# Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

# AHS Roadway Operational Analysis

U.S. Department of Transportation
**Federal Highway Administration**

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# PRECURSOR SYSTEMS ANALYSES

# OF

# AUTOMATED HIGHWAY SYSTEMS

## Activity Area K

## AHS Roadway Operational Analysis

Results of Research

Conducted By

Delco Systems Operations

# FOREWORD

This report was a product of the Federal Highway Administration's Automated Highway System (AHS) Precursor Systems Analyses (PSA) studies. The AHS Program is part of the larger Department of Transportation (DOT) Intelligent Transportation Systems (ITS) Program and is a multi-year, multi-phase effort to develop the next major upgrade of our nation's vehicle-highway system.

The PSA studies were part of an initial Analysis Phase of the AHS Program and were initiated to identify the high level issues and risks associated with automated highway systems. Fifteen interdisciplinary contractor teams were selected to conduct these studies. The studies were structured around the following 16 activity areas:

> (A) Urban and Rural AHS Comparison, (B) Automated Check-In, (C) Automated Check-Out, (D) Lateral and Longitudinal Control Analysis, (E) Malfunction Management and Analysis, (F) Commercial and Transit AHS Analysis, (G) Comparable Systems Analysis, (H) AHS Roadway Deployment Analysis, (I) Impact of AHS on Surrounding Non-AHS Roadways, (J) AHS Entry/Exit Implementation, (K) AHS Roadway Operational Analysis, (L) Vehicle Operational Analysis, (M) Alternative Propulsion Systems Impact, (N) AHS Safety Issues, (O) Institutional and Societal Aspects, and (P) Preliminary Cost/Benefit Factors Analysis.

To provide diverse perspectives, each of these 16 activity areas was studied by at least three of the contractor teams. Also, two of the contractor teams studied all 16 activity areas to provide a synergistic approach to their analyses. The combination of the individual activity studies and additional study topics resulted in a total of 69 studies. Individual reports, such as this one, have been prepared for each of these studies. In addition, each of the eight contractor teams that studied more than one activity area produced a report that summarized all their findings.

Lyle Saxton
Director, Office of Safety and Traffic Operations Research
and Development

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16. Abstract

This study considers the roadway operational requirements of an automated highway system (AHS) in light of corresponding operational requirements for existing conventional highways with traffic operations centers (TOC’s). Contrasts and similarities between TOC and AHS operations are identified.

Maintenance operations and activities are the focus of the study. Similarities and contrasts between AHS and conventional highways are considered, analyzed, and discussed to raise issues and risks. Urban/rural, passenger/heavy vehicle, and representative system configuration differences are covered insofar as there are significant differences among these categories of possible AHS operations. Maintenance needs and incident response requirements as they would impact an AHS operating agency are qualitatively analyzed. Two possible staged deployment scenarios for AHS are presented. The fault tolerance of the AHS is assessed. Results of interviews with personnel in charge of several existing TOCs have been summarized. The role of the driver in an AHS is discussed.

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## EXECUTIVE SUMMARY

Activity K — AHS Roadway Operational Analysis considers the operational and maintenance requirements of the Automated Highway System (AHS) in light of corresponding requirements for conventional highways. Some requirements of AHS are similar to those for conventional highways, while many are different or unique to AHS. This topic is not to be confused with AHS Roadway Deployment Analysis. The traditional operational measures of highway, freeway, and street networks, such as capacity and level of service, are covered in the AHS Roadway Deployment Analysis activity report. This activity report deals with the issues and concerns that an operating agency needs to deal with after AHS is deployed.

The surveillance needs of AHS include the surveillance elements similar to those of a freeway with a Traffic Operations Center (TOC). These surveillance requirements are those necessary to identify incidents and take appropriate response. AHS adds an additional surveillance requirement: That of monitoring the presence of non-equipped vehicles or vehicles with failed equipment in the AHS traffic stream. The topic of surveillance has heightened importance due to the higher speeds and/or densities on AHS, compared to traditional freeways.

Another surveillance need is that surveillance needed to prevent vandalism and sabotage. The possibility of counterfeit credentials or falsified check-in results are included in this category. Given the widespread nature of the highway network, the best approach to vandalism and sabotage may be to try for a damage-tolerant system rather than try to detect every act of vandalism and sabotage by surveillance.

While AHS may have some unique (from a highway operations perspective) security and surveillance issues to be dealt with, these issues are not considered insurmountable. Security and surveillance needs of an AHS would not be considered radically different from the elements of security and surveillance addressed by a wide range of entities and agencies, including airports, banks, utilities, and industrial plants. From an operating agency standpoint, it is desirable to minimize the amount of electronics located within the highway/control center infrastructure. This is due to the costs, complexity, and personnel requirements to maintain an operate these systems. It is therefore desirable (from this perspective) that RSC’s which are vehicle-intensive be deployed.

Maintenance operations bring special impacts to AHS. Any maintenance activity within the automated path requires cessation of automated operation or an automated detour. Dedicated

facilities, considered desirable for numerous reasons, complicate the maintenance picture. If a dedicated single lane AHS without a shoulder is deployed, any maintenance activity requiring stationary equipment or personnel in the AHS lane will require AHS operation to be shut down within the entire AHS link being maintained. The presence of a shoulder mitigates this problem by allowing at least some maintenance to be conducted from the shoulder while AHS traffic continues as usual. Alternatively, if work has to be done in the AHS lane, its shoulder is available for use as an automated detour, or for use by vehicles to whom automated operation has been temporarily suspended.

AHS is seen to have more rigorous maintenance needs than a conventional highway. Driver comfort and safety alone will require very high standards of pavement and bridge construction. The ability of present drivers to adjust their speeds as needed, based on prevailing conditions of pavement surface condition, will not be available under automated operation. However, the communications capabilities of equipped vehicles may result in real time reporting of highway deficiencies and other conditions requiring maintenance.

Automated control will bring to the operating agency the responsibility for a system maintained to the highest safety standards. The absence of the driver’s ability to take emergency evasive action requires the system to act instead. To mitigate this concern, some measure of driver responsibility to report and respond to emergencies is considered appropriate.

Traditionally maintenance of highway facilities has been funded from State sources. If it is established that AHS maintenance is more critical and more expensive than conventional facilities, other funding sources may need to be identified. Federal aid funding may be given consideration due to the costs and perhaps to increase the interest of State agencies who have extensive needs for their current maintenance budgets.

This project included analysis of incidents on conventional urban freeways with incident response capabilities. These ratios were applied to a future AHS roadway to estimate the expected number of incidents on a 16 kilometer section of AHS. Estimates of the realistic ranges of incident reduction for each category of incident were made. The expected remaining number of incidents capable of blocking an AHS lane was then calculated.

Even with very optimistic scenarios of incident reduction, a significant number of lane blockages remains and must be accommodated by the system. While an AHS shoulder has the negative attributes of cost, the presence of shoulders has a dramatic effect on incident management without a closure of the AHS.

It is likely that the current highway system would have to gradually evolve, in a planned manner, towards a mature AHS and that full deployment of AHS would consist of incremental steps each of which provides additional functionality at a commensurate cost. These incremental additions of AHS functionality would likely lead to corresponding increases in the scope and complexity of roadway operation. Thus a general discussion of AHS deployment is included in this AHS Roadway Operational Analysis activity.

The issues of low market penetration and the incompatibility of mixed automated and manual operation present hurdles to be cleared in the early implementation stages. Deployment difficulties include technology, infrastructure, human factors, vehicle, insurance, and public will. A staged deployment approach is presented that addresses these difficulties.

A twelve stage strategy for deployment is presented. Some of the stages can be implemented in parallel and can be overlapped. Variations to the strategy exist, and other deployment strategies should be explored. The twelve stages are:

- Stage One — The initial deployment strategy. Automated cruising takes place in a high occupancy vehicle (HOV)-like lane. Automated minibuses, with a professional driver in position, share the lane with manually-operated HOV’s. Control is entirely or predominantly vehicle-mounted.
- Stage Two — Construction of highway-to-highway HOV/AHS connector ramps and additional infrastructure-mounted control equipment.
- Stage Three — Vehicle fail-safety automation is complete with the provision of emergency resumption of manual control.
- Stage Four — Automation of automobiles.
- Stage Five — Dedication of one automated/transition lane for transition and then automated driving. At this stage, the lane is only for the use of AHS vehicles. There is no more mixed operation within the lane; however, vehicles enter the lane under manual control. Erection of barriers separating the automated/transition lane from non-AHS lanes begins.
- Stage Six — Automation of lane changing into the automated lane.

- Stage Seven — Dedication of one automated lane (elimination of transitioning) and automation of diverging/merging at (automated) highway-to-highway connector ramps.
- Stage Eight — Construction of automated on-ramps and off-ramps with barriers at busy locations. This stage would accommodate vehicles capable of utilizing fully automated entry and exit points. These would first be constructed where the demand for their use is highest.
- Stage Nine — Segregation of automated traffic from manual traffic. This would be accomplished by completing the construction of lane barriers to separate AHS lanes from conventional lanes.
- Stage Ten — Two automated lanes for capacity and a higher speed on the second AHS lane. This stage would result as market penetration and demand warrant.
- Stage Eleven — Automobile platooning on the second automated lane for higher capacity.
- Stage Twelve — mature AHS. The mature AHS is vehicle-centered and accommodates automobiles and transit vehicles. Platooning and free agency operational (lanes) are allowed. The AHS is completely physically separated from other traffic, and has its own entry and exit facilities. Multiple AHS lanes are possible and AHS direct highway to highway ramps are present.

AHS requires redundancy in sensing and control functions for safety and reliability. Reliability can be enhanced by fault-tolerance. Software verification and validation techniques can be applied to detect software and hardware errors in support of resolving errors in the planning and design stages of a system. Unanticipated design faults are more difficult to identify and respond to than those that are anticipated in design. Redundancy requirements for regional and zone control centers, while important, are not within the scope of this research work.

Design tradeoffs will need to be weighed relative to the level of fault tolerance the AHS is required to provide. These tradeoffs involve both institutional and technical issues, and should be viewed from the perspective of the entire AHS life cycle. Differences between software and hardware reliability must be taken into account in system design.

# INTRODUCTION

The research approach for AHS Roadway Operational Analysis, and for other roadway-oriented activities, was to consider the roadway operational requirements of an AHS in light of similar operational requirements for existing conventional highways with traffic operations centers (TOC's). This approach is useful for contrasts and similarities between TOC and AHS operations.

It is noted that this activity addresses maintenance operations and activities, not traffic operations. Traffic operations (capacity, level of service, and other related measures of effectiveness) are discussed in Activities H, I, and J.

Throughout this Activity, similarities and contrasts between AHS and conventional highways are considered, analyzed, and discussed to raise issues and risks. Urban-rural, passenger-heavy vehicle, and RSC differences are covered within each task, insofar as there are significant differences among these categories of possible AHS operations.

# REPRESENTATIVE SYSTEM CONFIGURATIONS

The representative system configurations (RSC’s) were generated very early in this Precursor Systems Analyses of AHS program. These RSC’s are used throughout the various areas of analysis whenever a diversity of system attributes is required by the analysis at hand. The RSC’s identify specific alternatives for twenty AHS attributes within the context of three general RSC groups.

Since the RSC’s have such general applicability to these precursor systems analyses, they are documented in the Contract Overview Report.

# TECHNICAL DISCUSSIONS

## Task 1. Security and Surveillance

### Security

Several attributes of the AHS will require that its security needs be addressed carefully. These attributes include the volumes expected, the possible high speeds, and the implications of down time.

In urban areas, AHS lane volumes will typically be at least twice the volumes presently seen on conventional lanes. For this reason the total shutdown of an AHS lane could be the equivalent of a two lane shutdown on a conventional freeway. An important driving force to deploy AHS is to add capacity without major widening, so closures have to be minimized. Because deliberate and accidental shutdown can be minimized through an effective security system, the issue is worthy of examination.

AHS has the potential for considerably higher travel speeds than today’s legal maximums. At these speeds (up to 160 km/h), implications of failure due to deliberate or accidental intrusions into the system are extremely serious.

Some security requirements may differ between urban and rural settings. In an urban setting security needs may be driven by the need to maintain high volumes at relatively low speeds (top speeds similar to today’s legal maximums). In a rural setting, higher speeds, lower volumes, and greater spacing between maintenance facilities may dictate different priorities in establishing a secure AHS environment.

Four major categories of security are given consideration: sabotage, theft, vandalism, and accidental damage or intrusion by unauthorized vehicles, pedestrians, or animals.

Sabotage is considered a very serious threat to AHS. AHS would be a highly visible target for saboteurs, with the potential for spectacular results of sabotage, including potentially huge traffic tie-ups and/or multi-car collisions. Numerous elements of the AHS could have the potential for sabotage: The communications infrastructure (radio and land line), the vehicle itself, and the Traffic Operations Center.

Communications sabotage could include deliberate RF transmissions to disrupt communications or alter operations, as well as deliberate damage to communications cable.

A non-catastrophic form of sabotage would be bootlegged credentials for use of the AHS; for example, using false credentials, stolen credentials, or altered credentials to avoid toll payment or inspection changes.

The TOC could be vulnerable to intrusion by hackers with malicious intent. Conceivably such hackers could alter systems to the extent that operations would be impacted, with the potential for disastrous results.

Another form of sabotage would be to interrupt the TOC power supply. While the conventional freeway is practically immune to power failures (with the exception of ramp metering and interchange signals), interruption of the TOC or infrastructure power supply could have extremely serious results.

Forms of sabotage not specific to AHS include such acts as dropping items off bridges into a stream of traffic; deliberate dumping of debris, oil, nails, etc. from moving vehicles, and similar acts. Mitigation of such acts is similar to available means of mitigation and includes adequate fencing and enforcement.

Compared to sabotage, theft is considered to be of relatively minor importance. It is felt that most elements of AHS would be fairly immune to theft for the following reasons:

- Of little value to thieves
- Too difficult to steal (heavy, embedded in concrete, etc.)
- In a facility that is continuously manned (TOC computers, monitors, etc.)

Prevention of theft of AHS elements is felt to be addressable through conventional means, including reasonable locks, bolted down equipment, and security guards at TOC’s as needed.

Vandalism is classified as conventional vandalism not intended to cause a catastrophic failure of the AHS. Such vandalism includes graffiti, damage to equipment, breakage of windows, etc. Management of such vandalism is not an AHS — specific enforcement issue and would be addressed in the same manner as it presently done.

Security measures also need to address accidental intrusions by unauthorized vehicles, bicycles, animals, and pedestrians. While the implications of the presence of these elements are serious for today’s highways, they are even more so for AHS. The nature of AHS, and specifically some of the RSC’s and alternative highway configurations, would make an air tight system difficult or impossible to achieve. The accidental intrusion issue may be dealt with as a combination security/surveillance issue: Take reasonable security measures to preclude such intrusions, but have a surveillance and incident response system that tolerates and/or mitigates events that do occur. This issue is addressed in a following section of this task.

## Incident Detection

Typically, up to the present time, freeway incident detection has utilized sensors (usually inductive loop detectors) in roadway pavements. These sensors detect vehicles as vehicles drive over the sensors. Various algorithms are used to detect incidents indirectly by observations of changes in speed or traffic density. Under conditions of light traffic volumes these incidents will not result in congestion or speed reduction, making detection of stopped vehicles difficult. (On the other hand, from the agency’s perspective such an incident is not as serious as one that causes delay.) The rate at which incident-related congestion propagates upstream is a function of pre-incident traffic flow rate, making incident detection a compromise between cost of sensors (installation and maintenance) and speed of incident detection.

## Surveillance

Surveillance activities in today’s TOC’s are typically conducted to verify that an incident has occurred; to identify the type of incident; and to ensure that the response to the incident is appropriate. While there have been efforts in the past to use manned video monitors for incident detection, this is generally considered undesirable due to human factors. Operators whose only task is to watch monitors for incidents become bored to the extent that they miss incidents when they do occur. On the other hand, operators with tasks other than watching monitors may miss incidents while on the other tasks. Today’s traffic operations systems usually utilize real-time monitoring of traffic flow for incident detection, using rapid changes of flow parameters (volume or density) to set off alarms. Video surveillance is then used to verify the incident and to determine the appropriate response.

A side benefit of traditional surveillance is to aid enforcement. For example, thefts of disabled or abandoned vehicles are sometimes observed in progress resulting in arrests.

In the future, video imaging may serve not only in a surveillance, but also an incident detection function. Video imaging for incident detection works by detecting the presence of new fixed objects in the image (stopped vehicle, spilled load, etc.) and setting off an alarm. The operator would then look at the image and intervene as necessary. Video imaging has the potential to eliminate, or at least reduce the number of in-pavement sensors, while providing visual verification of incidents. Video imaging for direct detection of incidents is in the early stages of development and is not yet a field-proven technology for this application.

AHS, with frequent or constant communication between vehicle and TOC, affords another means of surveillance. Assuming that equipped vehicles are able to detect and report their own impending breakdown, and also assuming equipped vehicles can detect and report on other malfunctions, the number of incidents remaining to be detected by the surveillance system is reduced to the following categories:

- Equipped vehicles with breakdowns which are neither self-reporting nor reported by other AHS vehicles.
- Non-equipped (unauthorized) vehicles.
- Spilled loads and debris such as tire fragments, mufflers, etc.
- Pedestrians, bicycles, animals, etc.
- Weather-related items (snow, ice, fog, rain).
- Pavement-related failures (potholes, cracks, blowups, frost heave, etc.).

