Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Contract Overview

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PRECURSOR SYSTEMS ANALYSES

OF

AUTOMATED HIGHWAY SYSTEMS

Contract Overview

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

NOTICE

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16. Abstract

This overview report encompasses all the activity areas of the Precursor Systems Analyses of Automated Highway Systems (AHS). The report presents the operational requirements, high-level architecture, technical requirements, comparative analysis methodologies, and a preliminary identification of issues and risks for all 16 areas of analysis. Representative System Configurations (RSC's) are generated for use in all analyses whenever a diversity of system attributes is required. The RSC's identify specific alternatives for twenty attributes within the context of three general RSC groups. Highlights of each of the 16 activity areas are included: a summary of each activity, key findings, conclusions, recommendations, and identified issues and risks. Conclusions and observations that transcend the individual activity areas and/or are best discussed in a manner which allows the development of inter-activity topics are also presented, with liberal cross-references to the 16 individual activity area reports. This inter-activity section discusses system characteristics, impacts, operations/maintenance, AHS deployment, and funding.

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EXECUTIVE SUMMARY OF ALL ACTIVITY AREAS

Advances in automotive, electronics, and communications technologies have provided opportunities to dramatically improve the quality of roadway transportation in the United States. The Intelligent Transportation System (ITS) represents one response of the transportation community to this opportunity. The ITS includes transportation management, traveler services, and a technologically advanced program, the Automated Highway System (AHS). The Precursor Systems Analysis (PSA) program has as its objective the comprehensive systems analysis of the AHS, in order to identify principal benefits, issues, design options, operational approaches, and deployment strategies which may be used as a preliminary functional description for a system specification.

Introduction and RSC's

The PSA analyzes three Representative System Configurations (RSC's): RSC 1, a platoon system controlled principally by the infrastructure, RSC 2 , a platoon system with primarily autonomous vehicles, and RSC 3, a uniformly-spaced vehicle system, again controlled primarily by the highway infrastructure. Enhanced safety, reduced travel time, greater driver comfort, potential reduction in fuel consumption and vehicle emissions, and reduced traffic congestion are significant benefits derived from these systems.

Many issues that require further analysis were identified during this study. For each RSC, the general design, operational plan, and maintenance requirements were developed. Revolutionary versus evolutionary strategies were compared and approaches to funding, a critical part of deployment, were considered.

Activity Areas

The PSA program consisted of analyses in 16 activity areas. The activity areas and their research results are:

Activity A — Urban and Rural AHS Comparison

This activity analyzes and compares the technical and operational requirements of an AHS in urban and rural environments. The characteristics of urban freeways and rural highways are compared to define common issues and risks and indicate areas of divergence in compatible system implementations. The comparison addresses three major areas: trade-offs among the goals of automated control in urban versus rural environments; the distinct operating characteristics of AHS subsystems in rural highways; and the design considerations for several AHS-specific elements. The issues and risks concerning the most cost-effective approach to instrumentation content in terms of the control loop dynamics and potential market penetration in both environments are identified.

Activity B — Automated Check-In

Requirements for an effective check-in system for vehicles wishing to enter an automated highway are analyzed in depth. The critical vehicle and driver functions are defined. Several methods for validating each function are proposed and analyzed. Infrastructure facilities are proposed to accomplish these tasks efficiently. This study identified many significant issues and risks; these are catalogued in the report.

Activity C — Automated Check-Out

Check-out consists of transfer of vehicle control from the AHS to the driver. Activity C evaluates potential automatic-to-manual transition scenarios in terms of relative feasibility, safety, cost, and social implications. Check-out alternatives range from minimal to extensive testing of the operator and vehicle. The vehicle functions analysis summarizes functions that are critical to safe manual operation and proposes several options for validation. Two possible check-out processes are discussed, one for AHS lanes dedicated to automated traffic, and one for mixed-mode lanes in which AHS and non-AHS vehicles are traveling. Transition to manual control includes preparing the driver to resume manual operation prior to release of vehicle functions. Proposed tasks that could be used to determine that the driver is ready to take control of the automated vehicle are examined.

Activity D — Lateral and Longitudinal Control Analysis

This activity consists of a preliminary control systems analysis of each of the RSC's in terms of expected performance, feasibility, complexity, effect on system safety, roadway capacity, driver involvement, operation, and maintainability. Communication systems and sensors are also discussed in their relation to vehicle control. Trade-offs are presented for a variety of system configurations to emphasize the options available to the AHS designer.

Activity E — Malfunction Management and Analysis

This activity identifies malfunctions of the AHS vehicle, wayside electronics, roadway, and driver subsystems, along with possible methods of detecting the malfunctions. Possible strategies to manage the malfunctions are proposed. Measures of effectiveness by which the strategies may be evaluated are defined, along with a method of using the measures of effectiveness. Based on this method, conclusions are drawn as to the effectiveness of the strategies. Issues related to management of AHS malfunctions are identified.

Activity F — Commercial and Transit AHS Analysis

When an AHS is deployed, its design and operational attributes will differ considerably depending on whether or not commercial and transit vehicles are accounted for. Activity F analyzes the implications of commercial and transit operations on an AHS. The physical characteristics of large vehicles are analyzed with regard to differences they may cause in AHS design and operation. The influence of operational issues, such as differences in acceleration and braking, on facility design are considered. Human issues, such as acceptance by passenger car occupants, safety, comfort, and actual versus perceived risks, are examined. Issues related to the expected number of heavy vehicles which would use AHS are addressed.

Social and political issues related to transit use of AHS are addressed. It is recommended that these issues be weighed along with technical issues as AHS planning proceeds.

Activity G — Comparable Systems Analysis

This analysis is performed in order to derive benefits from past experience in the design, implementation, deployment, and operation of comparable systems that could be applied to AHS. The activity identifies 12 existing systems that share a number of characteristics with AHS. Public interaction, safety, reliability, and complexity are emphasized. Three systems, the Bay Area Rapid Transit system, automotive air bag systems, and the TRAVTEK automotive navigation system, were chosen for analysis in detail. Lessons learned in the development and deployment of these systems offer insight into appropriate techniques for technical systems specifications, verification of system performance, initial pre-deployment, quality assurance, human factors, and maintenance. Non-technical issues are also explored including the effects of political pressure and management/funding philosophy. Concerns about privacy, liability, and public confidence are also examined.

Activity H — AHS Roadway Deployment Analysis

This activity addresses highway infrastructure topics that will be encountered when AHS is deployed. AHS right-of-way requirements are analyzed, based on the following criteria: width of AHS vehicle, ability of the system to keep the vehicle on the desired path, barrier width (for dedicated systems), presence or absence of shoulder (breakdown lane), and width of the shoulder.

AHS capacity is established by utilizing traffic densities based on platoon sizes, inter-platoon spacing, and intra-platoon spacing. Inter-platoon spacing considered several failure assumptions and the requirement that inter-platoon spacing provide safe braking distances based on the failure assumptions. Based on this analysis, it is concluded that AHS capacities as high as 6,000 vehicles per lane per hour would be feasible. This conclusion established the range of capacity used in further PSA analyses.

Activity I — Impact of AHS on Surrounding Non-AHS Roadways

This study considers the effect that AHS traffic would have on the non-automated freeway and street system as it approaches and departs from the automated roadway. The higher speeds and capacities possible with an AHS facility will attract traffic into the AHS lane from both the general-purpose freeway lanes and the parallel arterials. The increased AHS traffic will have both positive and negative impacts on the surrounding street system.

The analysis includes modeling and evaluation of the operations of a freeway corridor with and without an AHS lane. Effects of operations with and without an AHS lane on the surrounding roadways are then evaluated using traffic operations measures of effectiveness. The surrounding roadways include the general-purpose freeway lanes, freeway ramps, parallel arterials, and cross streets. Additional modeling analyzes the impact of the AHS traffic on the cross streets. The Highway Capacity Software (HCS) program is used to evaluate the level of service on alternative configurations of the cross streets and parallel arterials. The physical requirements of the AHS lane and ramps are analyzed to determine the impact on the surrounding streets. The modeling results are also used as input to Activity P — Preliminary Cost/Benefit Factors Analysis. Qualitative as well as quantitative impacts are addressed. AHS is reviewed from the perspective of an urban planner.

Activity J — AHS Entry/Exit Implementation

This activity focuses on the traffic operational impacts of AHS entry/exit facilities at the points where they interface with the local street network. Information and results from several of the other PSA activity areas are utilized in the conduct of the entry/exit research.

Various strategies for AHS entry and exit are considered and their attributes identified. Analyses determined the operating conditions based on AHS volumes and ramp volumes from other PSA studies. Measures of effectiveness are established to allow comparison of different entry and exit strategies.

Activity K — AHS Roadway Operational Analysis

This study considers the roadway operational requirements of an 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 this activity. Similarities and contrasts between AHS and conventional highways are considered, analyzed, and discussed to raise issues and risks. Significant urban/rural, passenger/heavy vehicle, and RSC differences are covered. 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 pre sented. The fault tolerance of the AHS is assessed. Results of interviews with personnel in charge of several existing TOC's are summarized. The role of the driver in an AHS is discussed.

Activity L — Vehicle Operational Analysis

Present and future designs of automobiles, light trucks, and heavy trucks are discussed. The analysis relates these hardware systems to the potential critical components of the AHS vehicle. Communications equipment and electronic control hardware and software are reviewed in detail. Reliability and retrofit issues are analyzed. Fail-soft design approaches which could be applied to the AHS vehicle system are discussed. Vehicle technologies which are common to AHS and non-AHS systems are catalogued.

Activity M — Alternative Propulsion Systems Impact

This study examines the impact of alternative propulsion systems and fuels on the deployment and operation of the AHS. Alternative propulsion systems and fuels are compared to the gasoline-fueled spark-ignition engine in the areas of: specific power, drivability, pleasability, emissions, infrastructure support, production readiness, cost, and energy efficiency. Issues and risks related to the deployment of a large fleet of alternative propulsion vehicles on the AHS are examined. Alternative AHS configurations are identified and analyzed for their compatibility with alternative propulsion systems and fuels. Long-term design issues and enabling technologies required to incorporate alternative propulsion and fuel systems into AHS are identified.

Activity N — AHS Safety Issues

This study addresses the issues of AHS safety from a system design standpoint. Four general areas of concern are discussed: failure prevention in the areas of vehicle subsystems, infrastructure instrumentation, and roadway mechanics; implementation of complex systems in terms of reliability and redundancy; structured methodologies for supporting systems assurance; and collision avoidance in the presence of external disruptions. The trade-offs involved in maintaining a certain level of safety using the most effective approach are addressed. The implications of system configuration in terms of headway maintenance policy and coordination units are presented. Examples are used to illustrate the relative vulnerability of each RSC to a variety of hazards. Recommendations are made concerning specific systems configurations attributes which have significant impact on system safety requirements.

Activity O — Institutional and Societal Aspects

This study addresses institutional and societal aspects of AHS in four areas: impact on State and local governmental agencies, environmental issues, privacy and driver comfort, and vehicle-driver interface. Issues relating to the feasibility and practicality of developing and implementing AHS are discussed and potential courses of action for issue resolution are identified.

The study discusses the impact of design, operations, and maintenance issues on State and local government agencies. Issues include: uniform design standards, educational capabilities, agency coordination, cost effectiveness, staff training, emergency response, liability, and maintenance needs. Environmental issues are discussed in three main areas: travel issues relating to demand, emissions, fuel usage, noise levels, and others; infrastructure and urban form issues such as visual impact, neighborhood cohesiveness, impact on non-automated roadways, seismic safety, and others; and institutional issues such as barriers among stakeholders, incomplete and inaccurate information, and lack of sufficient involvement by non-highway institutions. Suggestions for resolving these issuesinclude: models to more accurately forecast AHS impacts, education, communication, and participation to help dissolve barriers. Privacy and driver comfort issues include: vehicle and driver information requirements, potential technology requirements, psychological factors, and legal aspects. Vehicle-driver interfaces are illustrated with sketches of potential vehicle displays and controls. Driver interface concepts vary in complexity, hardware usage, and ease of retrofit. Typical AHS situations such as check-in, check-out, entry/exit, maintenance operations, and driver activities are also shown.

Activity P — Preliminary Cost/Benefit Factors Analysis

This analysis establishes a framework for the evaluation of benefits and costs of a hypothetical AHS highway project. The support of Federal, State, and local agencies for AHS programs will depend on strong projected economic returns from AHS. Analysis of a hypothetical AHS project examines the main risk elements as well as the principal sources of benefits. Guidelines for strategies of development and further research are provided. The benefit-cost analysis provides key findings in the following areas: travel time, improved convenience, economic activity benefits from congestion relief, urban form and livable communities, AHS and arterial congestion, operation thresholds, and vehicle cost.

Cross-Cutting Conclusions/Observations

Towards the end of this PSA program, all members of the research team met and developed a list of cross-cutting conclusions and observations. The following team vision of AHS is a synthesis of those cross-cutting conclusions and observations.

One of the fundamental aspects of AHS design is the division of instrumentation between the infrastructure and the vehicle. Certain system design elements, namely sensing and control, should be principally based in the vehicle. By so doing, the overall cost per user, assuming comparable performance, would be less. A failure in an AHS vehicle, especially on a multi-lane highway, would have less impact than the failure of an AHS infrastructure component. Vehicle components may be tested earlier in the AHS development cycle, before final system integration, and this is another reason for favoring in-vehicle control and sensing systems. Overall control of the relationship between vehicle cells or platoons, response to most malfunctions, and high-level vehicle guidance should be managed by the wayside infrastructure.

A platoon is a group of cooperative, coordinated, non-autonomous vehicles. Coordination of vehicles within a platoon is primarily determined by individual vehicle controls (merging into a platoon and splitting from it are cooperative with the wayside), whereas coordination between platoons is completely determined by the wayside command structure. Close inter-vehicle spacing reduces momentum transfer in a collision, thus enhancing safety, has aerodynamic benefits causing lower overall emissions and fuel consumption, and is more operationally efficient, thus reducing travel time and increasing capacity. Close spacing adversely affects driver acceptance, increases the frequency of minor incidents, and challenges current technological capabilities. Spacing can be increased to a distance which lacks the disadvantages of close spacing without risking high momentum transfer impacts if braking control can be coordinated through vehicle-to-vehicle communications. This increased spacing can provide almost the same efficient operation that close spacing allows.

The team reached several conclusions regarding roadway system design. Check-in and check-out stations are required; however, these operations should create little or no delay and should be associated with special AHS ramps, isolated from the regular ramps, except for the special case of RSC 3. Continuous in-vehicle self-testing, with the results communicated to simple, automated check-in validation stations, will minimize check-in delay. Automated vehicle check-out, with a minimal driver test, will produce the lowest possible check-out delay, but does increase the responsibility of the driver.

Some provision must be made in automated highway design for potential breakdowns and for the passage of emergency vehicles. The recommended solution is a separate second, breakdown lane large enough to serve as a second AHS lane if necessary. An intermittent shoulder of sufficient width may be adequate, but this concept requires further study. If the automated highway consists of one or more lanes side by side with a non-automated road (RSC 3), then a barrier between the two adjacent dissimilar lanes is required except where transition is allowed.

Operation and maintenance of the AHS should be the responsibility of the present highway operational agencies: the state Departments of Transportation, the toll road authorities, and the local highway agencies. The attitudes of these agencies towards operations must change, however, because of the system complexity and the need for pro-active maintenance. For example, specially trained operations personnel will be required, probably around the clock. Private organizations may be contracted to operate these facilities.

The driver will play a role in the automated system. Many stakeholders and focus groups, made up of agency personnel and the public, will want significant driver involvement. However, the driver cannot perform many control operations to the standards required by an automated highway. The driver can, however, identify potential hazards such as road debris and large animals running onto the road and notify the roadside infrastructure so that other vehicles can be managed around the obstacle. Thus driver input would initiate a controlled response, but not directly control the vehicle. The driver could also control the vehicle if the entire system shuts down and manual vehicle operation becomes the only method of clearing traffic.

A general rule for AHS design should be that the system must be safer than an equivalent non-AHS highway. Specific, quantifiable, and measurable safety goals are needed in order to demonstrate that this rule has been satisfied. There is a safety tradeoff: automation will avoid driver errors, which cause most highway incidents, but system malfunctions and external factors can degrade the safety of an automated system. Safety concerns mandate that special consideration be given to the requirements for reliability and maintainability of the AHS.

Establishment of national standards for an automated highway system will be one method for improving system safety. The existence of clear standards will ensure compatibility between the vehicle and the highway, and common vehicle design standards will reduce vehicle inspection and check-in costs. Care should be taken to avoid overly restrictive standards which would limit creativity, competitiveness, and efficiency.

The national transportation system is multimodal. The automated highway must be integrated with other transportation technologies and be a key, integral part of the transportation taxonomy. Certainly the automated system must provide for commercial vehicles, public transit vehicles, and public safety vehicles and should offer unique benefits to these vehicles.

Exit ramp queuing is one barrier to the integration of the AHS into the transportation system. If this issue cannot be mitigated or avoided with careful design techniques, then special solutions may be required, such as direct parking terminals at the exits or an entrance reservation system which guarantees that exit will be to an unblocked road.

Deployment of the automated highway system is difficult because any AHS will require major funding and an equitable distribution of benefits among users and non-users is not guaranteed. At issue is total functionality with the first implementation versus staged levels of functionality, probably with mixed flow in a separate lane as a first stage. It is recommended that, for the near term, the evolutionary approach should be adopted, without precluding a different final deployment methodology. The required subsystems and an open architecture can be developed within an evolutionary framework without a major expenditure for an entire system. Nothing is lost if a switch is made to attempt a fully-developed AHS at the first deployment. Automotive product functionality increases incrementally, in step with highway evolution. Early results are obtained from a Federal program based on an evolutionary strategy, thus reducing the risk that the program will be canceled because of cost or a major error. However, the evolutionary approach may provide only a small safety benefit initially, and the driver comfort benefit that is essential means that driver-in-the-loop evolution would be counterproductive. Also, the revolutionary approach offers significant immediate safety, driver comfort, travel time, and capacity benefits.

It was concluded early in the program that user benefits must be provided at all stages of AHS functionality. Besides safety, reduced travel time, driver comfort, and reduced traffic congestion, other significant benefits derived from AHS would be improved traffic flow at peak hours and improvement to the urban quality of life resulting from increased mobility. Induced demand could be mitigated by using a pricing strategy that penalizes single-occupancy vehicles and those who exceed a certain number of kilometers per week on the AHS. The automated system must be compatible with and contribute to the special interests of the stakeholder groups. In early stages of evolutionary deployment, the AHS may be synergistic with transit systems and high-occupancy-vehicle programs. A study is needed to determine the AHS's impact on vehicle miles traveled, vehicle emissions, and fuel consumption, as these are vital current topics.

One key benefit of AHS that should be achieved wherever the automated system is deployed is a strong economic rate of return. Certainly, sustained industrial participation in the program could not be achieved without a projected positive rate of return. On the other hand, development and infrastructure deployment will require strong Federal funding that demonstrates Federal commitment. There must be an assured source of funding for AHS operations and maintenance. This could be the Federal government, State or local sources, or a source distinct from the usual funding sources for highway and transit projects.

An automated highway system offers major benefits to the national system of transportation. This study was intended, however, to find the potential flaws in the system, rather than to characterize its many attributes. No insurmountable problems were identified during this study. However, the large number of issues and risks that were found certainly is a challenge to those charged with developing an automated highway system.

INTRODUCTION

This contract overview report encompasses the full complement of activity areas defined for the AHS Precursor Systems Analysis (PSA). The 16 activity areas are assigned consecutive letters of the alphabet for ease of reference, providing a shorthand expression for the full title of the individual activity areas. A summary description of the activity areas is provided to outline the organization of the analyses. The specific focus of the contract is presented, and issues addressed by activity area are summarized. A system framework is developed which supports an organized approach to the 16 areas of analysis. The guiding assumptions are summarized and the content of the full report is presented.

Summary Description of Activity Areas Addressed

Activity A — Urban and Rural AHS Comparison

The urban/rural comparison identifies the similarities and differences in the urban and rural AHS environment. The representative system configurations provide a realistic basis for definition of common implementation issues and risks involved with development, deployment, and operation of automated highways compatible with urban and rural user requirements. The urban/rural comparison presents an overview of the specific technical, social, and regulatory areas that are addressed in detail in the balance of the activity areas. The assumptions used in the various analyses were developed and documented early in the program and revised as further analysis provided more rigorous attention to specific aspects of the system requirements.

Activity B — Automated Check-In

The analysis of check-in options for evaluating vehicles focuses on preventing improperly equipped or hazardous vehicles from entering the automated lanes. A wide range of vehicle functions are analyzed, and potential evaluation techniques are identified, such as continuous invehicle monitoring, dynamic screening, and pre-entry certification. The issues involved with verification of driver competence are also addressed to evaluate the risks of taking automated control of the vehicle with the prospect of returning manual control to a potentially dangerous driver. Recommendations for system implementation are provided as they pertain to validation of vehicles and drivers. The study presents the primary aspects which must be considered to ensure the check-in process maintains a specified level of safe system operation in a cost effective and user-friendly manner.

Activity C — Automated Check-Out

The analysis of the check-out process is concerned with the issues and risks involved with the transition from automatic to manual control. The study focuses on the variables involved in verifying manual vehicle functions and the ability of the operator to resume manual control. The transfer sequence of specific functions is analyzed to evaluate the effect of timing and coordination on completing the check-out process safely. The implications of failing check-out are discussed and the alternative solutions to handling vehicles which fail the check-out process and their acceptability are defined and analyzed. The task studies the applicability of check-in functions to assess the degree of potential commonality with check-out requirements. Liability concerns associated with the responsibility of AHS to determine driver competence are identified and practical alternatives are recommended.

Activity D — Lateral and Longitudinal Control Analysis

The objective of the lateral and longitudinal control analysis is to define and analyze the AHS system requirements for automated control of the brake, steering and throttle functions. The lateral and longitudinal maneuvers associated with automated control are characterized, including entry merge, headway maintenance, lane change, exit, and emergency functionality. The system level requirements for sensor, controller, actuator, and communication capabilities are identified in terms of data capacity, update rate, and timing. The sensitivity of key control capabilities tospecific control parameters are evaluated. Examples include the impact of delay in brake actuation on vehicle separation, and the effect of control data update rate on lateral deviation. The preliminary analysis of control capabilities and limitations provides the background for the topic of coordinated control.

The concept of coordinated longitudinal control is explored and the advantages in terms of safety and potential capacity are outlined. Activity D addresses the considerations involved in determining safe vehicle spacing and summarizes headway maintenance control requirements. Platoon dynamics are discussed in detail with respect to control and maneuver requirements. The safety implications of manual intervention in close vehicle following modes is also considered here. The potential for existing and developing technology to meet automated lateral and longitudinal control specifications is evaluated and key enabling technologies are identified. The findings of this activity provide the basis for the concept of variable vehicle spacing, a system approach which permits headways to be increased or decreased based on current demand.

EXECUTIVE SUMMARY OF ALL ACTIVITY AREAS

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This analysis is performed in order to derive benefits from past experience in the design, implementation, deployment, and operation of comparable systems that could be applied to AHS. The activity identifies 12 existing systems that share a number of characteristics with AHS. Public interaction, safety, reliability, and complexity are emphasized. Three systems, the Bay Area Rapid Transit system, automotive air bag systems, and the TRAVTEK automotive navigation system, were chosen for analysis in detail. Lessons learned in the development and deployment of these systems offer insight into appropriate techniques for technical systems specifications, verification of system performance, initial pre-deployment, quality assurance, human factors, and maintenance. Non-technical issues are also explored including the effects of political pressure and management/funding philosophy. Concerns about privacy, liability, and public confidence are also examined.

Activity H — AHS Roadway Deployment Analysis

This activity addresses highway infrastructure topics that will be encountered when AHS is deployed. AHS right-of-way requirements are analyzed, based on the following criteria: width of AHS vehicle, ability of the system to keep the vehicle on the desired path, barrier width (for dedicated systems), presence or absence of shoulder (breakdown lane), and width of the shoulder.

AHS capacity is established by utilizing traffic densities based on platoon sizes, inter-platoon spacing, and intra-platoon spacing. Inter-platoon spacing considered several failure assumptions and the requirement that inter-platoon spacing provide safe braking distances based on the failure assumptions. Based on this analysis, it is concluded that AHS capacities as high as 6,000 vehicles per lane per hour would be feasible. This conclusion established the range of capacity used in further PSA analyses.

Activity I — Impact of AHS on Surrounding Non-AHS Roadways

This study considers the effect that AHS traffic would have on the non-automated freeway and street system as it approaches and departs from the automated roadway. The higher speeds and capacities possible with an AHS facility will attract traffic into the AHS lane from both the general-purpose freeway lanes and the parallel arterials. The increased AHS traffic will have both positive and negative impacts on the surrounding street system.

The analysis includes modeling and evaluation of the operations of a freeway corridor with and without an AHS lane. Effects of operations with and without an AHS lane on the surrounding roadways are then evaluated using traffic operations measures of effectiveness. The surrounding roadways include the general-purpose freeway lanes, freeway ramps, parallel arterials, and cross streets. Additional modeling analyzes the impact of the AHS traffic on the cross streets. The Highway Capacity Software (HCS) program is used to evaluate the level of service on alternative configurations of the cross streets and parallel arterials. The physical requirements of the AHS lane and ramps are analyzed to determine the impact on the surrounding streets. The modeling results are also used as input to Activity P — Preliminary Cost/Benefit Factors Analysis. Qualitative as well as quantitative impacts are addressed. AHS is reviewed from the perspective of an urban planner.

Activity J — AHS Entry/Exit Implementation

This activity focuses on the traffic operational impacts of AHS entry/exit facilities at the points where they interface with the local street network. Information and results from several of the other PSA activity areas are utilized in the conduct of the entry/exit research.

Various strategies for AHS entry and exit are considered and their attributes identified. Analyses determined the operating conditions based on AHS volumes and ramp volumes from other PSA studies. Measures of effectiveness are established to allow comparison of different entry and exit strategies.

Activity K — AHS Roadway Operational Analysis

This study considers the roadway operational requirements of an 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 this activity. Similarities and contrasts between AHS and conventional highways are considered, analyzed, and discussed to raise issues and risks. Significant urban/rural, passenger/heavy vehicle, and RSC differences are covered. 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 TOC's are summarized. The role of the driver in an AHS is discussed.

Activity L — Vehicle Operational Analysis

Present and future designs of automobiles, light trucks, and heavy trucks are discussed. The analysis relates these hardware systems to the potential critical components of the AHS vehicle. Communications equipment and electronic control hardware and software are reviewed in detail. Reliability and retrofit issues are analyzed. Fail-soft design approaches which could be applied to the AHS vehicle system are discussed. Vehicle technologies which are common to AHS and non-AHS systems are catalogued.

Activity M — Alternative Propulsion Systems Impact

This study examines the impact of alternative propulsion systems and fuels on the deployment and operation of the AHS. Alternative propulsion systems and fuels are compared to the gasoline-fueled spark-ignition engine in the areas of: specific power, drivability, pleasability, emissions, infrastructure support, production readiness, cost, and energy efficiency. Issues and risks related to the deployment of a large fleet of alternative propulsion vehicles on the AHS are examined. Alternative AHS configurations are identified and analyzed for their compatibility with alternative propulsion systems and fuels. Long-term design issues and enabling technologies required to incorporate alternative propulsion and fuel systems into AHS are identified.

Activity N — AHS Safety Issues

This study addresses the issues of AHS safety from a system design standpoint. Four general areas of concern are discussed: failure prevention in the areas of vehicle subsystems, infrastructure instrumentation, and roadway mechanics; implementation of complex systems in terms of reliability and redundancy; structured methodologies for supporting systems assurance; and collision avoidance in the presence of external disruptions. The trade-offs involved in maintaining a certain level of safety using the most effective approach are addressed. The implications of system configuration in terms of headway maintenance policy and coordination units are presented. Examples are used to illustrate the relative vulnerability of each RSC to a variety of hazards. Recommendations are made concerning specific systems configurations attributes which have significant impact on system safety requirements.

Activity O — Institutional and Societal Aspects

This study addresses institutional and societal aspects of AHS in four areas: impact on State and local governmental agencies, environmental issues, privacy and driver comfort, and vehicle-driver interface. Issues relating to the feasibility and practicality of developing and implementing AHS are discussed and potential courses of action for issue resolution are identified.

The study discusses the impact of design, operations, and maintenance issues on State and local government agencies. Issues include: uniform design standards, educational capabilities, agency coordination, cost effectiveness, staff training, emergency response, liability, and maintenance needs. Environmental issues are discussed in three main areas: travel issues relating to demand, emissions, fuel usage, noise levels, and others; infrastructure and urban form issues such as visual impact, neighborhood cohesiveness, impact on non-automated roadways, seismic safety, and others; and institutional issues such as barriers among stakeholders, incomplete and inaccurate information, and lack of sufficient involvement by non-highway institutions. Suggestions for resolving these issues include: models to more accurately forecast AHS impacts, education, communication, and participation to help dissolve barriers. Privacy and driver comfort issues include: vehicle and driver information requirements, potential technology requirements, psychological factors, and legal aspects. Vehicle-driver interfaces are illustrated with sketches of potential vehicle displays and controls. Driver interface concepts vary in complexity, hardware usage, and ease of retrofit. Typical AHS situations such as check-in, check-out, entry/exit, maintenance operations, and driver activities are also shown.

Activity P — Preliminary Cost/Benefit Factors Analysis

This analysis establishes a framework for the evaluation of benefits and costs of a hypothetical AHS highway project. The support of Federal, State, and local agencies for AHS programs will depend on strong projected economic returns from AHS. Analysis of a hypothetical AHS project examines the main risk elements as well as the principal sources of benefits. Guidelines for strategies of development and further research are provided. The benefit-cost analysis provides key findings in the following areas: travel time, improved convenience, economic activity benefits from congestion relief, urban form and livable communities, AHS and arterial congestion, operation thresholds, and vehicle cost.

Cross-Cutting Conclusions/Observations

Towards the end of this PSA program, all members of the research team met and developed a list of cross-cutting conclusions and observations. The following team vision of AHS is a synthesis of those cross-cutting conclusions and observations.

One of the fundamental aspects of AHS design is the division of instrumentation between the infrastructure and the vehicle. Certain system design elements, namely sensing and control, should be principally based in the vehicle. By so doing, the overall cost per user, assuming comparable performance, would be less. A failure in an AHS vehicle, especially on a multi-lane highway, would have less impact than the failure of an AHS infrastructure component.

Vehicle components may be tested earlier in the AHS development cycle, before final system integration, and this is another reason for favoring in-vehicle control and sensing systems. Overall control of the relationship between vehicle cells or platoons, response to most malfunctions, and high-level vehicle guidance should be managed by the wayside infrastructure.

A platoon is a group of cooperative, coordinated, non-autonomous vehicles. Coordination of vehicles within a platoon is primarily determined by individual vehicle controls (merging into a platoon and splitting from it are cooperative with the wayside), whereas coordination between platoons is completely determined by the wayside command structure. Close inter-vehicle spacing reduces momentum transfer in a collision, thus enhancing safety, has aerodynamic benefits causing lower overall emissions and fuel consumption, and is more operationally efficient, thus reducing travel time and increasing capacity. Close spacing adversely affects driver acceptance, increases the frequency of minor incidents, and challenges current technological capabilities. Spacing can be increased to a distance which lacks the disadvantages of close spacing without risking high momentum transfer impacts if braking control can be coordinated through vehicle-to-vehicle communications. This increased spacing can provide almost the same efficient operation that close spacing allows.

The team reached several conclusions regarding roadway system design. Check-in and check-out stations are required; however, these operations should create little or no delay and should be associated with special AHS ramps, isolated from the regular ramps, except for the special case of RSC 3. Continuous in-vehicle self-testing, with the results communicated to simple, automated check-in validation stations, will minimize check-in delay. Automated vehicle check-out, with a minimal driver test, will produce the lowest possible check-out delay, but does increase the responsibility of the driver.

Some provision must be made in automated highway design for potential breakdowns and for the passage of emergency vehicles. The recommended solution is a separate second, breakdown lane large enough to serve as a second AHS lane if necessary. An intermittent shoulder of sufficient width may be adequate, but this concept requires further study. If the automated highway consists of one or more lanes side by side with a non-automated road (RSC 3), then a barrier between the two adjacent dissimilar lanes is required except where transition is allowed.

Operation and maintenance of the AHS should be the responsibility of the present highway operational agencies: the state Departments of Transportation, the toll road authorities, and the local highway agencies. The attitudes of these agencies towards operations must change, however, because of the system complexity and the need for pro-active maintenance. For example, specially trained operations personnel will be required, probably around the clock. Private organizations may be contracted to operate these facilities.

The driver will play a role in the automated system. Many stakeholders and focus groups, made up of agency personnel and the public, will want significant driver involvement. However, the driver cannot perform many control operations to the standards required by an automated highway. The driver can, however, identify potential hazards such as road debris and large animals running onto the road and notify the roadside infrastructure so that other vehicles can be managed around the obstacle. Thus driver input would initiate a controlled response, but not directly control the vehicle. The driver could also control the vehicle if the entire system shuts down and manual vehicle operation becomes the only method of clearing traffic.

A general rule for AHS design should be that the system must be safer than an equivalent non-AHS highway. Specific, quantifiable, and measurable safety goals are needed in order to demonstrate that this rule has been satisfied. There is a safety tradeoff: automation will avoid driver errors, which cause most highway incidents, but system malfunctions and external factors can degrade the safety of an automated system. Safety concerns mandate that special consideration be given to the requirements for reliability and maintainability of the AHS.

Establishment of national standards for an automated highway system will be one method for improving system safety. The existence of clear standards will ensure compatibility between the vehicle and the highway, and common vehicle design standards will reduce vehicle inspection and check-in costs. Care should be taken to avoid overly restrictive standards which would limit creativity, competitiveness, and efficiency.

The national transportation system is multimodal. The automated highway must be integrated with other transportation technologies and be a key, integral part of the transportation taxonomy. Certainly the automated system must provide for commercial vehicles, public transit vehicles, and public safety vehicles and should offer unique benefits to these vehicles.

Exit ramp queuing is one barrier to the integration of the AHS into the transportation system. If this issue cannot be mitigated or avoided with careful design techniques, then special solutions may be required, such as direct parking terminals at the exits or an entrance reservation system which guarantees that exit will be to an unblocked road.

Deployment of the automated highway system is difficult because any AHS will require major funding and an equitable distribution of benefits among users and non-users is not guaranteed. At issue is total functionality with the first implementation versus staged levels of functionality, probably with mixed flow in a separate lane as a first stage. It is recommended that, for the near term, the evolutionary approach should be adopted, without precluding a different final deployment methodology. The required subsystems and an open architecture can be developed within an evolutionary framework without a major expenditure for an entire system. Nothing is lost if a switch is made to attempt a fully-developed AHS at the first deployment. Automotive product functionality increases incrementally, in step with highway evolution. Early results are obtained from a Federal program based on an evolutionary strategy, thus reducing the risk that the program will be canceled because of cost or a major error. However, the evolutionary approach may provide only a small safety benefit initially, and the driver comfort benefit that is essential means that driver-in-the-loop evolution would be counterproductive. Also, the revolutionary approach offers significant immediate safety, driver comfort, travel time, and capacity benefits.

It was concluded early in the program that user benefits must be provided at all stages of AHS functionality. Besides safety, reduced travel time, driver comfort, and reduced traffic congestion, other significant benefits derived from AHS would be improved traffic flow at peak hours and improvement to the urban quality of life resulting from increased mobility. Induced demand could be mitigated by using a pricing strategy that penalizes single-occupancy vehicles and those who exceed a certain number of kilometers per week on the AHS. The automated system must be compatible with and contribute to the special interests of the stakeholder groups. In early stages of evolutionary deployment, the AHS may be synergistic with transit systems and high-occupancy-vehicle programs. A study is needed to determine the AHS's impact on vehicle miles traveled, vehicle emissions, and fuel consumption, as these are vital current topics.

One key benefit of AHS that should be achieved wherever the automated system is deployed is a strong economic rate of return. Certainly, sustained industrial participation in the program could not be achieved without a projected positive rate of return. On the other hand, development and infrastructure deployment will require strong Federal funding that demonstrates Federal commitment. There must be an assured source of funding for AHS operations and maintenance. This could be the Federal government, State or local sources, or a source distinct from the usual funding sources for highway and transit projects.

An automated highway system offers major benefits to the national system of transportation. This study was intended, however, to find the potential flaws in the system, rather than to characterize its many attributes. No insurmountable problems were identified during this study. However, the large number of issues and risks that were found certainly is a challenge to those charged with developing an automated highway system.

INTRODUCTION

This contract overview report encompasses the full complement of activity areas defined for the AHS Precursor Systems Analysis (PSA). The 16 activity areas are assigned consecutive letters of the alphabet for ease of reference, providing a shorthand expression for the full title of the individual activity areas. A summary description of the activity areas is provided to outline the organization of the analyses. The specific focus of the contract is presented, and issues addressed by activity area are summarized. A system framework is developed which supports an organized approach to the 16 areas of analysis. The guiding assumptions are summarized and the content of the full report is presented.

Summary Description of Activity Areas Addressed

Activity A — Urban and Rural AHS Comparison

The urban/rural comparison identifies the similarities and differences in the urban and rural AHS environment. The representative system configurations provide a realistic basis for definition of common implementation issues and risks involved with development, deployment, and operation of automated highways compatible with urban and rural user requirements. The urban/rural comparison presents an overview of the specific technical, social, and regulatory areas that are addressed in detail in the balance of the activity areas. The assumptions used in the various analyses were developed and documented early in the program and revised as further analysis provided more rigorous attention to specific aspects of the system requirements.

