Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Vehicle Operational Analysis

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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.

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VOLUME IV — AHS SYSTEMS ANALYSIS

CHAPTER 5: VEHICLE OPERATIONAL ISSUES (TASK L)

1.0 EXECUTIVE SUMMARY

1.1 OVERVIEW

The purpose of this activity was to identify issues/risks involved in vehicle operation during the development of the Automated Highway Systems (AHS). The study primarily was concerned with evolution and deployment of AHS; and reliability and safety issues associated with in-vehicle components.

To identify existing and promising AHS related components, we conducted a comprehensive review of the projects related to the AHS and advanced vehicle control systems (AVCS). In this regard, the evolutionary path from today's vehicle systems to a fully-automated operation was analyzed in terms of several stages of deployment. At each stage, the AHS components to be developed and their operational, deployment, and reliability issues were discussed.

In-vehicle communication system needs and issues were also studied. These include problems associated with existing in-vehicle networking, increasing demand for vehicle electronics and growing bus load in future cars, and application of the multiplexing communication systems in AHS vehicle interfacing.

Some thoughts were also given to the retrofitting of the AHS components into the existing vehicles. Feasibility of retrofitting electronic sensors, problems involved in retrofitting of the mechanical actuators, and introduction of the electronic actuators in the future which may facilitate retrofitting process were some of the areas we considered.

1.2 KEY FINDINGS

Numerous issues/risks were identified under this study. For a summary of issues/risks, the reader may refer to Table 5-4 of this report. Some of the significant findings are addressed below.

- *Impact of Reliability*

  The addition of the required AHS components may result in a decrease of the reliability of the vehicle as a whole. It is believed that through preventive maintenance, periodic inspections, use of redundancy, and system health monitoring, a failure rate at least as low as today's experience can be maintained. Consideration must be given to the impact on reliability during the design process.

- *Impact of Redundancy*

Tradeoffs will need to be made between redundancy and cost impact. To make all AHS sub-systems redundant will, no doubt, result in pricing the AHS equipment out of the market. Car should be exercised during the design process to employ redundancy in areas where safety considerations dictate it, such as steering control systems. Built-in tests can be employed to detect a failure or below-specification performance, without the use of redundancy — provided that the malfunction can be managed. For example, if a forward-looking radar system fails, the vehicle can be brought to a stop in a breakdown lane. If the radar has a low failure rate such that few failures occur, this approach of stopping the vehicle may be quite acceptable as opposed to providing redundant radar sensors.

- *Impact of the AHS Scenarios*

Development and deployment of AHS components will be greatly affected by the selection of the AHS scenarios (e.g., a vehicle-based or roadway-based intelligence). Determining the feasibility of deployment of the proposed scenarios at an early stage, and selecting the appropriate scenario(s) for implementation is very crucial to the success of the project. This will provide a clear direction for research and development of the AHS components and also will speed up deployment process.

- *AHS Evolution*

Progression for AHS evolution will probably be warning, control assistance, and then eventually AHS, i.e., full automated control stage. Our team does not consider the system to be AHS until the operation is hands- off, feet-off.

- *Deployment of the AHS Vehicle Components*

Some of the early stage driving assist systems, such as intelligent cruise control will be entirely onboard the vehicle, without the need for involvement of any government agency or roadway facility. The addition of lateral control will probably require some additional infrastructure such as magnets or road stripes.

- *Software Cost*

Software development process may become a major cost element of the system development costs of AHS systems. Software cost on a per vehicle basis will be modest due to the large number of vehicles. At a 70% market penetration (70 million vehicles) a cost of $5 per vehicle would amount to 350 million dollars of software development.

- *Software Verification and Validation*

Since AHS Systems will employ sophisticated microprocessor-based systems for vehicle control, system health monitoring, and communication of signals and commands, software verification and validation monitoring will be of prime importance. Software verification must be part of the malfunction monitoring system and an integral part of the design process, rather than an after-thought, once the software is structured.

- *In-Vehicle Communications*

  Multiplexing of on-board communication systems has promising applications in the AHS vehicles. Some of the benefits of the system include: enhanced diagnostics, distributed control, and total wire reduction.

1.3 RECOMMENDATIONS FOR FUTURE RESEARCH

Deployment of a fully-automated system will require a great deal of research and development on sensors, actuators, communication systems, control algorithms and so on. However, at this stage of the study, we believe that in some areas of the vehicle operation more research is needed. These include:

- Determining the ultimate scenarios for deployment of AHS. This will facilitate development and deployment process of the promising technologies.

- For a higher reliability and safety, what AHS components need to be fully redundant or have backups with reduced performance: feasibility, cost, and reliability levels associated with each component should be discussed.

- On the issue of retrofitting, more investigation is needed to identify those elements of the AHS that can be retrofitted to the existing vehicles and also determine methods, costs, and reliability issues.

- What characteristics are needed to be included in communication protocols in order to deal with message prioritization in a high speed network.

2.0 INTRODUCTION

The purpose of this report was to provide study results of the vehicle operational analysis task. The task intended to study and review various in-vehicle components and identify major risks and issues surrounding deployment of an Automated Highway Systems (AHS) from the standpoint of vehicle operation.

The findings presented in this report mainly are based on an extensive review of the existing advanced vehicle control systems (AVCS) and AHS related projects within the United States and other countries.

2.1 PURPOSE

The primary objective of this task was to identify vehicle operational issues and risks which will need to be addressed during the development of AHS. These included reliability and maintainability, retrofitting of the new components to the existing vehicles, in-vehicle communications, and the evolution of the early stage equipment into a fully-automated operation.

2.2 TECHNICAL APPROACH

The methodology for this study constituted a matrix approach, in which the relationships between various vehicle components with respect to the AHS deployment could be identified and analyzed. Using this method, major in-vehicle components were evaluated under different AHS scenarios including current development, near term development, and AHS requirements.

There is a significant amount of activity worldwide associated with the development of AHS related systems. In addition to works in the United States, there have been other significant projects undertaken in Europe, Japan, and Taiwan. Therefore, we began our study with a comprehensive literature search on the existing AVCS and AHS projects in order to identify existing and promising AHS related components. Our emphasis, however, was to identify issues addressed in, and lessons learned from these projects, which could be applicable to our RSCs.

Approximately 100 articles were reviewed for this activity (see Reference Section). Based on this review, some of the most pertinent projects were identified, which are listed in Table 5-1. A review of these programs shows that the automated highway systems will utilize a wide range of the IVHS technologies, in particular the Advanced Vehicle Control System (AVCS) program. The goal of AVCS is to employ advanced sensor and control technologies to improve safety and increase highway capacity by providing information about changing conditions in the vehicle's immediate environment, sounding warnings, and assuming partial or total control of the vehicle. Therefore, the AHS represents the long term potential of AVCS for a fully automated vehicle on an AHS-equipped roadway.