Rates of occurrence of several of these incident types are known from experience on existing traffic operations systems. An analysis of several incident types, including assumptions made, is presented later in this task report.

Depending on system design, the same surveillance system could be used as an independent backup of the AHS control system. For example, volumes reported by the video imaging surveillance system and those reported by the AHS control system could be compared and discrepancies used to set off alarms.

## Security and Surveillance Hardware

The roadways which comprise the AHS are expected to require some level of electronic instrumentation to support automated driving. Instrumentation associated with the roadway is referred to as infrastructure electronics, and may include sensors, communications devices, and processors which reside at or nearby the roadway. Infrastructure electronics perform functions such as measurement of traffic density, environmental conditions, or vehicle location/identification. The highway instrumentation may also be required to provide a communications link between automated vehicles traveling in close proximity, or between platoons and a traffic operations center, for example. Processors may be implemented to provide processing of measured data or dissemination of control parameters. In addition to the highway itself, electronics will be required at the check-in and check-out facilities. Certain aspects of the following discussion are applicable to both the highway and the check-in facilities. For additional detail on issues concerning check-in instrumentation, refer to Activity B — Automated Check-In and Activity J— AHS Entry/Exit Implementation.

The electronic hardware may be physically located in roadside enclosures, elevated on poles, or positioned directly above each lane on gantries or overpasses. In the simplest case, a communications device may be placed along the roadside at relatively large intervals (perhaps 10 km) to allow for minimal roadside-vehicle communications capability. For AHS implementations which are vehicle based, 10 km spacing may be adequate. Infrastructure based implementations of AHS will likely require small infrastructure electronics spacing (perhaps 100 m). Table 1 describes various features of infrastructure electronics as they apply to roadway operations and the requirements placed on the electronics by each RSC defined in this analysis.

## Spacing of Roadway Electronics

RSC 1 and RSC 3 require sensing devices such as radar or infrared detectors along the roadside to measure the distance between vehicles and the velocity and acceleration of each vehicle. The measurement must be performed at least 20 times per second. The actual spacing of the sensors along the roadway depends on a number of factors such as the number of lanes, the speed and density of the vehicles, the angle of the sensors to the vehicles, and the accuracy and range of the sensors. Although velocity and acceleration can be measured with sensors placed at angles to the roadway, the distance between vehicles will likely require sensors either directly above the vehicle or on the side of the road looking perpendicular to the roadway. Table 1 shows spacing between 50 m and 200 m for the sensors required in RSC 1 and RSC 3. This is based upon an assumed ability of each sensor/electronics unit to process a few vehicles (2 to 8) and AHS capacity of 4,000 vehicles per hour per lane at 100 km/h. For RSC 2, most of the sensors will reside on the vehicle. The main infrastructure component will be the vehicle-roadside communications system. Using low power transceivers, spacing of 1 km to 10 km seems likely.

Table 1. Infrastructure Electronics Characteristics.

| Feature | RSC 1 | RSC 2 | RSC 3 |
|---|---|---|---|
| Spacing of Roadway Electronics | 50 m to 200 m | 1 km to 10 km | 50 m to 200 m |
| Electronics Redundancy | Overlapping Sensors and Communications | Overlapping Communications | Overlapping Sensors and Communications |
| Power Requirements | Backup Power Required | Degraded Mode when Power Fails | Backup Power Required |
| Location with Respect to the Roadway | At Roadside, Overhead | Best at Elevated Locations in Roadway right of way | At Roadside, Overhead |
| Maintenance | Regular Preventive Maintenance & Emergency Corrective Maintenance | Regular Preventive Maintenance & Emergency Corrective Maintenance | Regular Preventive Maintenance and Emergency Corrective Maintenance |
| Cost | High | Low | High |
| Complexity | Very Complex Electronics Infrastructure | Relatively Simple Electronics Infrastructure | Very Complex Electronics Infrastructure |

### Electronics Redundancy

The AHS system may implement redundant infrastructure electronics in all three RSC’s to allow the AHS to remain in operation when a single unit of the infrastructure electronic system malfunctions. Redundancy is achieved by overlapping sensors so that each sensor has a range which allows it to cover a portion of the territory of an adjacent sensor. This has an effect on the frequency of placement along the roadway, since curves and hills limit the range of some sensors. The spacing and actual placement of sensors must take into account the roadway geometry when providing for redundant electronics.

### Power Requirements

Alternating current (AC) line or direct current (DC) battery power must be provided to roadside electronics. The roadway instrumentation is an integral part of the lateral and longitudinal control system of the automated vehicle in RSC 1 and RSC 3. The operation of infrastructure electronics is critical to safety in RSC's 1 and 3, and provisions must be made to prevent complete power failure. Uninterruptable power supplies may be provided at each enclosure, or a secondary source of power may be required. There is an impact on the roadway in either case, because providing auxiliary power increases complexity by adding system elements to the infrastructure. Highway instrumentation may be limited to traffic flow functions in RSC 2, and loss of primary power to infrastructure electronics may not effect the safe operation of AHS. Design of special provisions for power failure will not be necessary in this case. The addition of inter-platoon communication via the infrastructure in RSC 2, would have a potential impact to the safety of vehicle maneuvers. Precautions to avoid loss of communications would become necessary if this implementation were used in RSC 2.

### Location on the Roadway

Sensors may be placed fairly close to the roadway in RSC 1 and RSC 3, and they may require protection from mud, dirt, and debris thrown by tires. Typical antenna systems used for radio communications are relatively durable; however, phased arrays used in many radar designs and lenses used in infrared devices may not withstand the harsh environment of the roadside unless they are protected. Physical methods such as cages or barriers may have to be used to shield roadway electronics. The minimum degree of roadway impact would involve allocating space along the roadside for installing the electronics enclosures. Certain types of sensors may be ineffective unless they are located above the roadway. The roadway must include some structure to mount overhead sensors at the required intervals if this type of sensor is chosen in the AHS configuration. The communications devices will be spaced at long intervals in RSC 2. Antenna height specifications may dictate mounting the radiating device on existing poles or installing poles at certain sites.

### Roadway Maintenance

Modern solid state electronic devices are typically very reliable. The Mean Time Between Failure (MTBF) of integrated instrumentation is often in the tens of thousands of hours. It would not be unreasonable to assume that a particular sub unit of the roadway electronic system would operate without failure for two to five years. In addition, electronic subsystems are commonly designed to perform periodic self tests in order to automatically detect failures. This capability can simplify field service procedures by allowing infrastructure electronic system elements to be replaced intact. Infrastructure electronics implemented using a modular approach can reduce roadside trouble shooting requirements, and allow the maintenance crew to simply swap a plug-in element. The failed unit could then be repaired in a facility by trained electronics technicians. Regular maintenance may be necessary to clean the surfaces of the sensors and to repair sensors that were damaged by rocks and other debris thrown from the road.

### Cost

The cost of infrastructure electronics and the associated mounting, enclosure, and power requirements could add substantially to the cost of the roadway. In addition, the added maintenance costs of the infrastructure electronics will increase as the amount of equipment increases. Skilled electronics technicians must be added to maintenance crews, although designing modular systems can transfer element repair to the depot. The amount of electronics equipment placed in the infrastructure is relatively high in RSC's 1 and 3, and this approach will be reflected in higher installation and maintenance costs. The impact to the cost of the automated highway will be related to the degree and spacing of the instrumentation placed on the roadway, and will be multiplied by the length of the AHS section. RSC 2 involves substantially less infrastructure electronics, and the life cycle costs associated with the roadway are expected to be much lower. The vehicle-centered instrumentation approach of RSC 2 will place the majority of the electronics in the vehicle, and thus increase the cost of the vehicle as opposed to the roadway.

### Complexity

System complexity is directly related to overall system availability for reliable service and the frequency of failure. A more complex AHS infrastructure electronics system could lead to longer periods of down time. Proper design for maintainability can mitigate the effects of increased complexity, but cannot eliminate all sources of failure. The pieces of electronics equipment on vehicles and the infrastructure may interact in complex, time dependent ways, causing equipment problems to become obscure and difficult to diagnose. The level of complexity at the electronics interface with the infrastructure must be minimized to allow simple maintenance procedures. The impact of increased complexity on infrastructure installation and maintenance will be a key factor in the instrumentation design, and should provide a modular interface to streamline these functions.

## Conclusion

Numerous elements of AHS surveillance and security needs have been reviewed. While it is felt that security and surveillance are of critical importance to the long range success and safety of AHS, no insurmountable concerns seem to be evident.

All the security issues raised have some similarity to the security concerns that are already being routinely addressed in a wide range of fields. For example, banks, airports, industrial plants, and utilities typically have widely scattered, diverse facilities subject to a wide range of security breaches. It is simply a fact of life these entities have to design security features into their facilities and to constantly update and monitor the features.

It is a finding and conclusion of this task report that all phases of AHS development and deployment need to continue to address security issues at the appropriate level.

## Task 2. Impact of Maintenance Activities on AHS

Maintenance routines on traditional highways occur regularly resulting in varying degrees of disruption to traffic. Some forms of maintenance, result in no degradation of traffic flows while others either cause minor disruption or total shutdown of the highway.

AHS is seen to have more rigorous maintenance needs than traditional highways. Many of the maintenance activities required for traditional highways, such as pavement rehabilitation; roadside requirements relating to safety, lighting and drainage; cleaning including street sweeping, and trash control; and seasonal procedures relative to snow and ice removal; will also apply to AHS facilities. In addition, maintenance routines will have to be developed to maintain electronic equipment unique to AHS.

While many of the above maintenance requirements can be performed without serious implications to traditional highway operations, the potential for traffic disruptions due to these maintenance requirements on AHS lanes could be great, depending on the AHS configuration. Even today, many congested urban areas schedule maintenance activities at night if at all possible. The same forces that result in such scheduling will be equally or more compelling for AHS maintenance. Impacts due to maintenance on AHS lanes could be categorized by different levels. For discussion three levels of impacts due to maintenance are defined.

**Level 1 — Total Shutdown**

Impacts could be either minor or major depending on the AHS configuration. If AHS has one lane and no shoulder, a total shutdown of the system would be required for any item that could not be attended to from a median or adjacent non-AHS roadways. Conversely, if AHS has one lane plus a shoulder, only major maintenance activities, such as some forms of pavement rehabilitation, would require a complete shutdown.

**Level 2 — Degradation of Operations**

Any maintenance that could be performed with degradation of traffic flow results in a level 2 impact. This maintenance impact could result from slowing of vehicles as a result of dynamic maintenance such as snowplowing or street cleaning. It could also result from diverting vehicles to the shoulder in order to work on the mainline.

**Level 3 — No Influence on Traffic**

Maintenance resulting in a level 3 impact designation would not affect AHS operations. Maintenance to electrical cabinets or other facilities accessible from adjacent non-AHS shoulders would be classified as maintenance resulting in a level 3 impact.

Maintenance resulting in level 1 or 2 impacts could be scheduled for low usage times (night work) in order to minimize disruption to AHS vehicles. If this type of maintenance occurs during peak usage time, impacts to AHS users and non-AHS users will be affected. As AHS operations degrade or cease altogether, potential AHS users will use non-AHS roadways resulting in potentially over saturated conditions on non-AHS facilities.

It is noted that maintenance resulting in level 3 impacts may not affect traffic flows on AHS roadways, but could cause slowing on adjacent non-AHS roadways if maintenance vehicles parked in the non-AHS shoulder cause a distraction to non-AHS drivers.

Some maintenance items may not just cause impacts to traffic, but may also impact AHS infrastructure. Seasonal maintenance including salting and sanding may cause corrosion of electronic devices required for AHS operations, which may result in equipment failure. Depending on the sensitivity of AHS elements to corrosive environments, traditional ice treatments such as salt or calcium chloride may be precluded completely. Snow removal equipment traditionally involves blading pavements which means all objects on AHS lanes have to be either embedded in pavement or “flush mounted” on the pavement, unless new snow removal techniques are developed.

## **Task 3. Maintenance Needs**

As in other activities and tasks within this project, the maintenance needs of AHS are addressed on their own and from the point of view of their similarities to and contrasts with the maintenance needs of a conventional freeway with a traffic operations system (TOS).

While the quantitative maintenance needs of an AHS are addressed at a high level, the primary thrust of the task is, as elsewhere throughout the study, the identification of issues and risks related to AHS maintenance needs.

Urban/rural differential maintenance needs are addressed as are differing maintenance needs related to the presence or absence of trucks and heavy vehicles. References to level 1, 2, and 3 maintenance activities are based on the definitions of those levels in Task 2, “Impact of Maintenance Activities.”

AHS has two attributes that make its maintenance needs more pressing than those of a conventional urban freeway: the sheer numbers of vehicles using the AHS, and the implications of shutdown of a fully automated system which drivers have learned to accept and depend on as an integral part of their transportation network. These attributes dictate a higher level of maintenance support than the conventional highway network requires. While a state-of-the-art control system should have several attributes (self-diagnostic equipment, redundant systems, etc.) that would reduce the requirement for maintenance, or at least make it schedulable, the consequences of failure are severe. In addition, especially in rural areas, AHS has the potential for speeds up to 160 km/h, requiring a smoother riding surface than required by today’s speeds, for driver comfort if not for controllability. Lack of adequate maintenance could have results ranging from driver discomfort to catastrophic accidents.

Not only will AHS control and maintenance facilities have to be staffed, the skills of the staff may need to be significantly different than those seen in typical highway agencies’ TOC’s, and certainly far different from those of normal highway maintenance crews and supervisors. While the controlled nature of AHS traffic should make roadside work safer, different skills and training for field personnel will still be required. Adding these classifications may face some institutional barriers which may well be avoided by contract maintenance and operations or by privatizing the entire AHS. These issues are discussed in more detail later in this task report.

The operations center of an AHS is seen to have a fundamentally different mission than that of a traditional TOC. A TOC is primarily reactive in its day to day operations. Terms such as incident <u>response</u> and accident <u>management</u> assume the existence of the incident and the need for appropriate damage control. By contrast, an AHS control center is expected to be in actual control of traffic, from the time its potential traffic gets near the AHS if not from the time the driver gets in his car. The implications of this level of control and operation are very serious for maintenance if AHS is to be more than a gadget or a curiosity. The system has to work and it has to be reliable, and generally speaking, reliability requires maintenance.

The operations center of an AHS is seen to have a another fundamental operating difference from that of a TOC: The “worst case” scenario of lack of maintenance of a TOC, due to its reactive nature, would be no operations at all. Under this scenario operations would simply revert to the case of a system with no management. While such a system would not have any of the benefits of traffic management, it would nonetheless operate albeit under degraded conditions. By contrast, failure due to lack of maintenance of the AHS operations center and infrastructure could result in accidents, or seriously degraded operations.

### Privatization of AHS Maintenance

AHS maintenance activities can be placed into three categories:

- Preventive Maintenance.
- Scheduled Maintenance.
- Emergency Maintenance.

Preventive maintenance activities are those that can be planned well in advance. Scheduled replacement of traffic signal lamps is an example from the highway field.

Scheduled maintenance is maintenance due to wear and tear or due to a failure, which can be performed at a time convenient to the agency without any significant risks. Replacement of cosmetically damaged guard rail could be considered to be in this category.

Emergency maintenance is work that must be performed immediately to avoid significant degradation of service or hazard to the public. Partial blockage of a lane due to a landslide or mudslide would come under this category.

While highway agencies generally do most or all their maintenance with their own employees, there are many examples of contract maintenance which have gone on for years. Bridge painting is an example of an activity that can easily be contracted. Other maintenance activities, such as traffic signal trouble calls, are more problematic as well as more related to some of the maintenance activities that can be envisioned with AHS. Problems agencies sometimes have with contract signal maintenance include lack of responsiveness. If privatization of AHS maintenance activities is to be examined, it is recommended that agencies who have used contractors for maintenance be identified and interviewed. A specific determination to be made is the success (or lack thereof) of agencies in enforcing responsiveness requirements in contracts.

Agency versus contractor liability is another issue germane to the subject of contracts. Typically agencies wish to be indemnified against the results of negligent acts of their contractors, while the contractors sometimes feel such indemnification is an onerous burden. Normally the contractor has to be bonded and/or buy liability insurance coverage. The cost of such insurance, and consequently the cost of indemnification, ends up being borne (directly or indirectly) by the contracting agency. An important issue to be resolved in AHS is how to fairly distribute the costs of liability insurance, as well as how to determine fairness in indemnification.

### Funding of Operations and Maintenance

An adequate, sustained funding source is critical to AHS maintenance and operations. Traditionally, federal funding has not been available to the states for maintenance of federal aid highways. Often, maintenance of existing facilities is in competition with construction of new facilities. Because state money for new construction is “leveraged” by matching federal funds (some projects are over 90 percent federally funded), the state agencies find that the most cost effective use of their funds is to defer maintenance. Many maintenance activities are somewhat flexible so this practice is seldom critical from a safety or traffic operations standpoint.