Activity B — Automated Check-In

The analysis of check-in options for evaluating vehicles focuses on preventing improperly equipped or hazardous vehicles from entering the automated lanes. A wide range of vehicle functions are analyzed, and potential evaluation techniques are identified, such as continuous invehicle monitoring, dynamic screening, and pre-entry certification. The issues involved with verification of driver competence are also addressed to evaluate the risks of taking automated control of the vehicle with the prospect of returning manual control to a potentially dangerous driver. Recommendations for system implementation are provided as they pertain to validation of vehicles and drivers. The study presents the primary aspects which must be considered to ensure the check-in process maintains a specified level of safe system operation in a cost effective and user-friendly manner.

Activity C — Automated Check-Out

The analysis of the check-out process is concerned with the issues and risks involved with the transition from automatic to manual control. The study focuses on the variables involved in verifying manual vehicle functions and the ability of the operator to resume manual control. The transfer sequence of specific functions is analyzed to evaluate the effect of timing and coordination on completing the check-out process safely. The implications of failing check-out are discussed and the alternative solutions to handling vehicles which fail the check-out process and their acceptability are defined and analyzed. The task studies the applicability of check-in functions to assess the degree of potential commonality with check-out requirements. Liability concerns associated with the responsibility of AHS to determine driver competence are identified and practical alternatives are recommended.

Activity D — Lateral and Longitudinal Control Analysis

The objective of the lateral and longitudinal control analysis is to define and analyze the AHS system requirements for automated control of the brake, steering and throttle functions. The lateral and longitudinal maneuvers associated with automated control are characterized, including entry merge, headway maintenance, lane change, exit, and emergency functionality. The system level requirements for sensor, controller, actuator, and communication capabilities are identified in terms of data capacity, update rate, and timing. The sensitivity of key control capabilities tospecific control parameters are evaluated. Examples include the impact of delay in brake actuation on vehicle separation, and the effect of control data update rate on lateral deviation. The preliminary analysis of control capabilities and limitations provides the background for the topic of coordinated control.

The concept of coordinated longitudinal control is explored and the advantages in terms of safety and potential capacity are outlined. Activity D addresses the considerations involved in determining safe vehicle spacing and summarizes headway maintenance control requirements. Platoon dynamics are discussed in detail with respect to control and maneuver requirements. The safety implications of manual intervention in close vehicle following modes is also considered here. The potential for existing and developing technology to meet automated lateral and longitudinal control specifications is evaluated and key enabling technologies are identified. The findings of this activity provide the basis for the concept of variable vehicle spacing, a system approach which permits headways to be increased or decreased based on current demand.

Activity E — Malfunction Management and Analysis

The study of malfunction management is closely tied with Activity N — AHS Safety Issues. Discussions concerning the severity of potential hazards and the effect of reliability and redundancy on system safety is included in Activity N. Activity E is primarily responsible for the analysis of what actions are required to maintain safe system operation in the event of a malfunction. Activity E assumes a failure, and summarizes the steps required to manage the malfunction safely. Topics include detection techniques, classification of failure severity, management strategies, and effectiveness of various options. Management methods such as redundant systems, backup functionality, evasive action, and system shutdown are proposed and discussed. The relative severity of a full range of safety-critical failures is presented and discussed in terms of the ability of alternate actions to prevent collisions. The study concludes by identifying several subsystems for which no effective management strategy exists, and provides recommendations for further analysis.

Activity F — Commercial and Transit AHS Analysis

The objective of the Commercial Transit AHS Analysis is to identify the impact on automated highway design of accommodating multiple-axle trucks and buses. Physical aspects such as length, width, height, weight, and bumper alignment are considered. Performance characteristics including acceleration, deceleration and cornering profiles are also evaluated. The influence of these parameters on the physical and geometric design of AHS facilities and the operational characteristics of AHS lanes are discussed. The feasibility of dedicated lanes for commercial and transit vehicles is examined. Shunt lanes, passing lanes, and pullouts are some of the options available to accommodate buses and trucks within passenger vehicle lanes. The platoon approach is studied to determine the impact of time-separated truck/bus platoons on AHS operations.

A demand forecast is developed which estimates the need for commercial and transit vehicle accommodations. Forecasts are based on typical mode splits and plausible numbers of AHS-compatible heavy vehicles. The costs of including commercial and/or transit vehicles in AHS design requirements is compared to the potential benefits to the trucking industry and passenger traffic patterns. Societal and institutional issues are identified, including the potential throughput improvements associated with support of transit vehicles, and emissions improvements associated with close vehicle following and elimination of idling.

Activity G — Comparable Systems Analysis

The goal of the comparable systems analysis is to evaluate existing systems that have similar characteristics to an AHS and to evaluate aspects of development, deployment, and operation in an effort to derive insight to the successes and failures encountered by each system. The study encompasses identification of a wide range of similar systems familiar to team members. A comprehensive list of candidate systems is described and three are selected for detailed analysis. Discussions of the three comparable systems center on performance factors which include: degree of public interaction, complexity, impact of safety, reliability, environment, diversity of subsystems, operation over geographically wide area, failure modes, and outage constraints. The performance factors are applied to each system to establish design considerations directly applicable to AHS. The systems analyzed in detail are the Bay Area Rapid Transit (BART) system, the TRAVTEK vehicle navigation aid, and Supplemental Inflation Restraint (SIR) automobile safety systems. Recommendations stemming from the lessons learned through the comparable systems analysis are summarized for each of the three systems.

Activity H — AHS Roadway Deployment Analysis

The objective of the AHS Roadway Deployment Analysis is to define potential AHS roadway configurations and identify issues and risks associated with implementation. Three roadway configurations are considered in the study: construction of a new facility on a new alignment, construction of AHS lanes in an existing freeway right-of-way, and conversion of an existing mixed flow or high-occupancy-vehicle (HOV) lane to an AHS lane. Methods available for expanding each of these alternatives are identified. The three configurations are also analyzed in terms of the interface between urban and rural sections and the interface between AHS and conventional roadways. The impact of AHS construction on the environment is a factor in the evaluation of each configuration.

The capacity of the AHS is determined in this activity, taking the following influences into account: control requirements, access/egress types and locations, entry merge dynamics, safety factors, vehicle characteristics, highway geometry, and capacity of non-AHS arterials to support AHS demand. Relative costs are estimated for the three alternatives. Roadway deployment estimates are based on lane kilometer costs of similar projects, such as recently constructed freeways, HOV median retrofits, and conventional-to-HOV lane retrofits. Recommendations of feasible options are summarized in terms of the deployment issues and risks.

Activity I — Impact of AHS on Surrounding Non-AHS Roadways

This activity identifies the effects that AHS implementation may have on the surrounding roadway network which provides access to the AHS corridor. The analysis focuses on the street network that feeds the AHS and is generally parallel to the AHS. This study is closely coordinated with Activity H — AHS Roadway Deployment Analysis, which concentrates on the configuration of automated lanes, access and egress points from the automated highway, and the interface between the AHS and conventional freeways. Activity I encompasses subjective analysis and modeling to evaluate effects, while Activity H concentrates on physical deployment considerations.

The primary impacts of the AHS on surrounding networks are classified into three areas: the impact to non-automated lanes within the AHS corridor, the impact to interface points between the arterial network providing access to the conventional freeway and the AHS, and the impact to the surface streets due to induced or redirected demand resulting from implementation of AHS. The operational condition of a hypothetical conventional network will be used as a base condition for impact comparisons. Modeling studies are conducted to determine traffic volumes associated with the implementation of an AHS corridor within a conventional freeway system. Issues are identified as they relate to interface point spacing, location, and capacity. Concerns regarding access to the AHS, attraction of users, and control requirements for the non-AHS roadway network are also documented. The factors which must be considered to develop an AHS without adverse impact to the surrounding conventional traffic flow are summarized.

Activity J — AHS Entry/Exit Implementation

The analysis of AHS Entry/Exit Implementation is concerned with the strategies available for efficient AHS access and egress. A number of options are evaluated, ranging from entry with no delay relative to conventional ramp access times to pauses on the order of 90 seconds. The entry/exit facility requirements are dependent on the definition of the check-in and check-out process and this analysis is coordinated closely with Activity B — Automated Check-In and Activity C — Automated Check-Out. The space required to queue and buffer vehicles is bounded within the range of proposed check-in and check-out times. Factors including the spacing of entry/exit points, number of AHS lanes, and speed and density of AHS traffic are also considered. The ability to effectively deny access to unauthorized vehicles is addressed to identify feasible control strategies. Based on the preliminary analysis, entry/exit options that can be eliminated due to unrealistic land usage are documented.

Activity K — AHS Roadway Operational Analysis

Operational functions of the AHS encompass the maintenance and staffing requirements associated with operating a fully functional AHS segment. This analysis is independent of the deployment study performed in Activity H, and focuses on extrapolation of existing Freeway Management System (FMS) operations to the expected complexity of AHS instrumentation. Functional aspects such as security, maintenance activities, and incident response are considered. The level of training for maintenance and operations personnel are issues in terms of both staffing and funding. Opinions of various Departments of Transportation (DOT's) are summarized to provide input regarding the potential impact of operating AHS roadways on maintenance and personnel budgets. Staffing and physical plant requirements capable of providing adequate system monitoring, routine and emergency maintenance, and incident response are estimated. An operational approach is recommended in terms of construction attributes which support a facility with minimum maintenance requirements, compatible with low levels of degraded system performance, resulting in optimum system economy.

Activity L — Vehicle Operational Analysis

The principal design factors associated with the development, operation, and deployment of advanced technology vehicles in an AHS are identified in this activity. Primary areas of investigation include: existing hardware capability, emerging technology trends, retrofit compatibility, and application of AHS features on non-AHS roadways. Issues related to maintainability, reliability, and fail-safety are discussed in terms of impact on system architecture, implementation costs, and producibility. Evolutionary deployment of AHS-specific vehicle functions and the importance of early introduction of Advanced Traffic Information Systems (ATIS) and Automated Vehicle Control Systems (AVCS) to proof-of-concept and public acceptance are key issues. Enabling technologies critical to successful AHS development are identified in the areas of communications, processing, and actuation.

Activity M — Alternative Propulsion Systems Impact

The impact of propulsion systems other than the gasoline-fueled spark-ignition engine (SIE) to AHS deployment and operation are assessed in this study. A broad range of alternative propulsion systems and respective fuel sources are analyzed in terms of feasibility and cost. The characteristics of alternate fuel systems are systematically compared with the baseline SIE to evaluate performance issues, environmental benefits, and implementation risks. The impact of alternative propulsion system characteristics on AHS roadway configuration is analyzed to identify deployment and operation issues and risks. Infrastructure considerations include modification and spacing of existing fueling stations, and emergency refueling on the roadway. Market penetration will be affected by the vehicle cost as well as the system deployment cost. Performance limitations of alternative propulsion systems may affect the ability to support mixed flow with SIE vehicles.

Activity N — AHS Safety Issues

The primary emphasis of the AHS safety analysis is placed on the prevention of malfunctions and anticipation of hazards. The ability to eliminate collisions when the system is operating correctly depends on a number of factors. The extent to which external factors are capable of interfering with vehicles in the system is a key consideration; accidents may be caused by unauthorized vehicles entering the AHS lane, by debris from accidents occurring in non-AHS lanes, or animals or pedestrians entering the roadway. A collision-free environment cannot be guaranteed unless intrusion can be prevented, and a certain degree of risk must be managed.

The role of the driver in AHS operations is a central safety issue. The abilities of the driver to anticipate and avoid potential collisions are lost if the system is completely automated. However, the potential for error in close following mode may be greater than the benefit of allowing the driver to intervene in a perceived emergency.

The risk of collision during the transition between automated and manual control is another concern. One option is to provide dedicated entry/exit facilities to eliminate the risk of collisions in transition lanes caused by vehicles under manual control. The safety of the AHS is also affected by the vulnerability of the system to events such as floods, earthquakes, and other natural occurrences.

Classical safety analyses promote headways which allow a vehicle to stop without a collision when a “brick wall” failure occurs to the preceding vehicle. Studies reviewed in the Activity D — Lateral and Longitudinal Control Analysis show that platoons with tightly spaced groups of vehicles with “brick wall” stopping distances between platoons can be safe, because in emergency maneuvers the vehicles traveling close together will be moving at nearly the same speed and energy transfer between them in the event of a collision will be very small. The platoon of vehicles will, however, be at a greater risk for multiple collisions than single vehicles spaced at the standard safe stopping distance. The statistical probability of a critical function failure must be extremely small, placing high reliability requirements on the system.

The effect of the system architecture on the cost of safe system design will be a primary consideration in the flow down of subsystem functionality. Improved component reliability and providing cross functionality among subsystems may provide higher safety benefits at lower overall cost to the system than introducing higher levels of subsystem redundancy. Safety permeates every level of the system design, and must be addressed at each stage of study, development, and deployment. Identification of safety as a system-level issue and establishing design practices and standards at the outset of the development phase are important steps toward creating a system that will meet AHS safety design goals.

Activity O — Institutional and Societal Aspects

The objective of this analysis is to identify the institutional and societal issues that will influence the feasibility of development, deployment, and operation of AHS. A comprehensive list of topics is compiled and evaluated to determine areas of greatest concern. An effort was made to ensure that the subjects addressed are distinct from those selected by other teams. The majority of effort in the report focuses on the areas of environment, privacy, and liability issues.

Environmental considerations include a wide range of concerns, such as level of emissions, latent demand, and long-term land use patterns affected by induced demand. An important aspect of the environmental analysis is the evaluation of transit goals. The ability to align transit interests and AHS interests is necessary in order to support compatibility between transportation alternatives rather than competition. AHS privacy issues are raised because of the ability to track vehicles precisely and the potential monitoring methods for verification of driver competence. Privacy can become a major factor in widespread acceptance of automated travel and will affect public attitudes toward increased collection and processing of personal data and driver willingness to trust technology. Legal impediments to AHS include the financial risk associated with tort liability cases. Protection for participants in the public and private sectors may take the form of risk pools, government standards, and legislative reforms. The impacts of liability on system design complexity and cost must be considered in several key areas, including access control, hazard prevention, malfunction management, headway control, and emergency maneuvers.

Activity P — Preliminary Cost/Benefit Factors Analysis

This study analyzes the costs and benefits associated with development, deployment, and operation of AHS. The benefit-cost evaluation follows a methodology which defines the input required, gathers specific data from the expert community, and applies benefit metrics to assess the defined system configuration performance. Benefit categories include efficiency, capacity, safety, induced demand, and economic impacts. The major stakeholder groups are identified and a benefits accrual matrix is developed which assigns benefits. A base case is proposed which characterizes the baseline against which AHS will be evaluated. The base case represents the expected typical highway configuration at the onset of AHS, which allows the benefits of AHS to be measured against an extrapolation of current conditions. The cost of implementing AHS is also compared with the base case cost, allowing an evaluation based on expected technological advances associated with various Intelligent Transportation Systems (ITS) technologies such as Advanced Traffic Information Services (ATIS) and Advanced Vehicle Control Systems (AVCS).

Based on estimates and ranges provided by industry experts, probability distributions are developed from algorithms which incorporate modeling of highway user costs and benefits. The results are used to conduct a risk analysis of the urban and rural scenarios for each of the alternative RSC's. The risk analysis defines the range of outcomes associated with each alternative and the probability of achieving each outcome. The conclusions of the detailed analysis include policy recommendations which will promote successful implementation of AHS.

Specific Focus of the Contract

The analyses performed within each of the activity areas are addressed in terms of four primary factors: vehicle, roadway, operator, and infrastructure electronics. The vehicle perspective encompasses subsystem functions associated with automated lateral and longitudinal control, extending sensor and actuation requirements to communication of control information. The roadway issues include the physical configuration of AHS sections from all aspects of design, implementation, and operation. Operator-related concerns involve public acceptance of AHS technology and alleviation of privacy issues, as well as human factors design of the user interface. The infrastructure electronics perspective encompasses the instrumentation required along the roadway, including sensors, communications, and Traffic Operations Centers (TOC's). The specific development, deployment, and operational issues and risks are discussed with respect to vehicle, roadway, operator, and electronics implications as appropriate in the individual activity areas.

Issues Addressed by Activity Area

Towards the end of the PSA work in the activity areas, all members of the research team identified the most important issues, risks, concerns, and conclusions which surfaced during the course of the several activity area analyses. These were documented using a specially generated database form. An example is shown in the appendix, figure 5. The completed forms were forwarded to Calspan Corp.[1] for entry into a database to be used by all PSA researchers. A summary of the 108 issues, risks, concerns, or conclusions identified by this team is presented in the appendix, table 5. This summary includes the following for each entry: the internal database item number, the activity area from which it was first identified, the database topic description, the item type (issue, risk, concern, or conclusion), and an indication of the subsection (System Characteristics, Operations/Maintenance, Impacts, AHS Deployment, or Funding) within the Overall Cross-Cutting Conclusions/Observations section of this report where further discussion may be found. Those identified with activity x were identified in the course of the cross-cutting team interactions. The majority of the database items are related to discussion in this report; however, some are only discussed within the indicated activity area report.

Overall Approach/Methodology Across All Activity Areas

A system framework is presented which forms a cohesive concept of AHS operation for the 16 related activity areas in the Precursor Systems Analysis. The goal of establishing the system framework is to define the high level architecture of AHS and generate a basic set of system performance and operational requirements. This task, performed at the beginning of the PSA program, is intended to provide a unified approach to the detailed analyses performed in the 16 activity areas. A common set of assumptions and operational goals for the representative system configurations is necessary to obtain a calibrated measure by which to evaluate the conclusions and recommendations formulated by members contributing to the individual analyses.

Preliminary Systems Analysis

The overall approach/methodology will be discussed in terms of operational requirements, high level architecture, technical requirements, comparative analysis methodologies, and issues and risks. The system framework relating these areas to the PSA program and the individual activity areas will be presented first, and then each of the approach/methodology topics will be addressed in detail.

Operational Requirements

The discussion of AHS operational requirements is focused on addressing the major goals outlined in the AHS Concept Analysis report. [2] AHS functional goals are interrelated with the more expansive goals of ITS. The goals are divided into several areas, encompassing operating effectiveness, transportation services, various facets of system desirability, and societal benefits.

Operating effectiveness is defined as throughput in AHS operation under the full range of weather conditions expected in the continental United States. The AHS must increase the amount of people, goods, and vehicles that can travel on existing highway right-of-ways. The safety of highway travel must be increased at the same time.

The level of service offered by the highway system includes the range of transportation options provided, the overall travel time for the system users, and the reliability of travel within the system. The AHS is viewed as a supplement to the nation’s roadway system. To attract users, it must serve a full range of vehicles, including passenger cars and light trucks, local and interstate trucks, and local and interstate mass transit vehicles.

Desirability of the system is viewed from the perspective of the user, the community, and the sponsoring agencies. The desirability of AHS travel from the user viewpoint is affected by several factors, including safety, mobility, comfort, and cost. The operational goals from the community aspect include reducing land usage required to increase capacity, eliminating negative property impact, reducing disruption due to construction, and minimizing emergency support required by decreasing accidents. The perspective of the sponsoring agencies is focused on the cost effectiveness of AHS relative to other transportation alternatives. In order to compete with other transportation options, it must provide a favorable cost/benefit ratio.

To obtain the full support of federal government agencies, the long-range AHS effort will focus on the nation's societal needs in several key areas, including stimulating the economy, nurturing the AHS industry, supporting national emergencies, and reducing fossil fuel consumption and vehicle pollutants. The economic benefits of AHS involve the following issues: contribution to stronger industry through faster, more dependable commercial transport; reduction of economic impact of personal mobility and transfer of goods; and minimization of the financial drain caused by accidents.

The system configuration defines the attributes associated with coordination of vehicle control, vehicle performance criteria, facility requirements, and other functions related to automated travel. Key issues in the determination of a viable system configuration include vehicle coordination units and driver participation in vehicle control within the AHS. These primary topics, in addition to several related concerns, are introduced as an organizational stepping stone into Activity D — Lateral and Longitudinal Control Analysis, Activity H — AHS Roadway Deployment Analysis, and Activity N — AHS Safety Issues.

High-Level Architecture

The AHS architecture is an outgrowth of the system operational requirements. The architecture is defined at a high level and will satisfy the requirements for AHS operation under any system configuration. The architecture is functional in the sense that it includes the functions of AHS without regard to the physical placement of these functions within the system. The architecture depicts the system functions independent of physical implementation. The flow of information between the major functions is assigned to clarify the operations performed by the functional blocks.

The initial architecture divides the system into eight major AHS functions. The Position Control function is responsible for controlling both the lateral and longitudinal position of the vehicle. The Traffic Management Flow Control & Maneuver Coordination function is responsible for coordinating the movements of multiple vehicles on the automated highway. The Check-in/Check-out function insures that both the operator and the vehicle systems comply with check-in and check-out requirements of the automated highway. The Entry/Exit function allows a vehicle to safely enter and exit the automated lanes of the highway. The Operator Interface function permits the operator to enter data into the system and informs the operator of the status of vehicle systems and provides alerts and failure notifications. The Hazard Management function responds to all hazards which occur on the automated highway. The Malfunction Management/Backup Operation function determines the appropriate response to a failure of any component of any subsystem of the AHS. The Diagnostics function continuously monitors the operation of the vehicle systems. Any failure detected by the Diagnostics function is reported to the Malfunction Management/Backup Operation function. The functional decomposition provides the preliminary division of responsibility between the activity areas related to system design and operation: Activities B and C — Automated Check-In and Check-Out Analyses, Activity J — AHS Entry/Exit Implementation analysis, and Activity E — Malfunction Management and Analysis.

Technical Requirements

The system operational requirements and high level architecture form the basis for the technical requirements of the subsystem elements. Requirements take into consideration the near term availability of technology relating to vehicle command and control operations, infrastructure communications and electronics, and the operator interface function. Quantitative system performance parameters are presented, providing sufficient detail to support the requirements analysis. The technical requirements definition forms the basis for Activity L –Vehicle Operational Analysis and Activity K — AHS Roadway Operational Analysis.

Comparative Analysis Methodologies

The scope and complexity of the AHS requires a structured approach to system design, which includes requirements specification and architecture development. The structured approach to complex systems design creates a practical system implementation from functional requirements through an iterative process. Structured methods consist of tools and techniques that illuminate specific aspects of the desired system during the analysis process. Structured methods are useful in defining what problem the system is to solve through requirements analysis, and through a tradeoff process determining how to solve it during architecture development. The concept of structured systems design and requirements analysis is presented in the belief that a systematic design methodology will be required to successfully manage the AHS life cycle.

Issues and Risks

Preliminary team organizational meetings held to define responsibilities among the 16 activity areas resulted in identification of seven broad categories of issues and risks. The issues and risks are grouped as follows: economic factors, safety, environment, liability, reliability, social/institutional, and technical. The specific areas of concern are presented within the system framework to identify the focus of individual areas of analysis.

Economic factors associated with the vehicle equipment costs and automotive manufacturing are discussed in Activity L — Vehicle Operational Analysis, while those concerning highway construction costs are discussed in Activity H — AHS Roadway Deployment Analysis. Economic factors associated with the relative benefits obtained are addressed in detail in Activity P — Preliminary Cost/Benefit Factors Analysis, those concerning benefits to society are discussed in Activity O — Institutional and Societal Aspects.

Safety issues and risks associated with vehicle control are addressed in Activity D — Lateral and Longitudinal Control Analysis, those concerned with failure management are discussed in Activity E — Malfunction Management and Analysis, and system assurance topics are discussed in Activity N — AHS Safety Issues. Reliability issues are closely related to system safety, and also receive treatment in Activity N in terms of fault tolerant design methodologies. Activity L — Vehicle Operational Analysis deals with reliability issues regarding vehicle subsystem design. The maintenance aspects of safety and reliability are addressed in Activity N — AHS Safety Issues in terms of system assurance. Activity B — Automated Check-In provides an overview of maintenance and test concerns associated with ensuring vehicle subsystem functionality. Activity K — AHS Roadway Operational Analysis includes discussion of staffing, budget, and equipment aspects of roadway maintenance.

Environmental issues such as air quality and noise associated with traffic congestion are discussed in Activity O — Institutional and Societal Aspects. Risks of induced traffic demand and issues concerning land use are addressed in Activity I — Impact of AHS on Surrounding Non-AHS Roadways, and Activity J — AHS Entry/Exit Implementation. Related issues regarding transit compatibility with AHS are discussed in Activity F — Commercial Transit AHS Analysis.

Liability associated with the assignment of fault in the event of collisions is a concern in the transition between manual and automated control. Issues related to liability are addressed in detail in Activity N — AHS Safety Issues in terms of emergency maneuvers. Activity C — Automated Check-Out addresses the issues involved with verifying the competence of the driver to assume manual control. Activity J — AHS Entry/Exit Implementation discusses the trade-offs involved with safe implementation of the entry and exit sequence. General liability concerns of system reliability are addressed in Activity O — Institutional and Societal Aspects.

The social and institutional issues that affect the viability of the AHS concept range across all activity areas, and take the form of performance, cost, and safety trade-offs in almost all areas of analysis. Specifically, user acceptance and equity issues are discussed in Activity A — Urban and Rural AHS Comparison. Privacy issues are discussed in detail in Activity O — Institutional and Societal Aspects, while user comfort concerns are addressed in Activity B — Automated Check-In.

The capability of existing and emerging technology to meet the challenges of AHS is addressed in several activity reports. Activity D — Lateral and Longitudinal Control Analysis covers the actuator, sensor and communications performance issues associated with automated vehicle control. Activity L — Vehicle Operational Analysis discusses the vehicle issues involved in manufacturability and increased subsystem integration. Activity E — Malfunction Management and Analysis studies the fault tolerance, functional redundancy and fault detection capabilities of AHS specific technologies. Activity H — AHS Roadway Deployment Analysis deals with the technical issues involved with deployment of a complex system in terms of the impact to existing traffic flows, while management of system operation and maintenance is addressed in Activity K — AHS Roadway Operational Analysis. Finally, Activity M — Alternative Propulsion System Impact discusses the technical challenges associated including alternative propulsion vehicles in the implementation of a mature automated highway system.

Operational Requirements

The definition of AHS operational requirements is focused on addressing the major goals outlined in the AHS Concept Analysis report. AHS functional goals are interrelated with the more expansive goals of ITS. The goals are divided into several areas, encompassing operating effectiveness, transportation services, various facets of system desirability, and societal benefits.

Operating effectiveness is defined as throughput in AHS operation under the full range of weather conditions expected in the continental United States. The AHS must increase the amount of people, goods, and vehicles that can travel on existing highway right-of-ways. The safety of highway travel must be increased at the same time.

The level of service offered by the highway system includes the range of transportation options provided, the overall travel time for the system users, and the reliability of travel within the system. The AHS is viewed as a supplement to the nation's roadway system. To attract users, it must serve a full range of vehicles, including passenger cars and light trucks, local and interstate trucks, and local and interstate mass transit vehicles.

Desirability of the system is viewed from the perspective of the user, the community, and sponsoring agencies. The desirability of AHS travel from the user viewpoint is affected by several factors, including safety, mobility, comfort, and cost. The operational goals from the community aspect include reducing land usage required to increase capacity, eliminating negative property impact, reducing disruption due to construction, and minimizing emergency support required by decreasing accidents. The perspective of the sponsoring agencies is focused on the cost-effectiveness of AHS relative to other transportation alternatives. In order to compete with other transportation options, it must provide a favorable cost/benefit ratio.

To obtain the full support of federal government agencies, the long-range AHS effort will focus on the nation's societal needs in several key areas, including stimulating the economy, nurturing the AHS industry, supporting national emergencies, and reducing fossil fuel consumption and vehicle pollutants. The economic benefits of AHS involve the following issues: contribution to stronger industry through faster, more dependable commercial transport; reduction of economic impact of personal mobility and transfer of goods; and minimizing the financial drain caused by accidents, lost productivity and litigation.

The following operating requirements are intended to define the parameters that will be used to measure the effectiveness of the AHS. The operating requirements must be defined in a quantitative manner before system design can begin. The actual quantities attached to the MOEs will not be defined until a system configuration is specified.

Capacity

AHS throughput is defined as the amount of people, goods, and vehicles that typically travels on the highway right-of-way. Capacity is typically calculated as speed times density times the number of lanes within the highway right-of-way. The capacity of a typical urban or rural AHS will be measured in vehicles per hour times the number of lanes. The capacity requirement may be met by increasing the number of lanes available for travel within the right-of-way or modifying vehicle spacing.

Driver characteristics such as variations in individual driving ability and style will not disrupt the smooth and constant flow of traffic. Congestion caused by driver fallibility under poor weather and road conditions will be eliminated by accurate vehicle control. The AHS will be capable of identifying and expediting the removal of incapacitated vehicles.

The AHS will serve passenger cars and light trucks as well as local and interstate trucks. The AHS will support high-occupancy-vehicle (HOV) and mass transit use of automated travel lanes. Provisions for HOV priority access and mass-transit stops will be included in the system design. AHS will provide future compatibility with driverless rapid transit vehicles.

Travel Time

Point-to-point travel time will be enhanced by minimizing entry/exit delays. The maximum access delay will be measured in seconds. Access points will be correlated with major traffic flow patterns. Access points will be located near existing traffic arteries, based on modeling of optimum travel flow. A target will be set for average speed on urban and rural AHS highways, and will be measured in km/h.

Operator Interface

The AHS vehicle user interface will allow the driver to enter travel destination information. The operator interface will provide status information to the driver concerning AHS entry/exit approval. The visual environment will produce a relaxing atmosphere for travel.

Deployment

Implementation of AHS will use less real estate than conventional highway systems with equivalent throughput. The AHS must enable smooth transition from the existing highway system. Vehicle specifications and standards will be established which assist in the transition of the vehicle population to AHS compatibility through addition of AHS equipment.

The AHS will implement rapid, staged construction techniques and/or new roadway surface designs. Roadway enhancements which are implemented prior to full AHS deployment will be designed to standards which will guarantee upward compatibility. The AHS will be able to meet the future demand of higher performance vehicles and specialized transport needs.

The AHS will provide long-term upgrades to the interstate highway system, allowing for greater efficiency and evolution through the 21st century. to avoid becoming obsolete during future improvements, the AHS will employ design modularity in electronic and software components thus minimizing the impact of incorporating technological advances.

Operating Environment

The AHS will be effective on both urban and rural freeways. The system will be capable of transition from urban to rural freeways, allowing graceful evolution into a national service connecting regional transportation networks.

Efficiency and Support of Alternative Propulsion

A primary goal of the AHS is reduction of fossil fuel consumption. The AHS will support vehicles using alternative fuel sources as well as mass-transit and HOV operation to optimize fuel efficiency. The system will be available to electric or natural gas powered vehicles.

Safety

AHS will provide accident rates lower than freeway mainline travel in the absence of system malfunctions. System malfunction management will be designed to limit the number and severity of collisions. The accident and fatality rates in the event of malfunctions will be measured in events per vehicle kilometer traveled. The result will be a system that is significantly safer than a non-AHS highway.

Reliability

Reliability of the AHS is defined in terms of dependability of service, and graceful degradation due to service interruptions. The system will be designed to provide an availability level greater than non-AHS highways, including down time due to system malfunctions and reduction in capacity due to maintenance operations.

Maintainability

The AHS design will include computer monitoring of system conditions, notification of impending maintenance needs, and rapid infrastructure and electronics maintenance.

Emergency Service

The system contains operating modes which establish priorities for emergency vehicles, mobilization for disaster relief or civil unrest, and emergency evacuations. Reaction times to emergency situations should be significantly reduced.

Cost

The AHS will provide lower fuel costs due to safer, more efficient travel. Overall vehicle operating costs should be reduced in comparison with non-AHS travel. The overall cost of the system must include affordability of vehicles to the general public. The increase in sticker price of the average passenger car due to vehicle instrumentation required for AHS compatibility can be minimized through division of costs between manufacturers, users, and government support of AHS technology. Another factor in the overall cost/benefit ratio is the elimination of extended periods of unproductive time spent traveling at low speeds.

The cost-effectiveness of the AHS relative to other transportation alternatives is a primary design consideration. In order to compete with other transportation options, it must provide a favorable cost/benefit ratio. The AHS design will provide modular implementation, allowing low-level service in some regions and higher-level service in other regions, depending on the market economy and demand. The cost of system implementation should be less than conventional highways with comparable throughput.

High-Level Architecture

The AHS architecture is an outgrowth of the system operational requirements. The architecture is defined at a high level and will satisfy the requirements for AHS operation under any of the three Representative System Configurations (RSC's). The architecture is functional in that it includes the functions of AHS without regard to the physical placement of these functions within the system. The architecture, as represented by a system level block diagram shown in figure 1, depicts the system functions independent of physical implementation. The flow of information between the major functions is also shown in the block diagram.

Eight major AHS functions are indicated on the block diagram. The Position Control function is responsible for controlling both the lateral and longitudinal position of the vehicle. The Traffic Management Flow Control & Maneuver Coordination function is responsible for coordinating the movements of multiple vehicles on the automated highway. The Check-In/Check-Out function will validate that both the operator and the vehicle systems comply with check-in and check-out requirements of the automated highway. The Entry/Exit function will allow a vehicle to safely enter and exit the automated lanes of the highway. The Operator Interface function allows the operator to enter requests to the system and informs the operator of the status of vehicle systems and provides alerts and failure notifications. The Hazard Management function will respond to all hazards which occur on the automated highway. The Malfunction Management/Backup Operation function will determine the appropriate response to a failure of any component of any subsystem of the AHS. The Diagnostics function will continuously monitor the operation of the vehicle systems. Any failure detected by the Diagnostics function will be reported to the Malfunction Management/Backup Operation function.

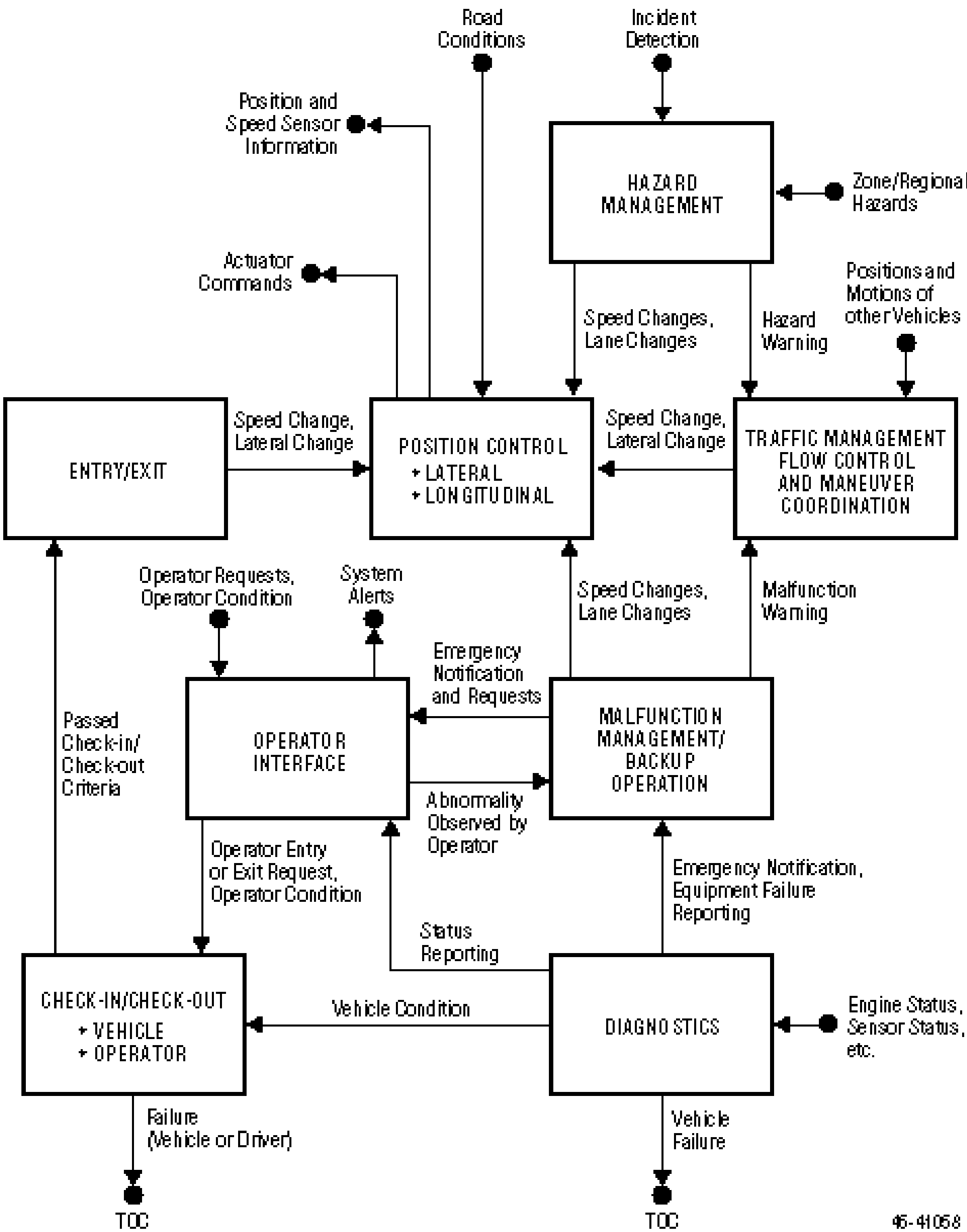

Figure 1. High-Level System Architecture.