Table 5-1. Existing AHS Related Programs

Program	Location	Objectives
IVHS *Intelligent Vehicle Highway Systems*	USA	ATMS, AVCS, ATIS, CVO, APTS
PATH *Program on Advanced Technology for the Highway*	USA	Highway automation, roadway electrification, navigation
NavLAB *Navigational Laboratory*	USA	Autonomous vehicle capable of outdoor navigation
PROMETHEUS *PROgraM for a European Traffic with Highest Efficiency and Unprecedented Safety*	EUROPE	Intelligent copilot (integration of vehicular systems linked by communication networks)
Prolab2	EUROPE	Autonomous vehicle
VaMoRs	EUROPE	Fully-autonomous vehicle
DRIVE *Dedicated Road Infrastructure for Vehicle Safety in Europe*	EUROPE	Functional specifications and standards
SSVS *Super Smart Vehicle System*	JAPAN	Intelligent driving system (implementation of advanced vehicle control system)
VICS *Vehicle Information/Communication System*	JAPAN	Vehicle navigation and information system
ASV *Advanced Safety Vehicle*	JAPAN	Risk prediction and information, automatic driving for risk avoidance
PVS *Personal Vehicle System*	JAPAN	Autonomous vehicle
ADVANCE-F *Advanced Drive Vehicle/Automatic Navigation and Control Enroute System-Freeway*	TAIWAN	Automatic highway/vehicle control system (using communications)

It is obvious that deployment of each major in-vehicle system will raise many issues regarding the levels of reliability and maintainability, ability to achieve graceful degradation in case of a temporary malfunctions, retrofitting of the new component on the existing vehicles, and so on. Recognizing the importance of these issues for a successful deployment of an automated operations, this activity focused on the following areas.

AHS Evolution. The evolutionary path from today's vehicles/freeway systems to an automated operation needs to be traveled through several stages. It is expected that a fully automated highway system to evolve from a partially automated (driving assistance) stage. The broad range of sophisticated technologies needed for autonomous driving systems will require a significant period of research and development before they can be deployed on AHS roadway. Therefore, it will be necessary to proceed with this development work in a step-by-step process, while maintaining a long-term vision of the future direction.

In-Vehicle Components. This subtask was to address issues related to the AHS vehicle components. This was done by first identifying the components required for an automated operation in an AHS environment, and then discussing the impact of AHS deployment on each vehicle component and addressing related issues/risks. Main systems include steering, braking, acceleration, sensors/vision, automatic headway control, collision avoidance, obstacle avoidance, communications, microprocessors, power, etc.

In-Vehicle Communications. Fully automated control of the entire system will require a high level of communication between in-vehicle components, among vehicles, between vehicles and infrastructure, and between various infrastructure subsystems . Different types of communication systems have a wide range of variations, and are applicable to many systems including driver information and vehicle control systems. For example, as stated in the proposal, communication within the vehicle would require a network similar to current state-of-the-art avionics, such as the MIL-STD-1553 serial data bus. Therefore, to identify in-vehicle communication requirements for the AHS, several resources including IVHS activities, recent state-of-the-art electronics, and possible development in communications of high-speed functions were considered for the study.

Reliability. Reliability is defined as the probability that a system can perform the assigned functions under the stated conditions for certain period of time. For an AHS-related component, reliability is defined in terms of dependability for service, and graceful degradation due to service interruptions. Considering the increasing number of safety-critical systems appearing in vehicles and the increase in vehicular electronics it is necessary to ensure functional reliability. This can be accomplished in terms of failure modes and effects analysis, environmental validation, and software verification and validation.

Retrofitting. One of the goals of the AHS design is retrofitting of the AHS components to manual controlled (existing) vehicles in order to enable them for an automated operation. There are many aspects involved in retrofitting the new equipment to an existing vehicles, such as availability of the space needed for the system, compatibility, methods of retrofitting, installation cost, etc. One possible way of looking into issues/risks involved in fitting after-market AHS products to the existing vehicles is to classify the AHS components into different groups such as mechanical elements and electrical/electronic elements.

Maintainability. To provide a safe operation on an AHS roadway and also reduce the incidence of vehicle components failure, a certain degree of self-diagnostics must be maintained. In addition to monitoring the major vehicle components , a self-diagnostic system will keep a record of the responsiveness of the major systems such as steering, acceleration and braking. Furthermore, a schedule of the routine maintenance on the vehicle such as tire changes, oil and fluid changes, and brake maintenance can be entered into the system to instruct the driver for the necessary service. It is also envisioned that a periodic vehicle inspection will be performed for all vehicles to be certified to travel on an AHS roadway. Since malfunction management activity will identify and address primary maintenance issues and requirements of the major vehicle components, our activity points out some of the issues related to reliability of in-vehicle components.

3.0 TECHNICAL DISCUSSIONS

This section presents some general discussions of the vehicle operational analysis and findings of this activity on areas such as the AHS evolution and deployment of the AHS components, in-vehicle communications, retrofitting of the new equipment to the existing vehicles, and reliability of the AHS vehicles.

3.1 OPERATIONAL ISSUES ASSOCIATED WITH EVOLUTION OF AHS VEHICLE COMPONENTS

To provide a smooth transition from today's vehicle/highway systems to a fully-automated operation, implementation of AHS should be accomplished through several stages. The implementation scenarios may include many types of control functions distribution between the vehicle and infrastructure. These scenarios may range from an AHS system with fully autonomous vehicles/no centralized control to a completely centralized control system. Regardless of what degree of control functions assigned to the vehicle or infrastructure, there will be a significant impact on the in-vehicle components, such as sensors, steering, braking, and speed control systems. To address these issues, it is needed to picture AHS deployment phases as well as evolution of the AHS related components.

There are numerous concepts of deployment scenarios of the AHS related components and functions indicating that the progression for evolution should be warning, control assistance, and then eventually to AHS (fully-automated control stage). Table 5-2 summarizes deployment of AHS technologies in terms of development stage and control functions distribution between the vehicle, driver, and infrastructure. These are addressed below. At each stage, components involved and related issues and problems on development and deployment of each component have been discussed.

3.1.1 Current System

Current system includes the existing vehicles/highways with no automation (possibly some advisory system, and traffic and weather information). Some vehicles may be equipped with driving assist systems such as cruise control to keep the vehicle at constant speed. The driver is responsible for all driving functions, such as speed and headway control, steering, lane keeping, lane changing, etc.

Table 5-2. AHS Deployment Stages

Deployment Stage	Equipment	Control Functions		
		Vehicle	Driver	Infrastructure
Current			All functions	
Early Stage	- Intelligent cruise control - Collision warning - Driver's blind spot detection - Navigation System	- Speed - Headway - Soft-braking	- Steering - Lane keeping - Lane changing - Emergency-braking	- Highway advisory - Traffic information
Near-Term	- Lane-center detection - Sensors to detect vehicles on neighboring lanes - Automatic trip-planner	- Speed - Headway - Soft-braking - Steering assist - Lane keeping assist - One-way veh-to- veh comm. (lead-to-follower)	- Steering - Lane keeping - Lane changing - Emergency-braking	- Highway advisory - Traffic information - Route guidance <u>Centralized Commands:</u> Speed & headway through one-way comm. between infrastructure & vehicle
Long-Term (Early AHS)	- Automatic steering - Lane changing assist - Full braking - Obstacle detection - Headway maintenance	- Speed - Headway - Braking - Lane keeping - Steering	- Lane changing - Emergency-braking	- Highway advisory - Traffic information - Route guidance <u>Centralized Commands:</u> Speed, headway & lane assignment through one-way infrast-to-veh communications
Fully-Automated Operation	- Obstacle avoidance - Automatic lane change (merging/splitting)	- Speed - Headway - Braking - Steering - Lane changing - Two-way veh-to-veh & veh-to-traffic control center	- Emergency-braking - Transition to and from automatic control	- Highway advisory - Traffic information - Route guidance <u>Centralized control:</u> Speed, headway & lane assignment through one-way infrast-to-veh communications

3.1.2 Early Implementation

Early implementation of AHS may include a number of driving assist systems, such as collision warning, ranging/imaging sensors, and soft braking capability, which together provide an intelligent cruise control (ICC) capability.