Using the air transport analogy, traditional highway maintenance is analogous to runway and taxiway maintenance. Deferred maintenance can result in a bumpier ride and more wear and tear on equipment but safety or even delay are not comprised. AHS maintenance is analogous to the air traffic control system, where maintenance related failures could result in delays at best and crashes at worst.

Table 2. AHS Maintenance Funding Issues

| **“Free” Funding Sources** | **Issues** |
|---|---|
| Federal Aid | 1. Not a traditional source of maintenance funding<br>2. Subject to Congressional approval every budget cycle.<br>3. Equity issues. |
| State Funded | 1. Traditional source of maintenance funds.<br>2. Competition with other uses of available funds.<br>3. Less conducive to a nationwide AHS than Federal aid funding. |
| Locally Funded | 1. Local funds are typically not used for State or regional roads.<br>2. Local agencies may not be able to maintain a long term financial commitment to AHS<br>3. Least conducive to a uniform, nationwide system. |
| **Toll Funding Sources** | **Issues** |
|  | 1. Number of trips sensitive to tolls.<br>2. Tolls cover capital costs as well as operating and maintenance costs.<br>3. Conducive to privatization.<br>4. May not be as conducive to nationwide uniformity as a Federally funded system.<br>5. May be most politically acceptable. (Users bear cost, tax outlay minimal) |

Maintenance requirements of AHS depend on the design standards used for its construction. To reduce future maintenance costs, a total life cycle approach to design can be used. Another approach, seldom used in the United States but common in Europe, is to require the contractor to guarantee the project for a set period of time after construction. This system gives the contractor the incentive to construct a more maintenance free project, or at least to identify the maintenance implications of his construction practices.

### Maintenance Needs Related to Commercial and Transit AHS

The consideration of the presence or absence of commercial and transit vehicles raises numerous maintenance issues. An AHS for vehicles up to and including full size passenger vans could require less maintenance because of the far less severe axle loading. Such a system could be designed with reduced vertical clearances and tighter geometry. Pavement sections could be thinner and bridge structures thinner. Any consideration of such a design has to be examined from a maintenance standpoint (as well as several other standpoints, discussed elsewhere). The following issues are to be considered:

Are the construction and maintenance savings expected from a passenger vehicle only design, offset by the requirement for specially designed, smaller maintenance vehicles?

Is it prudent to design a system that would preclude standard fire trucks and possibly other emergency equipment? Is a specially designed emergency fleet for the AHS a realistic expectation?

An extremely careful analysis should be made before any decision is made to exclude such an economically important segment of the transportation system. An AHS designed for passenger cars only is non-flexible in that trucks are precluded for the life of the system.

## Maintenance Needs Issues Related to the Contrasts and Similarities between Urban and Rural AHS

### Maintenance Needs.

Conventional highways allow operating agencies a great deal of latitude in scheduling maintenance. Funding sources and legislation can work against high levels of maintenance. Typically new construction costs are matched by federal aid, while maintenance is 100 percent state funded. This can result in deferred maintenance where state funds are limited. Given potentially high speeds, especially on rural AHS, a high level of maintenance will be required. Situations that would be tolerable at the current nationwide maximum Interstate

Highway speed limit of 100 km/h may be uncomfortable or unsafe at speeds of 160 km/h or even significantly lower speeds. These conditions include surface roughness, rutting, heaving, polished pavement, water ponding, and potholes. Maintenance related conditions not related to the pavement surface include ineffective drainage (blocked culverts or inlets), debris on the roadway, animals, guard rail and fence damage.

Systems chosen for AHS design should balance maintenance needs with tolerance to non-ideal conditions. It may be feasible to automatically degrade speeds based on unmaintained conditions until maintenance can be performed. For example, if a section of highway sustained frost heave that would not be economical to repair, operating speeds could be lowered in the interest of user comfort. Another example would be surface ponding. Speeds could be reduced, during and after rainfall, to a level where hydroplaning would not occur, then increased again during dry conditions.

**Response Time**

Compared to conventional highway maintenance, AHS maintenance activities may require faster response times. In rural areas, conventional maintenance facilities are typically widely spaced to save on labor costs. This spacing may be too great to have acceptable response times in case of an AHS highway infrastructure failure. As systems are developed it will be important to include consideration of travel distance and response times for AHS maintenance activities, especially emergency maintenance. Communications regarding the nature of the emergency may allow the system to suspend automated operation over a stretch of highway until maintenance can be performed.

Response times for maintenance activities are, by the nature of AHS, more critical than the response times for similar activities for conventional highways. On conventional highways, even critical maintenance activities, such as signal outages have the benefit of the human driver. Intersections with signals out can operate under police officer direction, until repairs can be made. An automated highway with a maintenance need requires more urgent response to avoid the requirement for resuming manual control, which would often be under greatly degraded operating conditions compared to automated control.

The forgiving nature of most highway maintenance activities, combined with the responsibility and ability of drivers to see, avoid, and report hazards, allows many maintenance activities to be prioritized and scheduled. Only the most critical activities are emergencies; quick response time is not a factor except for emergency activities.

It is felt that, due to the full automation of AHS and the potential limitations of the system to avoid hazards, AHS maintenance will necessarily be of a higher priority and will therefore require quicker response times. While the overall number of maintenance calls per vehicle kilometer traveled may be lower (due to higher standards of construction), the priority assigned to a typical call may be higher.

Rural AHS are expected to require maintenance response times similar to urban systems. Even through volumes would typically be lower in a rural setting, speeds would be higher and the implications of failure more serious for that reason.

While a numerical analysis of the difference in maintenance response time (AHS versus conventional, rural versus urban, etc.) is beyond the scope of a precursor study, this topic is considered of sufficient importance that it should be addressed early in the planning stages of a site-specific AHS.

AHS facilities with shoulders still have restricted access points; however, they offer the added flexibility of allowing manually operated maintenance vehicles to use the shoulders to reach the work site while automated travel occurs on the automated lane. The shoulder is also available for use by personnel and maintenance equipment without stopping AHS operation. While the desirability of such use of the shoulder is by no means certain, it is nevertheless possible and should not be ruled out without careful consideration.

The urban and rural nature of dedicated versus non-dedicated AHS is related to the likelihood that dedicated lanes would be found in an urban setting and non-dedicated in rural.

In some cases the AHS may partly help in improved response times by allowing maintenance vehicles to use automated lanes to travel to the site.

### Dedicated versus non-Dedicated AHS

Maintenance response requirements differ for dedicated and non-dedicated AHS. Dedicated AHS facilities are physically separate from the conventional freeway and have access and egress by direct connections to the outside system. Non-dedicated facilities are AHS lanes intended for the exclusive use of AHS traffic but which are not physically separated from adjacent non-AHS lanes. On a non-dedicated AHS, maintenance vehicles can move in the conventional lanes and need not be automated themselves. At least some maintenance activities can be conducted from the adjacent conventional roadway without impending flow in the AHS lane.

Dedicated operation places more constraints on maintenance work. A barriered, dedicated AHS allows vehicular access only at entry points, requiring maintenance vehicle travel on the AHS to reach the work site. Automated maintenance vehicles are therefore a requirement on AHS facilities without shoulders, unless the facility is shut down or degraded while manual maintenance vehicle travel occurs.

Insofar as maintenance needs are concerned, the dedicated lane AHS is not as accessible to maintenance vehicles. In addition, maintenance vehicles for a dedicated AHS would themselves have to be automated, or, alternatively, automated operation could be suspended within a zone ahead of and behind the manually operated maintenance vehicle. Also, if an AHS shoulder is present, the maintenance vehicle(s) could travel on the shoulder while adjacent AHS traffic operated unimpeded or perhaps at lower speeds.

By contrast, a non-dedicated AHS is accessible throughout its length from the adjacent conventional traffic lanes. Maintenance vehicles need not be automated nor are they required to use the AHS lanes for travel. (However, such operation could be exploited for quicker response times to locations needing maintenance.) Maintenance access is not considered to be an overriding issue in the decision between dedicated and non-dedicated AHS. However, it is important to evaluate maintenance access and design the highway infrastructure to account for it, especially in dedicated systems. While difficult to prove through analysis, it is the feeling of the researchers that an unbarriered, dedicated, high volume AHS would place a heavy burden on the system if safety is expected to be equal to or better than today’s freeway mainline. It is concluded that barriers should be a part of such a system even though they do complicate AHS maintenance and operations.

### AHS — Exclusive Maintenance

For purposes of considering maintenance alternatives, two extreme AHS designs can be envisioned. At one extreme would be a highly instrumental high volume urban network of AHS in a densely populated urban area. At the other extreme would be a non-dedicated rural AHS on a freeway with relatively low AHS and conventional traffic volumes, with a vehicle-intensive RSC.

In the former case the argument could be made that a dedicated maintenance capability is desirable. Justification for this includes frequency of maintenance operations and the safety, delay, and operational consequences of down time of the system. Specialty job skills, not typically associated with highway maintenance, would be required. Traffic volumes and public dependence on the system would warrant extremely rapid deployment of maintenance equipment and crews.

In the latter case, maintenance of the AHS lane is hardly any different from today's conventional highway maintenance activities. Little justification can be seen for a separate, dedicated AHS maintenance operation. Instead, maintenance could be provided by the highway agency, perhaps supplemented by specialty contractor crews if needed for communications, guidance, or sensing elements of the system.

### Non-AHS Exclusive Maintenance

A configuration could develop where an AHS lane could be applied to an existing freeway right-of-way under the operation and maintenance of an agency separate from the freeway operating agency. This could be analogous to a rail transit facility in the median of a freeway.

Taken to extremes, this scenario could result in a separate maintenance force for the AHS. The case for such a scenario could include the need for specialty skills for the repair, operation, and maintenance of the electronic elements of AHS. The case against the scenario is that duplicate maintenance forces would be inefficient, under-utilized, and wasteful. It could also be argued that such skills should be simply added to the maintenance forces of the existing agency, reducing the chance for wasteful duplication of manpower and facilities. The maintenance differential between AHS and conventional freeways is seen to be the greatest in an urban scenario due to the higher likelihood of a dedicated system and the greater instrumentation that platoon-based RSC's may require.

The solution to this issue is not in the scope of a precursor study. The concern is raised and the recommendation made that appropriate maintenance be "designed into" the AHS from the beginning of the planning stages.

### Terrain

Terrain has more of an impact on AHS maintenance in a rural setting than an urban one. The influence is related to grades, which can be steeper on rural freeway than is typically the case on urban freeways. Upgrades and downgrades have the same impact on the operating speeds of maintenance vehicles as on conventional traffic.

Other grade-related attributes that tend to be found more in rural environments include rockslides and mudslides. Mountain passes, where heavy snowfall is more common, tend to be in rural, undeveloped areas. The safety implications of such undetected events are serious in the case of higher speed rural AHS scenarios.

Special designs to preclude these events, or especially effective detection methods, may be required where these events are common.

## Task 4. Incident Response

### Incidents

A literature research was carried out in an effort to develop data on the number and nature of accidents and minor incidents (non-accidents) on urban freeways in the United States. From these, we can develop estimates of:

The number of accidents that might be expected to be eliminated as the result of an AHS operation.

The number and nature of minor incidents that would be expected to still occur on an AHS lane, even though an extensive check-in (including diagnostics) procedure might be used.

### Incident Rates

Lindley[1] defined an incident as any event, regardless of its nature, occurring on the freeway which would have the effect of reducing capacity and thus, interfere with smooth traffic flow. Data covering 24,680 kilometers of urban freeways in the U.S. were analyzed. It was concluded that incidents were occurring at the rate of about 49 incidents per million vehicle kilometers on freeways with shoulders; the rate on freeways without shoulders was about 125 incidents per million vehicle kilometers. The latter figure is felt to be more representative of the true number of existing incidents and is used for analysis in this report.

Lindley further separated the data into the type of incident (accidents, disablements) and the location of incident (in-lane, on shoulder) as follows:

Table 3. Freeway Incidents.

| **Type of Incident** | **Freeways with Shoulders** | | **Freeways without Shoulders** | |
|---|---|---|---|---|
| Accidents on Shoulder in Lane | 4.2% | 21.3% | — | 15.1% |
| Disablements on Shoulder in Lane | 95.8% | 78.7% | — | 84.9% |

Analysis of Lindley's data leads to the conclusion that, of all incidents occurring on urban freeways, about 12 percent to 15 percent are accidents; 85 percent to 88 percent are non-accident related.

These figures compare somewhat favorably with those which are emerging from work which is underway at California Polytechnic University, San Luis Obispo. They are reporting incident rates of about nine to ten times greater than accident rates on comparable freeway facilities.

Based upon the analysis of 70,455 incidents on the freeway system in the Chicago area in 1992, the Illinois Department of Transportation[3] reports that 8.6 percent of all incidents were accidents.

Based upon the work cited, it is reasonable to conclude that accidents comprise about 12 percent of the incidents on urban freeways; minor incidents (non-accident) comprise about 88 percent of total incidents. Further, it is concluded that, for our work, it is reasonable to use a <u>rate</u> of occurrence of non-accident related incidents of about 38 to 47 incidents per million vehicle kilometers traveled.

### Accident Types

Data relating to the nature of accidents and the mix of various types of accidents within the total accident picture were presented by both the Battelle Team and the Calspan Team at the

Interim Results Workshop. Calspan's data are based upon review of a national data base of accidents on the Interstate Highway System and from documents of several states; Battelle has based their figures on data from the Minnesota Department of Transportation in the Twin Cities area.

Table 4. Types of Accidents (Figures Presented at Interim Results Workshop)

| | **Battelle Team** | **Calspan Team** |
|---|---|---|
| Rear End | 51% | 39% |
| Side Swipe/Pass | 16% | 21% |
| Run-Off-Road | 18% | 15% |
| Head-On | 1% | 19% |
| Right Angle | 2% | 5% |
| Other/Unknown | 11% | |
| Backing, Etc. | | |
| Forward Impact | | |

Although there is a difference in some categories, and in some of the figures presented, it should be noted that the three types of accidents which are most subject to correction by AHS, namely, rear-end, side-swipe, and run-off-the-road accidents, show fairly good correlation. From the data presented, and considering the broadness of the data reviewed, it is concluded that the following figures are representative of that portion of the accident picture in which we are interested:

| | |
|---|---|
| • Rear End | 39% of total accidents |
| • Side Swipe | 21% of total accidents |
| • Run-off-Road | 15% of total accidents |

**Minor Incidents**

Reports from several Freeway Service Patrol programs (Los Angeles, Chicago, Minneapolis) were reviewed to determine the relative mix of the various types of minor incidents which are taking place on urban freeways today. Analysis of data presented yielded the following:

Table 5. Nature and Mix of Minor Incidents (Based Upon Service Patrol Reports).

| Nature of Incident | LA[2] | Chicago[3] | Minneapolis[4] | Average |
|---|---|---|---|---|
| Mechanical Problems | 27% | 32% | 22% | 27 |
| Flat Tire | 21% | 6% | 18% | 25 |
| Overheated/Cooling System | 10% | 12% | 6% | 9 |
| Electrical Problems | 8% | 13% | 6% | 9 |
| Out of Gas | 12% | 6% | 13% | 10 |
| Debris Removal | 3% | 6% | 10% | 6 |
| Other | 19% | 5% | 25% | 14 |

### Accident Reduction

It is concluded that virtually all of the rear-end, side-swipe, and run-off-the-road accidents (totaling about 78 percent of all accidents) would be eliminated with RSC's that feature separated, exclusive lanes and total longitudinal and lateral control. Of course, in the configurations in which some of the driving maneuvers (entering & exiting the lane) remain with the driver, one would expect that many (perhaps 50 percent) of the side-swipe accidents would remain.

### Remaining Incidents

AHS must be designed to accommodate large numbers of minor incidents, even though there might be extensive check-in systems and procedures. At best, out-of-gas incidents (10 percent) might be virtually eliminated; flat tire, cooling system, mechanical and electrical problems types of incidents (totaling 70 percent) could be reduced, but surely not eliminated; debris and other type incidents (totaling 20 percent) would not be greatly affected. Even if it is assumed that 95 percent of the incidents would be eliminated, there will still be a large number of minor incidents which will need to be accommodated in any AHS. A particular problem is anticipated with debris in the lanes; it is expected that much of the debris in the roadway will not be automatically detected by the system. In today's operation, most debris is detected by drivers, and they take steps to go around it. It is anticipated that, under an AHS operation, drivers will continue to offer the most effective means of detecting much of the debris in the roadway and of initiating action to avoid debris. This could be done while the vehicle remains under full control of the system... the driver spots the obstruction, notifies the system, and the system moves the vehicle (and following vehicles), under full control, around the debris and back into the AHS lane.

It is expected that detection of disabled vehicles will be extremely difficult; the presence of a disabled vehicle in the lane has the potential of bringing the AHS lane to a halt until the disabled vehicle is removed. Shoulders need to be provided; and the means for a vehicle to leave the platoon at any point along the route must be part of the system.

All of this speaks strongly for the driver to remain as an important element of the overall system, remaining alert to detect unusual (yet very common place) conditions and initiate notification of the system so that appropriate maneuvers, with vehicles remaining under control, can be undertaken. If the AHS is to take advantage of this visual detection, systems must necessarily include the means for the driver to initiate these actions.