Position Control Function

The Position Control function is responsible for the real time control of the vehicle whenever the vehicle is not under control of the operator. This real time control is performed by sending commands directly to actuators within the vehicle. Data and requests for speed/position changes from both internal and external sources are used to safely maintain the vehicle direction (or course) in the automated highway. Information regarding vehicle speed and position within a lane will be provided continuously to this function by sensors which can reside either in the vehicle or in the roadside. External information available to this function includes the road condition and weather information. The Position Control function also receives lane change and speed change information from the Entry/Exit function, the Hazard Management function, the Malfunction Management/Backup Operation function and the Traffic Management Flow Control & Maneuver Coordination function. Included in this category are emergency requests to change speed and position due to malfunctions and hazards.

Check-In/Check-Out Function

The Check-In/Check-Out function is responsible for determining that both the vehicle and the operator are capable of checking into or out of the automated highway. Depending on the equipment, the operator check-in and check-out could be as simple as pushing a button or as complicated as an automatic check of the operator’s alertness, sobriety, and physical condition, as well as license validation, credit check (for toll payment), and outstanding criminal warrants. Similarly, the range of checks to be performed on vehicles prior to check-in and check-out could vary greatly, depending on the ability of the vehicle to check itself. Vehicle checks could include fuel level, engine condition, tire pressure, brake functionality and records such as license and time lapsed since the last inspection. Vehicle features specific to AHS operation, such as actuators, sensors, and communications and radar subsystems, will also be checked.

The Check-In/Check-Out function will interface to external sensors which monitor the operator’s condition. This function will also report failures in the check-in and the check-out process to the Traffic Operations Center (TOC). Since failures in the check-out process may cause the vehicle to be directed to a holding area, other agencies (e.g. towing company) may also be notified. Internal interfaces exist between this function and the Diagnostic function, the Entry/Exit function and the Operator Interface function. The Diagnostic function will report vehicle condition to the Check-In/Check-Out function. The Operator Interface function will pass requests for entry to or exit from the automated highway to this function. The Check-In/Check-Out function will inform the Entry/Exit function that check-in or check-out was successful.

Entry/Exit Function

The Entry/Exit function consists of those tasks required to get the vehicle into and out of the automated highway. This function coordinates the actions of the vehicles in the platoon and the vehicle performing the entry to or exit from the automated highway. This coordination includes accepting speed and position parameters from either the infrastructure or the lead platoon vehicle as well as timing any acceleration/deceleration and lane changes as directed by the infrastructure or lead platoon vehicle. The vehicle requesting entry into the automated highway will first be directed to the appropriate speed and position to safely enter, and then will be commanded to enter. Similarly, the vehicle requesting exit from the automated highway will be safely moved out of the stream of automated traffic, and then directed to an appropriate speed and position before control is returned to the operator. In the case of a failed check-out request, the Entry/Exit function may direct the vehicle to a holding area, where the vehicle can be brought to a stop safely.

Interfaces to the Entry/Exit function include messages from the Check-In/Check-Out function indicating that the operator and vehicle have passed/failed check-in or check-out tests. The Entry/Exit function will also send requests for speed changes and lateral changes to the Position Control function.

Traffic Management Flow Control and Maneuver Coordination

The Traffic Management Flow Control and Maneuver Coordination function is responsible for coordinating the maneuvering of multiple vehicles on the automated highway. This coordination can be performed either by the infrastructure or by the lead platoon vehicle or distributed among the vehicles on the automated highway and the infrastructure. Using information on the global status of the system, this function can perform such operations as slowing down a platoon due to a hazard detected some distance away or redirecting vehicle routes in order to relieve congestion. In order to perform its function properly, the Traffic Management Flow Control and Maneuver Coordination function must receive information from a number of sources in a timely manner. Commands to perform speed changes or lateral maneuvers will be sent to the Position Control function.

Operator Interface Function

The Operator Interface function is responsible for processing input from the operator and providing status and commands to the operator. The operator interface itself could range from a small number of switches and lights to a CRT display and an input device capable of alphanumeric text entry. The operator interface may also include audio alerts. This function will accept status from the Diagnostics function and emergency notifications and requests from the Malfunction Management/Backup Operation function. The Operator Interface will inform the Check-In/ Check-Out function when a request is made to enter or exit the automated highway.

Hazard Management Function

The Hazard Management function is responsible for monitoring road hazards and for determining the response to a detected hazard. Hazards will be reported to this function from a number of sources, including vehicle mounted sensors and external sources such as roadway infrastructure sensors. Hazards will also be reported to the vehicle using the communications system. The hazard report will include information regarding the hazard type, safe speeds while passing the hazard, and alternate routing if the hazard caused a complete blockage of the highway. This function will process the report and determine the appropriate action to take. When the action includes speed and/or position changes, the Hazard Management function will notify the Position Control function of the changes. This function will send hazard warnings to the Traffic Management Flow Control & Maneuver Coordination function.

Malfunction Management/Backup Operation Function

The Malfunction Management/Backup Operation function is responsible for determining the course of action in the event of a failure in any of the equipment or subsystems which make up the automated highway. The notification of a malfunction will be sent by the Diagnostics function. The action taken by this function will range from using a backup sensor or subsystem in order to maintain normal operations, to immediately taking the vehicle out of the automated highway, to the extreme of shutting down the automated highway. The operator will be informed of malfunctions and switches over to backup systems. This function will send malfunction warnings to the Traffic Management Flow Control & Maneuver Coordination function.

Diagnostics Function

The Diagnostic function is responsible for monitoring all of the sensors, actuators, and subsystems, including those that are vehicle-based and those that are infrastructure-based. The type of monitoring will depend on the amount of self-test within the equipment and the type of equipment. This function will be coordinated with the Malfunction Management/Backup Operation function so that critical sensors and subsystems will be checked at a higher rate than non-critical sensors and subsystems. The Diagnostic function will accept inputs from sensors, actuators, and subsystems. Outputs from this function to both the Check-In/Check-Out and Malfunction Management/Backup Operation functions include the current condition of the monitored equipment as well as emergency notifications of equipment failure.

Technical Requirements

Technical requirements are an outgrowth of the system operational requirements and high-level architecture. Requirements take into consideration the near term availability of technology relating to vehicle command and control operations, infrastructure communications and electronics, and the operator interface function. Quantitative system performance parameters are presented, providing sufficient detail to support the requirements analysis. In some cases, the performance criteria are based on engineering experience. In such situations, technology does not support an exact quantitative parameter, and an estimate is required to facilitate overall progress within the activity.

Table 1 outlines the major functional areas presented in the top-level AHS architecture. The tasks each system function is required to perform are listed. The technical requirements of the individual system functions are discussed in the following text.

Table 1. System Functions and Their Performance Features.

System Function	Performance Features
Vehicle Position Measurement	• Provide lateral information • Provide longitudinal information
Vehicle Position Control	• Control lateral position • Control longitudinal position • Maintain ride quality
Communications	• Provide vehicle-vehicle information exchange • Provide vehicle-roadside information exchange • Provide maneuver coordination on local section • Provide regional information dissemination
Operator and Vehicle Diagnostics	• Monitor operator physical characteristics • Monitor vehicle system functions • Monitor vehicle travel range
Check-In Procedure	• Verify operator physical driving capability • Verify operator/vehicle license, insurance and toll account status • Verify vehicle functionality • Minimize operators/vehicle rejection rate
Entry Procedure	• Provide smooth transition from non-AHS to AHS roadway • Provide method to transfer unqualified vehicles back to non-AHS roadway
Check-Out Procedure	• Provide methodology for alerting operator to impending transition • Verify operator capability to resume vehicle control
Exit Procedure	• Provide smooth transition from AHS to non-AHS roadway • Provide alternative area for vehicles with unqualified operators
Road Condition Determination	• Report physical condition of roadway surface
Operator Interface	• Allow input of driver information and requests • Provide travel status and prompts as required
Malfunction Management	• Monitor vehicle systems • Flag maintenance items prior to breakdown • Detect vehicle system malfunction • Provide continued safe operation in failure modes
Hazard Management	• Provide optimum system operations under routine maintenance conditions • Maintain service at reduced level following occurrence of natural disaster

Vehicle Position Measurement

Vehicle position will be measured using a variety of sensors providing lateral information for lane changing, collision avoidance, and lane keeping, and longitudinal information for vehicle spacing, collision avoidance, and obstacle detection. The measurement function will provide the data necessary to determine the position of the vehicle longitudinally with respect to the adjacent vehicles. In terms of vehicle platoons, the relative longitudinal position will determine the vehicle spacing within the platoon. Longitudinal position must be measured to a resolution on the order of several centimeters for platoon management. Time/slot implementation will require determination of the location of the moving slot and the relationship of the vehicle to the slot. The accuracy of the longitudinal position must be on the order of one meter or less for the time/slot application.

The lateral measurement will determine both the position within the lane and distance to vehicles in adjacent lanes where applicable. Lateral position accuracy must be maintained to a resolution on the order of a few centimeters to support lane-keeping capabilities.

Vehicle Position Control

The control function will provide the signals to internal vehicle systems which will adjust the acceleration, speed, and steering of the vehicle. Position information will be processed by the control function and adjustments will be made at approximately 20 ms. intervals.

Communications

The AHS will require communications to provide certain functions. Communication modes include vehicle-to-vehicle and/or vehicle-to-infrastructure to provide input to the vehicle control loop concerning headway maintenance. Zone and regional traffic flow management and maneuver coordination will be accomplished via vehicle and/or infrastructure to regional communications centers. Emergency notification can be a function of vehicle- and/or infrastructure-to- regional communications. The vehicle-to-vehicle communications can include position information, which provides the capability to optimize vehicle spacing and speeds while minimizing collisions. Vehicle-to-vehicle communications may also be used to implement hazard or malfunction avoidance. Vehicle-to-infrastructure communications will facilitate the performance of route guidance and traffic flow management. Maneuver control may be coordinated through information passed among infrastructure beacons within a local zone. Regional communications will allow incident and weather conditions detected and processed at the regional level to be transferred to the vehicle and/or infrastructure.

Operator and Vehicle Diagnostics

Diagnostic capabilities will include monitoring of operator physical characteristics and vehicle system functionality. The operator characteristics will be selected to provide a method for determining the qualifications of the operator for supporting manual operation of the vehicle, particularly when exiting the AHS roadway. Target characteristics may include visual acuity, pulse, respiration, and response times. Vehicle function monitoring will provide information regarding fluid levels, brake condition, and engine reliability. The diagnostic system will be capable of providing advance notice when service will be required to prevent a system failure.

Check-In Procedure

The check-in function will provide verification of operator and vehicle characteristics monitored in the previous function. The procedure will compare individual characteristics against established standards and pass or reject vehicles and/or operators. In addition, the status of the operator and vehicle licensing, insurance and toll account will be verified. The screening procedure will be designed in order to maximize the safety of the AHS while optimizing the number of users to reduce unit costs and minimize disruption of traffic flow.

Entry Procedure

The AHS entry function will provide a smooth transition from non-AHS roadways. The procedure will include the process of taking control of the vehicle and setting the vehicle functions to disallow driver intervention. The goal of this function is to decrease access times such as those found on metered on-ramps during peak travel times while avoiding disruption of traffic currently traveling on the AHS.

Check-Out Procedure

The check-out process will have several functions in common with the check-in procedure. This function will provide verification of operator characteristics monitored in the diagnostics function. The procedure will compare individual characteristics against established standards and determine whether operators are fit to resume manual control. The check-out process will include activities designed to alert the operator to the upcoming change in driving status and prepare for transfer of control.

Exit Procedure

The AHS exit function will provide a smooth transition to the non-AHS roadway. The procedure will include the process of transferring control of all vehicle functions back to the operator. The transfer of control will be designed in such a way as to provide uninterrupted travel. The exit function includes a provision which allows vehicles with unqualified drivers to be shunted to an alternate area. The goal of the exit procedure is to ensure safety of the individual drivers as well as optimize safety of travel on the non-AHS roadways.

Road Condition Determination

The road condition function is responsible for monitoring the physical condition of the roadway surface and the immediate environment. Sensors will be used to detect such elements as degree of friction, visibility level, and wind-shear forces. Traffic conditions such as congestion and accidents will also be monitored.

Operator Interface

The operator interface will provide the capability to enter destination information into the vehicle control system. The interface function will allow the operator to access information concerning current travel times and routes and request route changes. The interface will be capable of influencing the operator's perception of the AHS travel environment by allowing alternatives to watching the bumper of the preceding vehicle. Status regarding maneuvers will be available to the driver, and updates will be provided at specified intervals. The operator interface is also responsible for providing the means to alert the driver of malfunctions and hazards or to prepare for transition to manual operation.

Malfunction Management

This function entails monitoring the status of vehicle systems and flagging maintenance requirements to prevent malfunctions. The malfunction management function will also be capable of detecting malfunctions and providing system backup operation alternatives. An example of backup operation is alerting the driver and transferring control of the vehicle steering in the event that the lateral control system fails. The reliability goals of the control functions are targeted to be in the millions of hours MTBF; however, each possible system failure will be matched with a backup operating procedure. Malfunction management will also process infrastructure and communications systems failures as they are related to vehicle control.

Hazard Management

The hazard management function will provide operational planning at the local (zone) and regional level. The operational plans will include operating scenarios for routine maintenance and construction areas. The goal of the function is to provide continuous operation of the AHS, maintaining service at a reduced level in the presence of hazardous conditions. Hazard management planning will include preparation for hazards involving unplanned obstructions to the AHS roadway caused by natural disasters or spilled loads.

Comparative Analysis Methodologies

The scope and complexity of the Automated Highway System requires a structured approach to system design, which includes requirements specification and architecture development. The structured approach to complex systems design creates a practical system implementation from functional requirements through an iterative process. Structured methods consist of tools and techniques that illuminate specific aspects of the desired system during the analysis process. Structured methods are useful in defining what problem the system is to solve through requirements analysis, and through a tradeoff process determining how to solve it during architecture development.[3]

In terms of the AHS Precursor Analysis, system analysis tools can provide a means to evaluate the Representative System Configurations within the 16 activity areas. A risk analysis approach summarizes the relative importance of requirements and yields a method to compare solutions. Matrix based tools facilitate the comparison of large quantities of information in a concise chart. This approach is demonstrated in Activity E — Malfunction Management and Analysis, and Activity J — AHS Entry/Exit Implementation, where measures of effectiveness are proposed and relative weights are assigned to provide a method for evaluating alternative configurations.

Structured methods allow a team to identify the design, development, and implementation processes required to satisfy critical system requirements. Modeling of system requirements and functionality may also be used to document top level system requirements. This approach allows system requirements to be decomposed into successive levels which detail the interactions of complex system elements. Structured decomposition provides a method for comprehensive documentation of subsystem interfaces, eliminating the risk of unnecessary duplication of functional elements or inadvertent neglect of critical functions.[4]

Issues and Risks

A major function of the Precursor Systems Analysis is the consideration of the full spectrum of issues and risks associated with development and operation of the Automated Highway System. A set of top level issues and risks involving AHS, as listed in table 2, are identified in order to form a framework for the related activities in the PSA. The issues and risks tabulated in this task encompass a broad range of concerns that will be addressed in a greater level of detail within the individual activities.

Table 2. Summary of AHS Issues and Risks.

Economic	Cost Vehicle Recurring Funding	Benefit Consumer Society Commerce
Safety	Catastrophic Failure Impact of Non AHS Automate/Manual Interface Comparison with Conventional Highway	
Environment	Air Quality Land Use Noise Visual	
Liability	Fault Assignment Personal Inconvenience Absolute Liability Mitigation of Risks	

Table 2. Summary of AHS Issues and Risks. (Continued)

Reliability	Component Failure Rates System MTBF Maintenance Fault Strategy
Social Insitutional	Legislation Equity Transporation Mode Distribution Perception/Exceptions/Comparisons Emergency Vehicles Privacy Institutional Arrangements
Technical	Component Requirements Overall System Feasibility Deployment/Management Strategy OEM vs. Retrofit Equipment

Economic Issues/Risks

The issues and risks associated with economic factors in AHS development can be divided into two related areas covering economic costs and economic benefits. A primary goal of AHS development is balancing costs and benefits while keeping the cost/benefit ratio high in terms of not increasing costs without deriving comparable benefits.

Cost Factors

The costs of AHS include the cost of vehicle equipment specific to AHS, the cost of infrastructure electronics, highway construction costs, and recurring costs due to operation and maintenance. An issue involved with vehicle costs is the extent to which car manufacturers will be required to invest development capital, with the risk that AHS does not gain wide acceptance or is not deployed in enough areas to recoup investment. Another issue is the cost of purchasing AHS components to the vehicle owner. The vehicle costs must be kept within an acceptable limit or the potential users of AHS will be limited to the elite.

The construction costs of AHS will be compared with conventional highways. The cost of up-grading existing freeways to AHS compatibility must compare very favorably with the cost of achieving comparable increases in capacity by building additional freeway lanes. Building new highways to AHS standards will require alternate sources of funding such as subsidies from commercial transport companies that will gain long term economic benefits.

Privatization of highway development is another alternative that bears the risk that the AHS will be underutilized if user costs such as tolls are too high.

Recurring costs include operation and maintenance of both the infrastructure and the vehicles. The cost to drivers of maintaining AHS equipment must be transparent or viewed as incidental to the increase in service. Government agencies must consider the recurring cost to be reasonable to reduce the risk of creating negative agency attitudes toward AHS.

Benefit Factors

The AHS will gain greater acceptance if the benefits are on a par with the costs. Significant savings in travel times in urban environments or highly reduced fatigue levels in long-distance driving will enhance user acceptance of increased vehicle purchase prices and maintenance costs. Trip time reliability is an additional benefit which may be accrued through implementation of AHS. The benefits to society in general will include improved productivity levels as non-AHS traffic conditions improve as a result of AHS implementation. Additional jobs will be created to support AHS construction and maintenance of both infrastructure and vehicles. Commerce will benefit from increases in trucking efficiencies and the creation of new AHS industries to support deployment and operation.

Safety

The event of catastrophic failure is a significant issue in AHS implementation because of the potential risk of user injury. The issue involves the level of importance placed on safety in the system design. Safety is of primary importance, and affects all aspects of system development, including cost, complexity, and user acceptance. One area affecting the safety of AHS is the impact of non-AHS vehicles on AHS lanes. The safety of AHS can be evaluated independently only if the AHS is designed in such a way that AHS vehicles are completely isolated. Another source of risk in the implementation of AHS is the interface between the automated system and manual control by the driver. Safety of the AHS will be measured relative to existing highway systems. While the safety of full AHS can be established and the safety of conventional highways is known, there is the issue of what risk factors are introduced during the transition between the two operating media.

Environment

Environmental issues include air quality, land usage, and noise. Reduced congestion will reduce pollution caused by idling vehicles and improve overall air quality. Smoother vehicle responses in acceleration and deceleration can also contribute to reduced energy consumption and emissions. A potential risk of implementing an AHS which greatly reduces travel times and increases capacities is that commuters will consider longer drives more acceptable, increasing vehicle miles traveled and offsetting reductions in pollutants gained by eliminating stop-and-go traffic. Implementation of AHS mass transit may provide large numbers of users significantly reduced travel times, potentially reducing overall emissions by reducing the total number of vehicles.

The land use associated with the deployment of AHS is also an environmental concern. The amount of land necessary to meet capacity requirements must be less than conventional highways and the design of AHS highways must not create a negative environmental impact such as unacceptable visual and noise effects due to factors such as elevated lanes. These environmental issues carry the risk of losing user and government agency support and acceptance.

Liability

A major issue with the deployment of AHS will be the assignment of fault in the event of collisions or other incidents. Owners of vehicles operating under control of the AHS can not be held liable for accidents caused by factors such as system malfunction or unauthorized access to the system. The liability of the operator of an AHS vehicle becomes less clear if the operator tampers with AHS equipment or otherwise interferes with normal system procedures. There are additional gray areas of responsibility in instances where the control of the vehicle is returned to the driver either during transition from the AHS or in the event of equipment malfunction.

Another area of liability can occur when the AHS system controls the route and schedule of the AHS traveler. Operators of AHS vehicles may be inconvenienced by deviations from expected travel times and experience missed appointments and lost opportunities for earnings. There is also the possibility of vehicle operators becoming crime victims in AHS holding areas or along an alternate route. The risk to the AHS system operator is litigation by inconvenienced or victimized drivers.

The issue of absolute liability must be resolved as well. Responsibility can be placed with vehicle manufacturers, highway designers, highway construction companies, or operating and maintenance agencies. Each party risks being held liable for various incidents involving anything from catastrophic failure of the AHS to accidents caused by vandalism.

Liability issues bring about the concern for mitigation of the risks. Legislation may be required to define the scope of liability and specify responsible parties. Limits may also be placed on the monetary responsibility of parties involved in design, deployment, operation, and maintenance of the AHS.

Reliability

The reliability of the AHS is dependent on several interrelated issues. The reliability of AHS equipment will be a factor, and will affect the overall mean time between failures (MTBF) of the system as a whole. System MTBF goals must also take into consideration the failure rates of non-AHS vehicle components (brake surfaces, shocks, tires, and etc.). The individual AHS components that must be considered in evaluating overall reliability include actuators, communications, processing units, and software in addition to traditional vehicle control equipment. Electronics integrated with the roadside infrastructure has an impact on the equation as well.

Maintenance of AHS vehicle and infrastructure equipment will affect system reliability. The issues of preventive versus corrective maintenance must be addressed. The frequency of maintenance routines will also be a factor in reliable system operation.

The strategy for dealing with fault tolerance is another reliability issue. The ability of the AHS to provide graceful degradation in services in the event of system failures or under adverse weather conditions will be of prime consideration. Soft failure modes will be addressed through component redundancy and/or back-up operating plans.

Social/Institutional

This area covers a broad range of issues that affect the viability of the AHS concept. User acceptance includes the general population in addition to commercial transportation industry and government agencies responsible for developing, operating, and maintaining the highway system. The users' perception of the viability and usefulness of AHS includes both the expectations held for its performance and its comparison relative to other highway systems.

Another issue is the equity each group holds in the system. The general driving population must view the AHS as accessible to all without regard to user class. The risk in designing a system which appeals largely to elite drivers is that the user base will not justify the development. Similarly, the mature AHS must accommodate all classes of vehicles, including mass-transit and trucks, to ensure equal access and a wider cost base. The fully implemented system must also appeal to travelers of varying trip lengths for the same reasons. The issue of distribution of transportation modes within the system, and how to safely support the various classes of vehicles follows from these requirements.

Successful implementation of AHS on a nationwide basis will depend on the development of standards to ensure compatibility between regions. Legislation may be required to provide the impetus toward transition to AHS and instill the confidence that funding agencies need to proceed. Institutional arrangements must be considered to balance implementation risks and costs and to facilitate regional/local coordination.

The effect of AHS on emergency vehicle services includes such issues as assigning relative priorities to different categories of emergency services. The effect of AHS accident rates on emergency requirements is a consideration as well. AHS may also pose an influence on disaster planning for evacuation and relief services.

Privacy issues are involved because of the ability of the AHS to monitor and track vehicles and the need to assess driver fitness before transition from automatic to manual control. Public willingness to accept a certain level of intrusion into areas previously completely under individual control is a risk that must be evaluated. Trust of technology and real versus perceived safety of the system are related issues.

Technical

The feasibility of AHS as a complete system is dependent on the technical risk involved in developing and implementing the individual components. There is little risk involved in the technologies proposed for implementing AHS. The state of vehicle control, communications, and infrastructure electronics is currently capable of meeting the majority of AHS technical requirements. Component requirements must be specified to meet safety, reliability, and maintenance requirements of the system as whole; however, this will place higher standards on each subsystem, increasing the technical risk and impacting feasibility.

Other technical issues involve deploying a system with the magnitude of AHS incrementally in a way that reduces impact to existing traffic flows. Management of system operation and maintenance is a technical issue since vehicle and infrastructure equipment will require monitoring and servicing that do not currently exist on a wide scale. The problem of providing an AHS-compatible vehicle population is also an issue. The alternatives range from requiring all vehicle equipment to be installed by the manufacturer, to limiting AHS to new vehicles, to allowing vehicles to have retrofit equipment, which may support incremental compatibility with the system.

Summary

The size and complexity of the AHS program will require a rigorous systems development approach capable of addressing varied aspects of the system requirements, such as operational, functional, and physical. The operational requirements of the system include increased capacity, safety, and cost effectiveness. The functional aspects of the system include processing, control, and timing. The physical requirements of the system include architectural definition and development of a subsystem hierarchy.

The system architecture must take into consideration the complexity of the design in terms of the ability to provide a reliable system cost-effectively. Complexity also affects the ability to maintain the system cost-effectively. System reliability is a necessary system requirement that encompasses the consideration of fail-safe design features and system cost and maintainability concerns throughout the project life cycle. Planning for reliability and maintainability must be accomplished as an integral part of the systems engineering process.

It is recommended that AHS require implementation of a system-level plan to ensure development and operation of a safe and cost-effective AHS that provides an acceptable level of service. Reliability and maintainability activities should occur during the planning, design, construction, startup, and operational phases of the life cycle.

The system configuration is a top-level system characteristic which lays the groundwork for subsystem design and interface requirements. The system configuration defines the attributes associated with coordination of vehicle control, vehicle performance criteria, facility requirements, and other functions related to automated travel. The system framework analysis identifies the primary concerns for detailed analysis in specific activity areas. Examples of key issues in the determination of a viable system configuration include vehicle coordination units and driver participation in vehicle control within the AHS. The vehicle coordination issue concerning platoon versus non-platoon configurations is addressed at length in the Lateral and Longitudinal Control Analysis. The issues pertaining to the role of the driver in automated travel are discussed in the Safety Analysis.

Preliminary system level analysis places a large percentage of concerns in non-technical categories. These include liability, funding, environmental, and other social issues. An issue of this type has the potential to prevent implementation of AHS. Detailed consideration of specific risks is given in the Activity 0 — Institutional and Societal Aspects report. The balance of the 16 activity areas address the top level issues and risks identified in the system framework analysis.

Guiding Assumptions

The 16 activity areas addressed under this contract each provide an analysis based on standard engineering practice. The technical feasibility of a specific option is considered in balance with the cost effectiveness of the approach. Recommendations are based on providing solutions which optimize system performance within the constraints of practicality. System safety is considered a primary goal in all areas of analysis, with the expectation that a certain standard of safety will be met, and variables such as capacity must be adjusted to maintain safety goals.

Three Representative System Configurations (RSC's) are defined to provide a range of technical options for detailed evaluation. The 16 activity areas each use the RSC's to perform trade-off analyses based on the attributes assigned to the individual system configurations. The specific attributes of the RSC's are chosen to allow examination across four major system characteristics: infrastructure impact, traffic synchronization, instrumentation distribution, and operating speed. The framework provided by the RSC's is used to examine issues and risk in each activity area in terms of specific implementation options. The detailed description of the RSC attributes is discussed in the Representative System Configurations section of this report.

Format/Content of the Full Report

The remainder of this Contract Overview Report consists of three major sections followed by references and bibliography. The first section, titled Representative Systems Configurations, documents the detailed attributes of the three RSC's used throughout the course of this PSA research program. The second section, titled Highlights of the Discussions of Each Activity Area, consists of highlights of each of the 16 activity areas examined. The highlights contain a summary of each activity, including key findings, conclusions, and recommendations. The third section, titled Overall Cross-Cutting Conclusions/Observations, presents overall AHS conclusions and observations which transcend the individual activity areas and/or are best discussed in a manner which allows inter-relationships of the several activity areas to be presented. Issues, risks, and conclusions with significant impact across several activity areas are discussed here with references to detailed material in specific activity areas as applicable.

REPRESENTATIVE SYSTEM CONFIGURATIONS

Three Representative System Configurations (RSC's) were developed. These RSC's were used throughout the various areas of analysis to provide a level of specificity and to introduce a variation of the four basis AHS characteristics: infrastructure impact, traffic synchronization, instrumentation distribution, and operating speed, as desired by the FHWA. The RSC's and their attributes are listed in table 3. The detailed assignments for each attribute will be discussed. An initial distribution of the major components and/or functional blocks of command, communication, and control for each of the RSC's are presented in figures 2, 3, and 4. As the several analyses progressed, additional RSC detail was necessary in a few cases. This additional detail is documented in the several activity reports.

The three RSC's are named: Infrastructure-Centered Platoon Control, Vehicle-Centered Platoon Control, and Space/Time Slot Control. Infrastructure-Centered Platoon Control is RSC 1. This configuration is intended to place the maximum practical system content in the infrastructure. The vehicle longitudinal and lateral position outer control loops are closed in the roadside equipment and generally minimizes the functional content of the vehicle. However, inner control loops for each actuator are located on the vehicle. A functional block diagram description of this mechanization of the command, communication, and control functions is provided as figure 2. The various attributes are identified in the column labeled RSC 1 of table 3.

Vehicle-Centered Platoon Control is RSC 2. This configuration is intended to place the maximum practical system content in the vehicle. With this configuration, the longitudinal and lateral position outer control loop as well as the inner actuator loops are closed inside the vehicle. A number of the command, communication, and control functions must still be located in the infrastructure as depicted in figure 3. The various attributes are identified in the column labeled RSC 2 of table 3.

Space/Time Slot Control is RSC 3. This configuration provides for a synchronous control of all vehicles into a specific moving space on the AHS roadway. The desired local vehicle speed or timing is controlled by the infrastructure, as is the spacing. However, the infrastructure utilizes different slot lengths for vehicles with widely differing performance capabilities and does have to modify slot synchronization in preparation for all merges. The vehicle controls its speed to track the slot dynamics commanded by the infrastructure. The distribution of the command, communication, and control functions is provided in figure 4. The various attributes for this RSC are identified in the column labeled RSC 3 of table 3.

Table 3. Representative System Configurations with Attributes.

Attribute	RSC 1 Infrastructure - Centered Platoon Control	RSC 2 Vehicle - Centered Platoon Control	RSC 3 Space/Time Slot Control
Coordination Unit	Small Platoon	Large Platoon	Single Vehicle Slot
Inter-Unit Control	Asynchronous	Asynchronous	Synchronous
Vehicle Class	Passenger and Light Truck	Passenger and Light Truck	Passenger, Light Truck, Heavy Truck, and Transit
Lane Width	Normal	Narrow	Normal
Performance	Inclusive	High Performance	Inclusive
Vehicle/Roadway Interface	Rubber Tires	Rubber Tires	Rubber Tires
Propulsion (ICE = Internal Combustion Engine)	ICE and Electric With On - Board Source	ICE	ICE
Lateral Control	• Wayside Communication - Based Sensing • Wayside Electronic Map Reference • Wayside Control	• Vehicle Sensing of Magnetic Markers • Vehicle Control	• Vehicle Optical Lane Sensing • Vehicle Control
Longitudinal Control	• Wayside Communication - Based Sensing • Wayside Electronic Map Reference • Wayside Control Enhanced by Vehicle Collision Avoidance System	• Vehicle Communication - Based Sensing • Vehicle Control Enhanced by Vehicle Collision Avoidance System	• Wayside Generation of Vehicle State Requirements • Vehicle Control
Collision Avoidance	Vehicle Radar System	Vehicle Radar System	Vehicle Vision System
Longitudinal Position Location	Wayside Communication - Based Ranging	Vehicle Sensing of Coded Magnetic Markers	Vehicle Wheel Speed Sensing Enhanced by Wayside Tag System or GPS
Check-In Delay Time	Delay	No Delay	Delay
Unqualified Vehicle Entry Prevention	Physical Barrier	Electronic Barrier	Enforcement
Entry To Automated Lane	Dedicated Facility	Dedicated Facility	Normal Highway Lane
Driver Monitoring For Check-Out	Localized Roadway/Vehicle	Localized Roadway/Vehicle	Continuous In-Vehicle Monitoring
Traffic Management	Regional	Regional	Regional
Inter-Vehicle Control	Zone	Vehicle	Zone/Regional
Malfunction Management	Zone	Vehicle/Zone	Zone/Vehicle
Communications Vehicle To Vehicle	None	Vehicle Based Communications/Ranging	None
Communications Vehicle To Roadside	Two-Way Communication Tag	Same As Vehicle To Vehicle Or Public	Two-Way Communication Tag

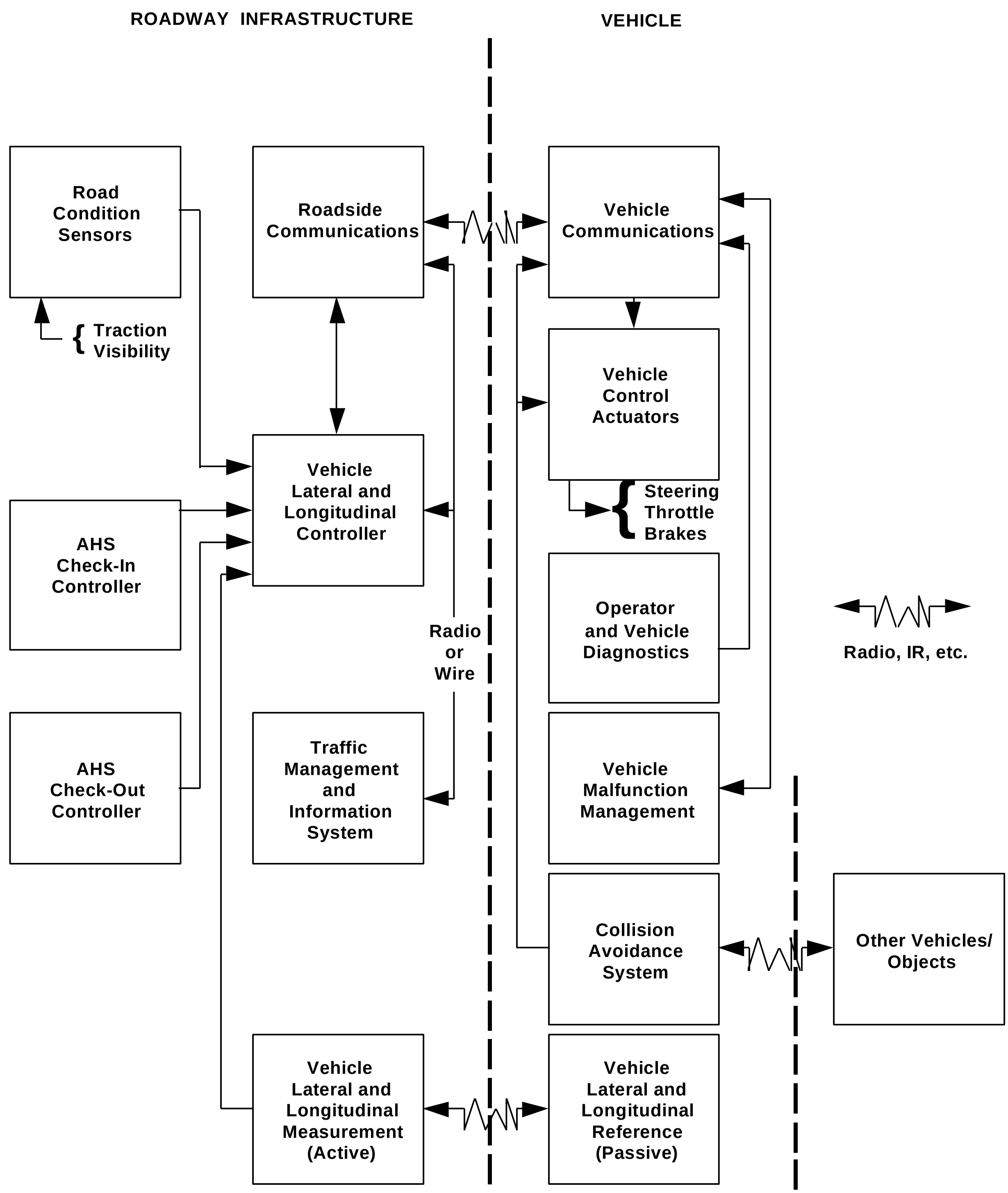

Figure 2. Infrastructure-Centered Platoon Control Configuration.