Intelligent cruise control system that automatically adjusts vehicle speed/ headway will evolve from the existing constant speed cruise control system. Figure 5-1 depicts a conceptual design of an ICC. Distance measuring sensors such as a laser or radar system, mounted in front of the vehicle measure the spacing between the vehicle and its leading car and the relative velocity. An onboard microprocessor controls the throttle to maintain speed or spacing if the lead vehicle is traveling slower than the set speed. The braking capability included in ICC can decelerate the vehicle and perform soft-braking whenever is needed. The driver, however, is responsible for the emergency (hard) braking. All lateral control functions (e.g., steering, lane keeping, and lane changing) will be conducted by the driver. The roadway may provide traffic and weather information using roadway sensors. Several intelligent cruise control systems will be offered as options on vehicles within a year or two. After market systems will be available in mid 1995.

3.1.2.1 Operational/Deployment Issues

Collision warning and near-obstacle warning systems issue warning to the driver, when the vehicle moves dangerously close to an object, such as when backing up or when moving into the path of another vehicle during a lane change. These systems could evolve to automatic obstacle avoidance, in which the vehicle would take the corrective action without the driver's intervention.

The National Highway Traffic Safety Administration (NHTSA) has let contracts to several firms to design, develop and test techniques to warn drivers of corresponding rear end and backing collisions and lateral collisions in a lane change. Programs have also been let for road departures (so called run off the road) and intersection collision avoidance. These programs should lead to products that will be available as original equipment or after market. The technology developed for lateral and headway collision avoidance could be integrated into the AHS control. Also the road departure system could possibly be used on an AHS roadway as a back up to the lateral sensor for lane keeping.

Obstacle warning systems in the vicinity of an automobile using ultrasonic have already been commercially available in Japan. In the United States, crash-avoidance radar for automobiles, installed in Greyhound buses has already been tested over 250 million miles. It should be noted that like other AHS components, while crash-avoidance radar for automobiles is possible today, it is likely to take many years to be widespread on the market. Recalling a USDOT study in 1990, a half-second earlier warning would reduce rear-end and intersection collisions by 50%, the collision avoidance radar should increase the safety and reduce the occurrence of rear end

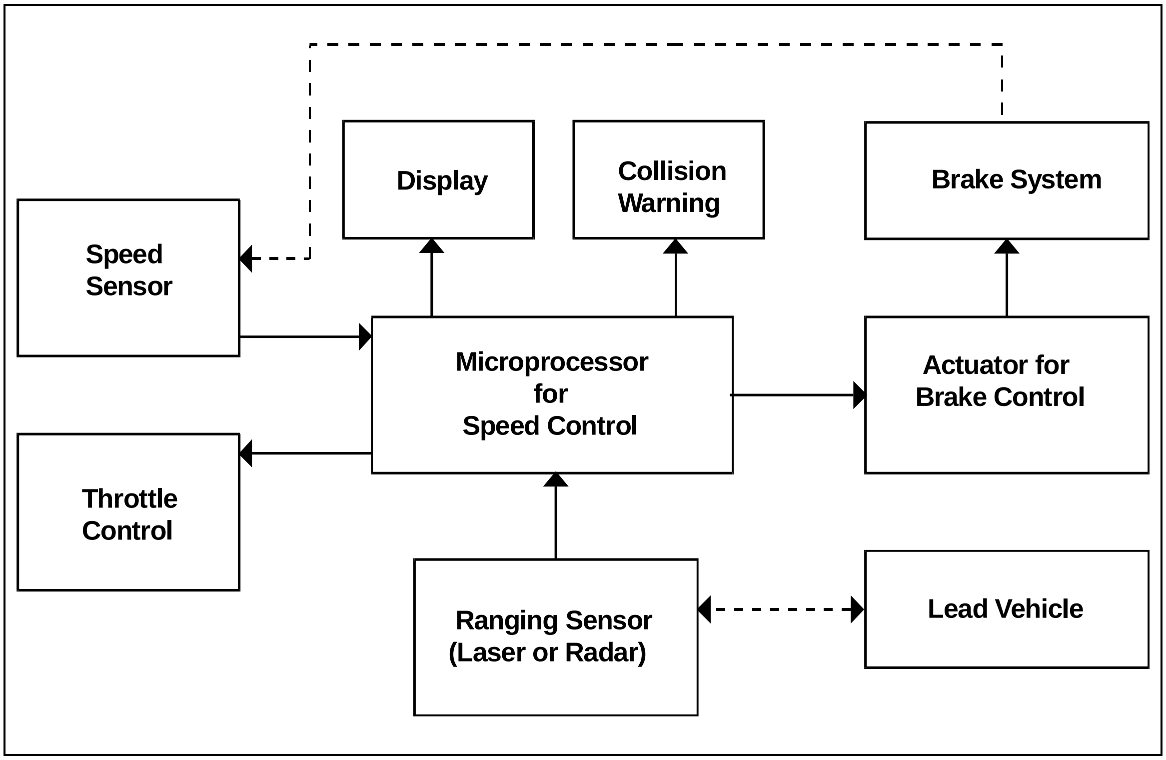

Figure 5-1. Intelligent Cruise Control (ICC)

collision in an AHS environment. Depending on the type of the radar system, there are however, numerous development and deployment issues some of which addressed below.

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Radar systems typically use either a microwave radar beam or a laser radar beam. The laser system incorporates a laser head which operates in coordination with reflectors mounted at the rear of vehicles. Lecia has had considerable success utilizing the reflections from the tail light lens. At this time it is unclear if additional reflectors are needed. It is possible to detect a vehicle at a forward distance of approximately 100 meters even with a relatively small-power laser. The system then, issues a warning if the driver does not maintain a safe distance to the vehicle ahead. The laser radar system has been commercialized as a headway warning system for heavy-duty trucks in Japan.

Microwave radar systems can also be applied to measuring the headway. They do have the advantage of measuring the relative speed (rate of change of the gap) between the vehicle and the lead vehicle, which is useful in the control system. Beam width required for AHS control will need to be relatively small in order to distinguish between vehicles in adjacent lanes and to handle curves in the road. Because of the small beam widths and limitations on size of the units it is envisioned that millimeter wave frequencies will be employed (35-95 Ghz)

One important issue regarding the above mentioned AHS components is their implementation requirements. These components can be implemented entirely onboard the vehicle, without requiring the involvement of any public agency or roadway facility. This could be an important factor to speed up the deployment process.

3.1.2.2 Microprocessor/Software Issues

AHS operations is expected to increase electronic system functionality through the incorporation of embedded computer systems. As the emphasis on AHS vehicle safety and efficiency increases, the higher automation level to support these areas will increase system and software complexity.

3.1.3 Near-Future Implementation

In addition to intelligent cruise control and collision warning systems, there are other realistic near-term opportunities available for significantly more dramatic electronic driver aids, performing higher level functions than those now available on automobiles. Examples of this include automatic steering compensation for external force disturbances and lane-center detection for driving assistance. These systems will eventually evolve to automatic lateral control system.

The steering assist system can compensate for the sudden external force disturbances such as pavement irregularities or wind gusts and stabilize the vehicle by adjusting the steering system. This will reduce the driver's effort for abrupt corrective maneuvers. The driver is, however, responsible for all driving functions.

The lane-center detection system automatically adjusts vehicle position within a lane. The system could help the driver steer in conditions of bad visibility (rain, snow, fog) or when he is fatigued, by supplying a dashboard or head-up display of the vehicle's position relative to lane center

The longitudinal control may also be improved utilizing vehicle-to-vehicle communications, transferring speed and acceleration data from the lead vehicle to the follower.