### Electronic Infrastructure Required for Incident Response

AHS highway infrastructure will be designed to allow easy access and egress for emergency vehicles to respond to incidents on the automated lanes. The infrastructure design may include passing lanes or shoulders for the emergency vehicles. Other options include turnout lanes to hold vehicles while the emergency vehicles pass and breaks in the barriers to allow emergency vehicle to move between automated and manual control lanes. Infrastructure electronics design should allow emergency vehicles priority access to the automated portion of the highway. These emergency vehicles should be allowed to move at high speeds and pass traffic when possible.

The infrastructure electronics will aid in the detection of incidents in the AHS lanes. This is particularly true of RSC’s 1 and 3, which have an extensive set of infrastructure-based sensors and can easily spot stoppages in the automated lanes. For RSC 2, the vehicle-based sensors will most likely detect the incident and report it to the infrastructure. Incident information can be transferred by the local infrastructure to the regional Traffic Operations Center for initiation of the incident response by appropriate authorities.

The actual response to the incident may involve emergency vehicles, including police, fire, and medical vehicles as well as tow trucks. These vehicles can be guided along the automated lanes and allowed to pass platoons as required in order to promptly arrive at the scene of the incident. Although the space to pass must be available on the AHS roadway, the electronics will control the flow of the emergency vehicles. A description of the roadway which includes paths that can be taken by emergency vehicles to pas platoons and allowable speeds for the emergency vehicles must be available to the control software. No additional infrastructure electronics is envisioned for the incident response. The major impact is in the control software, which must have the capability to recognize emergency vehicles and to provide a safe route for the emergency vehicles to the incident.

An alternate approach to incident response is to allow the emergency vehicles to retain manual control while in the automated lanes. The operator of the emergency vehicle would be free to move across lanes and to use the shoulder as required while responding to the incident. With this approach, the vehicles in the automated lanes would be commanded to either slow down or stop while the emergency vehicle is passing, or simply not be allowed to change lanes. The control software must also prevent vehicles from initiating emergency maneuvers when the non-automated emergency vehicle is detected.

With either approach, the control software must be carefully designed in order to allow the concurrent operation of emergency vehicles with the ordinary AHS vehicles.

### Shoulders

While the presence or absence of shoulders has received some discussion in the traffic operations activities, shoulders also have maintenance implications. Consider the case of a barrier-separated AHS with one lane and no shoulder. The width of such a lane would be the width of the design vehicle plus some space for deviation from the desired path of the vehicle, but no more, and certainly not enough to perform maintenance under AHS traffic. Under such a scenario, any maintenance activity requiring stationary equipment and/or personnel in the AHS lane would require total shutdown of the AHS. In the case of non-scheduled maintenance, vehicles beyond the previous egress point would be trapped in the AHS lane.

Table 5 and its related text contain an approach to estimating the number of incident and accident events that are seen on today’s freeways. It is noted that no maintenance activities (other than debris removal and incident response) are included in that analysis. All maintenance activities would be over and above the number of incident and accident related lane blockages.

Table 5 is not intended as a rigorous justification for shoulders. It is presented to demonstrate the magnitude of non-maintenance related incident issues that can be expected, based on the assumptions used for incidents expected on AHS. The benefits of AHS shoulders accrue to maintenance related as well as incident related events in the AHS.

An AHS with shoulders has two distinct attributes that have a profound effect on traffic operations if a lane blockage is required:

- Many maintenance activities can be conducted from the shoulder while traffic passes by unimpeded.
- The shoulder can be equipped for AHS guidance, allowing operation in either or both lanes as required by traffic demand, incidents, scheduled maintenance, failure or blockage of the primary AHS lane, or emergency maintenance.

Shoulders also offer the opportunity for snow storage. In the case of a barriered dedicated AHS in the median of a multi-lane freeway, snow plowing and snow storage is an important issue. The ability to store such snow within the AHS roadway is an important attribute of the AHS shoulder. Without the AHS shoulder, snow in the AHS would have to be blown over the barrier into the adjacent conventional shoulder (if present) or lane; loaded and hauled out of the AHS; melted by heat or chemical means; or tolerated.

Blowing the snow into adjacent traffic lanes means the snow has to be handled again to allow use of those lanes. Loading and hauling is felt to be impractical for cost and time reasons. Melting is impractical for environmental and/or cost reasons. Even light snowfalls could not be tolerated without serious degradation of operations on the AHS.

Shoulders also allow emergency vehicles to reach an incident without the requirement for the emergency vehicles to be equipped. They also allow those vehicles to reach an incident scene in the event of a total shutdown (blockage) or failure of the automated lane.

Shoulders could serve as acceleration/deceleration lanes under some dedicated AHS/dedicated entry/exit scenarios. This possibility has important implications on an urban AHS with both light and heavy vehicles. The acceleration distances required for truck and bus operations are far greater than those for light vehicles. Shoulder use for acceleration could have a dramatic input on truck/transit AHS design and operation.

It must be noted that some of the justifications for shoulders have the potential to conflict with one another. For example, if there is a blockage in the primary AHS lane and its traffic is shunted onto the shoulder, that section of shoulder is not available for use as a truck/bus acceleration/ deceleration lane. Nevertheless, the consequences of infrequent and short term absence of the shoulder for such operational uses are felt to be less serious than the full time total absence of shoulder.

This and related topics are covered in more detail in Activity F — Commercial and Transit AHS Analysis.

Table 6 presents an analysis which compares AHS incidents using varying incident frequencies. The base case for incidents is based on the number of incidents experienced on today's freeways. The incident rates are based on data collected in several urban areas in the United States.

The incident rates are applied to a 16 kilometer section of AHS with an average daily traffic of 50,000 vehicles/day in each direction to obtain the number of incidents. This corresponds to a peak hour volume of 4,000 vehicles/hour/AHS lane. These volumes and lengths result in vehicle kilometers traveled (VkmT) of 1,600,000 VkmT/day. (One million vehicle kilometers traveled per day is also expressed as 1MVkmT/day.) Based on the data cited above, 12 percent of incidents are accidents and 88 percent are non-accidents.

Once the number of incidents based on normal highway rates is calculated, a range of reduction factors are applied to each separate type of incident, based on opinions from members of the research team. Each member was asked to provide a minimum and maximum achievable reduction percent for each incident type. Central tendencies were used in completing table 6. It is emphasized that these numbers are not the result of any rigorous analysis; they are simply the opinions of a range of personnel from the automotive and highway engineering fields. The "remaining number" columns represent the remaining incidents that will still have to be dealt with by the AHS.

Using the assumed achievable reductions, the 16 kilometer AHS would still have to tolerate between 31 and 96 incidents per day, most of which would involve stalled cars. Statistically, 3.1 to 9.6 of these would be in the peak hour. Even if the most optimistic aggregate assumptions are pessimistic by the factor of ten, there would still be an incident capable of lane blockage approximately every third day.

Table 6. Achievable Accident and Incident Rate Reductions on AHS.

| **Incidents (Non-Accident)** | **Rate (#/MVkm)** | **Percent** | **Number*** | **Range of Achievable Reductions (Percent)** | **Remaining Number (Minimum)** | **Remaining Number (Maximum)** |
|---|---|---|---|---|---|---|
| Mechanical Problems | 29.5 | 27 | 48 | 60–90 | 4.8 | 19.0 |
| Flat Tire | 27.3 | 25 | 44 | 40–90 | 4.4 | 26.4 |
| Overheating/Cooling System | 9.81 | 9 | 16 | 60–75 | 4.0 | 6.3 |
| Electrical | 9.81 | 9 | 16 | 40–70 | 4.8 | 9.5 |
| Out of Gas | 10.9 | 10 | 18 | 80–95 | 0.9 | 3.5 |
| Debris Removal | 6.59 | 6 | 11 | 30–60 | 4.2 | 7.4 |
| Other | 15.3 | 14 | 25 | 25–70 | 7.4 | 18.5 |
| Total Incidents | 109 | 100 | | | 30.4 | 90.6 |
| Accidents | | | | | | |
| Rear End | 5.8 | 39 | 9 | 70–95 | 0.5 | 2.8 |
| Sideswipe/Pass | 3.1 | 21 | 5 | 75–95 | 0.3 | 1.3 |
| Ran Off Road | 2.2 | 15 | 4 | 80–98 | 0.1 | 0.7 |
| Head On | 0.12 | 1 | 0 | 90–99 | 0 | 0 |
| Right Angle | 0.0 | | 0 | 90–99 | 0.0 | 0 |
| Other/ Unknown | 0.0 | | 0 | 90–99 | 0.0 | 0 |
| Backing, Etc. | 2.9 | 19 | 5 | 90–98 | 0.1 | 0.5 |
| Forward Impact | 0.75 | 5 | 1 | 60–90 | 0.1 | 0.5 |
| Total Accidents | 14.9 | 100 | | | 1.0 | 5.7 |
| **Total Accidents + Incidents** | **124** | | | | **31.4** | **96.4** |

* Number of expected incidents in the AHS section analyzed, based on rates on the conventional highway w\system.

It is concluded that an AHS without a breakdown/incident response/maintenance activity lane is not practical due to the expected frequency of shutdown. It is noted that the figures in table 6 and the discussion above are based on incidents and accidents only. Maintenance activities and weather related incidents (snow accumulation) would be over and above the shutdowns expected from incidents and accidents. Justifications for shoulders are summarized below:

- Maintenance activities can be conducted from the shoulder.
- Shoulder can be used as a lane (if AHS lane is blocked or fails).

- System can maneuver vehicles (under system control) around lane blockage (by-pass accident/incident).
- Shoulder width (space) provides location for acceleration/deceleration at on and off ramps.
- System can steer disabled vehicle (under control) onto shoulder.
- Shoulder can be used for snow storage.
- Shoulders provide access for emergency equipment.

## Task 5. Stage Definition for AHS Deployment and an AHS Evolutionary Scenario

### Introduction

It is likely that the current highway system will gradually evolve, in a planned manner, towards a mature AHS. Deployment of AHS will consist of incremental steps each of which provides additional functionality at a commensurate cost. These incremental additions of AHS functionality will lead to corresponding increases in the complexity of roadway operations. These additions will impact on all aspects of roadway operations, not just the infrastructure. This activity report addresses the issues and concerns that an operating agency needs to deal with after AHS is deployed. In this task, AHS deployment is discussed in general terms. AHS deployment has a definitive and significant impact on roadway operational analysis and many other Precursor Systems Analyses study areas, such as Activity L — Vehicle Operational Analysis and Activity H — AHS Roadway Deployment Analysis.

Many major design options and issues for operating a fully automated AHS have been identified. Design of AHS deployment sequences [5,6,7] at this early stage is a difficult task because of the large number of possible evolutionary AHS operating scenarios, the existence of many technical and non-technical issues and uncertainties, and the difficulty in predicting scenario performance and acceptability in the presence of these uncertainties.

On the highest level, the process of AHS deployment can be viewed as overcoming various difficulties in exchange for the provision of desirable AHS functions. Since what is desired of AHS is its functionality or utility (personal or societal), not the enabling technologies, this analysis stays on the functional level and discusses only the evolution of automation functions. Since the functionality of a mature AHS cannot be realized suddenly, discrete functional steps must be identified and optimized. In this task an evolutionary stage towards a mature AHS is defined as any discernible functional increment whose realization may encounter considerable difficulties requiring a significant amount of conscious effort to overcome. A good evolutionary scenario consists of stages each of which provides sufficient additional functionality that justifies the required effort to overcome the associated difficulties. Given a feasible initial AHS deployment strategy and a target mature AHS, an evolutionary scenario can be viewed as a collection of intermediate stages, possibly overlapping and parallel, connecting the two ends. Six dimensions of deployment difficulties, with emphasis on specific difficulties, have been identified.[8] They are technology, infrastructure, human factors, vehicle manufacturing and maintenance, insurance, and public will.

“Fail-safety” and “fail-softness” are assumed for the final design but not for initial deployment stages. This task seeks to identify possible stages beyond automated driving along a lane. It considers the possibility of accommodating transit vehicles on AHS. It considers not only the technology dimension (of deployment) issues but also the dimensions of infrastructure, human factors, vehicle manufacturing and maintenance, insurance, and public will.

### Six Dimensions of Deployment Difficulties

The difficulties of AHS deployment are grouped in the following six dimensions:

- Technology.
- Infrastructure.
- Human factors (user-vehicle-system interface).
- Vehicle manufacturing and maintenance.
- Insurance.
- Public will.

#### Technology

There are several major sources of technology related deployment difficulties. Four areas are discussed in the following sections.

### Accommodation Scope

Accommodation scope refers to the types of vehicles to be automated on AHS. Vehicle types include: passenger vehicles of varying size and weight, light and medium duty trucks, medium to heavy transit vehicles, vehicles with alternative propulsion systems, and possibly others. These vehicles have greatly differing acceleration and braking capabilities, range on a load of fuel (or battery charge), widths, turning radii, and other dynamic and operational characteristics.

### Automated Driving Functions

Automated driving functions are the driving tasks that are automated and refer to the degree of driving automation (or the automation capabilities). Like many other technologies, automation technologies as well as the associated manufacturing and maintenance technologies will advance incrementally. Faced with the uncertainty of market penetration, industrial investment in research, development, marketing and manufacturing may be gradual. Therefore, initial deployment is likely to consist of simple and yet useful user service. Based on earlier successes as well as public acceptance, technologies will then be further developed, refined and proven. In other words, automation functions will be incrementally deployed. This characteristic could impact the whole AHS evolution process.

Major functional steps provided by the communication technologies include: no communication capability on the vehicle, communication (i.e. information exchange) between vehicles, communication between vehicle and infrastructure, and communication between vehicles and between vehicle and roadside. Sensing functions, when combined with communication technologies, can be expected to provide the following functional increments, among others, for highway automation:

- Providing sufficient sensing information about the traffic ahead in the same lane for automated driving along a lane so that the probability of collision with a vehicle ahead in the same lane, fully or partially, is minimized.
- Providing sufficient sensing information about the traffic on the neighboring lanes as well for safer automated driving along a lane so that early warning and reaction can be made about accidents spilling over from neighboring lanes or about the potential of abrupt invasion by vehicles from neighboring lanes.

- Providing sufficient sensing information about the traffic on the neighboring lanes for safe automated lane changing.
- Providing sufficient sensing information for automated merging and diverging of traffic at specified locations.

### Technology Maturation

Technology maturation refers to the gradual process of an automation capability to physically function as conceptually intended. It also refers to fail-safety and fail-softness. Vehicle and system failures do occur and absolute fail-safety and fail softness are assumed to be reached only gradually. To ensure safe automated driving, early generations of automation-equipped vehicles may need to be inspected and maintained frequently and rigorously. Before automated vehicles are made fail-safe, driver training for handling emergency may be required.

### Functional Diversity

Automation functions will likely be deployed incrementally. Therefore, at any point in time, there are likely to be multiple classes of automation-equipped vehicles each of which is capable of a particular set of automation functions. In other words, automation functionality will likely vary from vehicle to vehicle. A stringent requirement for any stage of the AHS deployment may be to support vehicles with varying automation capabilities. For example, it may be required to support both autonomous vehicles (without communication capability) and those vehicles with the close-spaced platooning capability (including additional capability of communication).

The existence of a large variety of vehicle automation capabilities may cause difficulty in vehicle operation. For example, a platooning-only AHS is infeasible if a large percentage of automation-equipped vehicles are autonomous vehicles and do not have any communication capability. Therefore, a few distinguishable levels of automation capability may be highly desirable for AHS operation. Different automation technologies could support a common driving function. Furthermore, completely different technological approaches may provide complete automation of all driving tasks. There may even be the issue of technology diversity, although the national Intelligent Transportation Systems (ITS) architecture is expected to set technology standards for nation-wide AHS compatibility which will resolve this issue. For example, different geographical areas may implement AHS concepts differently and different vehicle manufacturers may use different vehicle automation technologies.

<u>Infrastructure</u>

There are at least five infrastructure related issues:

- Support for automated functions.
- Modification and construction of the infrastructure for AHS.
- Relationship of the modification to the evolutionary step.
- Cost and financing of the modification.
- The rate of modification.

Two guidelines for developing alternative ITS infrastructure deployment strategies are that the functionality provided at each step should be useful by itself and not require full deployment of subsequent steps and that each deployment step must have a high likelihood of acceptance by the user. The first guideline implies that even if deployment is halted, the deployed functionality should continue to provide useful service. These two guidelines are particularly important for infrastructure modification. The functional steps in AHS infrastructure deployment include:

- Providing a continuous lane on one highway with sufficient support for automated driving.
- Providing continuity from a lane on one highway onto a similar lane on another highway.
- Allowing continuous automated driving from one highway to a crossing highway.
- Creating a network of such lanes with sufficient support for continuous automated driving across different highways.
- Creating a network of such lanes with special on-ramps and off-ramps dedicated to use by automation-equipped vehicles.
- Creating a network of such lanes that are physically segregated from the manual traffic.

Human Factors (User-Vehicle-System Interface)

Included as human factors issues are:[9,10] transitional (between automated and non-automated operation) tasks, driver monitoring during automated driving, emergency maneuvering, and driver comfort. Both the drivers and the passengers must be considered users of the AHS.