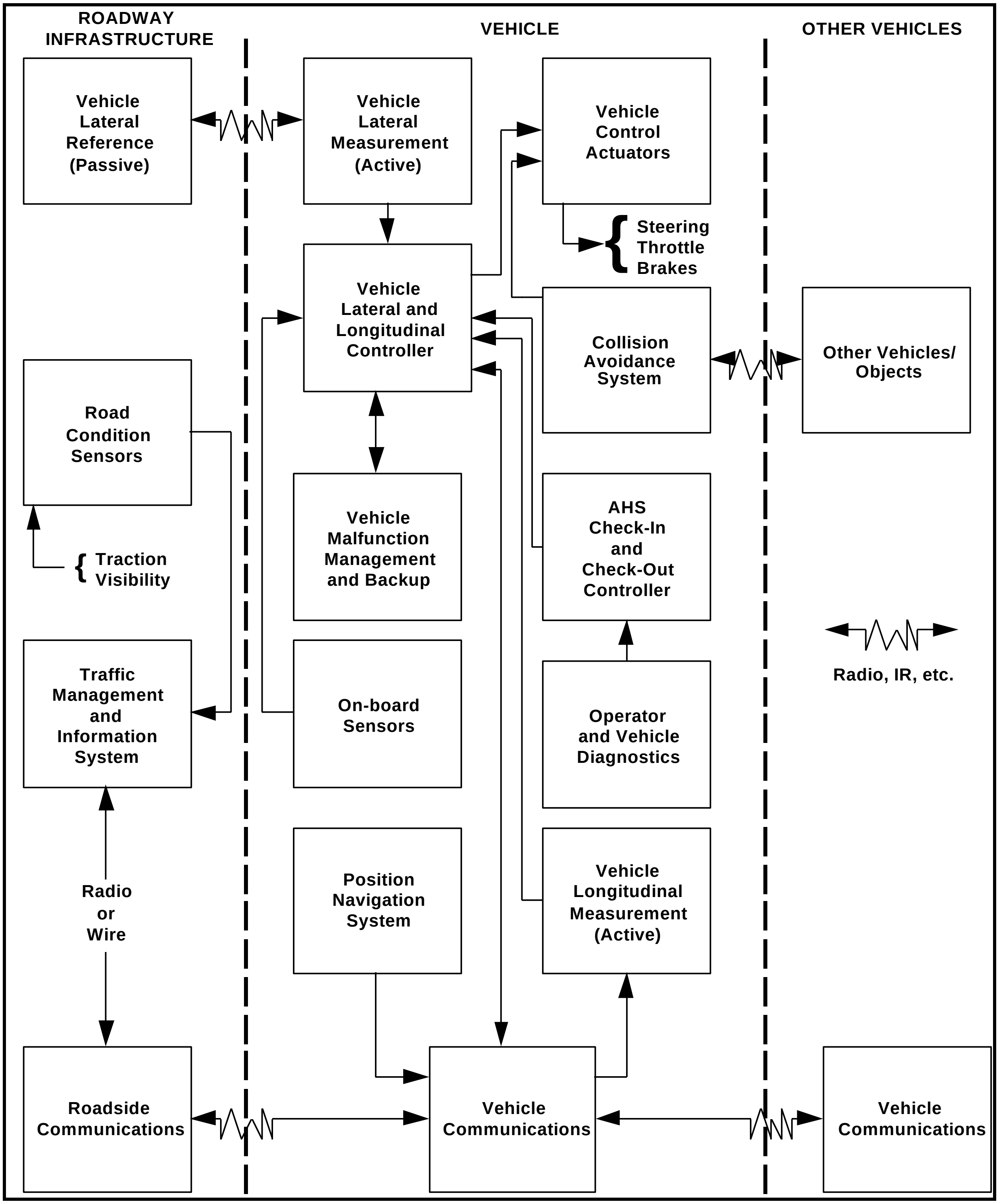

Figure 3. Vehicle-Centered Platoon Control Configuration.

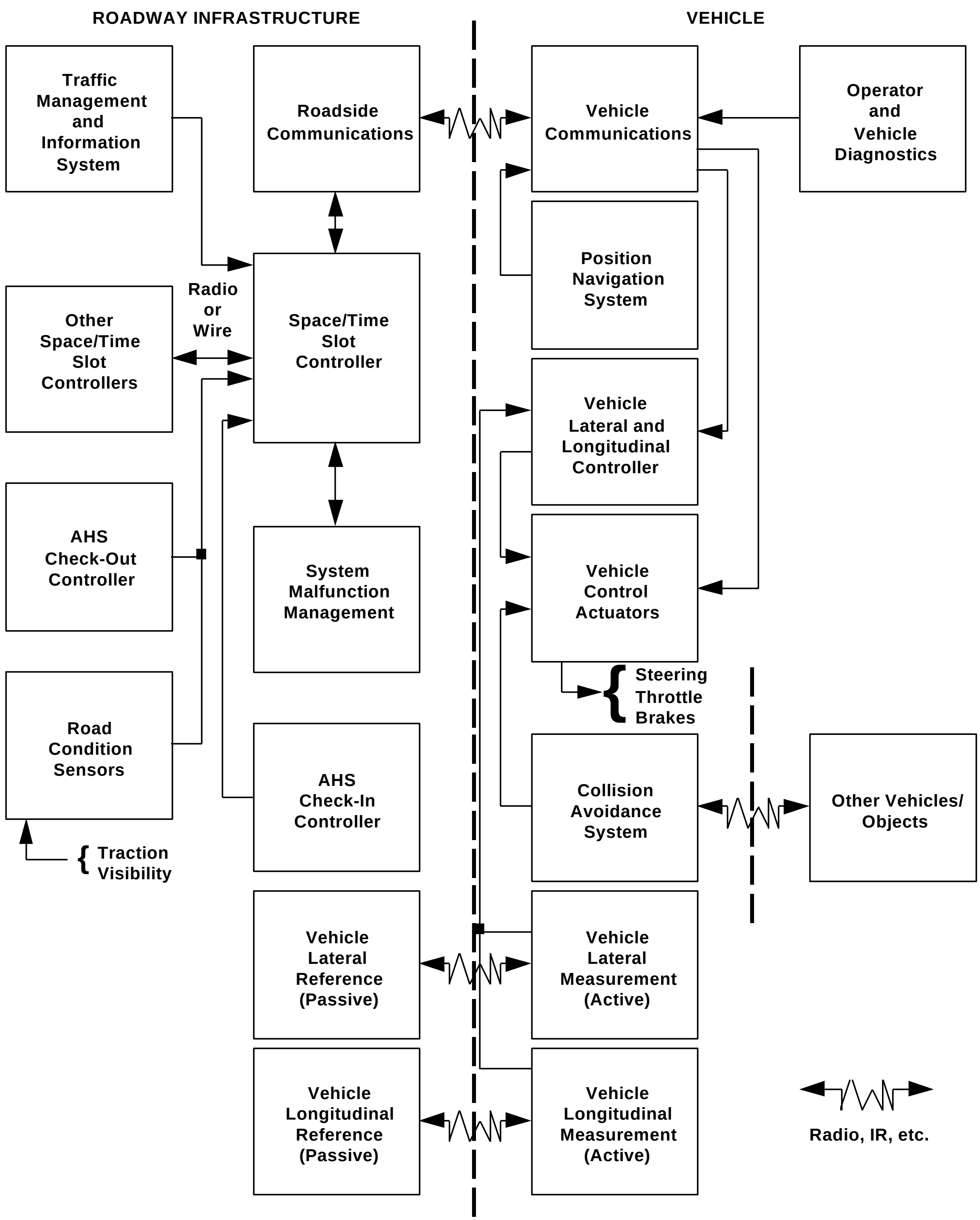

Figure 4. Space/Time Slot Control Configuration.

The details of the attributes listed in table 3 will now be discussed.

Coordination Unit

The coordination unit is the basic traveling unit on the AHS for which the infrastructure coordinates intersection merges and other traffic management functions. A small platoon may consist of from one to about five vehicles and a large platoon may consist of from one to about fifteen vehicles.

Inter-Unit Control

Synchronous control refers to the system wide coordination of the motion of vehicle slots. This form of control is sometimes called point following. In the classic case of synchronous control, all merge decisions are resolved at the time of assigning a vehicle to a control slot. Control between platoons is of an asynchronous nature. This means that control actions between platoons would be based on the specific conditions of the involved platoons only and would not be executed in a system wide coordinated fashion. The control of vehicles within a platoon is also asynchronous in that the details depend on local conditions only, and the decisions are made by the vehicles within the platoon. This form of control is sometimes called vehicle following and can have two modes, either vehicle following or velocity regulation, depending on the distance from the vehicle in question to the preceding vehicle.

Vehicle Class

One of the baseline assumptions imposed on the AHS is that all vehicle types must be supported by the mature system but not necessarily intermixed on the same roadway. Vehicle types may be divided naturally into two classes. One class includes the full range of passenger vehicles and light trucks. This class has vehicle widths up to about 200 cm, lengths up to about 580 cm, and loaded weights up to about 4,500 kg. The other class of vehicles includes heavy trucks and transit buses. These vehicles are typically up to 250 cm in width and have lengths and weights which greatly exceed the passenger vehicle/light truck values.

In order to maintain a reasonable scope for the infrastructure related analyses, while still maintaining a diversity of vehicle class options, heavy trucks and transit vehicles will be assumed to be mixed with light vehicles in RSC 3 only, while RSC 1 and RSC 2 will consider light vehicles only. As the AHS system matures, these RSC’s may support heavy vehicles through the use of separate facilities, particularly for urban deployments. This, however, is not included within the scope of the present analyses.

All vehicles are assumed to have automatic transmissions. Automation of the clutch and shift for AHS operation only is certainly a possibility. However, this is not central to a study of AHS and will not be further addressed.

Lane Width

Narrow lane width is ascribed to RSC 2 in keeping with its vehicle class and performance characteristics. RSC 3 must have normal lane width due to its vehicle class characteristics. RSC 1 is also assumed to have normal lane width due to the infrastructure placement of its lateral control reference, which could result in less accurate control as compared to RSC 2 and RSC 3.

Performance

The inclusive category of performance indicates an AHS which is compatible with the acceleration rates and sustained velocities which are achievable by all but a small fraction of vehicles falling into the vehicle class. High performance, on the other hand, indicates an AHS designed to require that vehicles perform to a select level of acceleration and velocity. These rates may be used as a parameter within the appropriate analyses.

Vehicle/Roadway Interface

The vehicle to roadway interface in chosen as the traditional rubber-tired vehicle riding on freeway-quality road surfaces. Thus pallets of all forms will not be considered in these analyses.

Propulsion

In general, traditional internal combustion engines (ICE’s) are assumed for vehicle propulsion. In the case of RSC 1, vehicles propelled with electric motors will also be considered. The basis performance capability of these electric vehicles is assumed to fall within the ranges established for ICE vehicles. The energy source for the electric vehicles is assumed to be on board the vehicle. The Alternative Propulsion Systems Impact study is not constrained to these RSC propulsion attributes.

Lateral Control

For RSC 1, in keeping with the intent to place the maximum system content in the infrastructure, the active lateral control sensor is placed in the road wayside. Infrastructure-based communication and control systems interrogate cooperative passing vehicles to determine their states (lateral components of position, velocity, and acceleration). These can be derived from triangulation techniques and are used in conjunction with roadway maps and other necessary vehicle information to provide roadside controllers with adequate input information. Lateral control is maintained by the transmission of roadside control signals to AHS vehicles and subsequent steering actuation.

For RSC 2 and RSC 3, the active lateral control sensor is placed on the vehicle and the lateral reference is located on the roadway. However, varying technology is assumed for the two RSC's as indicated. Magnetic markers are used in RSC 2 as a lateral control reference. Vehicles are equipped with magnetometers to sense the lateral deviation of the vehicle with respect to the markers. These markers are placed beneath the surface of the road in the center of each lane. They can be encoded with a positive or a negative polarity for the purpose of providing road curvature or static highway information. In RSC 3, vision systems are used to track lane lines and input resulting lateral deviations to the vehicle based lateral controller for the purpose of lane control. An adequate reference system (existing or enhanced lane boundary markings) must be maintained for this concept to work effectively.

Longitudinal Control

For RSC 1, infrastructure based communication and control systems interrogate cooperative passing vehicles to determine their vehicle states (longitudinal components of position, velocity, and acceleration). These are derived from triangulation techniques and are used in conjunction with roadway maps and other necessary vehicle information to provide roadside controllers with adequate input information. Longitudinal control is maintained by the transmission of roadside control signals to AHS vehicles and subsequent throttle or brake actuation. Vehicle-based collision avoidance systems function as backup longitudinal controllers in the event of a system malfunction. Under normal operating conditions, they provide ranging information to the wayside controllers to enhance vehicle longitudinal control.

In RSC 2, longitudinal ranges and range rates between vehicles in a platoon and between platoons are derived from communication signals. This information along with information communicated by the platoon lead vehicle and other appropriate vehicles is used by vehicle based longitudinal controllers to maintain specified headways and perform longitudinal maneuvers. Vehicle velocity can be accurately derived from the magnetic reference system. Vehicle based collision avoidance systems function as backup longitudinal controllers in the event of a system malfunction.

For RSC 3, vehicle based longitudinal controllers receive desired space/time slot state information from the wayside and vehicle state information from on-board measurement systems. This discrete information is then used to control vehicle throttle and brake actuators to minimize longitudinal errors.

Collision Avoidance

For RSC 1 and RSC 2, vehicle radar systems are used to detect objects on the roadway. These systems include microwave, laser, and infrared. In RSC 3, on-board vision systems function in a collision avoidance mode by measuring headways and closing rates to preceding vehicles or objects. Each system has the capability of commanding vehicle actuation systems to perform evasive maneuvers.

Longitudinal Position Location

The vehicle-roadside communication system is used in RSC 1 to determine the position of all AHS vehicles on the roadway. In RSC 2, vehicles sense coded information in the roadway-embedded magnetic markers which they use to determine their positions. Vehicles can also simply count the number of magnets that have passed from some reference point in order to determine their position. Wheel speed sensors are used in RSC 3 to provide an estimation of vehicle velocity and position. This information can be enhanced by obtaining exact vehicle location at discrete intervals from wayside tag systems or the Global Positioning System.

Check-In Delay

This attribute refers to the time lost because of the required AHS check-in procedure. The check-in delay is in addition to the time required to traverse a normal freeway entry ramp with unimpeded flow. Thus zero delay time means that the vehicle follows a normal freeway type entry velocity profile with no time lost due to the check-in procedure. The value of this delay should be a parameter for the appropriate analyses. A delay of from 10 to 30 seconds is indicated for RSC 1. Thus this check-in testing would likely occur while the vehicle continues to move at a slow speed such as 8 km/h. A delay of from 15 to 90 seconds is indicated for RSC 3. This check-in testing would be performed at an area separate from but connected with the normal freeway entry ramp.

Unqualified Vehicle Entry Prevention

This attribute refers to the method by which an unqualified vehicle is prevented from entering the automated portion of the AHS highway. The physical barrier approach is a fast rising or moving barrier which would physically prevent an unqualified vehicle from being purposely driven past the normal voluntary diversion point. An electronic barrier would prevent an unqualified vehicle from entering the AHS by means of an electronic override of some vehicle function. This presumes that Intelligent Transportation Systems (ITS) capability has incorporated such a feature for many years prior to the AHS, so that the entire vehicle fleet has this built-in capability. Finally, enforcement is the electronic issuance of a fine for illegal entry onto the AHS. This is incorporated into an RSC which does not support platoon operation and thus may be able to safely accommodate an occasional non-AHS vehicle on the system.

Entry to Automated Lane

Entry to an automated AHS lane or lanes is through dedicated facilities for both RSC 1 and RSC 2. For these two RSC’s, there is complete separation of AHS traffic and normal traffic. The transition from manual to automated control may occur at the entry and exit location or may be on AHS ramps located close to these facilities. RSC 3 uses normal highway lanes as part of the operating system. The AHS vehicle is tested for current suitability for AHS operation at the check-in facility located off the highway. Vehicles which pass the testing are electronically tagged and enter onto the normal highway. Once in the transition lane, the vehicle communicates its tagged status, initiates automated control, and transitions over to a parallel AHS lane.

Driver Monitoring for Check-Out

This attribute refers to the source and extent of driver monitoring in preparation for the vehicle to leave the AHS. Localized roadway/vehicle is monitoring which is performed only in the vicinity of an impending exit and which involves equipment located both on the roadway and in the vehicle. Continuous in-vehicle monitoring indicates that the driver of a vehicle on the AHS is monitored on a continuous ongoing basis by equipment located in the vehicle and the results are only communicated with the infrastructure at the time of an impending exit or emergency. Continuous driver monitoring is ascribed to RSC 3 because of its use of a normal highway lane as a transition lane.

Traffic Management

For all the RSC’s, the traffic management function is performed at the regional level. In all cases, this function would sense conditions that affect traffic flow, would determine changes required in flow, and would provide necessary guidance to zone control functions and entry controllers.

Inter-Vehicle Control

This attribute indicates where the inter-vehicle control loop is closed. It is closed either at the zone control level, the vehicle level, or at a coordinated zone and regional level in the case of the synchronous space/time slot control of RSC 3.

Malfunction Management

This attribute indicates the level at which impending malfunctions are sensed and mitigating actions are calculated and issued. Zone/vehicle indicates that the bulk of the function is accomplished with equipment located at the zone level of the infrastructure and that the vehicle provides a secondary level of management. Vehicle/zone reverses the levels of involvement. Finally, zone indicates that the vehicle has little or no involvement in malfunction management and all functions are accomplished by equipment located at the zone.

Communications Vehicle to Vehicle

The vehicle to vehicle communications used in RSC 2 is the combined communications and ranging technology identified under Longitudinal Control.

Communications Vehicle to Roadside

RSC 1 and RSC 3 use a fairly short-range two-way communications system associated with the vehicle tag system for tolling. RSC 2 could use the same communication for vehicle to roadside as for vehicle to vehicle. Communications based on public communications such as digital cellular or personal communications services are another options.

These three RSC's and the attributes as just identified provide significant variety among the four basic AHS distinguishing characteristics identified by FHWA. In particular, roadway design and land use impacts to the infrastructure vary due to the attributes: vehicle class, check-in time, unqualified vehicle entry prevention, entry to automated lane, and others. Traffic synchronization varies as per the inter-unit control attribute. Instrumentation distribution varies per the basic difference between RSC 1 and RSC 2 in that the first places the maximum of instrumentation on the infrastructure and the second places the maximum on the vehicle. Finally, operating speed is varied in the attribute performance and possibly in vehicle class.

HIGHLIGHTS OF THE TECHNICAL DISCUSSIONS OF EACH ACTIVITY AREA

The highlights of each of the 16 activity areas examined will be discussed in this section. The highlights will contain a summary of each activity, including key findings, conclusions, and recommendations.

Activity A — Urban and Rural AHS Comparison

The Urban and Rural AHS Comparison identifies and analyzes, at a high level, the technical and operational requirements of an AHS in urban and in rural environments. The characteristics of urban freeways and the needs of commuters and work-day truck and transit traffic are compared with the profile of rural highways supporting relatively long trips with typically low traffic volume. The RSC's are used to evaluate the compatibility of specific configurations to typical urban and rural environments.

The primary results of the urban rural analysis indicate that the goals of urban and rural AHS are not compatible. The impetus towards increased automation in the urban setting is to improve traffic flow and reliability of travel times, while in rural areas the main advantage of automation is reduced travel times and ease of travel. The challenge of the AHS design will be to develop a configuration which addresses both environments.

The division of instrumentation between the infrastructure and the vehicle must be determined by systems level design considerations which take into account the complexity, testability, reliability, and maintainability of the system. The design complexity and testability of the control loop system is directly affected by the placement of the equipment. Implementation of the vehicle control loop within the vehicle simplifies the timing of inputs to the processor, allows testing prior to system integration, and improves reliability in the sense that a failure affects a single vehicle only. Alternative infrastructure based configurations which reduce the individual processor load will increase the quantity of roadside processors and increase the complexity of coordination among processors. Infrastructure placement is not considered practical for the vehicle control loop function.

Functions which operate over a wide area are candidates for implementation in the infrastructure. Examples include route guidance planning, which can be handled at a regional traffic operations center, and zone or regional flow control, which may be communicated along the infrastructure most efficiently. The feasibility of AHS is dependent on evaluation of each subsystem element individually to determine the appropriate division of content. The system architecture must first be developed to determine the functional decomposition, at which point the most effective configuration can be established.

Instrumentation specifically required to support very tight headway tolerances in close vehicle following modes may not be necessary in areas with low traffic densities. A certain amount of AHS specific equipment will be required in the vehicle to support any proposed system configuration. The urban AHS may require highly accurate, rapidly updated vehicle position information to support platooning or tightly spaced vehicles. This will place stringent requirements on the capability of AHS instrumentation in the urban environment. It is possible to improve long-distance travel times and user convenience without increased throughput merely by implementing intelligent cruise control and lane keeping instrumentation. This may lead to a situation where vehicles which operate strictly in a rural area are over-equipped. Excess equipment affects both purchase price and maintenance costs. An AHS design which requires the same vehicle equipment for urban and rural operation would be ideal from a design standpoint but may not be practical from an implementation perspective.

There is a risk of creating a system in which user costs are not in balance with benefits in the early deployment stages, especially in areas with low traffic volumes. The cost of operating an AHS may be financed through fees collected from users of the AHS. The large number of vehicles and existing congestion in most urban areas is expected to generate a demand for the AHS, even if user fees are charged. There will be significantly fewer vehicles in rural areas from which fees can be collected. Drivers may choose to save money by not using the AHS in the absence of congestion on rural highways. Financing alternatives to usage fees or methods of distributing fees collected over all areas may be considered.

The goals of evolutionary deployment of AHS functions are different in urban and rural scenarios. Adaptive cruise control combined with lane keeping instrumentation are candidates for early AHS deployment which can provide safety benefits for travelers and trucks making long-distance trips. This capability is compatible with a rural environment but may not provide throughput benefits in an urban environment in which rush hour traffic densities prevent effective use of automated headway control. Similarly, a subset which addresses the congestion problem by providing higher vehicle densities in AHS lanes, but does not address heavy trucks, would be effective in an urban environment but would not be well suited to a rural environment.

The results of the urban and rural analysis indicate that a system configuration which places responsibility for the vehicle control loop dynamics in the vehicle is the most feasible. The conclusion is drawn that the evolutionary deployment of incremental AHS capabilities may provide limited safety and convenience benefits to some users; however, considerable throughput improvements cannot be achieved without full automation of vehicle control functions. It is recommended that the initial proof of concept be targeted to specific user requirements in a congested urban environment, with funding designed to include usage based fees to establish operational capabilities prior to wide scale deployment in connecting rural areas.

Activity B — Automated Check-In

The AHS is quite sensitive to vehicle malfunctions of a type which are common on a non-automated highway. Furthermore, the AHS vehicle has a variety of specialized equipment which is not required on a typical roadway and is also likely to fail occasionally. The notion of a system which inspects and approves vehicle entry, a check-in system, makes sense for an AHS.

The check-in operation is central to a successful AHS. A sensible check-in system will easily pay for itself due to the reduction of AHS malfunctions. The number of vehicle functions which might fail on the AHS is indicative of the fact that the check-in system must be comprehensive and reliable. A critical analysis of system functions and the development of methods for validating those functions have been the two principal means of describing the automated highway check-in system.

Among the standard vehicle functions that require inspection are engine, brake, and steering operations. These are critical functions, as are the specific AHS control functions, which include lateral and longitudinal sensors, automatic controllers for brakes, engine and steering, and the communications and data processing system which supports automated operations and relays instructions between vehicles and between vehicles and the roadside.

Windshield wipers, headlights, and other equipment which assist a driver but which would provide little benefit to an automated system are considered less critical. Vehicles that are carrying external loads, vehicles with loose or damaged equipment, and the current energy supply and available range of the vehicle are functions which are considered to be in an intermediate critical range.

Public service vehicle entry to an automated highway often requires different service than a private vehicle entry. This service is provided at the check-in station. During routine operation, the public vehicle should be inspected in the same manner as any other vehicle, but public safety vehicles should not be deterred from entering the AHS when there is an emergency.

Validation of vehicle functions is performed either at a special check-in station, during routine inspection, or while the vehicle is under manual control (continuous in-vehicle test). Special inspection stations were categorized according to their functionality. At a validation station, information is communicated from the vehicle to the station, and the vehicle is notified that it has either passed or failed the check-in evaluation. No delay is involved with this test. The data communicated from the vehicle includes all information from the built-in testing equipment and from the last routine inspection.

At a remote special check-in facility, the vehicle undergoes several minutes of rigorous inspection and is then certified to enter the automated highway. This type of station is associated principally with a highway which is divided into automated and non-automated lanes. Since both equipped and unequipped vehicles can enter the highway, testing must be done before the automated vehicle enters the roadway, and the results would be transmitted to a verification station before the transition to the automated lane took place.

The check-in station that is located at the on-ramp to a dedicated automated highway and is designed to evaluate vehicle functionality while the vehicle is at rest is similar to the remote facility except that the inspection must be of shorter duration in order to prevent the buildup of queues. Visual inspection is routine at such a station.

The final type of facility is a dynamic test area which compares vehicle performance after control has been transferred to the automated system with a standard for acceptable automated vehicle performance. The test is done while the vehicle is gaining speed to enter the automated highway and includes some on ramp curvature to demonstrate automated steering. If the vehicle fails the test, it is automatically steered off the ramp and into a lot for rejected vehicles.

A special analysis of communications and data loading feasibility determined that, for a properly equipped vehicle compatible with the automated highway, the communications and data requirements of a check-in facility would be met. Concerns about falsifying data in the vehicle computer or adjusting a critical piece of electronic equipment may be met by encrypting the information in the vehicle computer to prevent tampering.

Driver functional validation may be required because of health considerations or because of a concern that the same driver, when released into the non-automated traffic stream, may cause an accident for which the automated system would be liable. Privacy is a major concern, although equivalent privacy is yielded in everyday life. Liability and privacy remain major unresolved issues.

Many additional issues and risks were identified but were not addressed in detail. There are many issues related to non-standard equipment or multiple versions of the same hardware or software. Another general area of concern is the control and interception of vehicles which fail check-in but attempt to enter the automated highway illegally.

After reviewing the available literature regarding vehicle systems failure, it was concluded that a survey of vehicle system failure modes and frequency of failures was needed. This survey would relate only to loss of functionality which could be associated directly to failure on an automated highway. The result of this survey would be a comprehensive list of component details which fail and the likelihood that they would fail if they were not detected at check-in.

Activity C — Automated Check-Out

The goal of the check-out analysis is to evaluate potential automated-to-manual transition scenarios in terms of relative feasibility, safety, cost, and social implications. The check-out alternatives range from minimal testing of the operator and the vehicle to extensive testing of the operator and vehicle.

The transition from automated control to manual driving must follow a progression of steps that ensures the safety of the driver and surrounding vehicles in the AHS and non-AHS lanes. Potential check-out protocols must be capable of maintaining safety in a cost-effective manner while considering the technical feasibility and user appeal of the procedure. The check-in process used to validate the transition from manual to automated control has often been considered to be a vehicle-intensive task, while the check-out process used to validate the transition to manual from automatic has been considered as operator-intensive. This assumption focuses on the functionality of the automated control systems as the vehicle enters the AHS, and the qualifications of the driver to regain manual control as the vehicle exits the automated lanes. This study has determined that vehicle functional verification is also required to ensure a safe transition to manual control. It is recommended that the manual braking and steering functions be exercised prior to termination of automated control as a minimum. These two functions are critical to safe operation at the time that control of the vehicle is given to the driver.

The impact of a specific check-out procedure on the system configuration can be viewed from the perspective of coordinating decision-making tasks among the vehicle system, infrastructure, driver, and exit facility. The dedicated lanes protocol places most of the burden for decision-making and coordination on the vehicle and infrastructure. In contrast, the driver is assigned more decision-making tasks under the mixed flow lanes protocol. The level of coordination required among the vehicle system, infrastructure, and driver is greater in the mixed flow lanes protocol than for the dedicated lanes protocol. The complexity of the check-out decision rules and the rate at which these rules must be executed should be consistent with the abilities of the decision maker. The vehicle system and infrastructure are typically more efficient than humans at processing sensor data and complex decision rules, transmitting the results of processing, and performing multiple decision-making tasks currently.

The check-out protocols proposed for dedicated and non-dedicated exit scenarios assume that the exit maneuver is aborted if a fault is detected, regardless of whether the fault detection represents a false alarm. A conservative check-out policy may ensure safety at the risk of introducing liability issues, and will increase costs associated with handling detained vehicles and closed segments of the infrastructure. The potential for loss of goodwill resulting from user dissatisfaction with the AHS must also be considered.

The topic of storing vehicles which fail vehicle or operator validation procedures has extensive implications in terms of roadway deployment. There are multiple design issues associated with the use of depots or shoulders to temporarily store vehicles. The storage system design is based on the expected number of users and the duration of use. Construction and operational costs and land use issues are primary considerations in determining the effectiveness of storage areas. Vehicle diversion to centralized storage facilities is an option which may alleviate design issues concerning land usage, occupancy levels, and operating costs at the risk of causing poor user acceptance. The disposition of vehicles disqualified from manual operation will be a key consideration in the design of the check-out procedure.

The issue of driver readiness to resume manual control is related to issues of privacy and liability. There is a broad range of tests available to verify driver capabilities, including sensors to detect the presence of substances in the driver’s blood, prompts to gauge reaction times, or scanning of eye movement to evaluate alertness. The invasiveness of certain tests may cause concerns among privacy advocates and have an adverse effect on user acceptance. The assignment of liability in the event of an incident following the transition to manual control is a concern as well. Extensive tests may create the impression that the AHS is responsible for ensuring that no impaired drivers are allowed to have manual control. It is recommended that the driver check-out consist of a simplified routine that places the responsibility for assuming manual control completely with the driver. The check-out process might follow a screening of manual brake and steering functionality with a prompt to the driver. The driver will then respond with a positive action such as pressing a push-button to indicate readiness to assume control. Legislation may be required to clearly delineate the responsibility for accidents following transition from the automated lanes.

Eliminating complex operator verification tests and placing responsibility with the driver for accepting the manual driving task is one way to simplify the issue and reduce the risk of AHS being held liable for accidents caused by improper driving immediately following travel in the automated lanes. This approach is based on the premise that the AHS is not responsible for verifying driver readiness to safely operate the car prior to entering the AHS, and returning control to the driver following automated travel should not carry a burden beyond that of ensuring that the vehicle is functioning properly.

Activity D — Lateral and Longitudinal Control Analysis

The AHS will be designed to reduce travel times, increase highway safety, reduce congestion, decrease the economic, physiological, and psychological costs associated with accidents, lessen the negative environmental impact of highway vehicles, and increase lane capacity. Lateral and longitudinal control system development will play an important role in this effort. Hardware and software performance capabilities will directly affect the achievement of each of the stated AHS goals.

The emphasis of the lateral and longitudinal control analysis work is on defining significant issues and risks associated with vehicle control. Reference is made to numerous research results that describe the state of the art in vehicle control technology. These concepts are applied to representative system configurations which form a basis for system comparison and critique.

Vehicle platooning is a very feasible concept for an AHS. The choice of the intra-platoon spacing parameter presents a challenge as there is a perceived tradeoff between capacity and safety. Close vehicle spacing (1 m) may result in many low velocity collisions, while larger spacing (5 m to 20 m) may result in fewer collisions (possibly none under reasonable assumptions) with relatively high collision velocities. An adaptive control system in conjunction with accurate and timely vehicle-vehicle communication should be able maintain intra-platoon vehicle spacing under a variety of maneuver conditions. One significant question that remains is the likelihood of nonpredictable vehicle/roadway malfunctions that could cause a vehicle in a platoon to decelerate at a relatively high level. The coordinated braking scheme would potentially have difficulty responding to this malfunction in a manner that maintained all intra-platoon spacings. (Coordinated braking is fully discussed in the Activity D report, and highlights are presented in a separate subsection at the end of this report.)

In the event of a serious vehicle malfunction, a loss of lane control, or an intentional maximum braking maneuver, intra-platoon collisions in a closely-spaced platoon may result. In this case, it is important to understand the nature of the resulting collision dynamics. These dynamics are the physical interactions and resulting body motions between vehicles. Based on the results of this study, lateral and longitudinal controllers can be tested to ensure that they are able to maintain vehicle attitude control while the platoon brakes. Note that the front and rear ends of vehicles may not generally align well with other vehicles. At the time of a collision, the platoon may also be undergoing a turning maneuver, which would slightly misalign each vehicle with respect to surrounding vehicles. Individual vehicles would probably also brake before any collision. This would result in a vehicle that is pitched forward with respect to the previous vehicle, which if braking, is also pitched forward.

In the area of vehicle control algorithms, reasonable advancements in headway maintenance control systems for platooning vehicles have been made. Also, good lane keeping algorithms which produce acceptable performance levels have been developed. However, robust lane changing and platoon/vehicle merging algorithms that will provide ride comfort while meeting AHS requirements are still needed.

In order to develop, test, and analyze vehicle control algorithms, communication systems, and vehicle maneuvers, a comprehensive AHS simulation encompassing basic vehicle dynamics, vehicle interactions with other vehicles and with the roadway, multiple lanes (possibly mixed traffic), entry/exit lanes, various roadway configurations, and environmental effects (wind, rain, icy roads, etc.) must be developed. The simulation will serve as a testbed to develop flow/maneuver optimization, platoon control, merge/separate, lane change, entry/exit algorithms, and an understanding of the effects of various vehicle maneuvers. It will also help to determine the best mix of infrastructure and vehicle-based functionality.

Communication systems which guarantee error-free transmissions in the presence of electro-magnetic interference from such sources as AHS vehicle-roadside communication systems, AHS vehicle-vehicle (intra and inter-platoon) communication systems, and non-AHS signals are critical to the success of communication-based control systems. It is also important from a data transmission viewpoint as well. Various methods have been described to counteract the effects of interference, such as the use of spread spectrum techniques, the proper choice of overall communication bandwidth, and the use of specific transmission frequencies and message coding methods.

Sensor, communication, and control design needs to be as flexible as possible in a given roadway operational environment, since it is difficult to predict the transportation needs of the country five to ten years after a design is completed. To achieve this goal, system software should be carefully developed in a well documented, object-oriented manner to allow for various operational conditions. System hardware should also be designed to meet all expected performance requirements.

Activity E — Malfunction Management and Analysis

This activity is devoted to an investigation of the necessary reactions of the AHS subsystems to failures or degraded performance of the AHS functions. Pro-active measures to prevent malfunctions are often included in the traditional definition of malfunction management, but for the purposes of this investigation these pro-active measures have been declared as the province of Activity N — AHS Safety Issues and are addressed only incidentally. The following are the key findings, conclusions, and recommendations of this activity.

A total of 71 malfunctions were identified and analyzed. They were distributed into four general categories as follows:

- General vehicle malfunctions — 19.
- AHS-specific vehicle malfunctions — 28.
- Wayside electronics malfunctions — 15.
- Roadway malfunctions — 9.

There were no operator malfunctions identified for the RSC's defined other than the operator not being prepared to assume manual control on check-out.

Methods and technologies have been identified which enable detection of each of the identified malfunctions. A survey of current research found that a considerable amount of research is being conducted in industry and in universities with the aim of improving malfunction detection capabilities.

Analysis needs to be done to determine which of the identified detection methods are practical and cost-effective for use on AHS. Some of the methods and technologies identified are commonly used for malfunction detection in military and space applications, but may be too costly for AHS application. An example would be triply redundant processors with data sharing and majority voting.

Methods for automating the detection of roadway malfunctions, which are presently detected by manual inspection, were identified. Further analysis should be performed to determine which malfunctions require automated detection to meet safety and performance goals and which malfunctions are detected more cost-effectively by automated detection than by manual inspection.

The management strategy for each malfunction can be divided into two parts: a set of immediate actions to contain the malfunction and a set of actions to restore AHS operation. Five sets of immediate actions that cover all of the malfunctions and five sets of actions to recover from the effects of these immediate actions were also defined.

Where access to the AHS lanes is from parallel manual lanes via a transition lane (i.e. in RSC 3), it was assumed that the AHS lane is continuous. Therefore, so as not to interfere with access to the AHS lanes, the breakdown lane was placed as the farthest AHS lane from the transition lane. In the other RSC's, since access is intermittent, it is assumed that the breakdown lane is the lane adjacent to the exits, so as to facilitate self-clearing of malfunctioning vehicles when possible and to simplify extraction of malfunctioning vehicles by service vehicles when required. This should be a topic for further investigation by roadway operations analysts.

The evaluation of management strategies shows that most malfunctions can be managed effectively by the strategies defined. In the evaluation of malfunction management strategies for malfunctions which result in loss of lateral control, the scoring of safety-critical items show that these malfunctions are difficult to manage. This results from having no identified adequate backup for lateral control. The RSC most affected by malfunctions resulting in loss of lateral control is RSC 1. In this RSC, a large part of the control function resides with the wayside. A failure in this function affects multiple vehicles. Collision avoidance systems are assumed to be an adequate backup for longitudinal control. An investigation of what is required to provide backup for lateral control should be undertaken. Perhaps side-collision warning systems can be adapted.

From a safety-critical standpoint, the next most difficult malfunctions to manage are those associated with brake failures, tire failures, and failures of roadway pavements, barriers, and bridges.

Malfunctions that are difficult to manage for safe operation also are difficult to manage for maintenance of performance. Malfunctions that can be managed for safe operation but that require closing of AHS lanes, or even entire AHS sections, also have a large impact on performance.

On the non-automated highway, the operator is presently the major detector of malfunctions and implementor of malfunction management. Intuitively, it seems that the operator could continue to play some role in the detection of malfunctions, that there are some malfunctions that the operator could detect better than, or at least as well as, the automated detection system, and therefore could serve as a backup or alternative detector. One item that continually is brought up in discussions of the subject is that of animals on the roadside that may jump in front of the vehicles and how the operator may be better able to anticipate the animals' movements than the automated detection system can. Some further investigation of the operator's role in malfunction detection should be carried out, as well as a determination of how the operator can indicate the perceived malfunction and desired management actions to the AHS.

Results from studies of operator reaction capabilities suggest that virtually no operator participation in malfunction management be allowed in the mature AHS RSC's assumed in this activity report. The discussion found in the fifth task of Activity D — Lateral and Longitudinal Control Analysis reviews studies of driver reaction time and the possibilities of driver intervention in case of automatic control failure. The long reaction times shown in that task and accounts of accidents due to improper operator reaction or over-reaction to malfunctions (blow-outs, drifting out of lane) when the driver has had continual control seems to preclude sudden resumption of lateral control after a long period of no driver involvement with vehicle control. The analysis of this activity assumes that the operator will not have a role in any management strategies except in those cases where control can be assumed at the operator's leisure. The operator is allowed a role only in those cases where the vehicle can be brought to a complete stop before the operator assumes control, or where the vehicle can continue to operate in a near-normal fashion until the operator can assume control. If it could be shown that under some benign set of conditions, short of coming to a complete stop, the operator could safely assume control, this may mitigate some of the difficulty with managing loss of lateral control.