<u>AHS Scenarios Impact on Deployment</u>

One of the primary issues at this stage is selection of the AHS scenarios that will be followed for future implementation of the AHS. At this stage, it is not clear whether a vehicle-based intelligence with vehicles equipped with intelligent sensors, actuators, and microprocessors for decision making will be selected or the future system is expected to incorporate a roadway-based intelligence or a mixed command/control. Selection of either approach will significantly affect the development and deployment of the AHS components. For instance, depending on the level of command/control (e.g., I_1C_1 or I_2C_2 type RSCs) two different methods of headway and speed control may be used: a vehicle-based system (ICC in Figure 5-1) or a roadway-based system. The difference, however, is the technologies used to measure position, speed, and spacing. In a dedicated AHS lane (I_2, I_3), sensors can be located on the roadway to detect the position of vehicles in both the lateral and longitudinal planes and send messages to the on-board computer using one-way infrastructure -to-vehicle communication. The roadway may also send speed and headway commands to the in-vehicle processor controlling throttle, brakes and steering. In a vehicle-based AHS system (I_1C_1 type RSCs), the laser or radar systems detect the position and speed of the lead vehicle. The ICC microprocessor determines accelerating or decelerating needs and sends the appropriate signals to the associated actuators.

3.1.4 Long-Term Implementation

In the long-term, automatic steering and lane changing assist system may be incorporated into the vehicle control system. Figure 5-2 depicts a conceptual design for automatic steering. As seen in the figure, using sensors (e.g., photo sensors), mounted under the front bumper, the system detects the lane markers. An onboard microprocessor is then determines the steering angle based on the data received from lane detection sensors, speed sensor, etc.

The lane changing assist system is presented in Figure 5-3. Vehicle sensors such as microwave radar detectors mounted around the vehicle detect the neighboring vehicles on the left or right lane. Using data from lateral vehicle proximity detectors, the on-board microprocessor determines whether lane-changing is acceptable or not. A warning signal or sound informs the driver whether changing the lane is dangerous. Then, the driver is responsible for maneuvering the car and changing lane.

3.1.5 Fully-Automated Operation

Finally, a fully automated system may be implemented, which will provide for complete control of the driving functions for vehicles operating on specially equipped freeway facilities. The automatic driving system will be capable of lane following, lane changing, and obstacle detection.

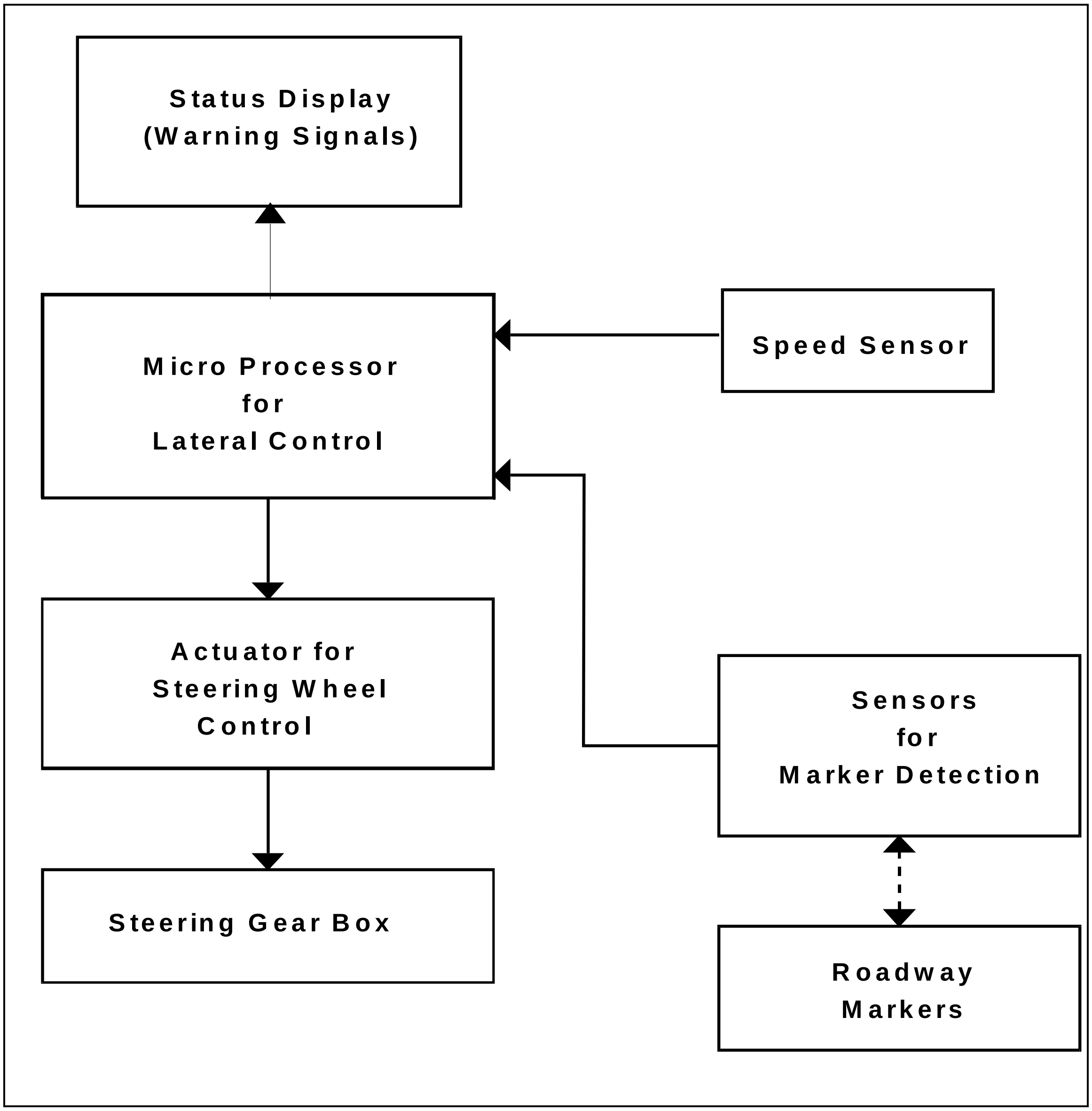

Figure 5-2. Automatic Steering Using Lane Marker Detection

The lane following system may include a combination of ground equipment and on-board sensors, wall along lanes and wall ranging systems, lane markers, lane lines, magnetic nails along paths of vehicles, inductive cables embedded under the road surface or located above the roadway, and detectors for ground equipment. However, AHS vehicles may employ a combination of sensors to provide fail-safe operation.

A typical conceptual design for an automatic driving is shown in Figure 5-4. It is seen that for a fully-automated operation, the previous vehicle detection system can be upgraded with a two-way vehicle-to-vehicle communication system. With this feature, each car will be capable of communicating with all neighboring cars running on the other lane, with leading and following vehicles, and also with traffic control center. The automatic control will be managed by an on-board electronic control unit.