Resuming manual control of the vehicle after a period of fully automated driving is a new task for drivers. It is possible that initial automation technologies, due to cost and other constraints, may not offer user-friendly transitions. Consequently, additional driving skills may be required.

Human errors account for about 90 percent of the current highway traffic accidents, and vehicle/highway automation has the potential of eliminating all accidents caused by driver errors. However, such automation requires additional equipment on the vehicle as well as on the roadside and it could introduce new kinds of safety hazards. Before the maturation of these automation technologies, the driver may be required to play an active supervisory role monitoring the operation of the automated vehicle. There are many possible AHS failure events that might require human intervention in vehicle/system operations, especially during the early stages of deployment when the automation technologies have not been perfected.

The requirement for transitional skills, the monitoring role and the emergency-handling responsibility may mandate driver training as a prerequisite to the use of the automated highway. This is not likely to entice car owners to purchase automation equipment. It is possible that, during initial deployment, only trained professionals, i.e. transit and commercial drivers with additional AHS training and credentials, would be qualified to operate on the automated highway.

Vehicle Manufacturing and Maintenance

Major obstacles to deployment include manufacturing commitment, i.e. commitment of automakers to manufacture and service automation-equipped vehicles, and the purchase and maintenance costs of automation-equipped vehicles.

The automakers will not commit their resources to making and servicing automation-equipped vehicles unless the venture is profitable. At the present time, a full-scale deployment of AHS technologies is risky. The manufacturer would prefer to start in the AHS vehicle business with a limited design modification rather than enter into a much larger but very uncertain market. Therefore, identification of an initial niche vehicle market for the automakers could be crucial. Expansion of the AHS product line also requires identification of a reliable market. Also, before wide public acceptance of the AHS, the vehicle costs, including manufacturing and maintenance, could be very high.

### Insurance

Commitment of the insurance industry to carry liability, including tort, product, and government liability and the cost of insurance will determine the nature of AHS liability insurance. Today, in many States, it is a legal requirement that each vehicle be insured for liability. This requirement will remain and perhaps become a national regulation after AHS deployment. Therefore, the interest and the attitude of the insurance industry must be taken into consideration in designing deployment strategies. Introduction of automation features may be delayed until rigorous safety requirements have been met by the new features and the previous deployment stage has been proven safe. Frequent and rigorous vehicle inspection and maintenance may also be required.

If liability insurance does become available, the premium and/or the deductible may be too high for individual owners of automation-equipped vehicles to afford. However, fleet operators could afford the insurance if the AHS reduced their operating costs and the result was a net profit. One alternative to liability insurance for large businesses or government agencies would be self- insurance.

### Public Will

User service and cost, user safety and perceived safety, societal service and cost, and environmental impact are associated with the public will to establish an automated highway system.

The automated highway system program must win the acceptance of various special interest groups and the general public. It could win their support by offering products that appeal to them, particularly in the areas of user service, safety, perceived safety, comfort, convenience, reduced travel delays, and lessened environmental impact. However, that may not be sufficient. It will be necessary to be forthright with eventual customers about benefits and drawbacks of new technologies and also sensitive to public perception of new technologies (which may be different from reality).[11]

It may be that the general public would reject revolutionary deployment of an AHS, but would accept it if it were introduced incrementally. Stages of deployment must be carefully determined and implemented so that interest, trust, and support by the general public can be cultivated.

### A Stage Definition Approach

The definition of an AHS deployment stage, i.e. the criteria for judging whether an incremental step in AHS deployment deserves to be designated as a deployment stage, was given earlier in this task. The utility of an automation function is judged according to public will, i.e. the desire of the driving population and the general public to support that function. The possible difficulties include those in the six dimensions discussed above. The smallest functional increment that could incur any type of difficulty that required conscious effort to overcome should be sought. Some stages may be skipped if the difficulties turn out to be minor and can be easily overcome. Using this methodology, no major stages will be neglected.

Sequencing deployment stages is difficult, and timing of deployment stages is even more difficult. Deployment of AHS functions shall be discussed without specifying the enabling technologies, since many alternative enabling technologies exist.[12] The functional approach is also justified by the fact that highway automation is needed to serve society's transportation needs, and those needs are usually translated into vehicle and highway functions, without reference to the enabling technologies.

In defining a deployment sequence, identifying the very first step, i.e. the first user service involving fully automated freeway driving (hands-off and feet-off), is particularly important and difficult. This implies that there are many factors that constrain the initial deployment and there may be only a few choices for the first stage. In the approach described here, first a good initial AHS deployment target (a target is defined as an initial, non-AHS transportation system) is identified, and then the intermediate stages between the initial target and the mature AHS system (there are many possible mature AHS systems) are built up. A good initial AHS target should not constrain future development so that some alternative AHS cannot be achieved because of the initial deployment.

### An Evolutionary Scenario For AHS

The evolutionary scenario consists of the intermediate steps connecting the initial deployment target and the mature AHS. The freeway shuttle van service is the initial AHS deployment target chosen for this analysis task.

#### A Mature AHS

The key features of the mature AHS are grouped in six different deployment difficulty categories as described above.

Multiple vehicle types are supported on the mature AHS. A vehicle-centered platooning technology is assumed. Support from the infrastructure may be required but the actual requirement depends on the actual automation technology. Two major groups of vehicle automation capabilities exist: platooning-equipped vehicles and non-platooning equipped vehicles (loners). When a vehicle travels alone without being part of any closely-spaced platoon it is said to travel in solitude.

Automated traffic is physically and completely separated from the manual traffic. The AHS consists of a dedicated network of automated highways that is at grade level, occupying inner lanes of highway, and basically within the current right-of-way. There are no barriers between any two automated lanes.

Special on-ramps and off-ramps (in addition to the current manual on-ramps and off-ramps) provide direct access to and egress from the automated lanes via the highway median. Special highway-to-highway connector ramps (in addition to the current manual connector ramps) provide direct connection between automated lanes. There is no need for real estate for check-in facilities at entrances.

An automated highway may have multiple automated lanes, and the number of automated lanes varies with highway section. On those automated highways with only one automated lane (the left-most lane), all types of automated vehicles share that lane, and platooning-equipped vehicles travel in “spontaneous platoons.” On two-lane automated highways, the second automated lane (i.e. the second lane from the median) is dedicated to platooning-equipped automobiles, while the first automated lane (i.e. the left-most lane) is shared by all vehicle types. In the second automated lane on sections of the automated highway with high density traffic flow and only during times of peak demand, vehicles travel in closely-spaced platoons. In the first automated lane, all types of automated vehicles travel only without close-spaced formations. Automobiles and transit vehicles traveling on the first automated lane travel in solitude, not in platoons. In the following illustrative evolutionary scenario, the focus is on a mature AHS with two automated lanes.

The driver on an automated highway may choose whether or not to platoon. If the platooning option is chosen and the infrastructure platooning conditions are met, the vehicle will be automatically driven into the second automated lane and will join a platoon. Otherwise he or she will travel on the first automated lane throughout the trip.

Vehicle manufacturers can and do manufacture affordable, reliable and fail-safe automation-equipped vehicles. Such vehicles are maintained properly, conveniently and affordably.

Liability insurance is available at an affordable rate.

The system is accepted and supported by the general public.

In the case of the evolution scenario presented in this task, automation of transit vehicles could be inevitable. Four reasonable assumptions made as part of the scenario support this statement:

- In the early stages there will not be sufficient demand or public will to justify the dedication of one lane for the exclusive use of automated vehicles. Therefore, automated vehicles will share the high occupancy vehicle (HOV) lane, including the HOV highway-to-highway connector ramps, assuming the lane is available and mixing of traffic modes is safe.
- When the demand becomes sufficient, the left-most lane is dedicated to automated traffic.
- At least one set of highway-to-highway connector ramps directly connecting the left-most lanes on any two crossing highways is constructed for each highway-to-highway interchange.
- It is not practical to construct two independent sets of highway-to-highway connector ramps, one for dedicated automated traffic and the other for HOV traffic.

On the basis of these four assumptions, when the demand for automation becomes sufficient to justify the dedication of one automated lane, the HOV highway-to-highway connector ramps will be dedicated to automated traffic and the HOV users will be unable to use any direct highway-to-highway connector ramps. Moreover, if special access/egress ramps which directly connect the left-most lane to the city streets are also built for the use of both modes at an early deployment stage, then HOV users would also lose access to those ramps. This would be unpopular and not likely to happen unless a significant percentage of the automated traffic were automated transit vehicles. In short, transit vehicle automation could be crucial for the eventual success of automobile automation because, without such automation, the conversion of HOV facilities into automation facilities may encounter significant public resistance.

## Twelve Evolutionary Stages

The evolutionary scenario consists of 12 sequential stages with possible overlap between consecutive stages. Each stage represents an increment in AHS functionality that is summarized by the title of the stage. Only the differences between any two consecutive stages will be described in the text, with the exception that, for the initial and the final stages, the complete scenario will be described. In this example, the automation technology is vehicle-centered and the infrastructure plays a supporting role. The degree of automation is determined from the available automated functions together with the role played by the driver. In the initial stage, driving along a lane is safely automated in the absence of vehicle failures and sudden intrusion by other vehicles or foreign objects.

### Stage 1 — The Initial Deployment Strategy

The initial stage consists of automated freeway shuttle vans and mini-buses supervised by professional drivers. The vehicles cruise in mixed traffic on an HOV lane.

The automation target at this initial stage is the van and mini-bus instead of the automobile. These transit vehicles provide a freeway shuttle service between two activity centers that are near freeway entrances and exits; e.g. the airport and a metropolitan downtown area. Driving along an HOV lane is automated. (The enabling technology varies. It could include some roadside sensing and intelligence. It could also reside completely on the vehicle.) The vehicles and the roadside system, if any, are not fail-safe. A professional driver with special training is in the driver’s seat at all times to perform:

- Manual driving on city streets.
- Manual driving from freeway entrance to the HOV lane next to the median.
- Transitional task from manual driving mode into automated driving mode.
- Supervision during automated driving.
- Emergency handling.
- Transition from the automated driving mode back to the manual driving mode.
- Manual driving from one highway to a crossing highway (by crossing the non-HOV lanes on each highway).

Automation technologies include self-lane safety sensing, automated vehicle following, automated speed holding, and automated lane holding. Vehicles are frequently inspected at the fleet operator's maintenance facility (and perhaps have continuous self-monitoring) so that there is no need to have a check-in facility at an entrance. Fleet operators bear the high initial cost of insurance. This type of shuttle service expands as infrastructure modification continues.

### Stage 2 — Construction of Highway-to-Highway HOV Connector Ramps and the Equipping of HOV lanes for Automated Driving

The major efforts in this stage include the construction of HOV highway-to-highway connector ramps and the equipping of a network of HOV lanes for automated driving. Preparation for deployment of a network of HOV lanes sufficiently instrumented for automated driving is the goal. A direct benefit is minimization of HOV traffic delays, which would encourage more ride sharing and increase the demand for freeway shuttle service.

At this stage, lane changing has not been automated, and a highway change requires take-over of manual control by a professional driver before diverging and manually driving over the HOV connector ramp and into the HOV traffic on the crossing highway. To enable continuous automated highway driving through an automated highway-to-highway interchange for approaching highway traffic from all four directions, eight additional highway-to-highway connector ramps are required.[13] Construction of these ramps will require widening of the current highway to allow for through traffic. Width to accommodate two additional shoulders will be added to the overall highway dimension. High speeds are anticipated on these ramps, so curve radii must be greater than present ramp values to properly address stopping sight distance requirements. The cost for a single interchange will be high.

During construction, traffic control is essential. A temporary reduction in the existing lane and shoulder widths may be required. This would allow widening of the existing highway and would provide the desired work zone for the implementation of the center lane HOV ramps. In both cases, temporary concrete barriers or barrels may be used to direct traffic. Left shoulder widths and lane widths may be reduced temporarily. The lateral reduction will lessen driver comfort which will cause the speed at which the driver travels to be lowered. A loss in highway capacity will occur. Highway capacity is also a function of allowed driver velocity with regard to stopping sight distance, which will be altered by the reduction in width. Should this distance be reduced beyond acceptable limits, the allowed speed must be lowered.

### Stage 3 — Fail-Safe Vehicle Available

At this stage, the technology for automated lane cruising has matured and become fail-safe. If a vehicle has fail-safe automated functionality, the manual controls become non-responsive during automated driving. Driver intervention during automated driving is allowed when exiting the automated lane and in specified emergency situations requiring approval from the vehicle control system. The professional driver is no longer required. The user-friendliness of the user-vehicle-system interface during transitional tasks is also achieved in this stage.

### Stage 4 — Automated Infrastructure Network Completed

Modification of HOV lanes for automated travel and construction of highway-to-highway HOV connector ramps are completed throughout the highway network. With this extensive HOV network available, automobile owners can use the automation feature continuously during freeway trips. Because of the fail-safe design and technological maturation of the vehicle, automobile check-in would only require status reporting by the vehicles to the roadside, and there would be no need for any additional real estate for check-in sites.

Stage 5 — Dedication of one Automated/Transition Lane for Transition and Automated Driving

When the demand for automated driving has reached a certain threshold, one lane can be dedicated to automated vehicles. Vehicles are not equipped with automated lane-changing capability. They enter and exit the automated lane manually and then transition into the automated driving mode. Diverging and merging at the special highway-to-highway connector ramps is still manual. The adjacent lane becomes the new dedicated HOV lane and is equipped for automated driving. Because the left-most lane is now the dedicated automated lane, there are no direct HOV highway-to-highway connector ramps. This is a potential social issue. Physical barriers are erected at the interchange, particularly at the merge point, to prevent lane changing and possible intrusion by manually-driven vehicles.

If the same number of non-AHS and non-HOV vehicles must be accommodated by the new design, the addition of a lane will be required. During construction of the additional lane, temporary inconvenience similar to that described in Stage 2 would occur. Once construction of this lane has been completed, the existing lanes can then be restriped to accommodate the HOV lane. Installation of permanent barriers will require a work zone width of at least 2 meters. Striping of the proposed HOV lane, barrier material delivery, installation of roadside automated driving equipment, etc. would result in a temporary capacity loss.

Stage 6 — Automation of Lane-Changing into the Automated Lane

At this stage a certain percentage of the vehicles are equipped to change lanes automatically. Those vehicles can transition between the automated and manual driving modes on the HOV lane and then are driven under automatic control onto the automated/transition lane. Those not so equipped are first manually driven onto the automated/transition lane and then transition into the automated driving mode. This automated lane-changing capability, which is crucial to the success of AHS deployment, evolves from the automated lane-cruising capability and is fail-safe, as was the previous capability.

If the transition tasks are user-friendly, transition should take very little time, and only a small fraction of vehicles traveling on the automated/transition lane are in the transitional process at one time. A vehicle can begin a lane-change maneuver into the automated/transition lane only after it has successfully negotiated with any nearby vehicles adjacent to the intended gap. It is assumed that vehicle-to-vehicle negotiation through communication is required for safety.

Negotiation is not possible during lane-changing out of the automated/transition lane into the HOV lane because not all vehicles on the HOV lane are automation-equipped. Before a vehicle can begin the lane maneuver from the automated lane into the HOV lane, it should notify and obtain consent from any nearby adjacent vehicles in the automated/transition lane. If a vehicle detects a safety hazard while changing lanes from the automated lane into the HOV lane, its abort will be safer because the adjacent vehicles are aware of the lane change. A vehicle cannot enter or vacate the automated lane until any nearby adjacent vehicles have already transitioned into the automated driving mode. Because few vehicles are in the transitional process at any one time, the wait to transition should be brief.

### Stage 7 — Elimination of Transitions in One Automated Lane and Automation of Diverging/Merging at Highway-to-Highway Connector Ramps

In this stage, the automated/transition lane becomes an automated lane, and manual driving is no longer allowed. Only those vehicles equipped with the lane-changing capability can use the automated lane. Those not equipped can only use the HOV lane, which is an instrumented lane, for automated driving. These vehicles have no access to the automated highway-to-highway connector ramps.

Communication between vehicles during traffic merging is necessary for safety. Negotiation is possible because all vehicles in the automated lane are under automated control at all times. Such negotiation may not be possible if transition is allowed on the left-most lane, i.e. if the lane is still dedicated as an automated/transition lane. If a vehicle is approaching the left-most lane of a crossing highway from a highway-to-highway connector ramp but some vehicles near the merge point are still under manual control, negotiation is impossible. Merging cannot wait as long as a regular lane change can, because it needs to take place at a specified location. Because automated merging is supported only when both traffic streams are under automatic control, this risk is avoided.

The automated diverging/merging capability enables continuous automated driving from end to end across different highways. Because all the vehicles on the automated lane are under automatic control, automated diverging off to the automated connector ramps and automated merging back into the automated traffic can be made safer than otherwise.

Functional upgradability from the automated lane-changing capability to the automated diverging/merging capability is important. At this stage, functional diversity encompasses non-fail-safe automated lane-cruising transit vehicles and automobiles, fail-safe automated lane- cruising transit vehicles and automobiles, fail-safe automated lane-changing transit vehicles and automobiles, and fail-safe automated diverging/merging (location-constrained lane-changing) transit vehicles and automobiles.