Activity F — Commercial and Transit AHS Analysis

The physical and operational characteristics of commercial and transit vehicles differ significantly for passenger vehicles. As a result, the implication of these differences must be accounted for in the design and operation of AHS facilities that accommodate such vehicles. Generally, physical characteristics relate to the infrastructure, while the operational characteristics refer to operations on the AHS facility. Physical characteristics of heavy vehicles require additional infrastructure compared to a passenger-vehicle-only facility. These additions include wider lanes, increased vertical clearance, and increased pavement thickness. In addition to the physical differences between heavy and light vehicles, operational parameters of heavy vehicles, including acceleration, deceleration, effect of grades, capacity, comfort and safety, off-tracking, trailer sway, load shifting, and use of automatic transmissions may affect overall operation of a mixed-use AHS lane.

Although provision of separate AHS lanes for heavy and light vehicles may alleviate many of the issues associated with the physical and operational differences between these two types of vehicles, the costs associated with this may be prohibitive. However, by comparing the demand and the overall operation of the lane, a combination of separate and shared lanes may provide the most cost-effective solution of providing access to heavy vehicles without adversely affecting overall operations. In rural areas, capacity is not a concern, and the nature of the rural AHS is such that each vehicle is adequately spaced so inclusion of heavy vehicles would not hinder operations. In areas where terrain severely hinders heavy vehicles operations, a separate lane could be provided in order for overall operations not to be degraded. In urban areas where high capacities are expected with AHS, public concerns may exist for inclusion of heavy vehicles on the AHS lane. However, it is felt that transit vehicles could share the same lane as passenger vehicles, as their operational characteristics are not as adverse as trucks. Inclusion of transit on a AHS lane will take away some passenger vehicle capacity; however, depending on the demand for buses, overall passenger throughput could increase, perhaps significantly.

In order for heavy vehicles to be included on AHS without separate lanes, a policy regarding headways between vehicles needs to be developed. This policy should address the following issues; multiple vehicle operation modes, exclusive passenger vehicles headway policy, actual and perceived risks associated with headway spacing, variations in vehicles performance, human factors, relationships to AHS subsection, interface to ITS, and institutional factors.

All the issues associated with inclusion of commercial and transit vehicles on AHS are only valid if demand for these vehicles to use an AHS facility exists. There are, in general, different issues relating to demand for both rural and urban situations. In urban areas, trip characteristics of transit vehicles match well with the expected operations of AHS, hence a potential for high demand exists. Trip characteristics of local trucks, whether large or small, are such that it is doubtful that AHS will provide any benefits, and as a result, demand from these types of vehicles is generally expected to be low. Certain types of intercity/interstate trucks will find urban AHS beneficial, especially in intermodal-type cities. In rural areas, issues affecting demand for trucks include travel time savings, safety, fuel consumption, maintenance cost, comfort and convenience, arrival predictability, initial equipment cost, and usage costs. In order for demand of heavy vehicles to exist in rural areas, the benefits associated with these issues must far outweigh any negative aspects of these issues. The issues presented here are general in nature and may not apply to all areas. Therefore, demand issues should be done on a site-specific basis.

Although the costs associated with inclusion of heavy vehicles on AHS are high, the benefits of inclusion of certain types of heavy vehicles, especially transit, are enormous. The most important benefit associated with transit use is the comfort and convenience for passengers, leading to increased ridership, potentially reducing congestion. Other potential benefits include lower operating costs, fuel efficiency, and decreased air pollution.

Interface requirements for heavy vehicles at AHS facilities must include check-in procedures that limit delay in order for the full benefits of AHS to be realized. However, due to the difference in components between light and heavy vehicles, light-vehicle testing procedures must be modified to address the following heavy vehicle issues: safety implications associated with testing of load security, frequency of tests, and verification of truck and trailer compatibility. In addition to the additional testing required between heavy and light vehicles, infrastructure requirements at interface points are much different. The acceleration of heavy vehicles requires acceleration lengths corresponding to urban interchange spacing (1600 m) in order to avoid degradation of the mainline AHS traffic. Solutions developed for this problem include limited access for transit and commercial vehicles, access at only terminus points, and exclusion of certain types of heavy vehicles in urban areas.

The same methods and issues associated with urban testing of heavy vehicles apply to rural testing also. However, the availability of offset testing is a concern, as situations may arise that require testing in rural locations where the cost of providing this type of service may not be cost effective. Infrastructure requirements for rural areas differ significantly, as it is assumed that access to AHS will be via existing freeway lanes and ramps, hence eliminating the need for an acceleration lane.

Activity G — Comparable Systems Analysis

Twelve complex systems were identified that correlated at least partially with AHS requirements. These systems included automated teller machine systems, military communications systems, nuclear power systems, air traffic control systems, rapid transit systems, airport ground transportation systems, automated aircraft landing systems, space program systems, automobile air bag systems, ship command and control systems, automobile navigation systems, and air defense systems. Of these twelve, three systems were selected for further analysis. The three systems selected are: the Bay Area Rapid Transit (BART) system, the Supplemental Inflatable Restraint (SIR) system, commonly called air bags, and the TRAVTEK navigation system.

The goal of the analysis of these three systems: BART, SIR, and TRAVTEK, was to present issues which have been addressed in the design and deployment of comparable systems in order to derive lessons learned and provide insight into design considerations relevant to AHS. The experience gained from the three representative comparable systems, BART, SIR, and TRAVTEK, offer a number of important insights into the application of new technologies to the field of passenger transportation. These lessons reflect the process of technology development and management that may also be experienced in the development of an automated highway system.

On the technical side, these systems offered additional insight into appropriate techniques for technical systems specification, verification of system performance, and initial pre-deployment testing and quality assurance. Given the potentially high complexity of the many systems involved in AHS, successful deployment depends critically on the ability to specify and test a highly reliable system. A related issue is the treatment of both system safety and reliability in the technical development and in system operation. In addition, the level of effort required to maintain the automatic systems is an important consideration. Specific recommendations from the technical side include the following.

Technical systems specifications:

- A complete AHS system requirements specification is necessary at the beginning of the development process. This specification should be the focus of strong scrutiny in order to avoid creating an unnecessarily complex system. Clear, comprehensive, documented, and testable requirements should be established at the beginning of the program and then subjected to a controlled review and change process for the life of the program.
- Trained human factors specialists should be utilized in the design of the driver interface. Personnel with the proper background know and can apply the basics of human/computer interaction research. It should also be ensured that the design is suitable to the wide range of people who drive. For instance, nomenclature testing was done on TRAVTEK to avoid the use of computer terminology with which many people are not familiar. In addition, the tasks must be designed to be almost intuitive to minimize driver training requirements. The entire driver task load during check-in and check-out must be considered. The addition of any task which may distract the driver from safely driving the vehicle must be carefully considered. That task must be designed to create the minimum distraction from primary driving tasks. In general, guidelines must be developed and applied which restrict the use of displays and controls during driving, reducing the density of visually presented information, and use of auditory tones to augment the visual displays. One of the most difficult, and therefore most often

ignored, design tasks is to design acceptable response times into a system. These need to be established at the beginning of the design process and then rigorously enforced as the design is implemented.

- Importance should be placed on defining and documenting subsystem interfaces, especially those between different suppliers. Various features of an AHS are the same as features for other ITS areas. Communications and the driver interface are just two. Standards for AHS must be compatible with those for ITS in general. Since the division of responsibilities on the TRAVTEK development program followed natural system boundaries, this made the preparation of a detailed and complete interface specification relatively easy. The fact that this detail was documented and available to both responsible partners certainly contributed to the interoperability of the system components. Division of the work among the participants should be such that simple and easy to define interfaces exist between their efforts.

Verification of system performance:

- A comprehensive set of performance parameters along with reasonable evaluation methods must be established. In some aspects, it proved very difficult to establish measurable performance parameters for parts of TRAVTEK. For instance, a measurable parameter was never established for the quality of traffic data from the Traffic Management Center. It turned out that the poor quality of this traffic data was the most serious performance flaw in TRAVTEK. Local users, familiar with Orlando traffic, preferred not to receive the TMC data. The lesson here is that performance parameters must be established and tested for all parts of the system.
- In the development and procurement of AHS technologies, a competent and independent technical review team should be retained in each phase of the technical development and testing of the system.

Initial pre-deployment testing:

- Functional testing should be sufficiently funded to be complete and rigorous. On TRAVTEK this activity was under-funded and skipped because of schedule constraints. The evaluation effort could only assume the underlying system was working. Because of funding problems, different completion dates of the system components, and schedule pressure to begin the evaluation phase, a rigorous functions testing of the completed TRAVTEK system was never accomplished. Although subsystem testing by the responsible partners did uncover most problems, some critical issues only came to light after the evaluation started. This led to more changes during the evaluation than were necessary and the loss of valuable time from the evaluation effort.

- The highest priority must be given to safety and reliability in pre-service testing. Safety issues should be given highest priority in determining the readiness of an AHS system before start of service. Systems which have an overriding impact on safety obviously require extensive testing. It should also be realized that the formulation of test procedures, standards, and specialized instrumentation requires long lead times which can be comparable to the system development time.
- Test and evaluation procedures must be a mix of actual testing and simulation to span all possible response scenarios.

Provide quality assurance:

- Sufficient time in the AHS development process must be left for product testing and quality control. This involves allowing ample time for suppliers to debug new technical subsystems, as well as time and resources to test and debug the fully-integrated AHS on site before beginning operation. Development of TRAVTEK continued throughout the evaluation phase. Software fixes were installed, design deficiencies were corrected, and of course, errors in the map database were corrected. It was found necessary to implement strict configuration control procedures so the evaluation team knew the configuration and the characteristics of the system being tested. Even at that, it proved difficult in some instances to usefully compare data recorded at the beginning of the evaluation period with data recorded at the end.

System safety:

- AHS development should include both safety and systems engineering functions from the earliest part of system planning, design and development. AHS specifications and standards must carefully balance the needs for technical innovation with the need for more specific design criteria to assure a safe and reliable system.

Reliability:

- System requirements must include diagnostics to alert operators of failed components. AHS specifications should include a strong emphasis on the design issues associated with service degradation, including equipment malfunctions in the vehicle, at the wayside, and in the infrastructure. In addition, these systems must be sensitive to the information provided to drivers during automatic operation and especially during degraded service conditions. Human factors research should emphasize the driver’s response to information especially in degraded service or emergency situations.

Maintenance:

- Maintenance issues should also be included early in the planning stages for an AHS, focusing on long-term maintenance requirements. For both vehicle- and infrastructure-based components, these requirements include maintenance equipment to identify and repair failures, common information systems, and clearly-defined procedures for addressing scheduled and unscheduled maintenance needs.

Non-technical issues included such areas as the continued political pressure to bring the system such as BART into revenue service, coupled with the early loss of public confidence. Typically, new technologies in transportation come under strong political pressure, as elected officials press for early photo opportunities and quick benefits to improve their political standing. The high expectations already placed on AHS ensure that the political process will have much bearing on the development and deployment of these systems. Furthermore, in considering the early stages of AHS deployment, safeguards are necessary to avoid quick loss of public confidence. Close scrutiny of AHS operations is unavoidable, but lessons from the three comparable systems may help avoid the erosion of public trust that may seriously hamper planned AHS projects. Specific non-technical recommendations include the following.

To minimize political pressure:

- Technical personnel should maintain high visibility in AHS decision-making throughout the development process. Administrative and management boards should include staff with a high degree of technical competence in AHS.
- As much as system design will allow, AHS projects should take advantage of incremental deployment. This may imply that an automated highway be deployed in a small corridor initially, allowing for system expansion to other corridors in the near future. The selection of an initial corridor should be based at least in part on the ability of that corridor to demonstrate significant first user benefits. The development of AHS systems will likely follow the trends of automotive systems such as the air bag with respect to the driving developmental influences, which are:

- First-generation systems are driven by the need to provide features which are pleasing to the customer, incorporate desirable technical, diagnostic, and service functions, meet overall cost targets, and meet applicable legislative requirements.
- Second-generation systems continue to meet the first-generation requirements while also placing increased emphasis of cost and packaging considerations (size, shape, weight, and location).
- Third-generation systems meet all earlier-generation requirements while also meeting the need to integrate functions both within the system and with other systems and address concerns for the recyclability of system components.

To increase public confidence:

- The introduction of a pervasive consumer-oriented system such as AHS needs the highest degree of coordination between government, manufacturers, consumer needs/wants, and technical state of the art. The public perception of the use, benefits, and operation of a system is fundamental to marketplace acceptance.
- The public needs to be educated as to the programmed response of the AHS in both normal and abnormal situations as well as how to correctly interface with the AHS. This will increase the public's level of confidence in the system as well as prevent attempts to override correct system response.

Management/funding philosophy:

- TRAVTEK operated under a "manage by consensus" style. Almost all important issues were discussed in open meetings with all project stakeholders present and able to express their concerns and position. After such open discussions, it was always possible to agree to a course of action which everyone agreed was the best possible under the circumstances. This approach was facilitated in three ways. First, there was a very natural division of responsibility between the partners, which greatly lessened the impact of one partner on the work of another. Second, the responsibilities of each partner were established in some detail at the very beginning of the effort. Third, the project held meetings at which all partners were present every six weeks for the entire length of the effort . In addition, careful minutes were kept in which all actions items were noted and assigned to a specific individual. This kept the dialogue between the partners going and ensured that critical items were not forgotten but regularly discussed until they could satisfactorily be resolved. Program management must emphasize the building of consensus. Achieving support from local agencies, either public or private, is very difficult and requires careful and sensitive planning.

- AHS development should include an aggressive and honest public information effort. This should include open public forums to discuss system planning and development and, as much as politically feasible, candid discussion of problems with development and deployment.
- On TRAVTEK, each major partner (General Motors, the American Automobile Association, and the public sector) funded its own effort. There was no prime contractor but three equal and independent partners. In addition, each partner had responsibility for clearly separate and relatively independent parts of the system. This made preparation of a statement of work easy and ensured that the funding responsibilities were usually obvious. This natural division of responsibilities greatly contributed to the smooth running of the project. A well thought-out statement of work for all participants and all activities, accompanied by adequate funding, should be the first order of business.

Privacy issue:

- TRAVTEK overcame a potential problem with premature disclosure of some project data. Since the two private partners were funding their own effort, they wanted to keep test and evaluation data out of the hands of competitors. This concerned the raw evaluation data and not the carefully analyzed results of the evaluation contractor. The problem arose because various public agencies, and to some extent private contractors being funded with public money, had legal requirements that might have led to disclosure of the data. The problem was resolved by ensuring that the raw data stayed in the possession of the concerned private partner. Only carefully extracted subsets were provided to the evaluation contracts. Of course, the evaluation contractor had complete visibility as to the types of data available to ensure they received everything they needed.
- Ethical concerns about ensuring that test subjects understood the nature of the tests and that their actions were being recorded for later analysis were overcome by having each subject sign an informed consent document.
- TRAVTEK was implemented such that is was possible to identify specific vehicles and to track the route of any vehicle. To ensure the anonymity of the assigned driver of any vehicle, all information as to the specific identity of the driver was impounded by either the AAA or the rental car agency and not released to the other partners or to the

evaluation contractor. For AHS, individual privacy must be considered in such areas as check-in/check-out, route planning, and toll collection.

To mitigate liability concerns:

- Concern about potential product liability was the basis of many technical discussions of proposed design features for TRAVTEK. It was, of course, an important issue in designing the driver interface. Product liability was also a concern to the AAA and led them to extraordinary efforts to improve the quality of the map database. But there also was a dark side to what sometimes was a preoccupation with product liability concerns. Occasionally, instead of stimulating the design of the highest quality product, it resulted in the fearful deletion of a desirable feature. Management must ensure that when a desirable feature is identified, product liability concerns can be met by building higher quality into the product.
- A liability budget should be firmly established early in the AHS development process. A manufacturer needs to clearly understand its liability exposure in able to properly budget the cost of liability into the AHS system's business case.
- An onboard recording device should be incorporated into the vehicle's AHS equipment in order to enhance diagnostics and discourage unfounded litigation.

In light of the preceding issues, the major risk for an AHS will be the public concern over price, benefit and safety. Drivers may like the features of the system and would utilize it if perceived as safe. An AHS demonstration project should be able to resolve the safety risk. However, people's expectations of a reasonable cost must be consistent with the anticipated benefits. Finding a way to overcome the benefit risk will be an interesting challenge which will hopefully be aided by the lessons learned from comparable systems.

Activity H — AHS Roadway Deployment Analysis

This analysis covers the entire range of highway infrastructure topics that will be encountered when AHS is deployed. The research team approached the deployment analysis problem by considering several alternative highway configurations, then making various sets of assumptions and conducting what-if analyses. Hypothetical freeway sections, based on sections of Interstate Highway 17 (I-17) in and near Phoenix, Arizona, were used for the analyses. Various design years were used for the traffic volumes used in the analyses.

A fundamental requirement to the modeling of every operational measure of effectiveness of the AHS/non-AHS system is the capacity of the AHS system. This research effort made assumptions regarding AHS mainline throughput capacities and determined that, given the assumptions used, the platoon-oriented RSC's will have extremely high mainline capacities. It is recognized that these top level capacities must be degraded to provide for entry and exit operations. Even so, it seems reasonable to expect that AHS capacities double or triple those of conventional lanes should be achievable. These capacities (4,000 to 6,000 vehicles per hour) were therefore selected for modeling use throughout the report.

Capacity assumptions were also developed for non-platooning operations. If assumptions regarding inter-vehicle spacing are the same as those for inter-platoon spacing, much lower capacities result. In fact, in some cases the capacities are even lower than those of manually operated lanes. It is necessary to make assumptions that coordinated braking is achievable for non-platoon operation to have capacities similar to those of platoons. (It should be noted that coordinated braking, or at least coordinated deceleration, is also a requirement for safe operation of platoons.)

While more difficult to quantify than capacity, repeatability of travel time is an important AHS advantage. By significantly reducing the number, severity, and duration of accidents and incidents, AHS will allow more dependable forecasting of travel times.

Various configurations of AHS lanes and shoulders for the AHS were considered. It was concluded that AHS shoulders are desirable for the operational benefits they bring. With shoulders, broken-down vehicles as well as snow debris or spilled loads can be stored while automated operations continue unimpeded. Without shoulders, these events would require the complete shutdown of single-lane automated facilities and severely decrease the capacity of multilane facilities.

The width of the AHS lane need not be the same as present day manual lanes due to the superior lateral control AHS will bring. Lane widths of 2.5 m (passenger cars only) and 3.0 m (trucks and transit vehicles) are expected to be adequate if a deviation of plus or minus 200 mm from the desired path is achievable. Shoulder width requirements are essentially the same as travel lane width, although slightly greater widths may be considered due to the requirement for manual operation within the breakdown lane.

While improved lateral control results in a reduction in lane width, deployment of a dedicated lane AHS scenario still involves construction of new pavement if the number of non-AHS lanes is to remain the same. Even if an existing HOV or mixed traffic lane is taken over for AHS, the requirement for the AHS lane, its shoulders, and its barrier result in a new pavement widening. This can be mitigated by using narrower lanes and shoulders on the conventional freeway but generally not without compromises to safety and traffic operations.

Activity I — Impact of AHS on Surrounding Non-AHS Roadways

This activity evaluated the impact of AHS lanes on the surrounding non-AHS roadways. The non-AHS roadways include the general purpose freeway lanes, freeway ramps, cross streets, and parallel arterials. For both urban and rural situations, the study evaluated key issues relating to non-AHS roadways including: 1) highway re/design issues; 2) the spatial requirements of AHS facilities and entry/exit facilities; 3) the traffic operations of both AHS facilities and the non-AHS surrounding roadways; and 4) the impacts of AHS facilities on land use.

The analyses undertaken for this activity resulted in findings that AHS lanes potentially can generate significant travel time benefits compared to conventional freeway and arterial lanes. The travel time benefits result from the ability of AHS lanes to accommodate relatively high speeds at high vehicle capacities. The resulting benefits will attract significant volumes of AHS traffic from the freeway and arterial lanes. The AHS volume which can be attracted to an AHS lane is limited by the capacity of that AHS lane. For the corridor studied, the volume of AHS traffic which could be attracted to one directional AHS lane is equal to approximately 40 percent of the corridor traffic (or 40 percent of total vehicles with AHS equipment). An additional AHS lane might be a possibility to accommodate more AHS vehicles as the market penetration of AHS equipped vehicles increases. The study found that the urban freeway corridors used for analysis can generally accommodate the spatial requirements of an AHS lane.

The performance of the AHS lane is limited by the ability of the AHS on and off-ramps to effectively accommodate traffic entering and exiting the AHS lane. The AHS ramp capacity is a function of the amount of traffic which can enter and exit the AHS platoons operating at maximum capacity. AHS ramp capacity is also a function of the traffic volumes which can be handled at the intersection of the AHS ramps with the adjacent street system.

The high traffic volumes which can be accommodated by an AHS lane can significantly impact the surrounding roadway system. The high entering and exiting AHS volumes will impact the cross streets carrying AHS traffic to and from the AHS ramps. The intersections of the cross streets with the parallel arterials will also be impacted. In addition, the overall traffic circulation patterns will be impacted by the changes in vehicle origins and destinations to enter and exit the AHS ramps. The high entering and exiting AHS volumes could generate significant vehicle delay within the corridor. This study found that as the AHS traffic volumes became high (generally greater than 40 percent of corridor demand), the benefits of the AHS lane to accommodate more volume began to decrease as a result of the additional delay at the entry/exit locations.

The opinions of the transportation experts agreed with the findings of the technical analysis that increased AHS ramp volumes could adversely impact the surrounding roadway system. The experts also expressed concern that AHS lanes could attract additional single occupant vehicles (SOV’s) and impact the overall vehicle occupancy within a freeway corridor. Future planning and research should investigate how demand management techniques can be used for AHS lanes to encourage higher vehicle occupancies.

The potential impacts on the surrounding roadway system have implications for planning and research. First, it is important that the planning of an AHS lane be carried out within a larger systems planning context to optimize the operations of the AHS lanes, cross streets, and parallel arterials. This is desirable from a technical as well as an institutional perspective. Second, the AHS traffic control and the street system signalization control must be integrated and coordinated to accommodate the additional AHS traffic and to respond to changing traffic patterns of AHS entering and exiting traffic. Another element which must be considered in planning and research is the impact of AHS facilities on the surrounding land use.

Activity J — AHS Entry/Exit Implementation

This activity considers the infrastructure elements required for accessing an AHS lane or freeway. Infrastructure requirements are a function of the AHS entry/exit strategy utilized, the level of performance desired, and the traffic demand on the facility. AHS check-in and check-out procedures have a profound effect on the entry and exit facility size.

Two main check-in and check-out procedures are possible with AHS: on-site testing and off-site testing. If on-site testing requires a testing-duration delay, then entry and exit facility sizes that are extremely large and unfeasible to implement could result, especially in an urban environment.

Entry and exit to and from the AHS lane can occur under two scenarios: through dedicated facilities or non-dedicated facilities. Dedicated facilities provide direct ramp access to and from the AHS lane. Non-dedicated facilities utilize the existing conventional freeway interchange; a vehicle enters or exits the AHS lane by weaving across conventional freeway lanes and entering from a transition lane. The focus of the work conducted for this report was on dedicated AHS entry/exit facilities in an urban setting.

The work performed resulted in identifying main issues associated with AHS entry and exit strategies. These main issues are:

- On-site check-in and check-out procedures should be limited to “on the fly” procedures that do not delay the AHS vehicles. Even with minor check-in or check-out durations, sizable queues of vehicles will form, large delays will be imposed to the entry and exit procedures, and the size of the facilities including the length of the ramps will exceed practical and realistic design parameters.
- For the corridor studied, market penetration rates of 40 percent will cause AHS ramp demands as high as 2,900 vehicles per lane (if unrestrained demand is assumed), which would cause the signalized ramp terminal to fail operationally. Current urban freeway ramps have a capacity of approximately 1,500 vehicles per hour per lane. AHS ramp volumes of this magnitude will not only affect AHS operation, but will affect the local street network operation as well.
- At approximately forty percent AHS market penetration, ramp delay affects overall corridor performance and diminishes the benefits achievable by increasing through capacity on the freeway by the AHS lanes. Entry and exit facilities will determine how well AHS operates and dictate the benefits achievable by AHS implementation.
- Increasing the spacing between AHS entry and exit facilities causes ramp demand volumes to increase. Ramp delay increases significantly and overall corridor performance degrades significantly.
- Dedicated entry and exit capacities are governed by where and how they interconnect with the local street system. These capacities can be increased by separating AHS and conventional freeway interchanges, separating AHS entry and exit procedures from the same location, and eliminating conflicting movements at the ramp terminals. Providing

for free flow movement at these points could increase ramp capacities to 2,300 vehicles per hour per lane.

- Entry and exit volumes must be collected and dispersed by the local street network. Operational and geometric changes to local streets will be required even at lower market penetration rates. Implementing one-way streets is one method that will limit physical widening of existing roadways locally.
- AHS design and implementation will require a collective effort between the FHWA, and State and local governments to ensure that a balanced system results.
- The cost of providing dedicated AHS entry and exit facilities will most likely be considerably higher than non-dedicated facilities, due to structure costs of the new interchanges. A slip ramp configuration would best suit dedicated AHS facilities. This would allow complete separation of the conventional and AHS freeway operations and minimize construction costs.

It is suggested that portions of the work conducted under this study be continued and investigated in the second phase of AHS development and prior to determining a preferred entry/exit strategy.

The research conducted on interchange spacing of AHS facilities was limited to 1.6 kilometer and 4.8 kilometer spacing. Longer spacing between facilities should be investigated that accounts for actual origin-destination of trips and how this affects market penetration and ramp volumes of AHS. The effects of eliminating short trips on AHS should be documented.

Modeling of the limited access AHS concept should be conducted with this modeling accounting for heavy vehicle and transit use.

The actual procedure for entering and exiting the AHS lane needs to be defined and quantified to ascertain the impacts on entry and exit design. Procedure details such as entry as single vehicles only, entry as mini-platoons, stopping to wait for gaps in AHS mainline traffic, etc. will have a profound effect on entry facility size, especially at higher market penetration rates.

The effects of reducing the conventional freeway capacity (through reduction in lanes converted to AHS) on non-dedicated entry and exit strategies needs to be quantified. In dense urban areas already experiencing congestion, the reduction in the number of lanes will add to the problems. Weaving, merging, and ramp operations should be quantified and compared to a dedicated entry/exit facility design.

Activity K — AHS Roadway Operational Analysis

This analysis considers the unique operational and maintenance aspects of AHS, as they are similar to and different from the operations and maintenance of a conventional highway system. The traditional operational measures of highway, freeway, and street networks, such as capacity and level of service, are covered in Activity H — AHS Roadway Deployment Analysis. This activity report deals with the issues and concerns that an operating agency needs to deal with after AHS is deployed.

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 present TOS's, but maintaining security and avoiding deliberate interference should not present difficulties different from other areas where radio communication security is important.

Maintenance activities present more of an impact to AHS than to conventional freeways, 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 on 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.

A good evolutionary scenario for AHS deployment requires stages which provide additional functionality and justify the required effort to overcome the associated difficulties. The categories of these difficulties are technology, infrastructure, human factors, vehicle manufacturing and maintenance, and public will.

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 Freeways be given the opportunity to be a consortium member.

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 system. 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.

Activity L — Vehicle Operational Analysis

The vehicle operational analysis addresses topics associated with the development, operation, and deployment of AHS vehicles. Each area of analysis presents a variety of aspects which affect the feasibility of the AHS from the vehicle perspective. Vehicle electronics are discussed in terms of recent trends in subsystem automation, existing state of the art, and expected future developments. The impact of subsystem reliability on the process of bringing new technology to the consumer car market is another factor. The methodologies for providing safe system operation in the event of subsystem failures is an important consideration in the design of AHS specific vehicle components. This analysis is also concerned with the ability to optimize early market penetration by supporting reverse compatibility in vehicle models as advances in automation are achieved. The benefits of AHS-specific vehicle subsystems in terms of potential user services while traveling outside of the AHS are also estimated.

AHS will be reliant on dependable communications between vehicles and between the infrastructure and vehicles. A high degree of research and development must be dedicated to RF communications and it’s role in AHS vehicles. Interference, power consumption, transmitting power limits, FCC regulations, RF congestion, frequency allocation, and communication protocol are some areas that should be researched.

The cost of electronics has been decreasing over time including electronics in today’s cars. The general trend appears to be that in the future the cost of automotive electronics will become less for production cars and light duty trucks. However, any AHS-specific item on that car will be more expensive, because the initial quantity produced will be small. Furthermore, AHS electronics will need to incorporate more sophisticated components capable of operating at faster speeds than what is normally needed on non-AHS cars. History has proven that new electronic technology does not drive the automotive electronics market, but Federal mandates may, and profit always motivates the market. Automotive manufactures will not install more expensive or sophisticated electronics in their products unless they have to or have financial incentive to. Therefore, the general trend of cheaper electronics in the future may not affect AHS, especially in the beginning phase. Also, the software development and systems development efforts will be substantially more complex. In order to make the AHS vehicle affordable to the public, automotive manufacturers and or the infrastructure stakeholders must be willing to spend funding to initially deploy AHS.

Vehicles are becoming more electronics intensive. Aftermarket suppliers of vehicle electronics are finding it more challenging to find space inside of the passenger compartments of automobiles and light duty trucks for their products. In the future, integration of electronics will become even more challenging. One current solution to decrease cost and to save space is to integrate two or three modules into one. This methodology will continue to be popular in the future. Research and development should continue in the packaging area, including wiring solutions and alternatives such as multiplexing and fiber optics.

The retrofit of AHS equipment into vehicles will be made much easier if proper hooks are put into the vehicle to accept the integration of actuators, control modules, and wiring. To create the proper hooks in the vehicles, vehicle manufactures must work toward phasing in AHS equipment incrementally.

Activity M — Alternative Propulsion Systems Impact

This activity analyzes the impact of propulsion systems other than gasoline-fueled spark-ignition engines on the deployment and operation of AHS and identifies key design issues and enabling technologies for these alternative propulsion systems. At the direction of FHWA, the analysis, as here reported, excludes roadway provided electric power, since that technology is being addressed in depth by another contractor.

The spark-ignition engine combines generally good characteristics, a long history of development and refinement, and an almost overwhelming infrastructure and production readiness advantage to present a propulsion system which is very unlikely to be significantly replaced without the exogenous market inputs such as legislative mandates within the time frame of this study.

None of the batteries currently under consideration can be said to be able to meet the mid-term goals set by the U.S. Advanced Battery Consortium (USABC) in actual vehicle operating conditions. Even when a battery that meets the mid-term goals is fully developed, it would still be disadvantaged in many respects relative to the current gasoline automobile. Limited range, long recharge time (measured in hours), high battery cost and short life, inferior acceleration performance, large size and weight, and performance deterioration in cold weather or as the battery reaches a low state of charge are among the problems faced. In addition, there is inadequate heat available for passenger comfort in cold climates, and air conditioning in hot climates significantly decreases range. However, analysis determines that electric cars should fit into the continuum of performance capabilities for which AHS would be designed. The rational is based on the following observations:

- Fuel economy regulations and fuel taxes will exert pressures on standard propulsion vehicles to not extend their present performance.
- AHS must be compatible with light duty trucks and sport utility vehicles exhibiting performance lower than standard vehicles because they are a large part of the fleet.
- Consumer pressures will force alternative propulsion system vehicles to improve performance until they fall at least into the lower portion of the continuum which includes the above categories of vehicles.

Two unique operational attributes are identified for the alternative power/fuel systems. The first is obvious: each requires a fuel which is unique to that system. This attribute is mitigated if the several alternative systems are available in bifuel form. The 85 percent methanol (M85) fueled system is the most likely to be capable of bifuel operation, since ordinary gasoline or reformulated gasoline (RFG) could be stored in the M85 fuel tank. Compressed natural gas (CNG) can be made in bifuel form, but this requires more modification and definitely a separate fuel tank. Battery-electric when combined with an internal combustion engine (a hybrid power plant) in effect then also becomes bifuel. Thus there is a likely possibility that each of the alternative power/fuel systems will appear as a unique fuel system even though some of their numbers may be bifuel.

The other unique operational attribute is associated only with the battery-electric system. All of the required motor, power management, etc. controllers are very different from the engine and transmission controllers on other powertrains. The sensors, actuators, diagnostics, and all aspects of the powertrains are different. Thus the battery-electric system will have a unique check-in requirement as it addresses this aspect of vehicle operation and preparedness for operating on an AHS.

The range of a battery-electric vehicle is very significantly impacted by the use of heating or air conditioning during the trip. Thus the range will vary with the ambient temperature at the time of the trip as well as the individual user’s heating or air conditioning setting preference. These factors may need to be considered in real time at vehicle check-in in setting the acceptable destination choice of a battery-electric vehicle. Uncertain environmental factors can also affect energy consumption during the trip period, such as depth of snowfall and unexpected traffic delays due to natural disasters and traffic collisions.

It is concluded that AHS need not provide routine refueling capability for alternative propulsion system vehicles as a part of the AHS infrastructure. The rationale is based on the assumption that alternative propulsion system vehicles and AHS must both be viable economic and consumer concepts independent of each other. A viable alternative propulsion system will generate the incentive for present refueling facilities to adapt or modify their capability so that they also serve the needs of the alternative propulsion system vehicle. Only should AHS evolve to a point where it resembles a toll road facility, which offers the only viable service in a travel corridor, would AHS need to provide refueling capability for all vehicles.

However, emergency refueling capability for alternative propulsion system vehicles should be provided on a limited basis. Analysis concludes that in order to facilitate the extraction of vehicles which run out of fuel while on the AHS, the AHS must consider the refueling needs of all vehicles for the run-out-of-fuel problem. Failure of certain vehicle fuel/power source systems or the check-in process could result in vehicles running out of fuel while still on the AHS. The AHS malfunction response capability must include provision for refueling (and/or possibly towing) such vehicles from the AHS breakdown lane. A refueling capability on an emergency basis for all forms of vehicles is one response for consideration.

Industry-wide standards may be needed to ensure AHS vehicle performance, since some aspects of vehicle performance that do not presently come under specific regulation may need to be commonized or required to meet some minimum level. The responsibility for setting these requirements must be determined as part of the AHS planning effort.

Activity N — AHS Safety Issues

This analysis addresses the issues of safety from a system design standpoint. The automated highway system will be required to meet a certain standard of safety, regardless of the system configuration which is chosen. A primary goal of AHS is increasing the safety of the nation’s highways. A general assumption is that by eliminating human error as an element in a large percentage of traffic accidents, the overall safety of vehicle travel will be significantly improved. This assumption may be valid if the AHS operates in isolation, neglecting the effects of all external factors, and if the number of failures due to AHS-specific equipment do not exceed those due to human error. A first area of study presents an array of factors which have the potential to impact the design and development of an AHS which meets the goal of collision free operation in the absence of malfunctions.

A stated goal in the development the AHS concept is collision free operation in the absence of malfunctions. Overall safety will also be affected by the extent to which external factors are capable of interfering with vehicles in the system. Operation of the AHS in conjunction with conventional travel lanes or in areas that are vulnerable to intrusion will create the potential for collisions with non-AHS vehicles. Accidents may be caused by unauthorized vehicles entering the AHS lane, by debris from accidents occurring in non-AHS lanes, or animals or pedestrians entering the roadway. A collision free environment can not be guaranteed unless all types of intrusions can be prevented, and there will remain a certain degree of risk which must be managed.

The role of the driver in the AHS is the center of debate in terms of safety. The human field of view and the benefit of experience allow a driver to anticipate and avoid many potential collisions in conventional driving. The AHS design must be capable of detecting and avoiding unplanned intrusions into the travel lane. A balance must be achieved between automated control and operator intervention. The spacing and grouping of vehicles has a great impact on the complexity of the problem. The potential for error in close following mode may be greater than the benefit of allowing the driver to intervene in a perceived emergency. One option which may be considered is allowing the lead vehicle in a platoon to retain some degree of manual control. This issue is one of the most pressing in terms of maintaining system safety, especially with respect to implementing platoons. The capability to prevent collisions is removed from system control if the operator is allowed to interrupt automated control at any time.

A major safety consideration involves the risk of collision during the transition between automated and manual control. The potential for human error exists if vehicles are allowed to enter or exit the AHS under manual control and the transition to automated control is made within the AHS lane. Similarly, if the vehicle is under AHS control in the non-AHS lane during a merge maneuver for entry or exit, then the AHS vehicle is susceptible to human error occurring among the vehicles operating manually in the non-AHS lane. One option to minimizing these risks is to dedicate entry/exit facilities to eliminate the risk of collisions in transition lanes caused by vehicles under manual control. A related issue in a configuration which allows the transition to take place in lanes with mixed flow is the assignment of liability in the event of a collision.

The degree of risk in terms of injury or destruction may be dependent on the system configuration. The failure of a critical function or a disruption such as a power failure in a close-following platoon has the potential to cause multiple collisions and/or injuries. The statistical probability of this type of event must be extremely small, placing high reliability requirements on the system. An important goal will be to maintain user confidence in the safety of the system, especially in the early stages of deployment. An analogy may be drawn with the airline industry, where accidents are very rare but can be catastrophic when they occur and often cause multiple deaths, adversely affecting public perception. This type of accident receives greater publicity in proportion to the number of lives lost than a comparable number of traffic accidents in the same time period. The system must be brought on line in a way which minimizes the risk of collision inducing failures, allowing a safety track record to be established which will promote user confidence. This may be accomplished by evolutionary introduction of increasing levels of automation and deployment of a platoon configuration after automated control of individual vehicles has been widely accepted.