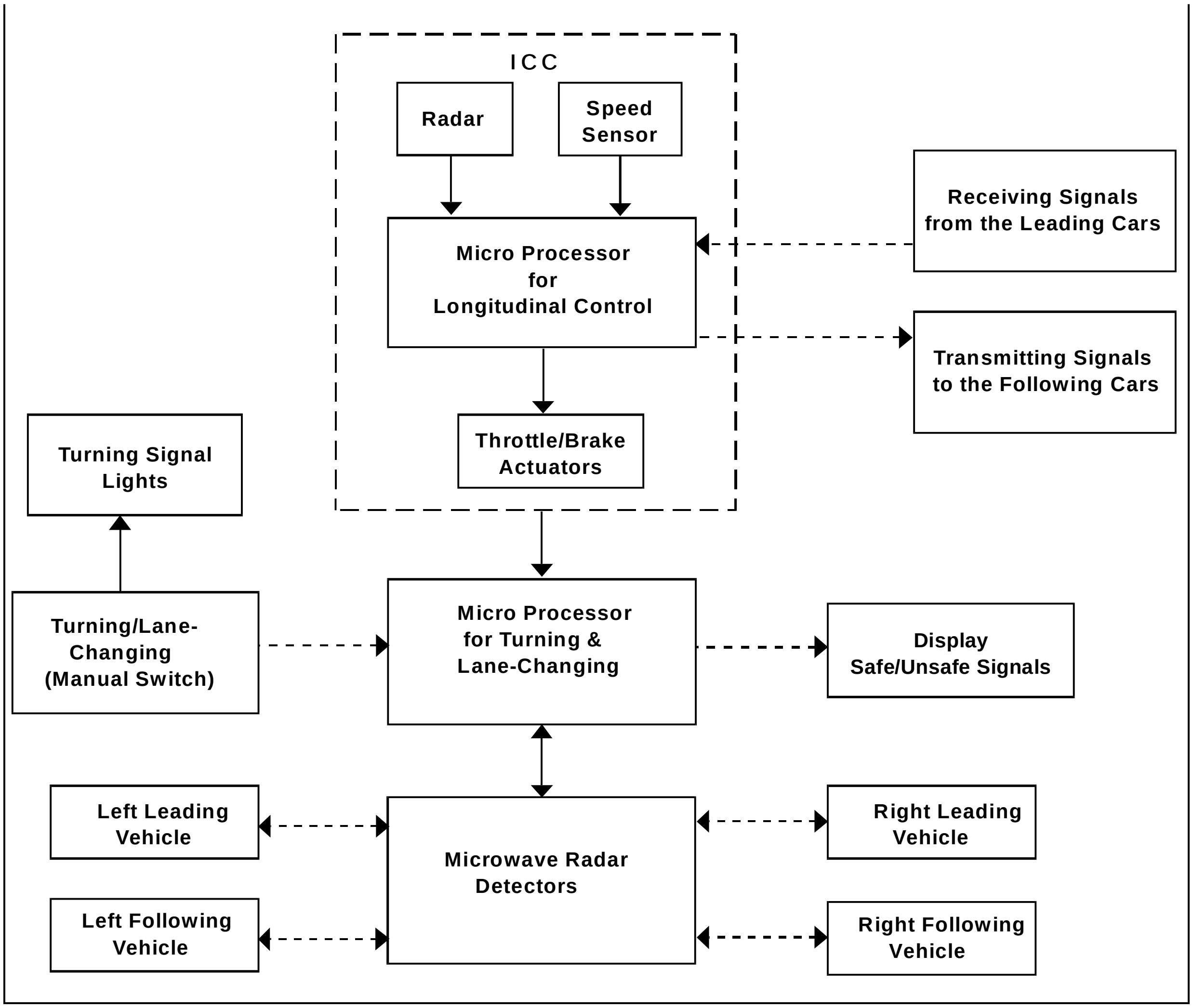

Figure 5-3. Lane Changing Assist System

Deployment Issues of the Road Geometry Recognition

If an I_1C_1 type RSC (existing highway/fully autonomous vehicle) is selected, a full capability of autonomous driving operations will not be possible without road geometry recognition. Development of technologies for recognizing the driving environment will be one of the most critical technical issues. In the foreseeable future, it will be difficult to achieve satisfactory recognition of the driving environment on the existing highways. A more likely approach would employ some form of infrastructure equipment to provide a lateral reference such as magnetic markers, which would not be a truly all autonomous system.

3.2 IN-VEHICLE COMMUNICATION ISSUES

In an AHS vehicle, the on-board processor should interface with many components such as actuators, sensors, on-board communication equipment, monitoring devices, driver-vehicle interface, and so on. To provide efficient and complete diagnosis of situations, the on-board processor must obtain a large amount of information from sensors. This includes:

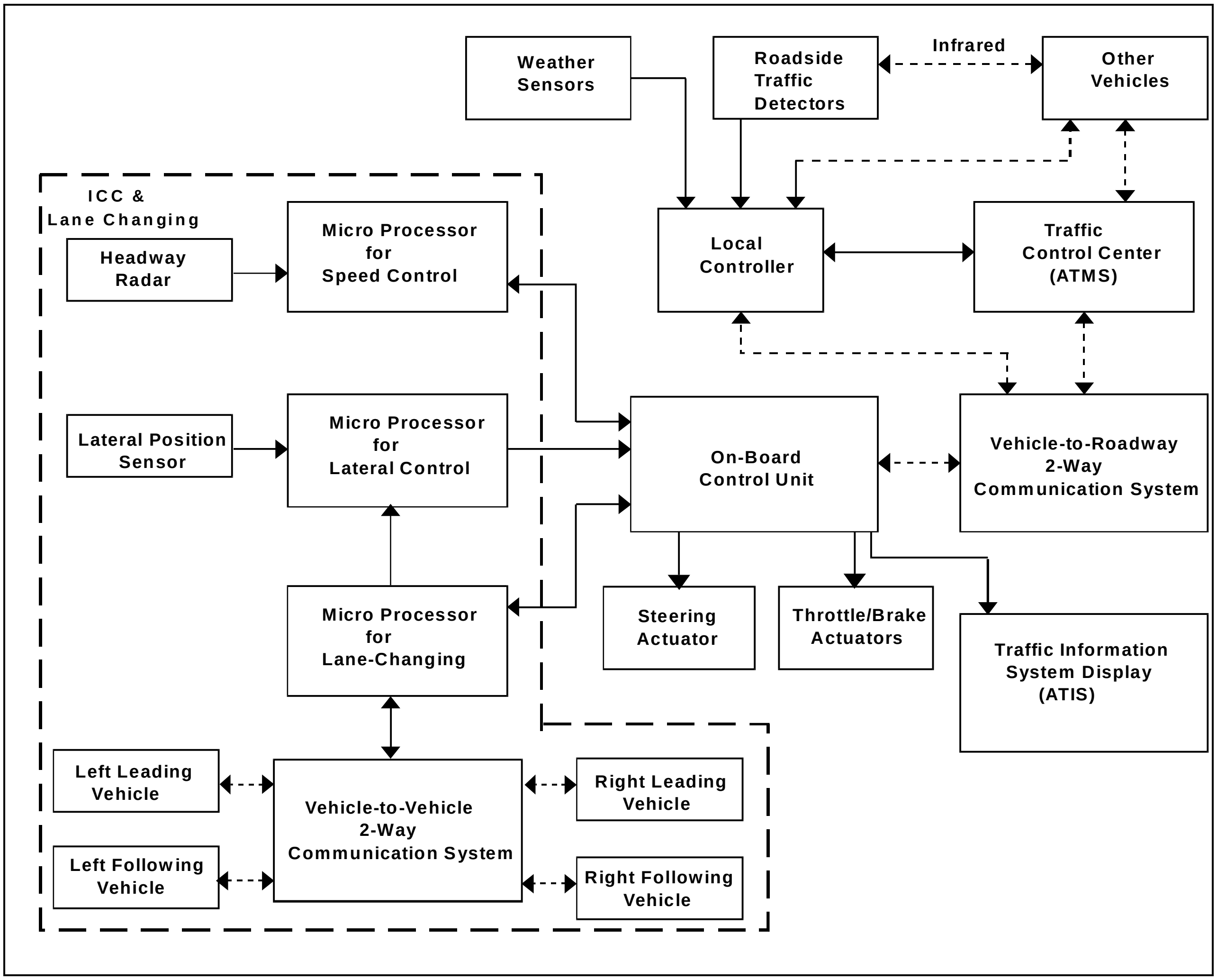

Figure 5-4. Fully-Automated Operation

1. Data provided by the external (exteroceptive) sensors such as radar, global positioning system (GPS), telemeter, lateral position sensors, cameras and so on which are used to detect and identify obstacles, geometry, and other vehicles in the platoon or on the adjacent lanes.