Stage 8 — Construction of Automated On-Ramps and Off-Ramps with Barriers at Busy Locations

As demand increases, construction of automated on-ramps and off-ramps connecting city streets directly with the automated lanes adjacent to the median, especially at busy locations, begins. This supports fully automated driving from any automated on-ramp to any automated off-ramp. Vehicles equipped with automated diverging/merging capability access and egress the automated lane through the automated ramps, where available. Physical barriers separating the automated lane from the HOV lane (transition lane) are erected for safety at the merge point where the automated lane merges with the on-ramp. Vehicles without automated diverging/merging capability can only access and egress the automated lane at locations where barriers are absent. Automated lane-cruising vehicles can use the HOV/transition lane only.

In order to maintain through traffic at each of these ramp locations, the existing highway alignment must be revised around the ramp/obstruction. As vehicles will still be traveling at high velocities, curve radii used in the development of the revised alignment must be large. The length of this revision will depend on the length of the ramp. This will depend on the resulting acceleration/deceleration requirements, which are based on velocity differences at the intersection point. Attention should also be given to existing roadway structures. As the width of the highway increases, so does the encroachment on existing structure abutments. At some point the existing structure will not be able to span the required distance and the structure must be replaced. Existing pier locations, with respect to the proposed alignment, could dictate replacement. Furthermore, if the check-in facility is to be placed on the overpass structure, assuming that there is not enough width to accommodate the facility, the structure must then be widened. Shoulder and construction traffic control requirements will be similar to those listed in Stage 2.

Although the cost of a highway-to-city-street interchange may be moderate, there may be a large number of such busy locations, implying the necessity of a large total capital investment and potential financing problems. The rate of construction could be slow.

### Stage 9 -— Segregation of Automated Traffic from Manual Traffic for Safer and High-Speed Automated Driving

This stage is marked by the erection of physical barriers between the automated lane and the HOV lane to segregate the automated lane from the manual traffic. This is motivated by safety, high-speed automated driving, and an unmanned transit vehicle operation on the automated lane. The possibility of spill-over of traffic accidents from the manual traffic is minimized. Therefore, given the fail-safe feature of the automated diverging/merging vehicles, the previous virtually care-free driving (the only traffic monitoring by the driver during automated driving was for the possible spill-over of accidents) is upgraded to completely care-free driving.

Such segregation establishes a separate highway network system, with convenient access from and egress to the network for manual traffic. Only those vehicles equipped with automated diverging/merging capability can use the segregated automated lanes. Other automated vehicles can still use the HOV lane for automated driving, but cannot access the automated highway-to-highway connector ramps.

The separation of the AHS and HOV lanes may require the addition of two shoulders to the existing highway configuration, one on each side of the barrier. Temporary precast concrete barriers are suggested for this barrier. As widening of the existing highway continues, so does the importance of the shoulder edge profile.

### Stage 10 — Two Automated Lanes

As demand continues to increase, a second automated lane is dedicated. This will increase the capacity and accommodate higher speed on the new automated lane.

If the same number of non-AHS lanes is desired, the existing highway must be widened again. Shoulders constructed in an earlier stage must be shifted. Either temporary barriers must be reset or permanent barriers installed at the new location.

### Stage 11 — Automobile Platooning on the Second Automated Lane for Higher Capacity

Addition of a second automated lane continues. Where higher capacity is needed, automobile platooning is introduced. Automated lane-cruising or automated lane-changing loner vehicles, fail-safe or not, cannot use the automated lanes and have no access to any direct automated highway-to-highway connector ramps. All automated diverging/merging (fail-safe) vehicles can use the first automated lane, which interfaces with the automated on/off ramps. Automated diverging/merging platooning-equipped vehicles may use the second automated lane at any time. At congested locations and during periods of congestion, only the platooning-equipped automobiles can use the second automated lane, and they travel in platoons. On those sections where only one automated lane is available, and when higher lane capacity is needed, “spontaneous platooning” may be required of the platooning-equipped automobiles.

Stage 12 — A Mature AHS

By now, the evolution has reached the mature AHS described previously.

## An Evolutionary/Revolutionary Approach

A hybrid evolutionary/revolutionary approach is described below. This brief description serves as a contrast to the evolutionary deployment approach described above.

The system would begin with the construction of a dedicated facility in a congested area. This would help ensure the existence of the demand needed for this scenario's success. The dedicated facility would be built in the median of an existing freeway without taking away an existing lane.

Automated or partially automated buses and vans would be authorized to use this dedicated facility. At the earliest stages of deployment, the fleet of equipped single occupancy vehicles (SOV’s) would be very small, so these vehicles would also be allowed to utilize the facility. Subsidies of HOV’s and possibly SOV’s would be needed at this stage to ensure the presence of a fleet large enough to utilize the facility at a significant fraction of capacity.

The evolutionary aspect of the scenario is that the AHS would operate at high speeds, offering the incentive of high speed, dependable travel to potential users. Increasing demand for equipped vehicles would lower the cost, further increasing demand. As demand increased, higher density operations would evolve on the AHS. Eventually the system would become a platoon operation.

## **Conclusion**

The process of AHS deployment can be viewed as the action of overcoming various difficulties in exchange for the provision of desirable AHS functions. An evolutionary stage towards a mature AHS was defined as any discernible incremental functional step whose realization may encounter considerable difficulties requiring a significant amount of conscious effort to overcome. A good evolutionary scenario consists of stages each of which provides sufficient additional functionality that the required effort to overcome the associated difficulties is justified. Six dimensions of deployment difficulties — technology, infrastructure, human factors, vehicle manufacturing and maintenance, insurance, and public will — were identified.

Initial AHS market penetration could be the most difficult stage of all. Comparison of the desirability of the different mature automated highway systems is also difficult. Given a feasible initial AHS deployment strategy and a target mature AHS, an evolutionary scenario can be viewed as a collection of intermediate stages, possibly overlapping and parallel, connecting the two ends. An evolutionary scenario consisting of a sequence of stages connecting the two ends was defined. The functional increments and the difficulties associated with each step were also discussed.

From a feasibility standpoint, the design should be developed to its final configuration to determine the overall construction impacts and right-of-way requirements. Reconstruction of existing structures or an entire highway section could prove to be costly.

Only one mature AHS was studied in this task; however, other equally valid AHS's could have been evolved if conditions were altered. For example, if provision for dedicated automated on-ramps and off-ramps was infeasible because of a lack of available land, design complexity, or high cost, then an alternate mature AHS could be a non-segregated one that has two automated lanes without dedicated automated on-ramps and off-ramps. In such a system, platooning as well as unmanned transit vehicles could be supported on the left-most lane while the second left-most lane could be used to accommodate loner automated vehicles only.

Because of the large number of possible mature as well as evolutionary AHS scenarios, judgments based on preliminary analysis may have to be made to gauge the desirability of the functions provided by the individual stages, measure the associated difficulties and the required effort, and then select a manageable collection of evolutionary scenarios. Detailed analyses, evaluations, and comparisons can then follow so that a small number of superior scenarios can be identified.

## Task 6. Redundancy Requirements

### Fault Tolerance

There are differences among the functional requirements defined for the three representative system configurations (RSC). If the translation of the requirements to designs is done correctly, then the differences in requirements are preserved in the designs. The designs can also differ between and within RSC’s as a result of design tradeoffs, such as hardware versus software implementation of algorithms, or alternatively, acquisition of commercial off-the-shelf components versus development of custom components.

One of the candidate AHS requirements is that of fault tolerance: The AHS shall prevent faults from causing system failures. A related requirement is that of graceful degradation of service: The AHS shall provide for degraded modes of service in response to faults. That is, in the event of a fault, the AHS shall continue to operate at a reduced level of service. Fault-tolerance techniques can be used to implement degraded modes of AHS operation.

From an institutional perspective, frequent or prolonged disruption of AHS service can affect, for instance, public acceptance of AHS, especially if the failures resulting from faults are catastrophic in nature. Likewise, if the AHS is shutdown each time a vehicle or the infrastructure detects a fault, even if the fault is benign, then AHS throughput can be severely affected. After AHS deployment, in addition to maximizing AHS throughput while ensuring safety, TOC’s major responsibilities also include evicting/removing faulty vehicles and clearing up incidents. Fault-tolerance techniques can also be used to reduce the burden on the TOC staff.

From a system safety vantage, when an automated vehicle experiences a fault, that vehicle needs to continue to operate until it no longer poses a hazard to the vehicle’s occupants or other users of the AHS. In analyzing and specifying the AHS fault tolerance requirement, the goal of producing a safe AHS should not be confused with that of producing a reliable AHS. The overriding concern in system safety is the prevention of hazards rather than faults; that is, system safety involves managing the risks associated with AHS mishaps-mishaps result from some combination of system hazards and environmental conditions. For example, an unreliable vehicle control system, in conjunction with environmental factors (e.g., a wet road surface or heavy traffic volume), can result in an unacceptable risk. If, however, the vehicle with the unreliable (i.e., faulty) vehicle control system is denied entry at check-in, then a mishap due to a vehicle control system failure is avoided.

Although the requirement for fault tolerance transcends all three RSC's, its implementation can differ between and within RSC's. To illustrate this point, we compare the RSC's in terms fault tolerance for the following three functions: (i) sensing, (ii) data fusion, and (iii) communication. See table 7.

Table 7. A Relation among Representative System Configurations.

| **Function** | **RSC 1 Infrastructure Platoon Control** | **RSC 2 Autonomous Vehicle Platoon Control** | **RSC 3 Space/Time Slot Control** |
|---|---|---|---|
| Sensing | Infrastructure-Based | Vehicle-Based | Infrastructure- and Vehicle-based |
| Data Fusion | Infrastructure-Based | Vehicle-Based | Infrastructure- and Vehicle-based |
| Communication | Infrastructure-to-Vehicle | Vehicle-to-Vehicle | Infrastructure-to-Vehicle |

<u>Sensing Function</u>

Let us begin our analysis with the sensing function. In RSC 1, sensing is performed by sensors located in the infrastructure. One means of achieving fault tolerance in this scenario is to provide for static or dynamic sparing of infrastructure-based sensors, in the event that one or more of the primary sensors fail. This hardware fault-tolerance technique can be costly to implement, both in terms of the procurement of additional sensors, structural overhead, and operational time overhead. For instance, the minimum number of sensors and minimum level of communication bandwidth required for effective and efficient vehicle control is high for RSC 1 in comparison to the other RSC's, even before accounting for the overhead associated with fault-tolerance techniques. Similarly, from a technical perspective, there can be constraints on the placement of sensors along the roadway due to, for example, potential inter-sensor electrical interference or ease of maintenance. Hence, the physical constraints implicit in the design of a sensor affects the extent to which each type of hardware fault-tolerance technique can be used with that type of sensor.

Sparing of sensors is also a candidate technique for use in RSC 2. However, sparing of vehicle-based sensors does not mitigate the effects of single points of failure, such as a complete failure of the vehicle electrical system, assuming that there is only one electric power source onboard the vehicle and all of the sensors are powered by electric current. Two ways of resolving this particular single point of failure are to provide for (i) dynamic sparing of the vehicle electric power generation system (e.g., a primary and backup alternator) and (ii) N-modular redundancy of the power generation system. Both of these alternatives are costly in terms of, for instance, adding to the weight of the vehicle. Also not that if the sensors or their power sources have design defects in common, neither redundancy nor diversity will afford an improvement in fault tolerance.

In RSC 3, the sensing function is divided between the infrastructure and the vehicle. Redundancy is implicit in the system design if the same sensing function is performed both by the vehicle and the infrastructure. Further, the power source and communications links can be diverse in such a scenario, adding to the level of fault tolerance; for instance, the infrastructure and vehicle can have separate (i.e., physically isolated) and diverse power sources. Likewise, the vehicle-based and infrastructure-based sensors can turn out to have independent design defects.

### Data Fusion Function

As in the case of the sensing function, redundancy and diversity can be used to improve the level of system fault tolerance in terms of the data fusion function. Suppose, for the purpose of this analysis, that data fusion is performed in software. The characteristics of software differ from those of hardware with respect to faults. hardware reliability is commonly framed in terms of its remoteness and mission life. For instance:

- Remote hardware, such as sensors embedded in the AHS roadway, can be difficult to replace when they fail.
- AHS hardware deteriorates over time, such as sensors experiencing drift, or a vehicle control system computer’s disk storage unit media surface wearing out.

In contrast, software can be remotely accessed and does not wear out. As a result, software reliability tends to be couched in terms of operational consequences of software faults and the cost to fix faults (i.e., software maintenance).

Two component properties for software fault tolerance that have been forwarded by the software engineering community are:

- Self-protective — Each software module must insulate itself from the behavior of other modules that use it.
- Self-checking — Each software module must detect and signal any errors it makes on its own so that faults do not “silently” affect other modules that use it.

For example, in terms of fusing data, the fusion task can be functionally decomposed into subtasks, such as:

- Synthesis of track data.
- Identification of target (i.e., a vehicle).
- Confirmation of target.
- Assignment of one or more sensors to track the target.

Following the two rules set forth above, each of the software modules corresponding to these four tasks can be organized such that requests from one module to another must be performed through a common interface, prohibiting direct access to the internals of a module by other modules.

In addition, N-version programming can be used in support of the module self-checking function. However, studies have shown that programmers tend to make the same types of errors, and therefore variants of the same algorithm can contain common design faults.

Software reliability can be further enhance by via the use of a fault-tolerant operating system and database management system. For example, an operating system that supports heavy weight tasking will continue to operate when a process fails. Similarly, database management systems can provide for roll back and recovery systems for use in case one or more transactions abort, or in the case when volatile or stable storage mechanisms fail.

### Communication Function

In RSC 2, communication between the lead car and the other vehicles in the same platoon is critical. From the perspective of longitudinal control, the platoon leader coordinates the spacing, acceleration, and braking of platoon members. Thus, if communication fault occurs in which the lead vehicle and one or more of the other platoon members loses communication with each other, some means of restoring the communication is needed, or alternatively, some protocol for spacing the platoon members further apart until they can exit or until they can resume communication needs to be in place. Since there is no support from the infrastructure in this particular RSC, fault tolerance of the communication hardware and software must be achieve solely through the components onboard the vehicles.

In contrast to RSC 2 both RSC 1 and RSC 3 involve communication between vehicles and the infrastructure, so designs for fault tolerance for these two RSC's can include both infrastructure and vehicle based component redundancy and diversity techniques. For instance, error-correcting codes can be implemented in hardware or software, and at the infrastructure or vehicle level. Error-correcting codes can be used to detect and resolve communication transmission errors. Note that the encoders and decoders themselves cannot be assumed to be defect free.

### Levels of Fault Tolerance

No system is completely fault tolerant; that is, no system prevents all possible faults from causing failures. Except for trivial systems, it is theoretically impossible to make a system completely fault tolerant since the inputs to a system from the environment are outside the engineering design space (i.e., the environment cannot be controlled), and even if it were possible, the cost of doing so would be prohibitively expensive.

What can be done in the case of an AHS is to begin by listing the type of design and physical faults that we want the AHS to tolerate. For example, AHS software can:

- Attempt to perform an illegal operation.
- Take an incorrect path as it progress through a computation.
- Produce an incorrect result.
- Exhibit some combination of performing illegal operations, taking incorrect paths, and producing incorrect results.

Software verification and validation techniques can be applied to detect software and hardware errors (i.e., an error is a manifestation of a fault in the system) in support of resolving errors before a system is made operational. this process effectively reduces the number of faults that need to be tolerated. Note that unanticipated design faults can be difficult to uncover, and physical faults become visible after a system is put into operation.

Following the application of verification and validation techniques, the remaining list of faults to be tolerated can be ordered, and specific fault-tolerance techniques assigned to each of the fault types. Table 8 lists the fault-tolerance techniques discussed in the case study of RSC functions.

Table 8. Partial Listing of Hardware and Software Fault Tolerance Techniques

| **Hardware** | **Software** |
|---|---|
| Stand By Sparing | Recovery Blocks |
| N Error-Correction Coding | N Self-Checking Programming |
| N-Modular Redundancy | N-Version Programming |

The ordering and assignment can be based on criteria such as the criticality of a function affected by a particular type of fault and the cost-benefit ratio of applying a particular technique for a specific type of fault. The costs associated with each of the techniques can be compared in terms of their distribution across the AHS life-cycle.

The cost to implement the techniques listed in Table 8 varies from one technique to another. For instance, error processing in N self-checking programming techniques can be performed through either detection by acceptance tests or detection by comparison, with the judgment on result acceptability as absolute with respect to the specification and relative on variant results, respectively. Both error processing regimes entail a parallel execution scheme and terminate execution of the function during the time interval over which result switching takes place. One example of the difference in cost between these two types of N self-checking programming techniques is the number of variants required to tolerate *f* sequential faults, as shown in table 9; that is, there are costs associated with developing and maintaining *f* variants of a software program.