Classical safety analyses promote safe stopping distances between vehicles which allow a vehicle to stop without a collision when a “brick wall” failure occurs in the preceding vehicle. This stopping distance is greater than the current following distance commonly used on congested freeways. An AHS which requires large headways will sacrifice throughput. Alternative studies show that platoons with tightly spaced groups of vehicles with “brick wall” stopping distances between platoons can be safe, because in emergency maneuvers the vehicles traveling close together will be traveling at nearly the same speed and energy transfer between them in the event of a collision will be very small. The problem occurs when an intrusion to the AHS occurs, such as an unauthorized vehicle cutting into the safe gap, or an animal entering the roadway. These situations will cause a collision if the obstacle is closer to the lead vehicle than the safe stopping distance. The platoon of vehicles will be at a greater risk for multiple injuries than single vehicles spaced at the standard safe stopping distance.

The ability to safely maneuver incapacitated vehicles out of the flow of traffic will require instrumentation to support longitudinal and lateral control outside of the automated lane. A system configuration which places all of the functionality for latitudinal and longitudinal control within the vehicle will not be constrained to operation within an instrumented lane. Lateral and longitudinal control which depends on interaction with the roadway will require instrumentation in any travelway in which control must be maintained. One option is to implement a two lane AHS in which both lanes are used for travel, or configured as a travel lane with a breakdown lane or shoulder. One lane can be used by the traffic operations management to allow malfunctioning vehicles to be parked while oncoming traffic is maneuvered into the second lane and back as necessary. A concern with a single dedicated lane with barriers on each side is how much horizontal clearance is necessary to maneuver safely around incidents within the automated corridor.

Lanes dedicated to automated control introduce the concern over how to safely limit access. Barriers between the automated lane and manual lanes decrease the likelihood of intrusion into the AHS by unauthorized vehicles, animate obstacles, or debris. Allowing manually controlled vehicles to operate in the same lanes as system controlled vehicles makes it more difficult to design a collision free system. The AHS must be responsible for controlling all vehicles within the system; in mixed mode traffic, there is additional work load added by accounting for unpredictable movements of manually controlled vehicles.

There is a certain level of risk in traveling on conventional highways associated with such events as floods, earthquakes, and other natural occurrences. Evaluating the safety of the AHS must consider the vulnerability of the system to this type of occurrence. The susceptibility of the system configuration to natural disasters must be considered to prevent creation of a greater safety risk than that encountered on conventional highways in the event of these occurrences. The design of the AHS must also avoid increasing the cost associated with prevention of environmental effects out of proportion to the benefit attained. Safety can be maintained economically through a range of approaches, including such measures as rerouting traffic in adverse weather conditions or eliminating certain sites from consideration for AHS deployment.

The impact of system safety at the subsystem design level is another important concern. Safety can be improved by introducing higher levels of subsystem redundancy, but this tends to increase the system cost out of proportion to the benefit. Improved component reliability and providing cross-functionality among subsystems may provide higher safety benefits at lower overall cost to the system. AHS systems can use existing vehicle subsystems such as engine controllers or ABS as models for reliable, cost-effective, safe implementation. The effect of the system architecture on the cost of safe system design will be a primary consideration in the flowdown of subsystem functionality.

Safety has been established as one of the primary influencing factors on the success of AHS. It is an area of concern that permeates every level of the system design, and must be addressed at each stage of study, development, and deployment. It is recommended that system safety be addressed as an integral part of subsequent contracts. A system safety program can be implemented which consists of safety related activities in the planning, design, construction, deployment, and operation phases of AHS projects. A primary goal of the safety plan is the elimination or mitigation of failures through design criteria which indicate areas of concern. System safety emphasizes the verification and demonstration of the overall safety of the system as implemented for subsequent long term operation. Identification of safety as a system-level issue and establishing design practices and standards at the outset of the development phase are important steps toward creating a system that will meet the safety design goals.

Activity O — Institutional and Societal Aspects

This activity is devoted to the investigation of institutional and societal issues and risks of importance for the implementation and operation of AHS, focusing on the following four areas of inquiry:

- Impact on state and local governmental agencies.
- Environmental issues.
- Privacy and human factors.
- Public acceptance — user interface.

The first task is devoted to a discussion of the grouping of issues and concerns as summarized in table 4. Risk indices and risk indices descriptions have been chosen for quantification and prioritization ranking for increasing levels of concern as follows:

- An issue is *.
- A concern is **.
- A serious concern is ***.
- A major concern is ****.

Table 4. Risk Assessment Rank Areas and Prioritization

Risk Indices	Risk Indices Description	Design Issues (Risk Index In Parentheses)	Operational Issues (Risk Index In Parentheses)	Maintenance Issues (Risk Index In Parentheses)
*	Issue	Uniform design standards (*)	Adequately trained staff (**)	Technical capabilities and equipment
**	Concern	Educational and technical capabilities (*)	Emergency response (*)	
***	Serious Concern	Agency coordination and cooperation (*)	Transition period (*)	
****	Major Concern	Agency coordination and cooperation (*)	Liability (***)	
Key: * or ** (Solvable)		Program management (*)		
*** or **** (Requires more investigation to resolve)		Funding (****) Cost effective design (**)		

Beyond PSA, it is strongly recommended that more definitive risk assessments be made once a baseline AHS approach has been chosen from the RSC's. For example, prior to a bid award, a detailed risk analysis should be performed to determine risk rating tradeoffs of probability of occurrence vs. severity of impact (in dollars). Information and conclusions derived from Activity P — Preliminary Cost/Benefit Factors Analysis could be used as additional inputs in further quantifying, controlling, and re-evaluating risks during long-term AHS implementation.

Of all the design issues discussed and summarized, funding is a major issue which can lead to a number of other issues and accompanying risks. For example, inadequate institutionalized funding resulting in substandard AHS designs and inadequate system safety designed into AHS (e.g. design for minimum risk concept-fail/safe, hazard analyses, hazard mitigation, systems assurance) causing AHS-related fatalities is unacceptable.

It is recommended that a plan of action using transit expertise to justify the necessary funding for adequate AHS design be a forum for discussion. The rationale for this approach is that system safety design and much of the cost justifications and proven system design methodologies exist, especially in the area of train control (wayside and vehicle).

In summary, uniform design standards, educational and technical capabilities, agency coordination and cooperation, program management, and cost-effective design are solvable if sources of risks have plans of actions early in post-PSA programs. Once these aforementioned areas are addressed, then funding is fundamentally reduced to a liability concern related to how AHS is operated and maintained beyond the design phase.

Liability has been a long-standing issue that affects how one views the AHS concept implementation. In brief, in the AHS concept, the control of the vehicle is assumed by the AHS system. The issue of a privately-owned vehicle on a public right-of-way will have a variety of liability issues that depend on the chosen RSC (infrastructure or vehicle based). The safety issues that cause liability concerns for all RSC's are summarized in the Activity N — AHS Safety Issues report. There are two categories then to consider, liabilities common to all RSC's (e.g. system safety hazards-direct liabilities) and liabilities unique to a specific RSC. Prior discussion on various ways to handle tort liability clearly depend on making a highly reliable and safe AHS.

Inadequate funding for operating and maintaining AHS that affects system safety impacts liability and would probably stop further funding of future AHS projects because of fatalities shown to be a direct result of inadequately operating and maintaining AHS.

As discussed earlier the acceptance of system safety and maintainability principles as a necessary step at all phases of AHS development is integrally related to the number of fatalities, injuries, and equipment failures on AHS. Increased emphasis on maintainability using preventive with corrective maintenance planning for AHS and non-AHS public right-of-ways is a paradigm shift in current thinking that is critical to the long-term success of AHS and the safety of our private citizens.

An analysis of environmental issues associated with AHS was made. The principal sources of information used in the analysis, individual interviews, and focus group participants in the engineering, planning, economics, and environmental areas allowed for a deep probe into views that might otherwise not come to light.

Environmental issues associated with AHS fell into three major categories: travel-related, infrastructure and urban form, and institutional. Travel-related issues arose from concerns over the consequences of automated highway systems implementation and operation on how much additional travel will be generated, by what means, and its secondary impacts on vehicle emissions and fuel usage. The major infrastructure and urban form issues relate to impacts from infrastructure changes resulting from automated highway systems such as visual impacts and seismic safety concerns, as well as the impact on the local neighborhood as a result of potentially substantial increases in vehicle access and egress to and from non-automated roadways. The institutional issues are centered around the relationships among the participants in automated highway systems research, development, deployment, and operation. Examples of such issues are the barriers that exist between the two major groups of participants in this research, as well as the lack of complete and accurate information and attitudes that each group believes about the other group.

Primary suggestions for resolving these issues include:

- Further research into developing modeling tools to more accurately represent the automated highway driving mode to produce reliable estimates of the impacts in areas of travel volume changes, mobility, land use, emissions, and energy consumption.
- Investigation of current methods for environmental impact review processes for applicability to the automated highway systems case, determining and making necessary modifications.
- Incorporating an aggressive process of education, communication, and participation to help dissolve the barriers and help forge a more common vision of a future transportation system with automated highway systems as an integral component.

The most significant recommendation of all would be to make every effort to begin the process of resolving these issues as well as issues in other areas of investigation in the near term, and not delay this process. Delay would only add to the difficulty by contributing to the exacerbation of the issues and probably the expense of resolving them.

Privacy issues, driver comfort, and driver acceptance was next discussed. Current studies indicate that the driving public will be more likely to use the AHS if a concerted effort is made to offset the privacy issue. This can be accomplished by providing a full explanation of the AHS system operations and highlighting the benefits. The evolutionary deployment of AHS technologies, such as toll debit cards and incident surveillance cameras through ITS implementation, would be an initial step. The remaining AHS requirements including vehicle inspection and driver monitoring can be introduced with the added benefits of increased safety, reduced travel time, and operating costs. Gradual introduction of control features and associated electronics will allow the driving public to benefit from the convenience of the system in proportion to the level of risk to privacy.

The level of driver comfort during the operation of a vehicle in automated mode is discussed from the perspective of in-vehicle AHS equipment and potential psychological stress factors. In vehicle equipment the driver would use to operate the automated vehicle must be user friendly, easy to operate, and be designed for as complete a user capability profile as possible, including age and reaction time differences. A driver-vehicle interface must take into consideration the potential for driver work overload if manually entered input is required. The combination of high speed, automated control, potentially very close vehicle following would likely contribute to added psychological stress that must be addressed. Research is needed to accurately assess the extent of this problem and develop and assess potential solutions. Driving simulators could be used, but their effectiveness may be limited, since there really is no risk of an accident in a simulator, yet stress may still be present. Alternative test strategies to evaluate driver responses may include test tracks and demonstration rides. Methods to address the potentially stressful effects of automated driving by reducing the perceived trip length include diverting the driver’s attention with information, either trip-related or recreational.

An investigation of the AHS vehicle-driver interface consisted of the development of concepts to depict the possibilities for driver interface and for representative AHS situations. Important design concerns for vehicle displays and controls include their orientation, method of implementation, styling, and illumination. Driver interface concepts include potential electronic interface units and their positions within the vehicle; typical AHS situations include check-in/out, entry/exit, various vehicle types (commercial and transit), maintenance situations, and potential driver activities while using the automated facility. These concepts generate numerous issues among which include the compatibility with malfunction management strategies of allowing certain vehicle components (steering wheel, foot pedals) to be moved to different positions to provide the driver more room for other activities, the potential need for standardization of details of AHS control and communication interfaces among vehicles, the degree to which driver-vehicle interface is extended to encompass the front seat passenger or possibly back seat passengers as well, the extent to which the AHS interface would be able to use components already present as part of the more general ITS interface.

Activity P — Preliminary Cost/Benefit Factors Analysis

The research in this activity area establishes a framework for the evaluation of benefits and costs of a hypothetical AHS. The willingness of State and local authorities to undertake AHS projects as well as the continuing federal support for AHS will depend on the potential for strong economic returns from AHS. The analysis of a hypothetical AHS project will expose risk elements as well as the principal sources of benefits. In so doing, these can be used to provide guidelines for deployment strategies and identifying areas of further research.

The following presents a summary of the key findings of the analysis:

- Travel time — One of the principal AHS benefits categories is improved travel time. In the urban environment, the AHS will likely have a moderate impact on travel time during the peak hour of operation and a greater impact on travel times in the peak period outside the peak hours (the peak period margins). Under normal operating conditions, with adequate penetration of AHS-equipped vehicles, there will likely be a phenomenon of temporal shifting of demand to the peak hour: Many of the AHS-equipped vehicles will travel in the peak hour while the additional capacity made available in the non-AHS lanes, through the diversion of AHS vehicles, will result in a greater number of trips by non-AHS vehicles being accommodated in the peak hour. Consequently, greater traffic volumes would flow in the peak hour. However, more substantial improvements in time savings per trip would occur in the peak period margins which will operate with lower volumes of traffic.
- Improved convenience — A greater number of trips being accommodated in the peak hour represents a significant benefit for many travelers. Urban congestion forces many commuters to travel at off-peak hours which results, sometimes, in lost economic opportunities as well as personal inconvenience (e.g., lost leisure opportunities, time spent with families).
- Improved safety — The AHS has the potential to significantly reduce accidents by assuming control of vehicles in the AHS lane, and by reducing congestion in conventional lanes and arterial streets. Benefits associated with improved safety include fewer fatalities, injuries, and property damage. It is estimated that the AHS could reduce

accidents by around 70 percent for users of the AHS by assuming control of AHS vehicles removing driver error as the cause of many accidents.

- Economic activity benefits from congestion relief — Urban traffic congestion represents a serious impediment to the development and retention of particular types of economic activity. Urban business centers grow and develop due to what has been called “economies of agglomeration.” Many industries (e.g., wholesale and retail trade and business services) require that the majority of employees be on site during principal business hours in order to maintain smooth, profitable operations. Congestion frequently makes that difficult or costly resulting in businesses abandoning the urban centers. Relief of traffic congestion promotes conditions that enable cities to flourish as business centers. AHS, insofar as it accommodates greater numbers of people being able to commute to business centers for principal business hours, will likely contribute to improved economic activity.
- Urban form and livable communities — The phenomenon of urban sprawl, low-density housing, and two-vehicle families have been facts of U.S. development for many decades. Many communities face the problem of growing congestion in daily commutes between suburbs and cities, contributing to both the decline of the cities as well as the quality of life in suburban communities. In the long run, rail and transit may represent a solution for some growing communities. However, achieving sufficient ridership thresholds to justify rail may be many years away. AHS may provide a lower cost and, overall, more acceptable solution for many communities. AHS could keep business centers attractive, thus preventing further sprawl and contribute to more balanced regional development.
- AHS and arterial congestion — The highway and benefit-cost activities make clear that AHS represents a viable traffic alternative for regular commuting traffic only if congestion on surrounding arterial routes is relieved to an adequate degree. In the absence of arterial relief, AHS could be viable for periphery-to-periphery trips. An additional alternative might be a “many-to-few” AHS configuration where vehicles enter the AHS at many points but can only exit in the business district during rush hour at designated parking facilities. However, the many-on/many-off urban AHS would result in unacceptable ramp queuing if arterial congestion were allowed to exacerbate. A conclusion to be drawn from the above is that AHS needs to be developed within the framework of multimodal regional planning.

- Operation thresholds — The benefit-cost analysis, which included an analysis of traffic distribution on a hypothetical AHS over the entire peak period (not just peak hours) reveals that a minimum penetration threshold for operating the AHS during the peak hour would be at about 9 percent (assuming that most of the AHS vehicles will choose to travel in the peak hour). For levels of penetration below 9 percent, AHS operations would actually reduce the total capacity of the highway system. In order for AHS to improve overall highway operations in the peak period margin hours, the estimated level of penetration would need to be 33 percent. Below this threshold, AHS operations would reduce total capacity in the peak period non-peak hour under the planning assumptions examined.
- Vehicle cost — From the point of view of a consumer, the willingness to pay for AHS equipment and service will be a function of how the individual values his own time. If, for instance, AHS results in a 15-minute time savings per day, and, supposing that the consumer makes 200 commutes per year and values his/her time at $10 per hour, then he/she would be willing to pay $500 per year for AHS. This, of course, assumes that the consumer derives no additional benefits (e.g., reduced stress) from AHS and that there are no other acceptance problems. Vehicle cost will be a key component in the acceptability of AHS for all stakeholders concerned (travelers, public sector, vehicle manufacturers). In order to attain the relatively high thresholds of penetration required in a timely manner, the cost of equipment and services need to be maintained at sufficiently low levels.

The results show that given the assumptions of the analysis, a hypothetical AHS project has a high likelihood of providing a strong economic rate of return. Key assumptions which are crucial to the analysis include the following:

- A successful evolutionary deployment of AHS and ITS systems and products.
- The ongoing development of an AHS roadway network in Phoenix (the site location for the detailed analysis) and other metropolitan areas.
- Continued public funding of AHS development.
- Implementation of multimodal planning and investment to relieve arterial congestion.
- Technological development and market acceptance keeps pace with scheduled deployment.

Highway projects, in general, generate most of their benefits through time savings and convenience benefits, with safety and other benefits a much smaller proportion of the total. The principal benefits which are expected to be derived from the AHS project are time savings and convenience made possible through added capacity in the peak hour. The benefits to non-AHS users are projected to comprise the majority of benefits even for levels of AHS penetration as low as 20 percent.

It was apparent from the highway operations analysis that AHS would be clearly not viable unless implemented within a multimodal planning context. Without complementary planning and improvements to supporting roadways, ramp queuing on the AHS would rapidly make any prospective urban AHS a non-starter. Within a multimodal planning context, AHS could potentially relieve congestion in crowded corridors. While not captured in direct benefits, the relief of congestion from AHS could contribute to the preservation of business districts and prevent continuing urban sprawl. This could be the case in areas with relatively low housing densities which could not support a rail project yet still need a cost-effective solution to congestion.

Further clarification of the deployment scenario will be crucial to firming up estimates for economic benefit-cost and rates of return. The benefits from added convenience and AHS benefits which are less readily quantified (e.g., reduced stress, mobility for the elderly) still require research to determine the value of these benefits.

OVERALL CROSS-CUTTING CONCLUSIONS/OBSERVATIONS

Towards the end of this Precursor Systems Analysis (PSA) of Automated Highway Systems (AHS) program, all members of the research team met and identified a common list of cross-cutting conclusions and observations. By their nature, such topics are sometimes difficult to categorize. However, the identified conclusions and observations have been grouped into five general areas: system characteristics, impacts, operations/maintenance, deployment, and funding. In addition, the identification of coordinated braking is included as an important technical observation. These conclusions and observations are drawn from all of the PSA activity areas. In order to help the reader in pursuing the various topics, an abbreviated form of referencing the several activity reports has been adopted. For example, the notation [A-1] would be a reference to the discussion of the first task of the Activity A — Urban and Rural AHS Comparison report.

System Characteristics

The various analysis activities associated with the precursor study of AHS have highlighted a number of issues regarding top-level system characteristics. A system architecture which is intended to serve as a baseline for AHS development must take into consideration several key aspects of system characteristics. The system configuration is a top-level system characteristic which lays the groundwork for subsystem design and interface requirements. The primary system configuration issues presented in this study are concerned with platoon versus non-platoon vehicle coordination units, the role of the operator in steady-state and emergency maneuvers, and the division of instrumentation between the vehicle and the infrastructure.

Another facet of system architecture development is concerned with implementation related issues. Topics include challenges in the development of key AHS technology, the importance of standards, the interface between AHS vehicle systems and the user, the transition between non-AHS lanes and automated lanes, roadway deployment concerns, and lessons learned from implementation of comparable systems. Encompassing all functional areas of AHS development are issues related to the safety of the system. This analysis focuses on three topics, the importance of design for reliability and maintainability, vehicle subsystem functional verification, and the aspects regarding malfunction management in safety assurance. The material is presented in three sections covering issues in the areas of configuration, implementation, and safety.

Configuration

The system configuration defines the attributes associated with coordination of vehicle control, vehicle performance criteria, facility requirements, and other functions related to automated travel. The issues which surfaced repeatedly in various activity areas and are of most significance in the determination of a viable system configuration include vehicle coordination units, driver participation in vehicle control within the AHS, and placement of instrumentation in the vehicle or along the roadway. The three areas of concern are discussed in the following paragraphs.

Platoon/No Platoon

Vehicles can be placed on the roadway under a variety of headway conditions. Issues such as safety, control performance, driver acceptance, capacity [H-4], emissions [I-5, 6], and fuel economy will affect the choice of vehicle spacing. Vehicles can be grouped into coordination units, referred to as platoons, where intra-platoon spacing is assumed to be less than the inter-platoon spacing, or can be controlled individually and remain separated by reasonable distances [D-3].

Control performance may be an issue in the case of platoons with relatively small intra-platoon spacing on the order of one to three meters, especially with rather long platoons of 15 to 20 vehicles. Safety is a concern since the possibility exists for many impacts to occur between vehicles involving very small velocity differences, but very few large velocity differential impacts are expected to occur. Driver comfort may also be a concern, as drivers may not like close vehicle spacing. Closely-spaced platoons have the potential for tremendous capacity increases in comparison with moderately spaced platoons or no platoons. Platoons will likely benefit from emission reduction and fuel economy improvements due to the effects of drafting in the close following mode.

Platoons can also be defined by larger intra-platoon spacing, on the order of five to twenty meters. An emergency stop may present significant safety concerns in this case, as the vehicles have the potential for high velocity difference collisions. The potential benefits of close vehicle spacing such as increased capacity, reduced vehicle emissions, and improved fuel economy are also diminished. However, driver acceptance may improve, since this spacing is typical of that observed on congested highways today.

Vehicles can operate in a platoon at virtually any spacing and maintain overall system and vehicle safety by employing a coordinated braking system among the platoon vehicles [D-3]. In a coordinated braking scenario, the platoon lead vehicle would communicate a target platoon deceleration level based on the lowest braking performance capability of the vehicles in the platoon. All vehicles would then initiate braking simultaneously and vehicle based control would maintain the desired rate. A brief discussion of the coordinated braking concept is presented in a following section.

The alternative to forming platoons in the absence of a coordinated braking system is to establish larger vehicle spacing, such that a safe operating environment exists. Motivating factors for this configuration might include the lack of user acceptance for close vehicle following, concerns for safety in a platoon, lack of congestion on the target roadway (rural consideration), inadequate technology to meet platoon control requirements, or the potentially high cost of implementing platoon control [D-2]. Larger vehicle spacing has an advantage in terms of operator perception and reduced control complexity in comparison with the platoon concept, but the decreased potential throughput significantly detracts from the benefits [D-3, H-4].

Driver Role

The driver currently contributes significantly more to the safe and successful performance of the driving function(s) than just physically controlling the vehicle. Driver awareness of the roadway environment, including the actions of adjacent and preceding drivers and their vehicles, of roadway conditions, and of the existence of debris, pedestrians or animals ahead, leads to the collection of invaluable information which can critically affect the safe operation of the vehicle. Detection and processing of these conditions by automated systems is extremely challenging. This human resource and the information it can collect and process may be an asset in the operation of vehicles on automated highways. The best approach for allowing driver inputs to the AHS system is a major issue for continued study.

There are several obstacles which must be resolved before the driver can be made an integral part of the control function. First, the driver must not be allowed to directly control the vehicle during automated travel. The entire platoon may be subjected to rapid deceleration or potentially high differential velocity collisions if the driver is permitted to manually control emergency maneuvers during platoon operation. The driver may make poor decisions regarding the nature of an emergency. There is a risk that some drivers might suddenly assume manual control if they decide to exit the automated lanes earlier than planned, causing unsafe maneuvers. Other drivers may be naturally conservative and decide that an emergency exists when there is no actual danger to the platoon.

These types of problems can be partially mitigated by educating the drivers as to conditions which require emergency actions or by suspending AHS privileges if the driver misuses the emergency system. An approach which allows the AHS to take advantage of driver inputs without allowing manual control is another solution. The driver would be called upon to remain alert during AHS travel and to retain responsibility in carrying out the driving function. The system would maintain the lateral and longitudinal control functions, but the system would provide the ability for the driver to initiate maneuvers that are executed by the system. The driver thus assumes a "brain-on, hands-off, feet-off" role in the operation of the vehicle.

Another problem with requiring the driver in the loop is the need to maintain alertness during automated travel. There is a tradeoff between a system which allows the driver freedom to read or work during automated travel and one which requires the driver to perform all of the functions associated with manual driving except for steering, braking and throttle control. The system design cannot allow such things as a drowsy or inattentive driver to affect overall safety. This requirement implies that safety must be maintained at the highest level without driver inputs. The rationale for accommodating driver inputs to increase safety becomes redundant in this case [K-8]. Resolution of this issue could significantly impact the requirements for Activity B — Automated Check-In, Activity C — Automated Check-Out, and liability issues discussed under Activity O — Institutional and Societal Aspects.

Vehicle/Infrastructure Content

There is concern that placing a large percentage of the instrumentation for AHS within the vehicle will raise direct consumer costs to an unacceptable level. The division of instrumentation between the infrastructure and the vehicle must be determined by systems level design considerations which take into account the complexity, testability, reliability, and maintainability of the system. The design complexity and testability of the control loop system is directly affected by the placement of the equipment. A vehicle-based implementation simplifies the timing of inputs to the processor, allows for testing prior to system integration, and provides reliability in the sense that a failure affects a single vehicle. The vehicles affected by each control station in an infrastructure-intensive configuration vary in time as the vehicles move along the highway. Precise timing for each vehicle is extremely complex, and the capacity of the communications system will increase. The testability of the system is more difficult, since it cannot be completely tested until system integration. Finally, reliability is a greater concern, since a single-point failure of an infrastructure component may affect a large number of vehicles. The most cost-effective and reliable approach is to place the control loop instrumentation in the vehicle to minimize complexity and enhance testability [A-Conclusions].[3] Because vehicle manufacturers strive for the maximum level of commonality for unseen components such as communications buses, the placement of AHS instrumentation on the vehicle will tend to distribute costs for component compatibility, testability, reliability, and etc. across the entire vehicle model production including non-AHS equipped vehicles.

Functions which operate over a wide area are candidates for implementation in the infrastructure. Examples include route guidance planning, which can be handled at a regional traffic operations center, and zone or regional flow control, which may be communicated along the infrastructure most efficiently. The feasibility of AHS is dependent on evaluation of each subsystem element individually to determine the appropriate division of content. The system architecture must first be developed to determine the functional decomposition, at which point the most effective configuration can be established.

Implementation

Successful development and deployment of critical AHS subsystems is dependent on a variety of factors. Two common concerns across many activity areas are the technology challenges associated with implementation of AHS functions and the effects of standardization on developing technology. Other issues include the level and method of interaction between the operator and the system, the optimum approach to supporting the interface between AHS and non-AHS highways, and the roadway features critical to AHS implementation. Finally, a set of findings compiled by the analyses of comparable systems that can be used to influence the process of development and deployment of AHS are presented.

<u>Technology Challenges</u>

Implementation of automated vehicle control will present challenges in the areas of accurate position determination, actuator technology, obstacle detection capability, communication of control information, and software functionality. The technical feasibility of the AHS program is dependent on the ability to produce reliable subsystems cost effectively. Feasible solutions must lend themselves to low cost and high volume production in the automotive environment. Many of the technologies necessary to implement AHS functions have been proven in military environments, demonstrating highly reliable systems capable of operating in complex environments. The next step towards high-volume, low-cost production must incorporate requirements applicable to AHS-specific operating parameters.[5]

Position Determination and Headway Maintenance

Establishment of vehicle position is an integral part of the automated control loop. Accurate position location can be used to evaluate vehicle spacing and assist in maneuver coordination. It is also a key input to vehicle navigation and route planning operations. Information regarding vehicle velocity and acceleration is also required to maintain lateral and longitudinal control of AHS vehicles. Velocity and acceleration inputs are used to determine the adjustments necessary to maintain specified headway between vehicles. The primary requirements for automated headway control are safety, smooth control response, and fuel economy. The feasibility of measurement and communications techniques will rely on the complexity and related cost of implementation [D-2, 6].

Actuators and Microprocessor-Based Vehicle Subsystems

Current model automobiles utilize electronic control systems to improve the efficiency of power trains and to make cars safer and more pleasurable to drive. Examples of such systems include engine and transmission control, air bags, antilock brakes, suspension control, and heating, ventilating, and air conditioning (HVAC) controllers. Each of these microprocessor-based control systems depends on reliable input data from sensors in order to output the proper commands to solenoids and actuators.

The introduction of many features of Intelligent Transportation Systems (ITS) will increase the level of vehicle based electronic control. AHS will raise the level even more. The processing power of AHS vehicles is expected to significantly surpass that of today’s in-vehicle controllers. A large percentage of the processing power will be dedicated to tasks related to fail-safe operation. Redundant system checks, redundant processing, redundant hardware, fault detection algorithms, fault mitigation algorithms, and data synthesis will be some of the activities necessary to aid in safe operation. The challenges that present themselves to the industry include: reduce the cost of electronics required to implement fail safe operation, increase the amount of memory and the speed of integrated circuits, increase the reliability of integrated circuits, and improve low cost sensor reliability [L-2].[6,7]

The AHS vehicle will need actuation capability that is reliable, cost effective, and require low maintenance. Reliable steering, brake, and throttle control will be a key factor in implementing AHS functions. Actuators and the actuation techniques needed to achieve AHS operating parameters require further research, testing, and validation. Current hydraulic actuation used for some developmental steering systems are slaved to microprocessor-based controllers. Future implementations may consider an electric actuator approach to eliminate high pressure hydraulic lines and other negative attributes such as the load the hydraulic pump presents to the engine. The challenge lies in producing highly reliable new technology at costs comparable to existing equipment [L-3, 4].

Obstacle Detection

Designers of collision avoidance systems will face the challenge of developing a product capable of detecting a large range of objects, such as vehicles of all sizes, people, animals, and debris on the road. The system would ideally be capable of discriminating between objects that must be avoided and objects that are not a threat to the vehicle or its passengers and thus do not require a maneuver. Vehicle based sensing would be augmented by wayside sensors, particularly to eliminate blind spots where highways curve or crest over hills. Existing obstacle detection systems installed in vehicles, often using radar sensors, are intended to enhance blind-spot awareness. Low cost radar currently has limited capabilities in terms of sensitivity and range. Fine resolution is necessary to differentiate relatively small features, such as spilled materials. Alternate solutions may be necessary to achieve the sensitivity, small size, and low cost necessary for AHS application. Higher frequency radar with smaller size profiles may become viable as gallium-arsenide circuitry becomes cost competitive with silicon. Signal processing in integrated circuits has the capability to improve resolution economically, and range-gating techniques may be considered to achieve all three objectives. Coordination with vendors while the technology is emerging may be necessary to ensure that developing technology will be compatible with AHS requirements in the evolutionary deployment of safety and convenience features [D-2, 6, K-4]. (See also references 8, 9, 10, and 11.)

Communications

The architecture of the communications system is a key issue. The long term viability of the AHS depends on a communications system which provides sufficient data rate and user capacity in the mobile environment. The AHS communications link may be subject to multipath and fading problems. The optimum frequency band, modulation scheme, multiple access methodology, and data transfer rate are all parameters which must be defined to enhance performance under these conditions. These features must be specified to support the potential high AHS traffic density of urban environments and be flexible to support the rural environment as well [D-2].

The access protocol of the AHS communications link is another key issue. Conventional access schemes may not provide the millisecond response times necessary in automated emergency maneuver situations. The access protocol must allow all vehicles to achieve data update rates consistent with vehicle control loop requirements. The message formats must be defined to ensure highly reliable vehicle identification when maneuvers are requested and performed [D-6].

The requirements of supporting real-time control of vehicles moving at high speeds is a prime area of consideration. The communications system design will provide vital information in support of safety-critical functions such as steering and braking. Communications supporting the longitudinal control function must have high update rates, low error rates, and high data rates. The systems must be robust in resistance to interference. The reliability of both the communications hardware and the network are important. The communications system reliability will be dependent on both the error rate of the link as well as the hardware failure rate. The robustness of the system design must take into account the high degree of variability in signal environment as well as the large number of potential users and great ranges covered by regional networks. The network design must incorporate redundancy in components and/or interconnects to provide single failure protection [N-2].

Software Assurance

Software and specification verification and validation will play a key role in assuring the dependability of AHS software. Some of the challenges regarding AHS assurance include the following:

Prior to software verification, the AHS specifications will need to be tested for completeness and consistency. The methodologies and automated tool support for checking and maintaining specifications for large, complex systems are still evolving, constituting part art and part science.[12] In addition, both the AHS as well as the methodology for verifying the correctness of its implementation need to be validated. The application of formal methods can be expensive in terms of the required amount of highly skilled labor, even with the assistance of automated verification and validation support tools.[13]

The size and complexity of the AHS software will have a bearing on the ability of developers and maintainers to adequately test the software. Existing software testing methodologies can be used to demonstrate reliability levels on the order of 10^6 executions without failure. Demonstration of AHS software reliability in the ultra-reliable region (i.e., greater than or equal to 10^9) may be required due to the actual and perceived risks borne by AHS developers, users, and operators. This level of reliability is not presently achievable and would require further advances in software testing technology.[14]

Furthermore, AHS specifications can be expected to change over time due to such factors as shifts in AHS policy and advances in AHS technology. Similarly, maintenance of AHS software will involve making modifications to AHS programs to account for such events as the discovery of latent software errors and modification of AHS specifications. A change in an AHS specification or program can result in a change in AHS behavior, both in functional and nonfunctional (i.e., performance) terms. Therefore, it is necessary to reverify and revalidate the AHS specifications and programs each time a change is made. There are many approaches available to minimize the amount of reverification and revalidation that must be performed, including modular software design and the separation of safety-critical AHS functions from all other AHS functions. For example, a safety kernel approach can be used to separate the safety-critical (i.e., protection system acting as a limit switch) functions from all other (e.g., lateral or longitudinal control) functions, with the safety kernel having absolute priority over all AHS functions. This approach allows modifications to be made to the non-safety-critical functions without affecting the safety kernel.[15,16,17]

Standards

Standardization will play an integral role in building and maintaining a national network of compatible and interoperable highway systems. A lack of adequate standards among AHS equipment manufacturers can lead to a limited number of sources (e.g., vendors) for each subsystem element in a projected installation. Limitations in cross-vendor compatibility can be reduced by high quality, internationally accepted definitions of interface requirements among subsystem elements.[18] Standardization should be achieved in a manner which allows technological innovation to flourish: the risk of introducing barriers to technological innovation exists whenever standards are adopted. Care must be taken in establishing the content and number of standards in order to allow for widespread implementation of a national AHS architecture which allows continuing incorporation of state-of-the-art technology.

A national AHS will require some level of cooperation among Federal, State, and local governments [O-1]. The interests of each of these entities can conflict, potentially resulting in the conflicts becoming embedded in regional AHS standards. An example which illustrates this point is the difference among states in terms of their transportation policy, which is evident in the differing level of priority and funding allocated to emerging Intelligent Transportation Systems (ITS) projects. States with high degrees of traffic congestion might place greater importance on increased capacity, while States with long stretches of rural highway might emphasize the improved safety and increased speed of travel aspects of AHS [K-7]. Experiments with Automated Vehicle Control Systems (AVCS) have shown that some level of AVCS compatibility and interoperability is necessary to field a safe and maintainable nationwide AHS.[19] What that minimum level of standardization should be remains an open question.[20,21]

Corporate involvement in the AHS effort is driven by a profit motive; the automobile manufacturers and related AHS industries are concerned with issues of competitiveness, return on investment, and market penetration [P-4]. Overly restrictive or poorly formulated design standards can have an adverse effect on competition, profit, or market potential. One area in which design standardization is producing lower cost automotive components is in the relay market. The emergence of low cost readily available relays that meet European, Japanese, and original equipment manufacturer established standards has steadily reduced the use of special purpose relays in U.S. produced vehicles.[22]

Current efforts by the European collision avoidance and intelligent cruise control community towards definition of an enhanced standard are aimed at facilitating release of products within three to four years. Broad proliferation of these devices may not occur until the recommended frequency band is converted to a formal standard and system interference issues are addressed by recognized performance specifications.[23]

A recent example the positive effects of automotive industry standardization involves the development of a multiplexed vehicle electronics bus. Prior to ratification of the J1850 standard by the Society of Automotive Engineers (SAE), individual car manufacturers pursued proprietary approaches to multiplexing in an effort to eliminate redundant wiring. The industry effort to produce a standard is a response to U.S. Car, the government/industry consortium, which has set stringent mileage requirements for new passenger vehicles. The advantages of multiplexing include reduced weight and increased reliability resulting from fewer and simpler connectors. A common bus provides the capability to implement other cost saving improvements, such as sharing clock and memory resources among subsystems, and facilitates addition of optional features to a base model. Establishment of an industry standard will allow vehicle manufacturers to meet emerging requirements for a standard diagnostics port for emissions verification without an intermediate interface. Adoption of multiplexing among car manufacturers has the potential to save U.S. auto makers hundreds of millions of dollars annually in design and assembly costs, quality related costs, and costs resulting from mandates for fuel economy and emissions diagnostics. This case can be used as a model approach to the implementation of AHS standards, in which regulatory agencies and vehicle manufacturers reach a cooperative agreement on industry standard performance specifications for AHS equipment.[24]

Man/Machine Interface

One of the stated goals of the AHS is to improve user desirability of the highway system through expanded mobility for older and handicapped drivers and increased comfort of travel. These objectives must be taken into consideration when the user interface is designed to ensure that the interface is compatible with a wide population of potential users. A complex user interface carries the risk of reducing the potential user base and increasing the level of competency required to operate in the system, relative to existing highways.[2]

The effort to support a broad range in ages and physical capabilities of drivers who will use AHS must consider the following aspects in the driver vehicle/system interface:

- The driver display/control suite must be easy to use with minimal attention demand.
- The design must minimize driver workload by simplifying interaction with on-board equipment.
- The design must consider the knowledge, skills, attitudes, and physical capabilities of the user.