2. Data provided by the process (proprioceptive) sensors which monitor velocity, longitudinal and lateral accelerations, wheels orientation, yaw rate, brake position, etc.

The addition of this information, will greatly increase the volume of data transmission. The data transmission system will need to deal with many requirements, including:

- Satisfy the strict requirements on the latency time for real time control

- Provide an effectively failure diagnosis system

- Provide an effective driver support information system

- Provide an effective vehicle movement managing system

To satisfy the above requirements, the structure of an in-vehicle communication system must include the following three subsystems: 1) in-vehicle networking, to provide physical connection between vehicle dynamic systems and vehicle sensors, 2) main processor for decision making and vehicle control, and 3) dynamic data manager, to interface the perception part with the decision part. In the following sections, some of the related issues/risks involved in interfacing are addressed.

3.2.1 In-Vehicle Networking

AHS vehicle communication systems are expected to not only improve performance and increase safety, but also provide fail-safe operation. The communication system must provide for the integration of many intelligent sensors and actuators into the vehicles. Among several safety requirements, any in-vehicle communication system should deal with two primary reliability issues:

1. Each electronic control unit should operate independently in order that failure of one system does not affect the operation of the other systems or if common computers are used, methods must be employed to insure extremely low failure rates, such as redundant systems.

2. During a failure of any component, the overall system control should be capable of degraded operation to bring the vehicle's dynamic behavior to within a safe operating range as quickly and smoothly as possible.

To meet the AHS demands for higher safety and performance, a modular, flexible system design is needed. This has been realized in state-of-the-art vehicles with the use of multiplex systems which provide for growth at a reasonable cost and minimum reprogramming.

3.2.1.1 Multiplexing Technique

The multiplexed wiring technique, which has been developed in recent years, replaces the conventional wiring system with a single wire or cable, thereby reducing the vehicle weight, complexity, and cost. This technique allows the control messages flash between sensors, actuators, instruments, engine/body computers on a single line. The system is capable of sending each message to its intended destination, while avoiding data collision between signals.

Figure 5-5 depicts a typical multiplexing control system. As seen in this figure, a multiplex system consists of several systems connected together by means of the BUS. The output signals from each individual electronic control unit (ECU) are applied to the system itself and the network through communication integrated circuit (IC). This provides a highly reliable communication system which includes the following benefits:

- No system will be affected by either failure of the network or other individual systems.
- Addition of new systems or elimination of the unnecessary ECUs will be possible.
- Simplified and fault diagnosis will be available.

The self-repair feature of the multiplexing system will also increase the reliability of the vehicle's electronics which is a major requirement for AHS operation. This feature allows key components to repair themselves and keep operating until the vehicle can be taken in for service. Another distinct feature, is that the system facilitates vehicle diagnosis in just seconds. Recalling that integrity monitoring and preventive maintenance are major safety requirement of the AHS vehicles operation, this feature is very promising. In summary, the benefits of multiplexing communication include: enhanced diagnostics, distributed control, and total wire reduction.

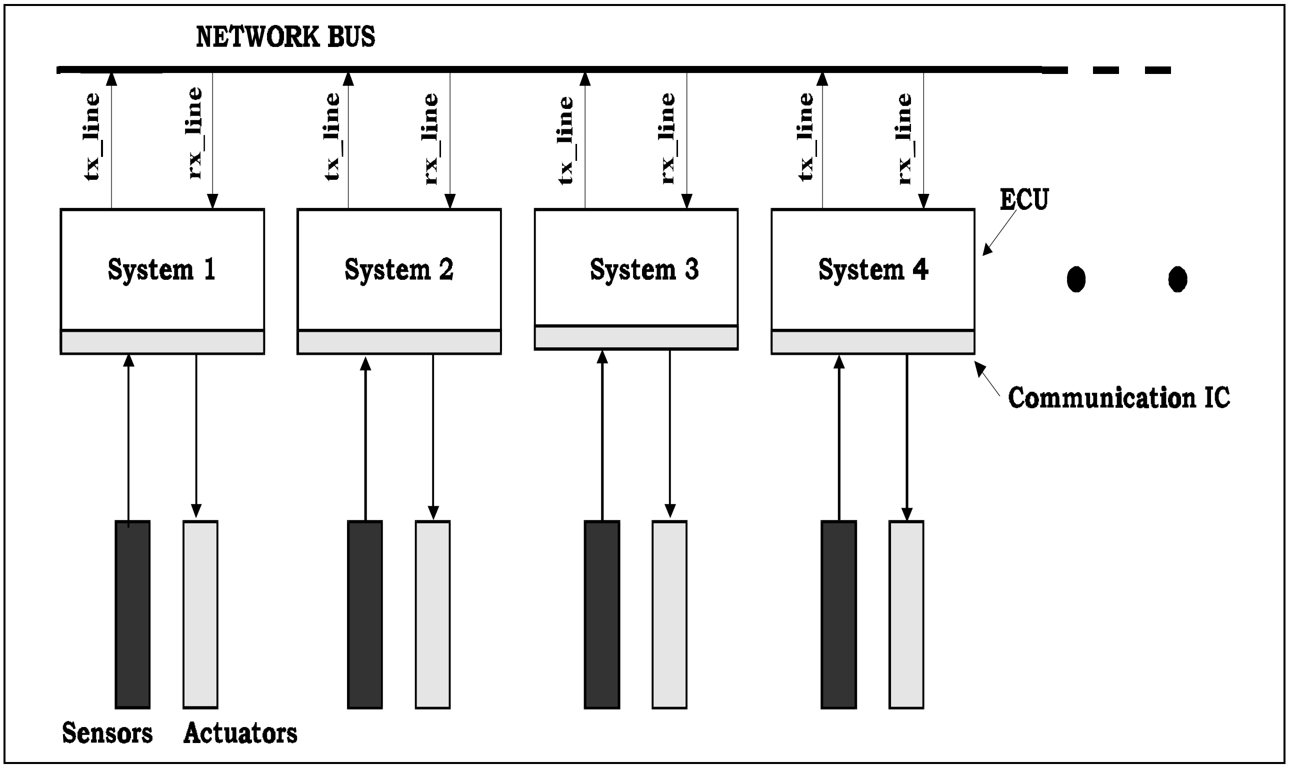

Figure 5-5. A Multiplexing Communication System

Numerous protocols have been developed for multiplexing communications, which cover all types of applications from low speed (Class A) body electronics to high speed (Class C) real-time applications. Table 5-3 lists the three classes of automotive data links. The class type is defined by the frequency at which these signals are generated. The high speed communication is the method, which will handle the information exchange in an AHS vehicle.