Table 9. Relationship Between N Self-Checking Programming Method Error-Processing Technique and Number of Variants to Tolerate *f* Sequential Faults

| **Error-Processing Technique** | **Number of Variants to Tolerate *f* Sequential Faults** |
|---|---|
| Detection by Acceptance Tests | $f + 1$ |
| Detection by Comparison | $2(f + 1)$ |

In addition, there are costs associated with verifying that the behavior of the variants is not correlated in terms of design faults. An example of structural overhead entailed by error detection by comparison is the requirement for result switching and comparator mechanisms. Examples of operational time overhead entailed by error detection by comparison are:

- Comparison execution.
- Variant execution synchronization.
- Result switching.

There is a performance cost associated with the execution of these processes.

### Summary

Design tradeoffs will need to be weighed relative to the level of fault tolerance the AHS is required to provide. These tradeoffs involve both institutional and technical issues, and should be viewed from the perspective of the entire AHS life cycle. Moreover, the characteristics of software and hardware differ with respect to system reliability. These differences need to be taken into consideration in partitioning responsibility for system fault between hardware and software.

## Task 7. Interviews with Operating Agencies

In keeping with the approach that AHS can be considered an evolutionary step from today’s Traffic Operations Centers (TOC’s), interviews were conducted with responsible personnel from several TOC’s. The interviews were conducted informally with members of the Transportation Research Board Committee on Freeway Operations.

A list of personnel and agencies interviewed is found at the end of this task report. It was agreed before the meeting that individual comments would not be for attribution. It should also be noted that the comments have been paraphrased by the research team; however, every attempt has been made to accurately report the interview findings.

Before beginning the interviews the participants were briefed on the AHS; however, all participants already were somewhat informed on the program.

The comments of the agencies are summarized below. The comments following the bullet items are conclusions and recommendations of the researchers if the bullet items are not self-explanatory.

- The “chicken and egg” topic came up. One agency suggested a deployment option where all vehicles would be buses, van pools, etc., owned or subsidized by the operating agency. A long haul operation with truck emphasis may be more feasible initially.
- A dependable or built in revenue source will be needed before AHS can become a reality or before adequate staff can be kept. Privatization was mentioned. Equity is an issue: will AHS be perceived as benefiting the well-to-do only?
- Chief Administrative Officers from the States need to be kept abreast of the project and its implications to operating agencies.
- A high level of communication between HQ and Districts in the States will be required during the development of AHS if the end users (the Districts) are to be kept well informed on the research.
- Concern was expressed that AHS will hurt (detract funds and attention from) other ITS activities that were perceived as more worthy uses for available funding. AHS should be considered only to the extent that other elements of ITS are incremental parts of AHS.
- In discussions of check-in requirements, statements were made that AHS will be used only if it is perceived as convenient. How much driver information will be obtained by the agency? (Privacy issue) How much responsibility should the agency assume, and how much should remain with the driver?
- Concern was expressed that the volumes envisioned for AHS would overload the surface street system.

- It was not evident to the agencies that the AHS program recognizes the importance of the requirements of other parts of ISTEA or of air quality legislation, particularly in non-attainment areas.
- The operators urged the researchers to treat maintenance of AHS roadway elements as equally as important as operations.
- Who represents the agencies in the RSC decision? The smart car/dumb infrastructure vs. dumb car/smart infrastructure is a fundamental issue to the agencies. The agencies represented expressed the need to be in on the decision.
- The issue of agency liability was discussed, such as agency's vs. driver's responsibilities. The added responsibility of the lead vehicle in a platoon was discussed.
- The agencies tend to feel that the initial deployment of AHS may be in a rural environment. The gradual and incremental deployment of AHS is seen as a more realistic scenario.
- The agencies see present-day traffic operations centers as being reactive (e.g. detect a problem and respond to it), whereas an AHS operations center would have an active, real time operating role. Such an operation would have different personnel requirements.

The researchers appreciate the input of the participants and believe their comments are valuable to the project.

The personnel who participated are considered responsible and well informed individuals. As TRB Freeway Operations Committee members or friends of the committee, they are innovative and well informed. Their comments were well thought out and their questions to the point. It is therefore a conclusion of this task that TRB, and especially the Committee on Freeway Operations or a subcommittee thereof, be given the opportunity to have an official role on future AHS work.

In so doing, the consortium will have on its team the group of highway personnel who would be impacted the most by AHS development. As evidenced in the comments, these personnel are cognizant of many issues, predominantly administrative, that could impede AHS progress if not addressed. As operators of existing systems, they have the technical and administrative knowledge to deal with these issues. It is the feeling of the researchers that the Committee would be an extremely valuable asset for the program in its dealing with highway infrastructure issues.

The following is a list of agencies and personnel represented in the interviews:

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## Task 8. The Role of the Driver

The role of the driver is considered a very important element of all subsequent phases of AHS development. By allowing as much responsibility as feasible to remain with the driver, new responsibilities and liabilities for operating agencies can be minimized. In the early stages of the evolutionary scenario described in Task 5 of this research project, the driver is a professional driver and is required to closely monitor his vehicle and surrounding traffic at all times. The subsequent stages progressively increase the amount of automation. Nevertheless, regardless of the degree of automation, it is felt that there will always be some events that only a driver can detect. It has been stated, for example, that an animal in the roadway may be difficult to detect with a high degree of reliability. Another example is an animal near (but not in) the roadway, which would not be detected by the system but which is nonetheless a real potential hazard. Spilled loads are also in this category.

It is the feeling of this research team that the driver is a resource who should be utilized. Scenarios which would allow or tacitly encourage the driver to read, sleep, or move out of position are not felt to be in the best interests of safe operation. These scenarios may also bring added responsibility to the system to provide totally fool proof operation.

It is not argued that the driver should be allowed to arbitrarily assume manual control in the midst of high-speed, high density automated traffic. However, means other than instantaneous resumption of manual control may be available. It is recommended that scenarios which would exploit the presence of the driver, alert and in position, be studied in the subsequent phases of AHS research.

One scenario which may be feasible is described below:

- A lone driver or platoon leader notices a spilled load, previously undetected by the system, in the roadway ahead.
- The driver applies his brakes, steers around the hazard, or both. (Such action is permitted by the system. Drivers have to receive special training to understand the implications of such action). The driver’s operation of the brakes and steering signals the system that he is responding to an emergency.
- The driver’s action is transmitted to vehicles behind, which mimic his action, ensuring that all vehicles avoid the hazard. Operation is gracefully degraded further upstream to

the extent that, eventually, vehicles steer or brake normally as contrasted to the braking and steering undertaken in an emergency avoidance maneuver.

- The system contacts the operator of the vehicle who took the initial action to learn what the problem is and to initiate an appropriate response. If the driver caused a false alarm, appropriate legal action can be taken.

The scenario above presumes that coordinated braking, steering, and combinations of the two are feasible. Other scenarios involving lesser demands on the system may also be feasible. One is described below:

- The driver sees a hazard, as yet undetected by the system.
- The driver presses a “panic button” which alerts the system of a problem.
- The system gracefully degrades upstream operations and immediately contacts the driver (by cellular phone, two-way radio, telemetry) to interrogate the reporting driver.
- The driver (verbally or perhaps by keyboard entry) describes the problem to the system.
- The system takes appropriate action, which could include more or less degradation to upstream operations.

The two scenarios above describe two possible extremes of definitions of the role of the responsible driver. Regardless of the precise role of the driver, it is considered important that this resource be given due recognition as AHS is developed.

# CONCLUSIONS

The security and surveillance needs of AHS, while more stringent than those required for an advanced traffic operations system (TOS), are nonetheless felt to be within the means of present technology. AHS brings elements of radio communication not present in today’s TOS’s, but maintaining security and avoiding deliberate interference should not present difficulties different from other areas where radio frequency communications security is important.

Maintenance activities present more of an impact to AHS than to today’s highways, due to the requirement that automated operation be either terminated, or an automated path around the work site be provided. It is therefore a conclusion and recommendation of this report that maintenance activities be given careful consideration throughout every stage of infrastructure planning and design.

It is recommended that AHS planning be based on the premise that the AHS will provide a superior service to the motoring public compared to conventional freeways. This includes travel speed and occupant safety and comfort. To address this requirement, subsequent AHS planning and design should account for the combination of design life and maintenance requirements needed to provide this superior service.

The analysis of incident rates an existing freeways, and an estimate of achievable reductions to these incidents, led to the conclusion that incidents on AHS will still have to be dealt with. Incidents must be mitigated by designing an incident-tolerant system and by providing a service to respond to incidents quickly.

Without an AHS shoulder, the densities on which the research was based would quickly back up and halt AHS operations in the event of an AHS lane blockage. The alternative to shoulders would be a form of incident response that would require extremely short response times and the ability to mitigate the incident without using the AHS lane to reach the incident. Such scenarios are believed to be unrealistic and/or prohibitively expensive; therefore, the recommendation is made that shoulders should be included in AHS planning and design.

It is likely that the current highway systems would have to gradually evolve, in a planned manner, towards a mature AHS and that full deployment of AHS would consist of incremental steps each of which provides additional functionality at a commensurate cost.

These incremental additions of AHS functionality would likely lead to corresponding increases in the complexity of roadway operation.

A serious challenge to deployment is expected to be initial AHS market penetration. The evolutionary scenarios presented address this challenge. However, only two scenarios are defined in this report. A recommendation is made that more scenarios be developed, based on candidate sites for AHS deployment. A manageable number of these scenarios should be evaluated in detail and a small number of superior ones selected for possible deployment.

Interviews with operating agencies verified many concerns and findings of the researchers. Significant concern regarding sustainable funding, not only of construction but of operations and maintenance, was heard. Communications regarding AHS development within State DOT’s was also a concern. It is a conclusion, based on these inputs, that funding be kept at the forefront during the System Definition Phase, to avoid successful completion of technical work but ending up with a product that will not be deployed due to lack of funding. To maintain communications between the consortium and the freeway operations community, it is recommended that the Transportation Research Board Committee on Freeway be given the opportunity to be a consortium.

Early descriptions of AHS included the possibility of the driver reading, sleeping, or moving out of position during automated travel. It is the finding of this research effort that this brings many burdens, including increased tort liability exposure and even more severe incident detection requirements, to the operating agency. It is therefore a recommendation that systems be developed which exploit, not ignore, the capabilities of the driver. This is not a recommendation that the driver be able to assume manual control at will, but that the system recognize the driver’s ability to respond to certain emergencies that would be extremely difficult to design for.

# APPENDICES

(S1) The Initial Deployment Strategy: Automated Lane Cruising in Mixed Traffic on HOV Lane for Vans/Minibuses as Transit Vehicles, Supervised by a Professional Driver

| **Infrastructure** | |
|---|---|
| Functions Added | Continuous HOV lane, without additional highway-to-highway connector ramps dedicated to HOV/automated traffic |
| Construction | Not needed; no check-in facilities needed at the on-ramps (check-in performed by the fleet operator at their maintenance facilities) |
| Usefulness | Promoting HOV use; if AHS deployment halted, lanes useful for HOV purposes |
| Cost and Financing | Low cost involved, except for dedication of HOV lanes; special lane markers possibly required; no financing issue |
| Rate of Modification | Fast |

| Technology | |
|---|---|
| Accommodation Scope | Transit vehicle, i.e., van or minibus |
| Automated Functions | Automated lane-cruising loner vehicles<br>• Loner vehicle (not platooning-equipped)<br>• Self-lane safety sensing: The vehicle knows the position and kinematic information of the vehicle ahead within the brick-wall stopping distance. Once another vehicle moves into its lane (i.e., passing the lane line) in front of it, it immediately recognizes that vehicle as the vehicle in front and reacts according to position and movement of that vehicle.<br>• Automated vehicle following: sufficient automatic longitudinal control for following the vehicle in front at a safety distance.<br>• Automated speed-holding: when the vehicle in front is beyond the safety distance, it travels at the highest speed that is no higher than the speed set by the driver and the safe speed calculated with respect to the vehicle movement in front.<br>• Automated lane holding: sufficient automatic lateral control for lane holding. |
| Technology Maturation | • Not fail-safe or fail-soft yet<br>• Frequent inspection required |
| Functional Diversity | • All automated vans or minibuses perform identical automation functions |

| Human Factors | |
|---|---|
| Transitional Task | By the professional and trained driver |
| Monitoring | Driving monitoring during automated driving required for possible failures of the vehicle and possible sudden intrusion in front by foreign objects or vehicles from neighboring lanes, including possible “spill-overs” of incidents and accidents from neighboring lanes |
| Emergency Handling | Driver responding to vehicle failures and other dangers |
| Comfort | No issue |

| Vehicle Manufacturing and Maintenance | |
|---|---|
| Commitment | • Cautious commitment by the manufacturers<br>• Maintenance performed at fleet operators’ facilities |
| Cost | Very high due to the small market size and heavy investment in research and development |

| Insurance | |
|---|---|
| Commitment | Cautious commitment |
| Cost | Very high but borne by the fleet operator |

| Public Will | |
|---|---|
| User Service | Freeway shuttle service |
| User Safety & Perceived Safety | Frequent inspection; professional driver specially trained for the operation |
| Societal Service | Encouraging transit |
| Societal | Initial government subsidy on investment for the fleet operators possibly required |
| Environment | Transit reducing solo driving |

### (S2) Construction of Highway-to-Highway HOV Connector Ramps and Equipping HOV Lanes for Automated Driving

| **Infrastructure** | |
|---|---|
| Functions Added | • Direct HOV-lane-to-HOV-lane connection on crossing highways<br>• Pervasive infrastructure modification sufficient for regionwide automated freeway shuttle service |
| Construction | Highway-to-highway HOV connector ramps (4 structures) per interchange |
| Usefulness | Minimization of delay for HOV traffic |
| Cost and Financing | Moderate per interchange; limited number of such interchanges |
| Rate of Modification | Moderate |

| **Technology** | |
|---|---|
| Accommodation Scope | Same (van/mini-bus) |
| Automated Functions | Same (manual diverging and merging at the HOV connector ramps; diverging and merging to be automated only when through traffic is fully automated, i.e., when the left-most lane is dedicated to the automated traffic without manually operated vehicles in the lane) |
| Technology Maturation | • Human interface being improved<br>• Technology maturing |
| Functional Diversity | Only non-fail-safe automated lane cruising loner transit vehicles |

| **Human Factors** | |
|---|---|
| Transitional Task | Being made more user-friendly |
| Monitoring | Continuing |
| Emergency Handling | Continuing |
| Comfort | No issue |

| Vehicle Manufacturing and Maintenance | |
|---|---|
| Commitment | Stronger |
| Cost | Declining |

| Insurance | |
|---|---|
| Commitment | Stronger |
| Cost | Declining |

| Public Will | |
|---|---|
| User Service | • More useful; higher availability of the automated freeway shuttle service<br>• Direct highway-to-highway connector ramps, eliminating the need to cross slow lanes on both highways<br>• Reducing delay for HOV traffic at highway-to-highway interchanges |
| User Safety & Perceived Safety | Same (professional driver monitoring) |
| Societal Service | Further encouraging use of HOV lanes |
| Societal Cost | Moderate |
| Environment | Friendly |

(S3) Vehicle Fail-Safety

| **Infrastructure: HOV Lane Modification for Automation and Construction of Highway-to-Highway HOV Connector Ramps Continuing** | |
|---|---|
| Functions Added | None |
| Construction | None |
| Usefulness | None |
| Cost and Financing | None |
| Rate of Modification | N/A |

| **Technology** | |
|---|---|
| Accommodation Scope | Same |
| Automated Functions | Same |
| Technology Maturation | • Fail-safety achieved for the automated lane-cruising loner vehicles (noting that subsequent technologies will be introduced with fail-safety)<br>• Manual controls unresponsive during automated driving<br>• No driver intervention during automated driving, except through taking over manual control or the use of a panic button<br>• Less frequent vehicle inspections required<br>• User-friendly human interface achieved |
| Functional Diversity | • Non-fail-safe automated lane-cruising loner transit vehicles<br>• Fail-safe automated lane-cruising loner transit vehicles |

| Human Factors | |
|---|---|
| Transitional Task | More user-friendly |
| Monitoring | • Continuing<br>• Panic button for reacting to accident spillover |
| Emergency Handling | Discontinued |
| Comfort | Improved |

| Vehicle Manufacturing and Maintenance | |
|---|---|
| Commitment | Stronger |
| Cost | Same (cost of additional capability possibly offset by the increased demand) |

| Insurance | |
|---|---|
| Commitment | Stronger due to the fail-safe technologies |
| Cost | Declining |

| Public Will | |
|---|---|
| User Service | Virtually care-free fully automated driving |
| User Safety & Perceived Safety | Fail-safety |
| Societal Service | Additional step (safety) for transit |
| Societal | No public spending required for fail-safety if no roadside equipment required |
| Environment | Increased ride sharing |