- The system interface must consider the various user groups, including older and impaired drivers.

It is recommended that the complexity of the user interface be minimized [G-3.3]. One method which can improve interoperability among various manufacturers is adopting display conventions and standardized display symbolism. Uniform locations for AHS specific interface equipment and common symbols will promote ready user familiarity. Voice information systems may be implemented to simplify the input process. Voice recognition can be used to avoid manual entry of data for such functions as operator validation and input of route information. Audio notification of en route system status may also minimize the driver workload by eliminating glances toward AHS displays [K-8].[25]

Transition To and From Manual Control

The transition from automated control to manual driving must follow a progression of steps that ensures the safety of the driver and surrounding vehicles in the AHS and non-AHS lanes. The check-in process used to validate the transition from manual to automated control has often been considered to be a vehicle-intensive task, while the check-out process used to validate the transition to manual from automatic has been considered as operator intensive. These early assumptions were based on the premise that the functionality of the automated control systems were of greatest import as the vehicle enters the AHS, while the qualifications of the driver to regain manual control are most important as the vehicle exits the automated lanes. This study has determined that there remains a certain amount of vehicle functional verification required to ensure a safe transition to manual control. It is recommended that the manual braking and steering functions be exercised prior to termination of automated control as a minimum [C-5, 6]. These two functions are critical to safe operation at the time that control of the vehicle is given to the driver.

The issue of driver readiness to resume manual control is related to issues of privacy and liability. There is a broad range of tests available to verify driver capabilities, including sensors to detect the presence of substances in the driver's blood, prompts to gauge reaction times, or scanning of eye movement to evaluate alertness. The invasiveness of certain tests may cause concerns among privacy advocates and have an adverse effect on user acceptance. The assignment of liability in the event of an incident following the transition to manual control is a concern as well. Extensive tests may create the impression that the AHS is responsible for ensuring that no impaired drivers are allowed to have manual control. It is recommended that the driver check-out consist of a simplified routine that places the responsibility for assuming manual control completely with the driver. The check-out process might follow a screening of manual brake and steering functionality with a prompt to the driver. The driver will then respond with a positive action such as pressing a push-button to indicate readiness to assume control. Legislation may be required to clearly delineate the responsibility for accidents following transition from the automated lanes.[26]

Eliminating complex operator verification tests and placing responsibility with the driver for accepting the manual driving task is one way to simplify the issue and reduce the risk of AHS being held liable for accidents caused by improper driving immediately following travel in the automated lanes. This approach is based on the premise that the AHS is not responsible for verifying driver readiness to safely operate the car prior to entering the AHS, and returning control to the driver following automated travel should not carry a burden beyond that of ensuring that the vehicle is functioning properly [H-2].

AHS/Non-AHS Interface

Concepts for entry and exit to AHS lanes include ramps dedicated to automated users and transition lanes open to AHS and non-AHS vehicles. Dedicated ramps are defined as feeding AHS traffic directly onto the AHS lane. Non-AHS vehicles do not have access to dedicated ramps. On the other hand, a transition lane allows AHS vehicles to enter the automated lane directly from conventional non-AHS traffic. In this concept, AHS vehicles use traditional interchange ramps along with non-AHS vehicles to access the freeway corridor, and maneuver through non-AHS traffic to reach the AHS lane.

AHS entry and exit facilities spaced on the order of 1.6 km combined with low-end market penetration of 30 to 40 percent correspond to projections of large AHS entry and exit volumes in certain corridors. Volumes on the order of 1,500 to 2,000 vehicles per hour are forecast, based on a hypothetical freeway/AHS system [I-3]. Accommodating expected large ramp volumes will require entry and exit facility designs which mitigate the impact on local street network and travel patterns. Large entry/exit volumes also require check-in and check-out of AHS vehicles without delays to avoid excessive queues. Delays resulting from either process, whether associated with a stop or rolling condition, will cause entry and exit ramp facility size to become impractical.

Accommodation of large AHS ramp volumes will require the following actions:

- Separate the AHS entry facility and the AHS exit facility.
- Separate the AHS ramps from conventional freeway interchanges.
- Provide free flow to and from ramps.
- Reduce conflicting movements at signalized intersections adjacent to the AHS entry and exit ramps.
- Implement demand management to redirect traffic from congested AHS entry or exit facilities.
- Provide closer spacing of interface points to help distribute AHS ramp traffic volumes.

This study concludes that the implementation of AHS lane(s) within an existing freeway corridor requires access to and egress from the AHS to occur on dedicated ramps providing no check-in/check-out delay at the entry and exit points [H-2, I-2, 3, 4, 6, and 7, J-1, 2, 3].

Cross Section Considerations

Cross section includes all elements which add up to make the total width of a roadway. Cross section elements include barriers, travel lanes, shoulders (also referred to as breakdown lanes), buffer spaces, transition lanes, space dedicated to drainage requirements, retaining walls, and landscaped areas. Minimizing cross section requirements for AHS is a critical need, especially in urban areas. Several attributes are prevalent in typical urban areas where AHS may be considered for implementation:

- Densely developed, high-cost property adjacent to freeway rights-of-way.
- High traffic volumes.
- Existing non-standard cross sections due to previous lane width reductions and/or shoulder usage to accommodate addition of high-occupancy-vehicle (HOV) or mixed traffic lanes.
- Sensitivity of the community to environmental concerns.
- Closely spaced interchanges with fixed horizontal clearances at cross street structures.

These attributes are not conducive to inexpensive or simple cross sectional widening. It is therefore important that AHS have characteristics that minimize the requirement for widening, within reason. This study concludes that the elements defined below, at a minimum, comprise the net cross section change required to achieve a one-way AHS lane added to the median of an existing urban freeway [K-4]:

- A 0.6 m buffer between the AHS lane and the left barrier or left edge of the pavement. This buffer is for occupant comfort only and is somewhat arbitrary.
- A lane width of 2.6 m to accommodate passenger cars only, or 3.0 m to accommodate commercial/transit vehicles.
- Lane width is based on American Association of State Highway and Transportation Officials (AASHTO) design vehicle widths and the criterion that AHS vehicles can stay within 200 mm of their design lateral path. The lane width deviation is based on vehicle control expert opinion.
- A right shoulder (breakdown lane) of 2.6 m or 3.0 m, based on passenger cars only or cars plus transit vehicles, respectively. The recommendation for a full width shoulder is based primarily on the need to avoid a complete shutdown of the AHS lane from an incident location to the next AHS entry upstream in the event of a blocked lane. AHS is expected to eliminate the majority of causes for lane blockage, but a significant number will not be eliminated. The inclusion of a shoulder makes the system forgiving of incidents, and has other uses including snow storage and maintenance activities. Since the breakdown lane would need to be instrumented it may also serve as a second AHS lane during peak demand periods.
- A barrier of 0.6 m width to separate AHS and non-AHS traffic.

Using these values, the conversion of a single lane of an existing AASHTO standard one-way three-lane freeway to a single AHS lane would result in a net widening of 2.7 m. The width requirement can be reduced at the expense of design standards on the conventional lanes as follows:

- Reduce lane widths.
- Reduce shoulder widths on one or both sides.
- Eliminate shoulders on one or both sides.

All of these deviations from standard highway design practices come at the expense of safety and optimal operating conditions on the conventional lanes [H-1, 3]. The expected impacts of such reductions in standards should be evaluated on a site-specific basis and used in the benefit-cost analysis of the AHS project.

Lessons Learned

A study of comparable systems including rapid transit, automobile air bag, and automobile navigation systems identified similar characteristics to an AHS in terms of public interaction, safety, reliability, and complexity. The three systems were analyzed in detail to derive the lessons learned in their design, implementation, deployment, and operations that could be applicable to the development of AHS. The Activity G — Comparable Systems Analysis report identified 38 specific recommendations regarding AHS development. A subset of the recommendations dealing with system characteristics is summarized here in two categories, development process and specific technical capabilities.

Development Process

Many of the recommendations focused on specific management and engineering processes which if neglected or de-emphasized result in a negative impact on a project [G-3.1].

Independent Review

Several comparisons emphasized the need for independent review. A competent and independent technical review team is essential in each phase of the technical development and testing of the system. AHS project development should include mandatory public forums to discuss system implementation, both before initial project authorization and during the project design and construction.

Program Management and System Engineering

The comparisons emphasized the importance of various program management disciplines. Program management must emphasize the building of consensus, and include staff with a high degree of technical competence in AHS. A well thought-out statement of work for all participants and all activities, accompanied by adequate funding, should be the first order of business. Work should be divided among the participants so that a simple and easy to define interface exists between their efforts.

The specific focus of certain system engineering activities should include a common failure reporting system and common information systems to track components and their specifications. A liability budget should be firmly established early in the AHS development process. Product liability concerns should be channeled into increased product quality.

Specifications and Standards

All comparisons emphasized the need for specification discipline. AHS specifications and standards should carefully balance the needs for technical innovation with the need for specific design criteria. Explicit mean-time-between-failures and mean-time-to-repair requirements should be included to assure a safe and reliable system. Up-front system requirements should provide for rigorous system-level performance testing at the end. Standards for AHS should be compatible with those for other aspects of ITS. A comprehensive set of performance parameters along with reasonable evaluation methods should be specified.

Hazard and Safety Analysis

The prime importance of safety was repeatedly recognized. Safety and reliability requirements for system operations should be included in the specifications. Detailed hazard analysis of vehicle, wayside, and infrastructure systems should occur early in the design process. Safety engineers qualified in appropriate technologies are necessary to conduct independent safety analyses. Safety issues should have high priority during system development and in initial phases of deployment.

Human Factors

All comparisons pointed out the need for trained human factors personnel and good human factors practices. Sound human factors principles are necessary in the design of the driver interface to ensure that the added tasks do not interfere with the primary driving task. Human factors research should emphasize the driver’s response to information, especially during degraded service conditions. The public needs to be educated as to the programmed response of the AHS in both normal and abnormal situations [K-8].

Testing

The comparisons highlighted the need for rigorous testing. Sufficient time in the AHS development process must be allocated for product testing and quality control. Safety critical subsystems will require extensive validation. A mix of actual testing and simulation to span all possible response scenarios should be utilized. An all too common practice of shortcutting the functional and performance testing effort when schedule and budget over runs occur must be avoided.

Specific Technical Capabilities

The comparisons recommended a set of specific technical capabilities, including a graceful decay for degraded service modes, a built-in maintenance function, onboard recording devices to enhance diagnostics, and operator alerts which identify failure events [G-3.2].

Safety

The AHS must provide a level of safety that is as good as or better than existing highway safety levels. The issues of ensuring safety are system level concerns and must be addressed in all phases of the AHS program. The relationship between reliability and safety in complex systems is discussed, and the importance of maintainability to enhance continuous safe system operation is also addressed. The major issues associated with validating vehicle functionality and managing malfunctions effectively are also presented.

Reliability/Maintainability

Reliability and maintainability of the AHS are interrelated with the inherent safety and level of service provided by the system [G-3.1]. AHS system reliability will reflect the ability to operate continuously without collisions under stated operating conditions for a specified length of time. AHS system maintainability is concerned with minimizing the amount of time, expense, and support resources necessary without adversely affecting the system operating conditions.

The system architecture must take into consideration the complexity of the design in terms of the ability to provide a reliable system cost-effectively. Complexity also affects the ability to maintain the system cost-effectively. System reliability is a necessary system requirement that encompasses the consideration of fail-safe design features and system cost and maintainability concerns throughout the project life cycle. Planning for reliability and maintainability must be accomplished as an integral part of the systems engineering process.

It is recommended that AHS require implementation of a system level plan to ensure develop-ment and operation of a safe and cost-effective AHS that provides an acceptable level of service. Reliability and maintainability activities will occur during the planning, design, construction, startup, and operational phases of the life cycle. The primary goals [N-2] of reliability and maintainability are:

- To improve operational readiness and level-of-service of the major AHS system elements.
- To reduce item demand for maintenance manpower and logistic support.
- To minimize impact of system reliability and system maintainability on overall cost.

This issue is relevant to infrastructure instrumentation as well as vehicle components. The cost of ensuring system reliability and maintainability may increase the sticker price of AHS-equipped vehicles, and may also be borne by the consumer indirectly for infrastructure costs through usage-based fees or taxes. The reliability and maintainability requirements should flow down from the system level to the vehicle and roadway instrumentation functions, and must be considered at all phases of the project life cycle to maintain an effective cost balance [N-2].

Check-In and Check-Out Functional Verification

The system check-in design is driven by the requirement to minimize the number of AHS subsystem malfunctions. Recognition of the critical AHS in-vehicle functions and development of a methodology for validating those functions before the vehicle enters the highway is the key to meeting this requirement. The principal categories of functions which must be checked include steering, braking, drive train performance, and longitudinal and lateral sensors plus the electronics which accompany these functions. Continuous in-vehicle testing is considered the preferred check-in, but considerable historical performance and failure data [B-5] is needed in order to determine whether supplemental testing is required.

Three broad types of check-in techniques have been identified [B-2]. Continuous in-vehicle tests coupled with a verification station can quickly verify on the fly that the vehicle has passed all required performance tests. A second technique, dynamic testing, is primarily associated with entry via a dedicated on-ramp. Dynamic testing involves placing the vehicle under automated control on a specified section of the ramp and testing automated features while the vehicle is brought up to entry speed. A third method of testing is at a static inspection site. Static inspection tests are of two types. The nominal test set is part of vehicle maintenance and can occur at specified times at specified inspection stations. Another, brief testing program can be conducted shortly before a vehicle enters a highway which transitions directly into an AHS without designated on ramps. It has been determined that no delay during passage through the on ramp or while transitioning to the AHS lane is acceptable [J-1, 2, 3]. Delay congestion was discussed in the previous section of this report titled AHS/Non-AHS Interface.

Check-in failures also affect system design. The driver should be notified of failures. The vehicle must be conducted to an exit ramp if it is under AHS control. The ability to prevent entry to the automated highway without authorization may require the use of barriers to stop the vehicle before it enters the automated lanes [B-3].

The vehicle properties which may be examined at check-out are steering, braking and drive train performance [B-2]. No check-out delay will be required under normal operation; however, a dynamic test of manual vehicle properties is necessary. It is recommended that the ability to brake the vehicle be tested against a nominal profile at the off-ramp. Braking should remain under the control of the AHS check-out facility to prevent an incident if the manual system fails. It may be preferable to perform dynamic testing during a continuous transition from AHS to non-AHS lanes by turning vehicle steering over to the driver under automated supervision, before releasing the vehicle to full manual control [B-3, C-1].

Malfunction Management

The definition of effective malfunction management strategies is dependent on exhaustive identification of malfunctions for each of the major AHS sub-systems, including wayside electronics, vehicles, operator, and roadway [E-1]. The identified malfunctions must have a cost effective method of detection. The response to a particular malfunction will incorporate a set of specific actions to be taken by one or more of the major AHS sub-systems. The effectiveness of the strategies is another key factor in managing malfunctions [E-4].

Each management strategy can be defined in two parts — a set of immediate actions by the AHS sub-systems to achieve a safe condition and a set of recovery actions to recover from the end result of these immediate actions and restore the AHS to full operation. The immediate actions can be organized into five sets which cover all of the malfunctions identified. Specific actions by the vehicle, wayside, and operator are defined. Additional actions following mitigation of a malfunction may be required to bring the AHS back to full operation. Five sets of recovery actions are also defined to restore normal AHS operation [E-3].

Detection of certain malfunctions can be automated. The most cost-effective method of detection varies with the specific function. The necessity of automating malfunction detection needs further evaluation in terms of the cost benefit for each function [E-2].

A key finding of the malfunction management analysis concerns the need to prevent certain types of failures. Malfunctions that lead to a loss of lateral control are difficult to manage since an adequate backup for lateral control has not been identified. Further investigation is required to define the necessary backup. Evaluation of proposed management strategies indicated malfunctions that are difficult to manage for safe operation are also difficult to manage for maintenance of throughput. The effective management of this type of malfunction is critical to maintaining safe and efficient operation of the AHS [E-5].

The operator has been assigned very little role in malfunction management. The role of the operator as a malfunction detector needs exploration [E-3, 5, K-8]. Operator involvement in the vehicle control process was discussed in the section of this report titled: Driver Role.

Impacts

The impacts of AHS, including both short- and long-term, is a very significant topic that poses some serious concerns and that will play a significant role in determining the level of success of AHS. No matter how it is implemented, AHS will have impacts on society. AHS must be sensitive to all the following issues, and implementation approaches should be chosen which minimize negative impacts wherever possible. What adds to the seriousness is the current lack of complete information concerning precise measurements for some of these impacts. Such quantitative measurements must wait until further research is conducted. During the course of the precursor systems analysis research, the focus of AHS impacts was placed on the following areas of investigation: privacy, system safety, the environment, travel related impacts, travel time, and system capacity.

Privacy

Deployment of AHS related technologies has the potential to raise concerns with privacy advocates. Privacy issues are generally raised in regard to the data collected in conjunction with the check-in and check-out process and as part of the route guidance function. The check-in procedure may include processing of financial, medical, or driving records to verify potential users' qualifications. There is concern that an exhaustive check-out screening will be perceived as invasive if it involves monitoring of such attributes as sobriety or reaction time to verify the driver's ability to regain manual control. The objections to gathering this type of data include fear that the security of the data will be compromised, and overall discomfort with the modern trend toward routine collection of personal data. Recent media attention on the proposed "clipper" chip proposed to standardize government communications has highlighted this fear. This technology includes a provision for accessing private data by government agents with proper court warrants. This issue can be resolved by insuring that data collected for purposes of AHS authorization is kept to a minimum and providing guarantees that the data will not be accessible for other purposes [O-3].

A related area of concern involves the ability of the system to track vehicle position. Collection and storage of vehicle routes and travel times for toll or billing purposes may be viewed as a potential invasion of privacy. This concern can be mitigated by selecting a system configuration which uses position data only for real-time vehicle control and does not require storage of route data. Fees for usage can be implemented using a prepayment method of toll collection which involves a fare card which is purchased and automatically debited without creating a record of vehicle movement. This type of electronic tolling can demonstrate the advantages related to drive time reduction and convenience associated with automated driving while alleviating driver concerns with excessive data collection. AHS funding based on subsidies, fuel taxes, or vehicle costs is another approach which eliminates the need for vehicle travel records. The issues related to privacy may pose concerns unless adequate steps are taken to provide assurance to stake holders and users that personal data collection will be minimized and stored data will be secure. Privacy concerns can be resolved through careful design of the system architecture and identification of the appropriate level of data and security measures required [O-3].

System Safety

The potential for improving the safety of highway travel is a major foundation in the development of the AHS concept. Statistics gathered by the Fatal Accident Reporting System (FARS) indicate that the vast majority of accidents which occur on controlled-access roadways are due to improper driving. Replacing the driver with a reliable automated control system has the potential to eliminate a large portion of accidents caused by human error by eliminating such occurrences as head-on collisions and run-off-the-road accidents. This assumption may be valid if AHS accident statistics neglect the effects of potential external disruptions such as unauthorized manually operated vehicles, and if the number of failures due to AHS-specific equipment does not exceed the number due to human error. The ability to use improved highway safety as a selling point for automated travel depends on mitigation of the risks associated with external disruptions and system malfunctions to maintain the anticipated safety gains.

It is expected that the AHS will provide collision-free operation in the absence of malfunctions. The ability to meet this standard of safety cost-effectively requires a structured approach to ensuring safety from the system level down to the individual components. The system design must take into consideration the relationship between technical feasibility and cost of implementing a given level of safety. System safety assurance is a methodology which may be followed to insure appropriate steps are taken to maintain safety at each phase of AHS design, development, deployment, test, maintenance, and operation. A priority of system safety assurance is the prevention of hazards by design. This objective can best be achieved by early and rigorous implementation of safety assurance processes. It is imperative that a system safety program be established during the initial stages of architecture design because it may be technically impossible or economically infeasible to correct safety hazards in later phases of the program. It is also important to emphasize the importance of a structured approach to safety assurance to all members of the contracting team and require safety analyses at each phase of the system life cycle.

Environmental Issues

Automated highway systems may have environmental impacts in terms of changes in vehicle emissions, fuel consumption, noise, and visual aesthetics. For emissions and fuel consumption, the net impact depends on numerous factors. AHS may lead to increases in driving, which on an aggregate basis in terms of total emissions tonnage and fuel consumed could mean emissions and fuel usage increases. Certain pollutants and fuel consumption could increase with speed increases associated with an AHS that allows more freely flowing traffic. Vehicles accessing or egressing an AHS forming lengthy queues could result in emissions and fuel consumption increases from idling at on- and off-ramps. However, AHS research and development will proceed along with technological advances in areas such as emission control technologies, clean fuels, and alternative propulsion vehicles. The focus of these activities includes the reduction of emissions on a per-kilometer basis. In addition, possible increases in the national corporate average fuel economy (CAFE) standards would result in reduced fuel consumption on a per-kilometer basis. AHS has the potential for smoothing out the traffic flow, removing or at least reducing stop-and-go, idling, and sharp acceleration and deceleration driving modes, which are known to contribute to vehicle emissions and vehicle fuel usage increases. In the context of automated vehicles traveling with much smaller headways than presently possible, i.e., in platoons, preliminary research has indicated there are emission reductions and fuel efficiency increases for all vehicles, including the lead vehicle. The true net effect on vehicle emissions and on fuel consumption is unknown at the present time [O-2, I-3].

With a potential increase in automated highway lane capacity by a factor of two or more over conventional non-automated lanes, noise increases are possible at and adjacent to an AHS facility. Also, in certain very dense urban areas where an AHS may be deployed, there could be infrastructure modifications. These could be either new AHS facilities in new rights-of-way (ROW) or lateral expansion within existing ROW to accommodate added lanes, medians, and shoulders. Construction of elevated facilities may be necessary if there is no space for lateral expansion. Such infrastructure changes could have negative visual impacts.

Some suggestions [O-2] for resolving these issues include:

- Developing modeling tools and supporting data to more accurately represent the automated highway driving mode to produce high-fidelity estimates of emissions, fuel usage, and noise impacts of AHS.
- Identifying AHS-related technology applications with potential environmental benefits, such as diagnostics upon AHS check-in to determine vehicle emissions and fuel economy profiles.
- Continue identifying advanced technology research areas with potential AHS applications and investigating methods to develop beneficial linkages, such as through emission control technologies or alternative propulsion vehicles.
- Investigating the feasibility of linking more closely with AHS such measures as travel demand and land use management, and congestion and parking pricing.

Such research could be conducted at academic institutions, national laboratories, regional Metropolitan Planning Organizations (MPO’s), U.S. Department of Transportation, or private companies with transportation area expertise. Establishing an appropriate time frame for this research should be investigated in the next AHS research and development phase [K-Conclusions, I-6].

Travel-Related Issues

The current transportation paradigm or model of “the way the urban transportation system works” has at times been described as people driving alone in their cars on urban freeway networks that has led to urban sprawl over time. The issue is that AHS, as currently envisioned, is seen by some as only encouraging the continuation of this type of behavior, that is: more driving, more single-occupancy-vehicle (SOV) driving, and more sprawl. AHS is seen as emphasizing further highway development and making SOV driving more attractive by increasing its convenience and comfort at the expense of other travel modes, such as public transit and high-occupancy-vehicle (HOV) driving. A considerable level of resources have already been invested in such non-SOV travel modes. This investment should be continued, however, AHS is seen by some as counter to this [O-2].

More SOV driving would mean an increase in trips, trip length, and volume of drivers, even above what such increases may be over time without an AHS. These effects could occur unless there are strong measures in place to counteract them, including transportation demand management, congestion and parking pricing, and land use planning and management. The AHS program is currently viewed as not having such mitigating measures centrally incorporated into the program.

More SOV driving could also mean an emphasis on a single mode of travel, ignoring the multimodal nature of the transportation system. AHS research and development work should not exclusively focus on the automated mainline portion of a trip, but should consider the entire trip from origin to destination, which could involve the use of more than one travel mode.

Associated with the potential encouragement of longer trips with AHS is the potential for a decrease in use of other travel modes used primarily for shorter trips, such as walking and bicycling, possibly leading to a degradation of what is referred to as the short-trip network or infrastructure in local neighborhoods.

Suggestions [O-2] for resolving these issues include the following:

- Developing modeling tools and supporting data to more accurately represent the automated highway driving mode to produce high-fidelity estimates of the impacts of AHS, in the areas of travel volume changes, mobility, and land use impacts.
- Developing applications of AHS in the context of multimodal transportation systems, with particular emphasis on alternatives to SOV driving modes, such as public transit and HOV driving.
- Investigating the feasibility of linking more closely with AHS such measures as travel demand and land use management, and congestion and parking pricing [I-6, K-Conclusions].

Travel Time

Travel time savings is one of the primary potential benefits associated with automated highway systems vis-à-vis congestion relief and reductions in travel delay. It is thus important that an AHS be deployed, operated, and maintained in a manner which realizes such savings to ensure user acceptance of AHS technologies.

Results of modeling freeway corridor travel indicates that the greatest time savings will be realized in urban areas during congested periods. Moreover, earlier modeling research results have shown delay reductions on non-automated roadways as well. The roadways having reduced congestion included both conventional non-automated freeway lanes adjacent to the automated facility and neighboring arterials in a deployment scenario in which an automated highway facility shared the right-of-way with conventional highway lanes. During non-congested periods of the day, travel time savings diminish as normal freeway lanes operate under less congested conditions reflecting the shrinking of the speed differences between automated and non-automated travel. This same phenomenon is characteristic of rural sections, where congestion rarely occurs [O-2].

There are, however, circumstances which could increase travel time on an AHS and hence dissipate travel delay reductions relative to non-automated travel. Such conditions include the infrastructure deployment, roadway geometric characteristics, and operation of an AHS. For example, if an AHS is sharing right-of-way with non-automated lanes, then the entry/exit configuration will impact travel on both the automated and conventional lanes. If dedicated entry/exit facilities are not provided for the AHS, then AHS vehicles would be required to weave through conventional lanes to access the automated facility. This would result in added congestion on the conventional lanes. Moreover, conventional lane congestion would reduce automated lane capacity, as such congestion would affect access to and egress from the automated lanes. Dedicated entry/exit facilities provide for physical separation of automated and non-automated lanes and would avoid this problem. The way check-in and check-out is managed will also impact travel on the automated facility. Thus delays associated with AHS check-in and check-out should be minimized [I-3].

The discussion here is to highlight general benefits and issues relating to travel time savings. Each corridor would realize different savings as congestion, infrastructure deployability, operations, and geometric elements are unique to each area. Further study is required to accurately quantify the benefits of travel time savings on a site specific basis [I-3, J-1, 2, 3].

Capacity

A fundamental issue to the design and success of the AHS is its capacity. In this report, capacity is given its Highway Capacity definition: "...the capacity of a facility is defined as the maximum hourly rate at which persons or vehicles can reasonably be expected to traverse a point or uniform section of a lane or roadway during a given time period under prevailing roadway, traffic, and control conditions."

Conventional freeway capacity results from individual driver's reactions to other vehicles and to roadway and control conditions. By contrast, AHS capacity will be governed mostly by the vehicles' control systems. The infrastructure deployment configuration of the AHS facility will also impact traffic on both the AHS and the non-automated highway lanes.

Two major elements of AHS capacity are seen: the ability of the system to provide steady state throughput on a long, uninterrupted section of mainline without entry/exit points; and the amount of degradation such a system sustains if entry/exit points are present. For the purposes of this report the former element is given primary consideration. It is believed to be technically feasible to design a system with capacity of 6,000 to 8,000 vehicles per hour. Such extremely high capacities bring several issues. One of the most important of these is interchange design and location. Every AHS trip has at least two manual links: those parts of the trip prior to and after the AHS link. It is therefore a design requirement that all entry/exit points and adjacent street sections be capable of handling the AHS load that will utilize them; otherwise queues and congestion will develop on cross streets as vehicles approach the AHS, and mainline operations will degrade if all exiting traffic cannot be accommodated.

Modeling conducted in Activity H — AHS Roadway Deployment Analysis and Activity J — AHS Entry/Exit Implementation leads to the conclusion that cross street and ramp congestion can be expected at relatively low market penetrations using traffic growth forecasts from the metropolitan planning organizations. It is noted that the conclusions drawn are based on the operational modeling of a specific hypothetical freeway corridor and assumed market penetration rates. It is recommended that future work be based on the demand model and population and employment forecasts of an actual candidate location for AHS implementation. It is further recommended that market penetration rates used be based on more than just "what if" assumptions. For example, market research techniques could be used to estimate demand for equipped vehicles based on realistic cost estimates for equipped vehicles [H-2, 4, J-3].

Impacts Highlighted by the Cost/Benefit Analysis

The impacts described in this section follow from an analysis of cost and benefit factors. The analysis examined a hypothetical AHS project on an urban freeway where a fourth lane was converted to a dedicated AHS lane. Operations of the AHS project were to begin in the year 2010 and the penetration of AHS vehicles in the region's vehicle fleet was forecast as a function of parameters relating to vehicle cost and regional deployment. Given forecast traffic and levels of AHS vehicles over a 30-year planning horizon, highway operations were examined with attention paid to changes in vehicle-kilometers traveled and vehicle-hours traveled, and changes in their distribution over a typical peak period. Benefit flows and impacts were evaluated from the changes in demand, the distribution of demand, and travel time.

<u>Travel Time</u>

One of the principal AHS benefits categories is improved travel times. In the urban environment, AHS will likely have a moderate impact on travel time in the peak hour and a greater impact on travel times in the peak period non-peak hours of the day.

Under normal operating conditions, with adequate penetration of AHS-equipped vehicles, there will likely be a phenomenon of temporal shifting of demand to the peak hour: Many of the AHS-equipped vehicles will travel in the peak hour while the additional capacity made available in the non-AHS lanes, through the diversion of AHS vehicles, will result in a greater number of trips by non-AHS vehicles being accommodated in the peak hour. Consequently, greater traffic volumes would flow in the peak hour. However, more substantial improvements in time savings per trip would occur in the peak period non-peak hours, which will operate with lower volumes of traffic [P-4, I-3].

Improved Convenience

A greater number of trips being accommodated in the peak hour represents a significant benefit for many travelers. Urban congestion forces many commuters to travel at off-peak hours which results, sometimes, in lost economic opportunities as well as personal inconvenience (lost leisure opportunities, time spent with families, etc.) [P-4].

Economic Activity Benefits From Congestion Relief

Urban traffic congestion represents a serious impediment to the development and retention of particular types of economic activity. Urban business centers grow and develop due to what has been called "economies of agglomeration." Many industries (wholesale and retail trade and business services, for instance) require that the majority of employees be on site during principal business hours in order to maintain smooth, profitable operations. Congestion frequently makes that difficult or costly resulting in businesses abandoning the urban centers. Relief of traffic congestion promotes conditions that enable cities to flourish as business centers.

AHS, insofar as it accommodates greater numbers of people being able to commute to business centers for principal business hours, will likely contribute significantly to improved economic activity [P-2].

Urban Form and Livable Communities

The phenomenon of urban sprawl, low-density housing, and two-vehicle families have been facts of U.S. development for many decades. Many communities face the problem of growing congestion in daily commutes between suburbs and cities, contributing to both the decline of the cities as well as the quality of life in suburban communities. In the long run, rail and transit may represent a solution for some growing communities. However, achieving sufficient ridership thresholds to justify rail may be many years away. AHS may provide a lower cost and, overall, more acceptable solution for many communities. In many communities, AHS could keep business centers attractive thus preventing further sprawl and continuing urban blight [P-6, I-6].

Operation/Maintenance

The operation and maintenance of AHS involves a number of challenging issues. Included among these are the responsibility for operation of the system, the orientation and the philosophy of the operating agency toward real-time operation of roadway systems, and the need for highly motivated and qualified personnel to operate the system. The character and significance of each of these issues will vary with different configurations of AHS, with the nature and degree of involvement in real-time operation to be carried out by operating agencies, and with whether AHS is developed as a vehicle-based system or an infrastructure-based system.

Responsibility

Implementation of Automated Highway Systems will, for the most part, be superimposed upon and become an operational part of existing freeway/highway systems. It is expected that operation, even though differing from today's operation, will be integrated into the overall freeway and arterial systems of tomorrow. In fact, if the full benefits of AHS are to be realized, it is felt that the integration of the operation of the automated and the non-automated highways is essential.

Given this, it follows that the responsibility for the operation of AHS should be retained by those same agencies that hold operational responsibilities today. The agencies are the State Departments of Transportation, local agencies, toll road authorities, etc.

Within the AHS and ITS community, there have been suggestions that a separate agency (similar to the Federal Aviation Administration) be created to operate AHS, citing perceived similarities between the need for control of air transportation and of highway transportation. In fact, there are more differences than similarities; there is no justification for the creation of an overall operating agency. Indeed, the creation of a new operating agency is viewed as counter-productive to the overriding need to operate highway-based transportation as a system which is totally integrated with its surrounding non-automated system.

The responsibility for maintenance of those systems located within the infrastructure should, for like reasons, reside with the operating agencies of the highway/freeway systems.

Resolution of this issue will have a significant impact on the issue of liability [K-1, 3, 4, O-1].

Organizational Orientation Perspective

In order for the responsible operating agencies to be successful operators of an AHS, there must be a significant shift in the thinking and philosophy of those agencies. They must become much more oriented towards “operations” than they currently are. Even those agencies that have moved into today’s real time traffic management, operate programs that tend to be reactive in nature, dealing with the congestion and incident problem after it has taken place. With AHS, a much more pro-active approach will be necessary. A round-the-clock operational staff will be needed; shift work will likely be required.

This will call for a conscious shift in thinking within the operating agency to move from the reactive mode to a real time, pro-active mode; prioritization within the agencies of operations-related activities will have to take place [K-3, 7].

Qualified Personnel

Obtaining, training, and retaining of highly motivated and qualified personnel to operate and maintain AHS will call for special attention by operating agencies. In many cases, this will call for the establishment of appropriate personnel classifications, salary structures, career paths, and etc. Training programs will need to be developed and carried out.

Operational personnel will need to be on hand and fully trained when the program goes into operation. on the job training and development during actual operation of the AHS is not viewed as a reasonable approach to meet the needs of the operating program. Adequate lead times to ready the organization and its staff for the acceptance of the operating responsibilities need to be provided.

An optional approach would be to contract with the private sector for operating and maintaining AHS. Today, some States are experiencing resistance from unions in contracting out work that can be done by State forces. Resolution of these issues will be necessary before contracting for these services can be seen as a viable option.

Resolution of the issue of availability of funding for on-going operations and maintenance activities will have major impacts on this issue [K-3, 7].

AHS Deployment

Deployment refers to the manner in which the system is introduced and installed as part of the national transportation system. All of the activities which are included in the precursor study are associated with deployment. Of particular importance, however, are the topics related to vehicle and roadway operations, safety, institutional issues, and costs and benefits. Getting started is a “chicken and egg” problem which must be resolved as early in the planning process as possible. This introduces an analysis of the relative merits of evolutionary deployment and of revolutionary deployment. Consideration of an evolutionary process leads to the discussion of the merits and hazards of mixing automated and manual traffic. This includes liability issues. What can be learned from past transportation systems deployment, such as BART? What difficulties does the automobile manufacturer face during startup, how will other modes of transportation such as transit and commercial operations be included, and what can be done to enhance market penetration of AHS equipment? Finally, the deployment of AHS will have to be compatible with the goals of other transportation institutions and must conform with current and future regulations.

Evolution Versus Revolution

AHS deployment involves at least the following six categories of challenging issues: technology, infrastructure, human factors, vehicle manufacturing and maintenance, insurance, and public will. The process of AHS deployment can be viewed as overcoming various difficulties in exchange for the provision of desirable AHS functions (user services) [A-1, 4]. There are two major deployment strategies: evolution and revolution. A fundamental issue is which strategy to adopt. The decision will have tremendous impact not only on deployment but also on research and development [K-5].

The evolutionary approach is based on the assumption that the functionality of a mature AHS cannot be realized suddenly and hence intermediate functional steps must be identified and optimized. An evolutionary stage towards a mature AHS can be 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 provide sufficient additional functionality that justifies the required effort to overcome the associated difficulties. An evolutionary approach is compatible with the automotive industry practice of gradually introducing increasing levels of component sophistication. Although the evolutionary strategy may be amenable to many aspects of AHS deployment, it is likely to require safe mixing of automated vehicles and manually controlled vehicles on the same lane and possibly even safe operation, without physical separation, of automated vehicles on a lane neighboring non-AHS lanes. Therefore, the evolution strategy may necessitate more sophisticated and costly technologies than those that would be required without such mixing [P-3]. This leads to the revolutionary approach.