3.2.1.2 High Speed In-Vehicle Network

As described earlier, to satisfy the latency time requirement of real time control systems, each control system of the network should have access to all information. This however, will raise the question of priority and will require high speed signals to be transmitted between ECUs. To meet the high reliability requirement of the AHS vehicles, the high-speed system must include the following characteristics:

- The failure of any controller's communication IC must not affect transmission between other devices.
- The system must have the ability to detect errors in transmission and to retransmit the signal.
- Transmission must be simultaneously received by all ECUs (current vehicle systems utilize a transmission rate of at least 1 Mbps). Actual data speed will be determined from a bottom up study of data flow requirements and message accuracy and dynamic range.
- For real-time control, message length must be short.
- Maximum delay time must be compatible with data latency requirements.
- The system must offer modular and flexible design.

One important reliability issue associated with this technique is achieving a global prioritization, where the message with the highest priority on the entire network is guaranteed first access. The problem with this scheme is that frequent high priority messages can "hog" the network and cause large latencies for low priority messages. This problem, however, has been addressed in some of the protocols under study in which the impact of high priority messages on latency will be assessed. There are many other issues on operation, reliability, cost and so on, some of them listed below.

Table 5-3. SAE Classes of Automotive Data Links

Class	Description	Characteristics	SAE Protocol
A	Dedicated use links	Low speed, 0-1 Hz	
B	Data sharing application	Medium speed, 1-100 Hz	SAE J1850
C	Real time control	High speed, above 100 Hz	SAE J1583

3.2.1.3 Operational/Reliability issues

- In a multiplexing communications, partial loss of a transmission of periodic data can be estimated with the information stored from the previous transmission and the information transmitted subsequently.

- Lost information during a fault, can be estimated from hardware redundancy and detection filter.

- A loss of event-driven data can be prevented by reducing the transmission period at the cost of an increased bus utilization and longer transmission delay times. It should be, however, noticed that transmission delay could be a crucial factor in a control system, in particular in a real-time control system. Therefore, it is essential that the delay be minimal. This problem may be overcome by evaluating the effect of the selected delay times before implementation.

- The transmission rate is a key factor in defining the cost of the network. High bandwidth systems require more stable clocks, faster microprocessors, and high quality media that may increase the system cost.

3.3 RETROFITTING ISSUES

Although at this stage, retrofitting of the promising components into the existing vehicles may seem infeasible, but considering the actual implementation of the AHS system within the next 20 to 50 years, many changes will be made in manufacturing of the new vehicles. These gradual changes will eventually facilitate retrofitting of the AHS components into the non-AHS vehicles at that time. There are however, many issues regarding the achievement of an autonomous driving capability for a manually controlled, ordinary-size vehicle. Some of the important issues which need to be considered include:

- *Size* - Integration of many new vehicle components, such as sensors, actuators, signal processing equipment and other on-board devices on the vehicle would require additional space inside the vehicle. It should be, however, noticed that even with acceptable sizes of the in-vehicle equipment, retrofitting may not be possible for all cars. It is expected that the spaces and requirements for retrofitting of each major in-vehicle system will be introduced with a certain model year, depending on the deployment of that component.

- *Actuators* - Each make and model vehicle has a different layout of engine/control components and steering components, which may have a unique problem on the issue of retrofitting it with actuators. However, electronic actuators are coming into use on vehicles already for non-AVCS purposes, so future retrofitability should be possible.

- *Standardization* - Retrofitting needs for standardization of interfaces. Regulations must place responsibility on manufacturers of apparatus for ensuring its compatibility and compliance. This standardization must be driven by government. Also, system reliability and manufacturing quality standards will need to be developed and monitored by an appropriate agency.

- *Liability* - In addition to the feasibility of retrofitting an AHS component into a non-AHS vehicle, retrofitting needs clear understanding of liability issues.

- *Cost* - Retrofitting new components on an existing vehicle are expected to be considerably more expensive than if they were installed as original equipment. This added cost may preclude any significant retrofitting.

3.4 RELIABILITY ISSUES

The overall reliability of the AHS including corrective maintenance of the AHS vehicles and microprocessor/software reliability will be addressed under Activity E (malfunction management). Also, throughout this report, we addressed reliability issues of the AHS components, where applicable. This section, however provides an overview of the general issues associated with reliability of the AHS vehicle operations.

In a fully-automated operation, the reliability of the AHS vehicle components is required to be very high. On the other hand, it is a known fact that reliability may be decreased by increasing the complexity of the in-vehicle components due to the introduction of various types of sensors, actuators, communications equipment and so on. There are however, some exceptions to the above statement, such as driving assist systems. Systems such as collision warning, intelligent cruise control, ranging and infrared imaging sensors may increase the overall reliability of the vehicle operation while the control system remains dependent on the driver. It is assumed that the driver does not totally rely on these driving assist systems and he employs them to enhance his senses and driving capabilities.

Electromagnetic compatibility and software verification/validation will also add new dimensions to the reliability of in-vehicle equipment. Computer software will be central to the safe operation of the AHS vehicles. It should be noticed that in many systems, hardware fail-safe devices cannot protect the vital role of the control software. An example is the fly-by-wire systems for inherently unstable aircrafts for which no hardware fail-safe is possible and the reliability of the aircraft depends on the reliability of the software.

Possible Solutions

There are several ways to meet these requirements and assure the general public of the safety and reliability of the AHS systems, such as:

- Continuous built-in test monitoring of all critical systems to detect malfunctions.

- Periodic inspections and preventive maintenance of the AHS will probably be employed on vehicles. This may seem to hinder acceptance of the AHS, however it will be necessary to detect deteriorating conditions that are not readily testable on-board the vehicle, such as brake wear. Today's vehicle can operate for long periods without requiring any maintenance or repair. We may expect that, to some extent, future vehicles AHS components will also be manufactured with similar quality.

- Ability of the system to provide graceful degradation(fail-soft) in case of a temporary malfunction. Fail-soft modes are required to ensure the reliability of the system. Such modes could be facilitated through component redundancy and/or back-up operating plans.

- Redundancy for fault tolerance. Redundancy is needed to cope with malfunctions. For instance, comparing a microwave radar system and a laser radar for longitudinal control, the laser system is preferred for its range measuring accuracy while the microwave radar system will perform in adverse weather conditions. Therefore, for an autonomous vehicle, combined use of both a microwave and a laser radar system could provide reliable operation. It is clear that this could increase the initial cost of the vehicle which will be another hindering factor. Thus, to come up with an acceptable level of reliability with an acceptable initial/ maintenance costs for the vehicle, detailed trade-off analysis will be needed.

- Development of specific standards and legislations to cover certain as-pects of reliability. An example is the regulations enacted by the European Community on the electromagnetic compatibility (EMC) of the vehicle electronic systems. This EMC directive covers all vehicular electrical and electronic systems sold or bought into service within the community.

4.0 CONCLUSIONS

The primary objective of the vehicle operational analysis activity was to Identify vehicle operational issues which will need to be addressed during the development of AHS. These included several areas such as reliability and maintainability, retrofitting of the new components to the existing vehicles, evolution of driving assist systems to a fully-automated operation, and in-vehicle communications.

This study mainly focused on overall reliability and operational issues associated with deployment of the AHS components including in-vehicle networking and retrofitability of the new components into manually-driven vehicles. These are summarized in the following sections.

4.1 SUMMARY OF ISSUES AND RISKS

Table 5-4 presents a summary of the issues and risks identified under this activity. The table also includes possible solutions and/or recommendations to the raised issues and the impact of each issue on the RSCs or other activities. For a detailed description of each issue, the reader may refer to the related subsections of this chapter.