(S4) Automation of Automobiles

| **Infrastructure: Networkwide HOV Lane Modification for Automation and Construction of Highway-to-Highway HOV Connector Ramps Completed** | |
|---|---|
| Functions Added | None |
| Construction | None |
| Usefulness | None |
| Cost and Financing | None |
| Rate of Modification | N/A |

| **Technology** | |
|---|---|
| Accommodation Scope | Automobiles also automated |
| Automated Functions | Same |
| Technology Maturation | Automobile check-in by status reporting (to the roadside) by the vehicle only (no additional real estate required for check-in) |
| Functional Diversity | • Non-fail-safe automated lane-cruising loner transit vehicles<br>• Fail-safe automated lane-cruising loner transit vehicles<br>• Fail-safe automated lane-cruising loner automobiles |

| **Human Factors** | |
|---|---|
| Transitional Task | Same (user friendly) |
| Monitoring | Continuing (for possible accident spillovers) |
| Emergency Handling | Same (discontinued) |
| Comfort | Possible automobile driver/passenger (non-professionals) discomfort due to relinquishment of manual control |

| Vehicle Manufacturing and Maintenance | |
|---|---|
| Commitment | Including automobiles |
| Cost | Moderately-priced automobiles |

| Insurance | |
|---|---|
| Commitment | Extending to automobiles |
| Cost | Moderate cost for automobiles |

| Public Will | |
|---|---|
| User Service | Automobile automation |
| User Safety & Perceived Safety | Increased (elimination of some driver errors) |
| Societal Service | Towards improvement of mobility |
| Societal Cost | No public spending for automobile automation over transit automation |
| Environment | Possible net adverse effect on the environment due to automobile automation |

(S5) Dedication of One Automated/Transition Lane for Transition and Then Automated Driving

| **Infrastructure** | |
|---|---|
| Functions Added | • Dedication of one lane (the left-most lane) as automated/transition lane to the automation-equipped vehicles for transition and then automated lane-cruising (vehicles are driven manually into the automated lane and then transition into the automated driving mode)<br>• Dedication of the adjacent lane as the HOV lane<br>• HOV traffic on the HOV lane but not the automated lane; HOV traffic deprived of the use of the now automated highway-to-highway connector ramps<br>• Equipping the HOV lane (second lane from the left) for automated driving |
| Construction | Physical barriers at the interchange starting the automated/transition lane from the HOV lane, particularly at the merge point, to prevent lane changing and possible intrusion by manually-driven vehicles |
| Usefulness | • Increasing safety (even safety under completely manual operation)<br>• Towards complete segregation of manual traffic from automated traffic |
| Cost and Financing | Low; limited number of locations needing physical barriers; lane conversion assumed not costly |
| Rate of Modification | Moderate |

| **Technology** | |
|---|---|
| Accommodation Scope | Same |
| Automated Functions | Same |
| Technology Maturation | Same |
| Functional Diversity | Same |

| **Human Factors** | |
|---|---|
| Transitional Task | Same (user-friendly) |
| Monitoring | Continuing (to watch for possible accident spillovers); early warning |
| Emergency Handling | Same (discontinued) |
| Comfort | Same |

| **Vehicle Manufacturing and Maintenance** | |
|---|---|
| Commitment | Stronger |
| Cost | Declining |

| **Insurance** | |
|---|---|
| Commitment | Stronger |
| Cost | Declining |

| **Public Will** | |
|---|---|
| User Service | More vehicle uniformity on the automated lane (although not all vehicles are under automatic control at all times due to need to transition between the automated lane-cruising mode and the manual driving mode) |
| User Safety & Perceived Safety | Safer due to vehicle uniformity |
| Societal Service | Disservice due to deprivement of use of median-to-median connector ramps by the HOV users |
| Societal Cost | Low |
| Environment | Same |

(S6) Automation of Lane-Changing into the Automated/Transition Lane

| **Infrastructure** | |
|---|---|
| Functions Added | None |
| Construction | None |
| Usefulness | None |
| Cost and Financing | None |
| Rate of Modification | N/A |

| **Technology** | |
|---|---|
| Accommodation Scope | Same |
| Automated Functions | • Automated lane changing between the HOV lane and the automated/transition lane<br>• Automation functional upgrade available from automated lane cruising to automated lane changing (noting the importance of upgradability)<br>• Automated lane-changing vehicles transitioning between the manual and the automated driving modes on the HOV lane; driven automatically onto the automated/transition lane after transition<br>• Automated lane-cruising vehicles driven onto the automated/transition lane manually followed by transition |
| Technology Maturation | Fail-safety coming with the new functions |
| Functional Diversity | • Non-fail-safe automated lane-cruising transit vehicle and automobiles<br>• Fail-safe automated lane-cruising transit vehicles and automobiles<br>• Fail-safe automated lane-changing transit vehicles and automobiles |

| Human Factors | |
|---|---|
| Transitional Task | Same (user-friendly) |
| Monitoring | Continuing (to watch for possible accident spillovers); early warning |
| Emergency Handling | Same (discontinued) |
| Comfort | Same |

| Vehicle Manufacturing and Maintenance | |
|---|---|
| Commitment | Stronger |
| Cost | Declining |

| Insurance | |
|---|---|
| Commitment | Stronger |
| Cost | Declining |

| Public Will | |
|---|---|
| User Service | Automated lane-changing |
| User Safety & Perceived Safety | Possible safety hazards due to automated lane-changing |
| Societal Service | Same |
| Societal Cost | None |
| Environment | Same |

(S7) Dedication of One Automated Lane (No Transitioning) and Automation of Diverging/Merging at (Automated) Highway-to-Highway Connector Ramps

| **Infrastructure** | |
|---|---|
| Functions Added | • Dedication of the automation/transition lane (the left-most lane) to the automated traffic as the automated lane, i.e., no transitioning on the automated lane<br>• Automated lane-changing vehicles transitioning in the HOV lane and driven onto the automated lane automatically<br>• All transitions between the manual and the automated driving modes performed on the HOV lane (i.e., transition lane for automation; HOV lane also called HOV/Transition Lane)<br>• Automated lane-cruising vehicles traveling only on the HOV lane and not on the automated lane (to prevent manual driving on the automated lane)<br>• HOV traffic on the HOV lane; HOV traffic deprived of the use of the now automated highway-to-highway connector ramps |
| Construction | None |
| Usefulness | • Increased safety (even safety under manual operation)<br>• Towards complete segregation of manual traffic from automated traffic |
| Cost and Financing | None |
| Rate of Modification | Fast |

| Technology | |
|---|---|
| Accommodation Scope | Same |
| Automated Functions | • Automated lane changing between the HOV lane and the automated/transition lane<br>• Automation functional upgrade available from automated lane cruising to automated lane changing (noting the importance of upgradability)<br>• Automated lane-changing vehicles transitioning between the manual and the automated driving modes on the HOV lane; driven automatically onto the automated/transition lane after transition<br>• Automated lane-cruising vehicles driven onto the automated/transition lane manually followed by transition |
| Technology Maturation | Fail-safety coming with the new functions |
| Functional Diversity | • Non-fail-safe automated lane-cruising transit vehicle and automobiles<br>• Fail-safe automated lane-cruising transit vehicles and automobiles<br>• Fail-safe automated lane-changing transit vehicles and automobiles<br>• Fail-safe automated diverging/merging, i.e., location-constrained lane-changing, transit vehicles and automobiles |

| Human Factors | |
|---|---|
| Transitional Task | Same (user-friendly) |
| Monitoring | Continuing (to watch for possible accident spillovers); i.e., early warning |
| Emergency Handling | Same (discontinued) |
| Comfort | Same |

| Vehicle Manufacturing and Maintenance | |
|---|---|
| Commitment | Stronger |
| Cost | Declining |

| Insurance | |
|---|---|
| Commitment | Stronger |
| Cost | Declining |

| Public Will | |
|---|---|
| User Service | Continuous automated driving from end to end across different highways |
| User Safety & Perceived Safety | Higher safety with all automated traffic on the automated lane |
| Societal Service | None |
| Societal Cost | None |
| Environment | Same |

(S8) Construction of Automated On-Ramps and Off-Ramps with Barriers at Busy Locations

| **Infrastructure** | |
|---|---|
| Functions Added | Supporting completely automated driving from automated on-ramp to automated off-ramp |
| Construction | • Automated on-ramps and off-ramps<br>• Automated lane-changing vehicles accessing/egressing the automated lane through the automated on-ramps/off-ramps, where available (automated lane-cruising vehicles using the HOV/transition lane only)<br>• Physical barriers separating the automated lane from the HOV lane (transition lane) at the ramps, particularly the merge point at on-ramps |
| Usefulness | Direct access to left lanes |
| Cost and Financing | • Moderate per highway-to-street interchange<br>• A large number of such busy locations implying large total capital investment and potential financing problems |
| Rate of Modification | Slow |

| **Technology** | |
|---|---|
| Accommodation Scope | Same |
| Automated Functions | Same |
| Technology Maturation | Same |
| Functional Diversity | Same |

| **Human Factors** | |
|---|---|
| Transitional Task | Same (user-friendly) |
| Monitoring | Same (continuing) |
| Emergency Handling | Same (discontinued) |
| Comfort | Same |

| Vehicle Manufacturing and Maintenance | |
|---|---|
| Commitment | Stronger |
| Cost | Declining |

| Insurance | |
|---|---|
| Commitment | Stronger |
| Cost | Declining |

| Public Will | |
|---|---|
| User Service | Completely automated driving from any automated on-ramp to any automated off-ramp |
| User Safety & Perceived Safety | Same |
| Societal Service | Direct access to left lanes, improving traffic flow |
| Societal Cost | High public spending on the infrastructure |
| Environment | Same |

### (S9) Segregation of Automated Traffic from Manual Traffic, Possibly with Exceptions, for Safer and High-Speed Automated Driving

| **Infrastructure** | |
|---|---|
| Functions Added | Segregated automated lane |
| Construction | Physical barriers between the automated lane and the HOV lane |
| Usefulness | A separate highway network system, possibly with convenient access from and egress to the network for manual traffic |
| Cost and Financing | Moderate to high |
| Rate of Modification | Moderate |

| **Technology** | |
|---|---|
| Accommodation Scope | Same |
| Automated Functions | Same |
| Technology Maturation | Same |
| Functional Diversity | Same |

| **Human Factors** | |
|---|---|
| Transitional Task | Same (user-friendly) |
| Monitoring | • Discontinued (accident spillover from manual traffic eliminated)<br>• Hands-off, feet-off and “head-off” driving<br>• Panic button remaining |
| Emergency Handling | Same (discontinued) |
| Comfort | Same (higher speed possibly causing some user discomfort) |

| Vehicle Manufacturing and Maintenance | |
|---|---|
| Commitment | Stronger |
| Cost | Declining |

| Insurance | |
|---|---|
| Commitment | Stronger |
| Cost | Declining |

| Public Will | |
|---|---|
| User Service | High-speed automated driving |
| User Safety & Perceived Safety | Improved |
| Societal Service | • Unmanned transit vehicle operation on the automated lane saving transit labor cost<br>• Elimination of intrusion by unequipped vehicles<br>• Higher capacity on the automated lane |
| Societal Cost | Moderate to high public spending |
| Environment | Same |

(S10) Two Automated Lanes for Capacity and Higher Speed on the Second Automated Lane

| Infrastructure | |
|---|---|
| Functions Added | • Two automated lanes<br>• Faster speed on the second automated lane<br>• Traffic merging at lane drop necessary<br>• HOV lane moved to the next lane |
| Construction | Move of lane barriers |
| Usefulness | Higher capacity |
| Cost and Financing | Moderate |
| Rate of Modification | Moderate |

| Technology | |
|---|---|
| Accommodation Scope | Same |
| Automated Functions | Same |
| Technology Maturation | Same |
| Functional Diversity | Same |

| Human Factors | |
|---|---|
| Transitional Task | Same (user-friendly) |
| Monitoring | Same (discontinued) |
| Emergency Handling | Same (discontinued) |
| Comfort | Same |

| **Vehicle Manufacturing and Maintenance** | |
|---|---|
| Commitment | Stronger |
| Cost | Declining |

| **Insurance** | |
|---|---|
| Commitment | Stronger |
| Cost | Declining |

| **Public Will** | |
|---|---|
| User Service | Faster speed on the second automated lane |
| User Safety & Perceived Safety | Possible increased probability of spillover of accident from one to another |
| Societal Service | Higher lane capacity |
| Societal Cost | Moderate |
| Environment | Same |

(S11) Automobile Platooning on the Second Automated Lane for Higher Capacity

| **Infrastructure: Continuing the Addition of the Second Automated Lane** | |
|---|---|
| Functions Added | Adding capacity |
| Construction | Lane conversion |
| Usefulness | More two-lane automated sections |
| Cost and Financing | Moderate |
| Rate of Modification | Moderate |

| **Technology** | |
|---|---|
| Accommodation Scope | Same |
| Automated Functions | • Platooning function added to only automobiles and to be used only where and when higher capacity is needed<br>• Functional upgradability assumed (important design issue) |
| Technology Maturation | Fail-safety of the platooning technology assumed |
| Functional Diversity | • Automated lane-cruising loner vehicles, fail-safe or not, and automated lane-changing vehicles using only the HOV lane with no access to any direct highway-to-highway HOV connector ramps<br>• Automated diverging/merging (fail-safe) loner vehicles using only the first automated lane or where and when platooning is not needed on the second automated lane<br>• Automated diverging/merging platooning-equipped vehicles, when so desired by the driver, using the second automated lane for platooning<br>• On sections where only one automated lane is available and when and where higher lane capacity is needed, “spontaneous platooning” required of the platooning-equipped automobiles |

| Human Factors | |
|---|---|
| Transitional Task | Same (user-friendly) |
| Monitoring | Same (discontinued) |
| Emergency Handling | Same (discontinued) |
| Comfort | Possible user discomfort about the short vehicle following spacing |

| Vehicle Manufacturing and Maintenance | |
|---|---|
| Commitment | Possibly an issue |
| Cost | Moderate |

| Insurance | |
|---|---|
| Commitment | A potential issue of insuring platooning-equipped vehicles |
| Cost | A potential issue that needs to be overcome |

| Public Will | |
|---|---|
| User Service | Faster speed and reduced delay |
| User Safety & Perceived Safety | A potential issue |
| Societal Service | High lane capacity |
| Societal Cost | No additional public spending, if no infrastructure support required |
| Environment | A potential issue |
| Others | New law possibly required for liability distribution |

(S12) The Mature AHS

| Infrastructure |
|---|

| | |
|---|---|
| Overall Functions Supported | • Complete physical segregation between automated and manual traffic<br>• A dedicated network of automated highways<br>• No physical barriers between two automated lanes<br>• At grade level, occupying inner lanes of highway, and basically within the current right-of-way<br>• Special highway-to-highway connector ramps providing direct connection and enabling continuous automated driving from one highway to a crossing highway<br>• Access and egress via median with special left-hand-side on-ramps and off-ramps<br>• No need for real estate for check-in facilities at special on-ramps<br>• At most two automated lanes and only one such lane along some sections<br>• The first automated lane dedicated to the automobiles while the second automated lane shared by all vehicle types<br>• On those automated highway sections with only one automated lane, all types of automated vehicles sharing that lane and platooning-equipped automobiles platooning spontaneously<br>• In congestion sections during congestion hours, only platooning-equipped automobiles allowed to travel in the inner lane and such vehicles traveling in platoons on the second automated lane |
| Overall Construction | Feasibility assumed |
| Overall Usefulness | Feasibility assumed |
| Overall Cost and Financing | Affordability assumed |
| Overall Rate of Modification | Acceptable rate assumed |

| Technology: A Vehicle-Centered Platooning Technology Assumed | |
|---|---|
| Accommodation Scope | • Transit Vehicles<br>• Automobiles |
| Automated Functions | Completely automated, i.e., hands-off, feet-off, and "head-off" |
| Technology Maturation | Fail-safe |
| Functional Diversity | • Platooning-equipped vehicles (including automated diverging/merging; also fail-safe)<br>• Fail-safe loner (non-platooning equipped) vehicles capable of automated diverging/merging<br>• Fail-safe loner (non-platooning-equipped) vehicles capable of automated lane-changing<br>• Fail-safe loner (non-platooning-equipped) vehicles capable of only automated lane cruising (i.e., not capable of automated lane-changing)<br>• Non-fail-safe loner (non-platooning-equipped) vehicles capable of only automated lane cruising (i.e., not capable of automated lane-changing) |

| Human Factors: Acceptability Assumed | |
|---|---|
| Transitional Task | Assumed to be user-friendly |
| Monitoring | Assumed to be not required (head-off) |
| Emergency Handling | Assumed to be not required<br>• Fail-safe<br>• Automated emergency handling |
| Comfort | Assumed |

| Vehicle Manufacturing and Maintenance | |
|---|---|
| Commitment | Ability and commitment to manufacture reliable and fail-safe platooning-equipped automobiles and loner transit vehicles assumed; also assumed being that they can be maintained properly and conveniently |
| Cost | Assumed to be affordable |

| Insurance | |
|---|---|
| Commitment | Assumed |
| Cost | Affordability assumed |

| Public Will | |
|---|---|
| User Service | Comfort, safety, and speed assumed; driver of platooning-equipped vehicle determining if he/she likes to use the second automated lane for platooning; higher speed on the second automated lane providing incentive to purchase platooning-equipped automobiles |
| User Safety & Perceived Safety | Assumed |
| Societal Service | • High highway capacity assumed<br>• Minimal travel delay for equipped transit vehicles throughout the freeway travel assumed |
| Societal Cost | Acceptability assumed |
| Environment | Assumed environment-friendly through increased use of transit and decreased per-vehicle emissions |

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