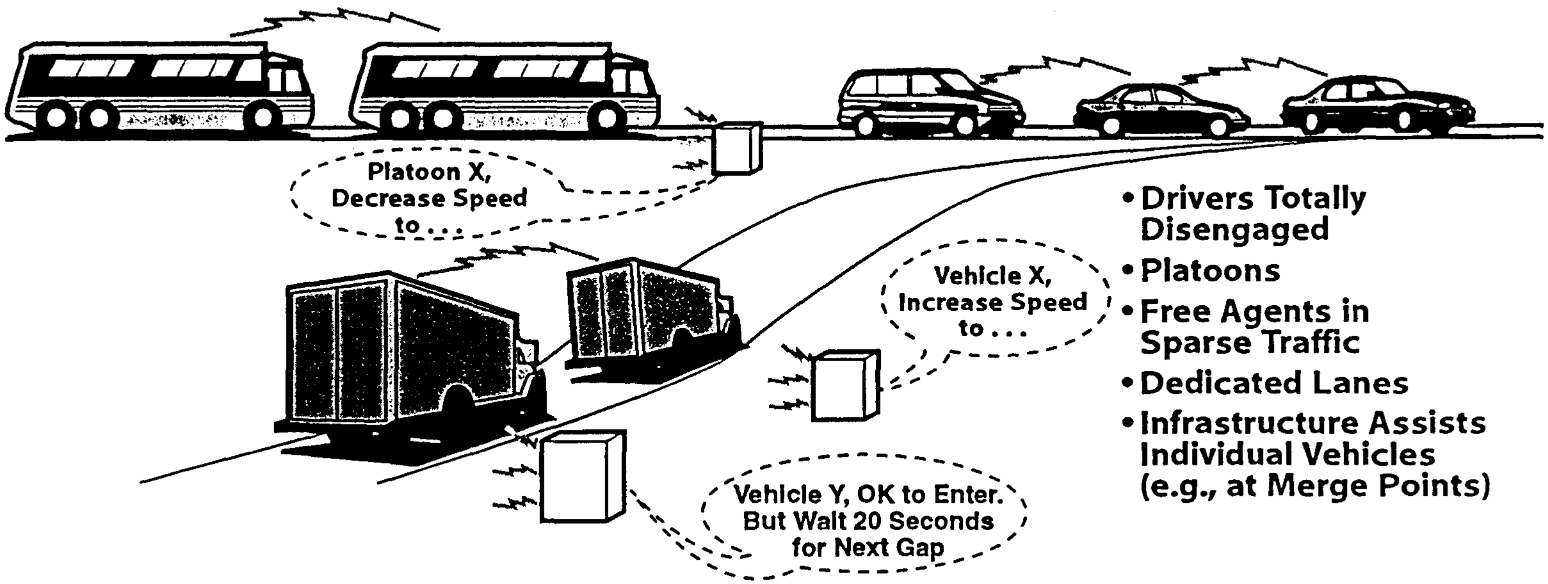
The following benefits and limitations apply specifically to the Infrastructure Assisted Concept (beyond those discussed in the Infrastructure Supported Concept).

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

Infrastructure Assisted

NAHSC

• High End Solution for Maximum Throughput



- Drivers Totally Disengaged
- Platoons
- Free Agents in Sparse Traffic
- Dedicated Lanes
- Infrastructure Assists Individual Vehicles (e.g., at Merge Points)

Figure D-1 Infrastructure Assisted Concept

Section E

Adaptable Concept

CONCEPT VISION

The Adaptable Concept envisions a flexible, layered approach to both infrastructure and vehicle automation systems. Local jurisdictions would tailor a mix of "Autonomous," "Cooperative," "Infrastructure Supported," and "Infrastructure Coordinated" layers (or modules) to meet their needs within an overall framework of standardized specifications across the system to ensure compatibility (See Figure E–1). (Note that several Adaptable Concept *layers* have names and characteristics similar to other AHS *concepts*. However, the Adaptable Concept is not a scheme for integrating the other concepts, and its layers are different from the AHS concepts of the same name. This distinction is described in Features/Attributes.)

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

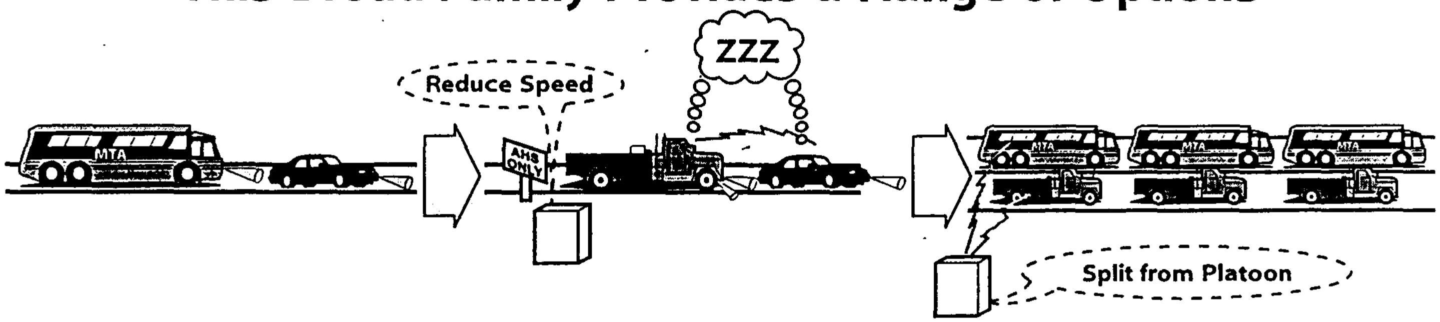
The Adaptable Concept is designed to maximize flexibility and options both in the vehicle and the infrastructure. It ensures compatibility across the country, while allowing communities and vehicle owners to pay for only what they need, adding more capability later. The concept is based on the idea there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