4.2 INDICATIONS

In addition to the issues/risks identified under this study and provided in the previous section, there are several potential conclusions which are worthy of considerations:

- The addition of the required AHS components may result in a decrease of the reliability of the vehicle as a whole. It is believed that through preventive maintenance, periodic inspections, use of redundancy, and system health monitoring, a failure rate at least as low as today's experience can be maintained. Consideration must be given to the impact on reliability during the design process.

- Tradeoffs will need to be made between redundancy and cost impact. To make all AHS sub-systems redundant will, no doubt, result in the AHS equipment out of the market. Car should be exercised during the design process to employ redundancy in areas where safety considerations dictate it, such as steering control systems. Built-in tests can be employed to detect a failure or below-specification performance, without the use of redundancy — provided that the malfunction can be managed. For example, if a forward-looking radar system fails, the vehicle can be brought to a stop in a breakdown lane. If the radar has a low failure rate such that few failures occur, this approach of stopping the vehicle may be quite acceptable as opposed to providing redundant radar sensors.

- Since AHS Systems will employ sophisticated microprocessor-based systems for vehicle control, system health monitoring, and communication of signals and commands, software verification and validation monitoring will be of prime importance. Software verification must be part of the malfunction monitoring system and an integral part of the design process, rather than an after-thought, once the software is structured.

Table 5-4. Summary of Issues and Risks

Issue No.	Issue/Risk Descriptive Title	Description/Recommendation	RSC Impact	PSA Task Impact	Where Discussed
VO-1	AHS components may decrease the reliability of the vehicle system by increasing the complexity	Preventive maintenance, component redundancy, back-up operations, ability of fail-soft mode, and self-monitoring/integrity monitoring will be required to assure an acceptable reliability level.	All RSCs	CI, CO, LL, MM	3.4
VO-2	Periodic inspection and maintenance of the AHS components may hinder acceptance of AHS because of the cost and time needed.	Auto manufacturers should provide components with acceptable reliability and long-term service/ maintenance required.	All RSCs	CI, CO, LL, MM	3.4
VO-3	Extensive redundancy may increase the initial cost of the vehicle	Trade-off decisions between required maintenance, redundancy and fault tolerance will be needed.	All RSCs	SI	3.4
VO-4	AHS operations will depend on the reliability of sophisticated microprocessor-based systems with complex embedded software.	Software verification and validation must be included in the integrity monitoring of the AHS vehicles.	All RSCs	CI, CO, LL, MM	3.4
VO-5	AHS components will increase number of vehicle electronic systems and consequently decrease the overall system reliability due to the greater number of wire harness and connectors	Multiplexing technique will replace the conventional wire connections with a single wire, thereby reduce the vehicle weight, cost and complexity.	All RSCs	CI, CO, LL, MM	3.2.1
VO-6	Frequent high priority messages can hog the network and cause large latencies for low priority messages.	Some communication protocols such as CAN assess the impact of high priority messages on latency.	All RSCs	CI, CO, LL, MM	3.2.1
VO-7	The evolutionary deployment of AHS components may require frequent changes and modifications to in-vehicle networking.	The promising communication system must include modular and flexible design to allow for the later addition or deletion of ECUs.	All RSCs	CI, CO, LL, MM	3.2.1

Table 5-4. Summary of Issues and Risks (continued)

Issue No.	Issue/Risk Descriptive Title	Description/Recommendation	RSC Impact	PSA Task Impact	Where Discussed
VO-8	A loss of event-driven data cannot be recovered and will affect the system.	Reducing the transmission period may prevent the problem. This however, may increase bus utilization and transmission delay times.	All RSCs	CI, CO, LL, MM	3.2.3
VO-9	Loss of data due to a faulty sensor will affect the system operation.	In a multiplexing system, lost information can be estimated from hardware redundancy.	All RSCs	CI, CO, LL, MM	3.2.3
VO-10	AHS vehicle control system will require real-time signal control with a high-speed network.	High speed communication with a large data volume will increase the system cost. However, drastic cost reduction is essential to provide affordable vehicles.	All RSCs	SI	3.2.1
VO-11	New equipment may not be compatible with the existing systems	Regulations/standards must be developed to place responsibility on manufacturers for ensuring the compatibility of the products. The standardization must be driven by government.	All RSCs	SI	3.3
VO-12	Retrofitting of new components may not be possible due to the different layout and design of the vehicle components.	Electronic systems may be retrofitted to majority of the existing vehicles. Mechanical elements such as actuators may cause problems and need a kit for each car type.	All RSCs	All	3.3
VO-13	Development of cooperation plans between public and private sectors may affect deployment speed of AHS components.	Some of the driving assist systems, such as intelligent cruise control can be implemented entirely onboard the vehicle, without requiring the involvement of any public agency or roadway facility.	All RSCs	CI, CO, LL, MM , S I	3.1.2

- A fully automated highway system is expected to evolve from a driving assistance stage. Deployment of the AHS related technologies for real world use will require a considerable period of research and development. It will be necessary to proceed with this development work in a step-by-step process, while maintaining a long-term vision of the future direction.

- Some preliminary versions of the AHS functions have already been developed and tested. Examples include intelligent cruise control (Mercedes Benz, Lecia, TRW), longitudinal crash warning detectors (VORAD Radars, installed in Greyhound busses), and Navigation system (Oldsmobile and Japanese manufacturers).

- Multiplexing communication system is the promising technology for AHS in-vehicles communications. This technology offers modular and flexible system design for automotive applications.

4.3 FUTURE STUDY REQUIRED

The broad range of sophisticated technologies needed for autonomous driving systems will require a considerable period of research and development before they can be deployed for real-world use. Some of these technologies have already been developed, some are underway and some are not expected in the near future. However, at this stage of study, some areas are needed to be completed in order to facilitate early deployment of the AHS. These include, but not be limited to the following areas.

- *AHS Scenarios.* There are many scenarios proposed for the future automated highway systems with different levels of intelligence assigned to the vehicle and the roadway. The development of the AHS technologies is dependent on the type of the selected scenarios, e.g., will it be a distributed or centralized system. It is very crucial at this stage of the work to study the feasibility of the proposed scenarios and select the ones which will be implemented in the next 50 years or so. Considerations needs to be given to how the AHS system can grow and enhance. Concepts and technology selected are not likely to change rapidly, but rather must evolve. This will provide a clear vision of the future system and speed up development and deployment process of the related technologies. In this regard, a trade-off analysis on the costs associated with the level of centralization and distributed control is needed to compare different scenarios and provide a basis for selection.

- *In-vehicle Communications.* One of the main features of an in-vehicle communication system is that it allows prioritizing the input signals to be delivered to different control systems. There are, however several problems with prioritization. One of the primary design concerns is the system response to emergency signals from vehicle sensors, other vehicles on the lane (through one- or two-way communications) and from roadside facility. How the system will process these signals and handle the data flow will require considerable study.

- *Reliability.* What elements and redundancy are required for a graceful degradation? What AHS components must be fully redundant or have backups with reduced performance: feasibility, cost, reliability.

- Algorithms needed to perform detection, discrimination and data analysis.
- *Driver-vehicle interface.* Types of alarm system, audio and/or visual systems, and location of displays in order to provide effective and efficient services while not distracting the driver attention.
- *Steering.* Reference systems needed to measure the lateral position error for the lane following function.
- *Retrofitting*. What elements of the AHS can be retrofitted to the existing vehicles: methods, costs, and reliability.

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