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

Adaptable

NAHSC

This Broad Family Provides a Range of Options



Autonomous
- Lane, Headway Keeping
- Driver Partially Engaged
- Mixed with Manual

Infrastructure Supported and Cooperative
- Dedicated Roadway
- Driver Disengaged

High End
- Infrastructure Coordinated
- Platoons

Local Options

- Low Cost
- Low Traffic
- Early Implementations
- Degraded Mode in Failure

- High Cost
- High Performance
- Dense Traffic
- Later Implementations

Figure E-1 Adaptable Concept

FEATURES/ATTRIBUTES

The key characteristics that distinguish the Adaptable Concept include:

- The concept allows Infrastructure Coordination (I/C) of incidents and platoon formation. Unlike Infrastructure Supported and Infrastructure Assisted, Infrastructure Coordinated gives the infrastructure the ability to manage traffic flow at any location when needed.
- Infrastructure knowledge of vehicle exits allows formation of more efficient platoons.
- The concept allows architecturally different solutions for different geographic areas.
- Deployment progressions can be tailored to the needs of different geographic areas.

The Adaptable Concept is a toolkit that affords a great variety of applications from four basic modules or layers.

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

Several Adaptable Concept *layers* have names and characteristics similar to other AHS *concepts*. However, the Adaptable Concept is not a scheme for integrating the other concepts, and its layers are different from the AHS concepts of the same name. For example, while the Cooperative layer of the Adaptable Concept has many similarities to the Cooperative Concept, there are also important differences. The Cooperative Concept is designed to handle the traffic problems of major urban areas without relying on an infrastructure. It does this by relying heavily on vehicle communication and processing capabilities. The Cooperative layer of the Adaptable Concept is expected to operate in major urban areas only in conjunction with the Infrastructure Supported or Infrastructure Coordinated layers. A Cooperative -layer-only AHS under the Adaptable Concept would probably be fielded in a rural area with very low traffic densities. Consequently, the requirements on the Cooperative Concept and the Cooperative layer of the Adaptable Concept are quite different, resulting in different designs.

Autonomous Layer

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

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

Infrastructure Supported Layer

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

Infrastructure Supported layer functions include:

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

Cooperative Layer

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

- Cooperative lane-changing and merging
- Recognition of rogue vehicles

- Local incident warning
- Platoon formation and dispersal

Infrastructure Coordinated Layer

The "Infrastructure Coordinated" layer is distributed between roadside processors and the Traffic Operations Center. It contains functions which allow the infrastructure to establish 2-way communication with individual vehicles, and to order changes in their speed, spacing, routing, or lane use. Infrastructure Coordinated layer functions include:

- Monitoring of vehicle positions and speeds by the infrastructure
- Infrastructure-directed lane changing and merging
- Infrastructure-directed platoon formation
- Emergency response to roadway obstacles and incidents

DEPLOYMENT STAGES AND TIME FRAMES

The following describes deployment phases for the Adaptable Concept.

Phase 0 and Phase 1 are very similar for urban, rural, and intercity deployments. Phase 0, which could be considered a "pre-AHS" phase, provides automated longitudinal speed and position-keeping along with lane-keeping. The vehicle will drive itself under ordinary circumstances; however, lane changing is done manually, and the driver has the option of taking over control of the vehicle at any time. In this phase, AHS vehicles and manually-driven vehicles mix on AHS-capable lanes; there are no lanes dedicated to AHS vehicles. If the AHS vehicle detects an obstacle or stalled vehicle in the lane ahead, it warns the driver, who may take over control and change lanes or begin braking. If he fails to take over control promptly, the vehicle will begin braking automatically. The vehicle will provide information (from ITS) on choices of routes and which exit to take; the driver is ultimately responsible for getting off at the correct exit, however.

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

The Urban deployment sequence has three phases remaining after Phase 1. The next two phases, Urban Phase 2- and Urban Phase 2+, are designed to be used either sequentially by a single regional traffic authority as AHS market share grows, or at the same time in different geographic areas with different population densities and needs. Urban Phase 2- is infrastructure supported, and is designed for smaller cities with moderate traffic density. Autonomous vehicles are driven on lanes dedicated to AHS. The infrastructure and the vehicles communicate by broadcasting information from short-range beacons to the vehicle and vice-versa. The infrastructure regulates traffic speed and spacing in order to enhance traffic flow, particularly at on-ramps and highway merge points. Urban Phase 2+, which adds a cooperative capability to Phase 2-, is designed as an intermediate phase for large urban areas with substantial congestion. At on-ramps and merge points, vehicle-to-vehicle communication is used to supplement infrastructure-ordered speed and spacing in matching vehicles in one lane to gaps in the traffic of the other lane. In addition, the cooperative capability makes platooning possible, thereby increasing throughput. The last phase, Urban Phase 3, is the end state which has already been described in some detail in this document. Intercity Phase 3, the end state for intercity deployment, is very similar to Urban Phase 3, substituting a dedicated truck lane (where practical) for the dedicated transit lane of Urban Phase

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

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

BENEFITS AND LIMITATIONS

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

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

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

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

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

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

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

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

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

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

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

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