The revolutionary perspective on AHS deployment is based on the idea that the full automation of AHS is a significant departure from conventional traffic operations in terms of capacity, safety, and travel times in congested locations. It would be exceedingly difficult and costly to develop the technology to enable fully automated vehicles to safely mingle with manually driven vehicles in mixed traffic. Under the revolutionary approach, fully automated vehicle control would initially be implemented in limited scope applications, e.g. in specific corridors where the separate roadway lanes for automated driving would be provided. The initial AHS vehicles would probably need to be subsidized by the public operating agency in order to bring the cost down to levels affordable to users. These initial implementations would be intended to catch public interest so that demand would grow for AHS vehicles and for further AHS lanes. The full AHS functionality would be offered to a limited number of users at a much earlier date than it would be under the evolutionary approach, and the additional cost and difficulty of developing a system that could coexist with manually controlled vehicles would be avoided [K-5].

It is the recommendation of this analysis team that, for the near term, the evolutionary approach should be adopted, without precluding a different final deployment methodology. The required subsystems and an open architecture can be developed within an evolutionary framework without a major expenditure for an entire system. Nothing is lost if a switch is made to attempt a fully-developed AHS at the first deployment. Automotive product functionality increases incrementally, in step with highway evolution. Early results are obtained from a Federal program based on an evolutionary strategy, thus reducing the risk that the program will be cancelled because of cost or a major error. However, the evolutionary approach may provide only a small safety benefit initially, and the driver comfort benefit that is essential means that driver-in-the-loop evolution would be counterproductive. Also, the revolutionary approach offers significant immediate safety, driver comfort, travel time, and capacity benefits.

Comparable Systems Analysis Deployment Lessons

There are several lessons to be learned about program organization, criteria for system design and choice of suppliers, and public relations from the deployment of the Bay Area Rapid Transit (BART) system. The BART staff lacked technical experience, which had a major negative impact on initial operations. The AHS managing and operating organizations should have several technical people on their staff from the beginning and the final operating staff that manages the system should be as technically experienced as the organization that built the roadway. This staff should provide technical monitoring of the various projects from the beginning. Because of the complexity and the number of different systems required in an AHS, the systems engineering and integration function should be established early as a separate unit of the technical staff to integrate AHS subsystems. A strong, independent safety department should be a part of the organization early in the program [G-3.1].

System design should emphasize safety. The requirements should include reliability, maintainability, and availability specifications. The system should allow for graceful degradation of service modes. Every contract for equipment or technical services should be based on previous test and evaluation of equivalent material, preferably at a test site associated directly with AHS. Infrastructure providers should also begin planning for maintenance requirements during the development process. Inevitably there will be system failures, hopefully non-injury related, which cause the AHS to lose functionality. System specifications should include performance in such degraded service modes so that system safety and capacity are not compromised. A detailed hazard analysis of the AHS should be given high priority in system design and development [G-3.1].

The public trust is a critical element in the success of any large, innovative public works program. Public information strategies, such as the use of public forums, should be developed and applied to discuss system implementation with the public. AHS should be incorporated in a regional transportation planning process and the impacts of AHS on the entire regional transportation system should be discussed. As much as politically feasible, problems with AHS development and implementation should be addressed candidly, both internally within the organization and externally with the public [G-3.1].

Mixing of Automated and Manual Traffic

It may be exceedingly difficult and costly to develop the technology to enable fully automated vehicles to safely mingle with manually driven vehicles in mixed traffic. In a segregated automated highway system, vehicle movements are coordinated through communication. Such coordination ensures safe operation, even with short inter-vehicle spacing. In mixed traffic, no such coordination would be possible and automated vehicles may have to rely primarily on their own sensors, which may have severe limitations. Therefore, such mixing raises issues of safety, capacity, and whether the driver should be in the loop or not [K-5].

The unpredictability of manually controlled vehicles poses safety hazards to automated driving. to ensure safety, ultra-sophisticated vehicle and roadside technologies may be required. An automated vehicle must be able to detect and react to any sudden and potentially dangerous maneuvers made by neighboring manually driven vehicles. Such maneuvers would include a manually driven vehicle's sudden cutting in at an unsafe distance in front of the automated vehicle. The automated vehicle will be required to detect accidents that spill over from the manual traffic lanes. Without physical barriers separating the automated traffic from the manual traffic, debris that falls from a vehicle in the non-AHS traffic lanes could reach the automated portion of the highway. Although the vehicle may be required to detect erratic behaviors and accident spillage, the detection false alarm rate must be low.

Since close spaced platooning in mixed traffic could lead to catastrophic accidents because of the unpredictability of manually driven vehicle maneuvers, accident spill over, and debris from the non-AHS lanes, such platooning may not be feasible. Without platooning, because of the same unpredictability and the limitations of vehicle sensors, the spacing between an automated vehicle and a longitudinally adjacent but manually driven vehicle may have to be larger than the typical spacing practiced by motorists today. If this were so, capacity gains resulting from automation would be negligible [K-5].

Startup and Market Penetration

There appear to be at least four major issues that are associated with market penetration:

- The necessity of benefits to the consumer.
- Explicit and implicit government financial aid to the manufacturer.
- Government/industry cooperation to avoid unnecessary manufacturing delays.

- Government/industry cooperation to synchronize infrastructure and equipment deployment.

No matter how much the government and the general public may wish to install and operate an automated highway system, the individual consumer must be convinced that the purchase of an automated vehicle will be personally beneficial. Without benefits, there is no reason for the existence of AHS vehicle customers, and therefore there will be no impetus for automated highway construction [P-3]. Some equipment may be provided initially by the after-market, thus reducing the time to market; however, most of the vehicle components require in-vehicle testing. This implies that the first deployment will be involve vehicles with AHS equipment installed as original equipment. Likewise, government financial support can encourage manufacturing and reduce the time to market. However, financial aid may be declined if it is less than required by the manufacturer to compensate for slow market penetration. Government support may be more welcome if vehicles were purchased by the highway administration for testing, for lease to the first system users, or for use in an automated transit program.

The existence of benefits equates to the level of market penetration and to the startup of AHS vehicle sales. After the final test deployment program (defined to be the last time the government invests large amounts of money to demonstrate the system) the three principal benefits will related to safety, throughput, and driver satisfaction [I-3].

<u>Safety</u>

The amount by which safety will be improved will depend on the trade-off between normal highway hazards eliminated or decreased by the presence of AHS and the introduction of new hazards associated with the presence of AHS [N-2].

<u>Throughput</u>

If the AHS operates in conjunction with an HOV, the HOV will probably transport more people per kilometer per lane per hour. However, automated vehicles may cause a significant reduction in highway congestion if they can operate in platoons, or at greatly reduced spacing. If an automated system shares an HOV lane, the vehicle speeds will be identical, therefore a driver cannot expect shorter travel times than if he were in an HOV.

Driver Satisfaction

The sum of automated driving without stress and the personal freedom associated with a choice of exits is a unique, realizable benefit. Market penetration may be linked directly to this benefit, so any major attempt to force the driver to concentrate on driving while on the AHS or to give up control of the destination may have a serious negative impact on deployment.

After the final successful pre-deployment test, there will still be a delay of at least several years to bring the system to market. The length of this production development period will be increased if technical deployment is by stages. Once a decision is made to manufacture a particular vehicle model, it takes up to four years in the production development cycle before the vehicle is actually in the market. If a major modification is made to the vehicle design, the cycle will start again, probably from the beginning. Until the first vehicle has been tested in the market, the severely redesigned vehicle may not be introduced into the cycle, even if the research is complete [I-1]. For example, if an AHS vehicle with longitudinal headway control is developed without lateral control, an AHS vehicle with coordinated longitudinal and lateral control would not be available for perhaps as many as four years after the market for the first AHS vehicle has been established.

Utilization — Congestion Reduction and Cost

The benefit-cost analysis, which included an analysis of traffic distribution on a hypothetical AHS over the entire peak period (not just peak hours) reveals that there is a minimum penetration threshold for operating AHS during the peak hour (assuming that most of the AHS vehicles will choose to travel in the peak hour). For levels of penetration below this level, AHS operations would actually reduce the total capacity of the highway system. There is also an estimated level of penetration required in the off-peak hours in order for AHS to improve overall highway operations. Below this threshold, AHS operations would reduce total capacity in the non-peak hour. (Strictly speaking, the capacity does not decrease but the utilizable capacity decreases if sufficient vehicles are not AHS compatible.) These conclusions are a result of the assumption that only AHS equipped vehicles can travel of the AHS lanes [P-4].

The above activity also makes clear that AHS represents a viable traffic alternative for regular commuting traffic only if congestion on surrounding arterial routes is relieved to an adequate degree. In the absence of arterial relief, AHS could be viable for periphery-to-periphery trips. An additional alternative might be a “many-to-few” AHS configuration where vehicles enter the AHS at many points but can only exit in the business district during rush hour at designated parking facilities. However, the many-on/many-off urban AHS would result in unacceptable ramp queuing if arterial congestion became chronic [I-6, J-3, P-6].

Vehicle cost will be a key component in the acceptability of AHS for all stakeholders concerned (travelers, public sector, vehicle manufacturers). In order to attain the relatively high thresholds of penetration required in a timely manner, the cost of equipment and services needs to be maintained at a level such that the consumer’s sense of an appropriate price is never exceeded.

The consumer’s willingness to pay for AHS equipment and service will be a function of how the individual values his own time, assuming the consumer derives no additional benefits (reduced stress, etc.) from AHS. If, for instance, AHS results in a 15 minute time savings per day, and, supposing that the consumer makes 200 commutes per year and values his/her time at $10 per hour, then he/she would be willing to pay $500 per year for AHS [P-4].

Liability

Tort liability is not a new concern, either for the automotive industry or for highway operating agencies. Highway agencies are frequently sued when accidents result from allegedly improper design, inadequate maintenance, and improper operation of traffic control devices. Automotive manufacturers have to defend themselves against suits alleging safety deficiencies in some automobile models. Suits with little merit are frequently filed in the knowledge or belief that the defendant will settle rather than spend the money and time for trial [A-4].

AHS brings a new set of concerns to highway operating agencies and the automotive industry [O-1]. Total control of vehicles on the roadway may mean that any accident resulting in loss to an occupant or owner will be felt to be the sole responsibility of the vehicle manufacturer and/or the highway system. The AHS “driver” is in somewhat the same position as a bus or airline passenger. Particularly in platoons or closely spaced non-platoon operations, there is little chance that the driver can play any beneficial role in recovering from a high speed failure. Therefore the public perception will be that basically all failures resulting in damage or injury will be the “fault” of the system.

According to automotive industry spokespersons, the industry has traditionally managed such risks by building the costs of damage suits into product costs [A-2]. It is expected that AHS vehicle risk can be managed in the same way. However, highway operating agency personnel from several States have expressed serious concerns about the tort exposure that AHS may bring to their agencies, representing the infrastructure part of AHS. Costs to defend these agencies against such suits typically come out of their operating budgets at the expense of other programs. An important part of further AHS development is felt to be the identification of the magnitude of tort exposure to operating agencies and of the means to successfully account for such exposure in funding the AHS program. If this issue is not effectively addressed early in the program, it is felt that part of the potential support base for AHS, the operating agencies, may continue to have serious misgivings about the subject of tort liability [O-1].

Impacts of Trucks, Transit Vehicles, and Alternative Propulsion Vehicles on AHS

Operational characteristics, especially acceleration and speed differentials, of truck, transit, and possibly alternate propulsion vehicles, differ significantly from passenger type vehicles [F-1]. As a result, a policy for handling these operational differences to avoid degradation of operations on AHS must be developed. This policy must account for the political and economic pressures associated with the inclusion of these types of vehicles while preserving operations for the majority users. The following issues and corresponding solutions do not apply equally to all areas. Further study is required to determine heavy and alternate propulsion vehicle policy on a site specific basis.

Present campaigns to reduce air pollution center on the development of alternate propulsion vehicles and the reduction of single occupant vehicle trips through effective use of transit and carpools. It is therefore important that development of any new highway system (including AHS) incorporate facilities that comply with these campaigns. Failure to make provisions for these issues in AHS planning and design would make AHS politically difficult to implement. In addition to the political pressure to include transit and alternate propulsion vehicles, there may be a demand from the trucking industry to be included on automated highways, especially in areas with a large truck presence (e.g. port cities). Issues relating to the operational impact of all these vehicle types on the AHS must be addressed [M-4, 5].

Research has shown that transit vehicles require up to triple the time that standard passenger vehicles require to accelerate from rest to average freeway running speeds, while trucks require six times the passenger vehicle time. The provision of long acceleration lanes to accommodate these slower vehicles is not only costly but in some cases impractical, as the lengths required exceed standard interchange spacing within urban areas. In areas of adverse terrain (long steep grades) a large speed differential (greater than two times) between heavy and passenger type vehicles exists. As a result, significant degradation of operations can be expected on AHS if these differences are not accounted for [F-2]. Possible solutions which accommodate speed and acceleration impacts include limiting heavy vehicle access to select interface points or terminus points, separate lanes for these vehicles, exclusion of certain vehicle types from the automated highway, allowing access by heavy vehicles only during late night low use hours, coordinated control to open extra long spaces for the merging of such vehicles, as well as combinations of the above [F-2, M-4].

It is felt that consumer pressure will force alternate propulsion vehicles, unlike commercial trucks and transit vehicles, to improve performance to be more closely equal to normal passenger vehicles. If this optimistic view is correct, no special accommodations will be required for alternate propulsion vehicles on an automated highway [M-3]. However, if this is not realized before AHS is implemented, a policy is required regarding the implications associated with accommodating this type of vehicle on the same AHS with both passenger vehicles and heavier vehicles [F-1].

Institutional Barriers

Automated highway systems research and development as currently envisioned and configured is not universally embraced by everyone as the solution to the nation’s traffic congestion and roadway safety problems. Numerous institutional issues focusing on environmental impacts exist which must be resolved prior to the successful deployment of AHS. These institutional issues are centered around the relationships among the institutional participants in AHS research and development, the level of accurate information the participants have about each other, and barriers to making progress in the work [O-1, 2].

The numerous participants in AHS research and development with differing views has led to a division along professional lines which contributes to barriers, both actual and perceived. The division is based on differences in educational background, professional training, and work experience and generally consists of engineers on one side and planners, economists, and members of the environmental community on the other side. However, a diversity of views and common ground exists between the groups with room for compromise. In addition, lack of complete and accurate information and the existence of misinformation that each group has about each other has contributed to the division. Unfamiliarity and misconceptions on both sides prevent a full and accurate appreciation of each other’s standard and traditional methods of analysis and problem solving. Another contributing element to these institutional problems is the lack of sufficient involvement in AHS research and development by non-highway institutions. The AHS program is perceived as too “highway” oriented, even in its name, with the need for much more active and central involvement in the program from the non-highway agencies at the Federal level. Increased involvement by the Environmental Protection Agency (EPA), the Federal Transit Administration (FTA), and Metropolitan Planning Organizations (MPO’s) at the regional and local level would mitigate this perception [O-1].

A principal suggestion for resolving these issues would be incorporating an aggressive process of education, communication, and participation to help dissolve the barriers and help forge a more common vision of a future transportation system with automated highway systems as an integral component. Specific suggestions [O-1, I-6] include:

- Promoting active participation of non-engineering disciplines in AHS’s next phase.
- Forging stronger linkages with non-highway institutions.
- Promoting engineering community participation in conferences, forums, committees, special projects, and other related meetings sponsored by planning, public transit, and environmental communities.
- Instituting research/policy forums for AHS modeled after similar ITS conferences.
- Reviewing national legislation for applicability to AHS.
- Wide distribution of the Compendium of Final PSA Reports to non-engineering communities for comment.
- Forging closer linkages among ITS America committees to help bridge gaps between the professionally disparate memberships, whose current committee structure focuses on individual subject areas and can result in insulating each committee within its own “world”.
- Investigating the use of FHWA’s recently initiated training courses on the ITS planning process and possible applicability of the courses to AHS.

AHS In Tune with Future Regulations

Deployment of automated highway systems technologies will have to conform to numerous pieces of Federal and possibly State and local legislation that have ramifications in the roadway transportation area. Deployment will also have to conform to some general measures, with applicability to AHS, and to other AHS-specific legislation that addresses potential AHS-related problems. Areas of particular significance include air quality, fuel usage, user accessibility, communications, commercial vehicle operations, and land use planning.

Examples of currently existing legislation that furnish regulations and have consequences in the transportation arena include the Intermodal Surface Transportation Efficiency Act (ISTEA), Americans with Disability Act (ADA), National Environmental Policy Act (NEPA), and Clean Air Act and its Amendments (CAAA). Each of these laws has relevance and applicability to AHS as AHS moves toward deployment. AHS research and development will proceed along with other technological advances (emission control technologies, clean fuels, non-fossil fuel energy sources, and low to zero emission vehicles) that have consequences in the roadway transportation sphere with an emphasis on air quality. This research and development effort would likely lead to additional legislation that would govern the way in which such technological advances are carried out. The set of standards governing average vehicle fuel economy, the CAFE (Corporate Average Fuel Economy) standards, is another related program which has the potential to cause modifications to existing regulations that emphasize air quality and fuel consumption [O-2].

AHS applications in the trucking industry may necessitate changes in work rules (or other areas of concern) that would require the involvement of the Interstate Commerce Commission. AHS-related vehicle safety enhancements will require the increased involvement of the National Highway Traffic Safety Administration. This could lead to regulations affecting the automotive industry, the producers of the automated vehicles. Rules and regulations governing the area of communications among vehicles and the area of communications between the roadway and vehicles will be part of the AHS environment involving at least the Federal Communications Commission at the national level. On a more local level, the metropolitan planning agencies will be intimately involved in the process of land use planning and management as it relates to automated highway systems deployment. This is a very significant area of concern to members of the general planning communities (land use, urban, and transportation) and the environmental community. Moreover, certain

States could have legislation that differs from the national model, and AHS will have to accommodate these differences. In California, for example, where air pollution is such a significant issue (relative to its importance in other areas of the country), the air quality standards are more stringent than the Federal air quality standards. The State has in fact legislated that, by 1998, 2 percent of new car sales in the state must be zero emission vehicles, which by default would be battery-powered electric vehicles [O-2].

Funding

Funding the AHS is seen as a fundamental concern, not only within the research team, but also by potential operating agencies. While demands for infrastructure improvements and maintenance increase every year, competition from non-transportation sectors also increases.

If is concluded that AHS cannot be built unless there is a reasonable assurance of sustained funding, at least for startup projects. Regardless of any possible evolutionary scenario, the totally automated AHS on a dedicated roadway requires a quantum leap of infrastructure construction and therefore a source of funding. The importance of funding the infrastructure side of AHS cannot be overstated. It is difficult to envision any free market scenario that could result in the construction of the facilities needed for AHS, without outright Government funding or at least Government backing.

Capital Funding

The biggest step and arguably the most important type category of funding is capital funding. Traditionally, major highway projects are funded from State funds, with the Federal share ranging from 50 percent to over 90 percent. This policy has been extremely effective in encouraging the states to invest in transportation projects due to the leveraging of State funds with Federal funds. It is envisioned that AHS capital funding would be all or predominantly Federal.

Operations Funding

Up until the very recent past, the role of the Federal government has been to provide capital funding only. All funding for operations and maintenance, even for the interstate highway system (90 percent federal construction funds), has been borne by the State operating and maintenance agencies.

AHS is expected to have significantly higher operating requirements and costs than traditional freeways. Even though more and more urban freeways are being equipped with traffic operations systems (TOS's), such systems are typically found only in the urban areas with the highest traffic densities. By contrast, any AHS implementation will require not only its own operating system, but also a very effective interface with the surrounding non-AHS system. At a minimum, such a system is required to ensure the surrounding system can handle the exiting AHS traffic volumes.

Furthermore, while a conventional freeway with a TOS can operate reasonably well if the TOS shuts down, it is difficult to imagine a fully automated AHS that could operate without a surveillance and control system. The importance of adequate and sustained operations funding is therefore not to be understated.

The research project included interviews with freeway operations personnel from several States. Maintenance funding was identified as a fundamental concern by these personnel, who are faced with continual efforts to maintain funding for their traffic operations systems in the face of competition from highway construction projects as well as other maintenance and operations activities [K-7].

Because the States have limited budgets, maintenance of existing highway facilities is in competition with funding for construction of new facilities. Because of the leveraging of State funds for construction, 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.

It is expected that maintenance of AHS may be more costly and will certainly be more critical than maintenance of conventional highways. The AHS infrastructure-mounted sensing and control elements must be kept in operating order. Even if designed-in redundancy is provided, inoperative control and sensing devices must be repaired and replaced to maintain redundancy. Conventional highway features such as pavement smoothness and drainage will have more severe requirements on AHS. This is primarily due to the speeds and reliability demands, and the possibility of pavement failure resulting in damage to or degradation of roadway-mounted sensing and control devices. Occupant comfort is also an factor in this more severe maintenance requirement. Deferred maintenance of these elements could have dramatic impacts on AHS reliability, safety, and operating measures of effectiveness (speed, throughout, and occupant comfort) [K-3, 4].

Funding Sources

Traditionally, massive highway programs are funded by the Federal government. This will no doubt also be the case for AHS, if for no other reason than to attract the interest of the States.

In informal conversations with State highway personnel, the research team has detected a perception that ITS in general and AHS in particular is a “solution in search of a problem.” Some see ITS/AHS proponents as marketers from the electronics industry developing markets for their products. While this is by no means a universal perception, it is heard from time to time. One way to defuse this line of thought may be to have ITS/AHS projects funded from a source which is separate from the sources for funding more traditional highway projects. By doing this, AHS could be viewed as not competing for funds with conventional construction and maintenance projects. Instead AHS projects would be considered as enhancements to the conventional system [K-3].

User fees may be considered to at least partially recover the capital and operating costs of AHS. This may be of particular importance in the case of a program that will not be usable by all vehicles (even though non-AHS vehicles will experience improved operation due to the AHS). Political and societal acceptance may be easier to obtain if there are direct user charges levied on the AHS. With the communications capabilities of AHS equipped vehicles and the fact that automatic vehicle identification and toll collection is in place today, user charges would not burden the system with any significant construction or operating costs.

Research and Development

Up to now, the discussion has considered infrastructure funding issues that have to be dealt with by the operating agencies. The other major requirement to be dealt with is research and development of the automated vehicle. While it is possible that an AHS vehicle may be produced with an incremental cost low enough to generate a critical market penetration, this is by no means assured. This problem is biggest early in the program, when the incentive to have an equipped vehicle is lowest (limited AHS facilities to drive on) and vehicle costs are highest (low production volume, research and development costs still being amortized).

It is therefore likely that AHS vehicles may have to be subsidized, either by government, the automotive industry, or both. Such a subsidy may be a hard sell politically, given the potential that initial users could tend to be high end, higher income individuals. This issue could be mitigated by linkage of subsidies to HOV and transit fleets [F-4, I-4, 5, 6].

Coordinated Braking

Platoons are generally considered by many to address some of the issues associated with an AHS, including highway capacity and to some extent, air quality. There are alternatives to platoons, such as the use of rather large vehicle spacing, but these concepts generally result in significant shortfalls in terms of required highway capacity. Vehicles within an uncoordinated platoon can be spaced at arbitrary distances from a control standpoint, but safety concerns will result. As the spacing decreases, vehicle braking reaction times may not be short enough to avoid intra-platoon collisions. Also, in an uncoordinated state, the platoon vehicles may brake at different deceleration levels which further increases the possibility of collisions within the platoon.

The coordinated braking concept first arose from the issue of how to maintain arbitrary intra-platoon spacing under nominal and emergency braking situations. The system can be very effective in allowing vehicles to maintain arbitrary spacing within a platoon while ensuring vehicle safety [D-3]. The flexibility inherent in the variable vehicle spacing will address human factors issues as well as deployment and throughput issues. At this point, the system is merely a concept with good potential. After some development and refinement, it could grow into a viable method of controlling vehicles in a platoon while meeting all of the applicable AHS requirements.

In a coordinated braking scenario, the platoon lead vehicle would communicate a target platoon deceleration level based on the lowest braking performance capability of the vehicles in the platoon. All vehicles would then initiate braking simultaneously. Internal control algorithms within each vehicle would ensure that the vehicle's deceleration was within some error tolerance of the target deceleration level at all times. As the conditions that initially prompted the braking maneuver change, the lead vehicle would issue appropriate target deceleration levels. Clearly, requirements such as minimum braking performance (determined at the AHS check-in station) and vehicle type (truck versus passenger car) must be passed before a vehicle would be allowed to enter a platoon. The coordinated approach will be designed to ensure no collisions between vehicles in a platoon while achieving a high level of overall platoon braking performance. To this end, the issue of communication and control system design will be critical to the success of the concept.

The ability of a vehicle to predict or sense a malfunction that may cause loss of control or a high deceleration level in a timely manner is essential to vehicle and occupant safety. At moderate intra-platoon vehicle spacing, the potential exists for relatively large collision velocities if a vehicle decelerates at a high level unexpectedly due to a malfunction that is not predicted or sensed. However, the causes of this type of deceleration are few and the functionality generally exists to provide enough warning to the following vehicles to decelerate before a collision occurs. This critical area of malfunction prediction and management will be an ongoing area for study and evaluation.

APPENDIX

Precursor Systems Analyses (PSA) Database Item **PSA Contract Team**

Item Number A01 Entry: date 8/22/94 by A. Cochran Review: date ______ by __________

Item Type:	Issue	Risk	Concern	Conclusion	Risk:	High	Med.	Low

Action: Assigned ____________________ Resolution ____________________

Sources:			Reference Documents		Researcher	
	Sub - Contractor	HAC	Reference Documents	Act. A Report	Researcher	A. Cochran
	Sub - Contractor		Reference Documents		Researcher	
	Sub - Contractor		Reference Documents		Researcher	

(check all items that apply)

Pertains To:					
	Safety	Efficiency	User Accept.	Environment	Legal
	Societal	Concept Selection	'97 Demo	Design / Devel.	Test / Eval.
	Deployment	Maint / Operation	Transition	Human I/F	Program
	Management	Funding	Cost	Benefits	

Description	Effective utilization in rural areas

Summary	AHS lanes will be heavily utilized in urban areas with high traffic densities. AHS will have a more limited user base in rural areas, due to the relatively low volume of traffic on rural highways.

(check all items that apply)

Sys. Function:				
	ALL	Check-In	Enter / Merge	Driver I/F
	Long. Control	Lateral Control	Maneuver Coord.	Check - Out
	Exit / Merge	Incident Mgmt	Zone Flow Mgmt	Regional Mgmt
	Environ. Sensing	Maint. / Operation	Operational Mode	

(check all items that apply)

Inf. Sys.:	ALL	Entry / Exit Configuration	Lane Configuration	
	Rdside Sen., Comm. / Proc.	Region Command Centers	Barriers	
	Surface Materials	Bridges / Tunnels	Rdway Maint. Equip.	
Veh. Sys.:	ALL	Steer. Actns	Braking Actions	Throttle Control
	Power Train Control	Lights	Suspension	Vehicle Electronics
	Sensors	Chassis	AHS Controller	
	Communications. (Intra-vehicle,	Road - road,	Road - vehicle,	Vehicle - vehicle)

(check all items that apply)

Concept Impact: ALL

- Veh. Type: Light Heavy Transit Pallet Special Maint.
- Inf. Type: Dedicated Shared w. Manual Barrier No Brier
- Entry/Exit Type: Dedicated Transition Lanes: (Periodic Unrestricted)
- Power Source: On-Bd. ICE On-Bd. APS Rdway Prvd. Electric
- Long. Control: Autonomous Vehicle Platooned Vehicle Point Following
- Lat. Control: Passive Rd (e.g., magnets, paint) Barriers Active Rd
- Control Location: Mostly Vehicle Mostly Infrastructure Balanced

Figure 5. Example PSA Database Entry

Table 5. PSA Database Item Summary

Item Number	Act.	Database Topic	Item Type	Contract Overview Report Section: Sys Ch	Op/Mt	Imp	Dep	Fnd
A01	A	Effective utilization in rural areas	Conclusion	x				
A02	A	Availability of communications infrastructure	Concern					
A03	A	Specialized equipment required for short headways may not be necessary in areas with low traffic densities	Conclusion	x				
A04	A	Response delay to emergencies or incidents	Conclusion					
A05	A	User costs may not be in balance with benefits	Risk	x			x	x
A06	A	Congestion reduction must be addressed from aspect of improved throughput as opposed to increased capacity	Conclusion	x		x	x	
A07	A	Evolutionary deployment has different goals in urban and rural scenarios	Conclusion	x			x	
B01	B	What is the relative value of peripheral equipment during check-in?	Issue					
B02	B	Safe management of check-in failures	Concern	x				
B03	B	Determination and management of intermittent electronic failures	Concern					
B04	B	What check-in techniques may be used for items which cannot be checked electronically?	Issue	x				
B05	B	Detection of alterations of in-vehicle check-in data	Risk					
B06	B	Can an information gathering system be developed to gather data for ranking check-in item?	Issue					
B07	B	Efficient check-in station design	Conclusion	x				

Table 5. PSA Database Item Summary (Continued)

Item Number	Act.	Database Topic	Item Type	Contract Overview Report Section				
				Sys Ch	Op/Mt	Imp	Dep	Fnd
B08	B	Automated equipment checking by dynamic check-in stations	Concern	x				
B09	B	Intruder prevention at check-in station	Risk					
B10	B	Will frequent testing and inspection be socially acceptable?	Issue			x		
B11	B	Requirements for fuel and mileage records	Conclusion					
C01	C	How can safe operations be maintained during check-out?	Issue	x				
C02	C	What will be the additional cost due to check-out?	Issue					
C03	C	False rejection of a quali- fied driver at check-out	Risk					
C04	C	How can depots best be used to store inoperative vehicles and/or impaired drivers?	Issue					
C05	C	Who assumes liability for collisions after AHS allows a driver to check- out?	Issue	x				
D01	D	Intra-platoon headway policy	Issue	x				
D02	D	Intra-platoon collision dynamics	Concern	x				
D03	D	Driver involvement for vehicle control	Issue	x				
D04	D	AHS simulation testbed	Conclusion	x		x		
D05	D	Collision avoidance system detection/ classification capability	Concern	x				
D06	D	Communication interference	Issue	x				
D07	D	Platoon air flow considerations	Issue	x				

Table 5. PSA Database Item Summary (Continued)

Item Number	Act.	Database Topic	Item Type	Contract Overview Report Section: Sys Ch	Op/Mt	Imp	Dep	Fnd
D08	D	Vehicle control on highway grades	Issue				x	
E01	E	No adequate backup defined for use in the event of loss of lateral control	Concern	x				
E02	E	Driver participation in malfunction management	Issue	x				
E03	E	Placement of breakdown lane	Issue					
E04	E	Automated detection of roadway malfunctions	Issue					
E05	E	Practicality of malfunction detection methods	Concern	x		x		
F01	F	What impacts do heavy vehicles have on AHS capacity?	Issue				x	
F02	F	Need of separate AHS lanes for trucks and buses	Conclusion				x	
F03	F	How can heavy vehicles be handled at entry/exit points on dedicated facilities?	Issue				x	
F04	F	Entry/exit strategies for commercial and transit vehicles	Conclusion				x	
F05	F	Does inclusion of heavy vehicles on AHS limit construction options?	Issue					
F06	F	Infrastructure requirements for commercial and transit vehicles on AHS	Conclusion				x	
F07	F	Will trucks use AHS?	Issue				x	
F08	F	Accommodation of trucks on AHS	Conclusion				x	
G01	G	The public must be in agreement with the concept of AHS if it is to come to fruition	Risk	x		x	x	
G02	G	AHS will require extensive system validation. The planning and execution of this is critical	Risk	x		x		

Table 5. PSA Database Item Summary (Continued)

Item Number	Act.	Database Topic	Item Type	Contract Overview Report Section				
				Sys Ch	Op/Mt	Imp	Dep	Fnd
G03	G	Sound human factors principles must be used in the design of the driver interface for an AHS	Conclusion	x				
G04	G	Sound systems engineering principles must be used during the development of the AHS prototype	Conclusion	x		x	x	
G05	G	Integration of AHS with ITS	Conclusion	x			x	
G06	G	Channel product liability concerns into higher product quality	Risk	x				
G07	G	Handling political pressure in project development and implementation	Conclusion					
G08	G	Including maintenance in project development and management	Conclusion	x	x			
G09	G	Including reliability issues in program and project development	Conclusion	x			x	
G10	G	Including safety issues in program and project development	Conclusion	x		x	x	
G11	G	Technical involvement in program and product development	Conclusion	x			x	
G12	G	Dealing with the public and potential loss of public confidence	Conclusion				x	
H01	H,F	What AHS lane width should be used?	Conclusion	x				
H02	H,F	Shoulders (area available for use as a breakdown lane) should be a standard design feature of AHS	Conclusion	x				
H03	H,I,J	What capacity should be used in designing specific AHS segments?	Issue	x		x		

Table 5. PSA Database Item Summary

Item Number	Act.	Database Topic	Item Type	Contract Overview Report Section				
				Sys Ch	Op/Mt	Imp	Dep	Fnd
H04	H,J	Addition of an AHS lane improves overall vehicle operation in the corridor	Conclusion			x		
H05	H	Rural AHS should be on an added lane, not a lane taken away from mixed traffic	Conclusion	x				
H06	H,F	What operating speed should be used for AHS design?	Issue	x				
H07	H	A physical barrier should separate AHS and non-AHS traffic in both the urban and rural scenarios	Concern	x		x	x	
I01	I,J	AHS volumes on local streets will negatively impact neighborhoods	Conclusion	x		x		
J01	J	What is the desirable minimum distance along the cross street from the AHS to nearest parallel street?	Issue	x		x		
J02	J	In an urban setting, existing interchanges cannot be retrofitted for AHS entry/exit	Conclusion	x		x		
J03	J	On-site check-in is not feasible	Conclusion	x				
J04	J	Demand must be managed at AHS entry points	Conclusion	x		x		
J05	J	Entry/exit ramps for dedicated facilities must be separated	Conclusion	x		x		
K01	K	Can AHS operating agencies attract and retain quality personnel?	Issue		x			
K02	K	Who should operate the AHS?	Issue		x			
K03	K	Will the States (or other operating agencies) accept the added tort liability AHS may bring?	Issue				x	

Table 5. PSA Database Item Summary (Continued)

Item Number	Act.	Database Topic	Item Type	Contract Overview Report Section				
				Sys Ch	Op/Mt	Imp	Dep	Fnd
L01	L	What AHS research should consider about RF communications	Risk	x				
L02	L	Will AHS vehicle components be produceable at an acceptable cost?	Issue	x				x
L03	L	Multiplexing systems in vehicles to reduce wires	Conclusion					
L04	L	After market products for AHS vehicles	Risk				x	
M01	M	Will APS vehicles have dynamic performance suitable for operation on AHS?	Conclusion				x	
M02	M	Will AHS need to provide routine refueling capability for APS vehicles?	Conclusion					
M03	M,E	Will AHS need to provide emergency refueling capability for APS vehicles?	Conclusion					
M04	M	Will the AHS check-in range of battery-electric vehicles be a real time function of environmental conditions?	Issue					
M05	M	Will industry-wide standards be needed to ensure AHS vehicle performance? And, who will be responsible?	Issue	x			x	
N01	N	What should be the role of the driver in handling emergency maneuvers?	Issue	x				
N02	N	Transition between automated and manual control	Concern	x				
N03	N	Effect of external factors on safety	Risk	x		x		
N04	N	Safety must be designed into the system cost effectively	Conclusion	x		x		

Table 5. PSA Database Item Summary (Continued)

Item Number	Act.	Database Topic	Item Type	Contract Overview Report Section				
				Sys Ch	Op/Mt	Imp	Dep	Fnd
N05	N	Catastrophic disruptions	Conclusion			x		
N06	N	How does the relative safety of platoon configuration impact relative safety?	Issue	x			x	
N07	N	A single automated lane will not allow maneuverability in the event of malfunction or disruption	Conclusion					
N08	N	Mixed mode traffic increases risk of collisions due to human error	Concern	x			x	
N09	N	What is the comparable level of risk due to natural disasters?	Issue			x		
O01	O	Travel related issues	Issue			x		
O02	O	Infrastructure and urban form issues	Issue			x		
O03	O	Institutional issues	Issue	x			x	
O04	O	Maintaining the infrastructure	Issue		x			
O05	O	Public acceptance of platooning	Concern	x			x	
O06	O	Secure adequate funding	Issue					x
O07	O	Public agencies vs. driver's responsibilities	Concern			x		
O08	O	How sensitive will potential users be to the operator qualifications and tests required for AHS travel?	Issue	x		x		
O09	O	What is the impact to user perception of the capability to accurately track and store vehicle location information?	Issue			x		
O10	O	Travel time	Issue	x		x		
P01	P	Manufacturers will widely use throttle-by-wire in response to normal market	Conclusion	x				
P02	P	Manufacturers will widely use brake-by-wire in response to normal market	Conclusion	x				

Table 5. PSA Database Item Summary (Continued)

Item Number	Act.	Database Topic	Item Type	Contract Overview Report Section				
				Sys Ch	Op/Mt	Imp	Dep	Fnd
P03	P	Steer-by-wire is not clearly driven by market forces, however, it will be an enabling technology	Issue	x				
P04	P	Vehicle communication and collision avoidance may not cost effectively meet the requirements of AHS	Issue	x			x	
X01	X	Reliability/maintainability	Issue	x				x
X02	X	National standards	Concern	x			x	
X03	X	Evolutionary deployment	Issue				x	
X04	X	Equipment development/emerging technologies/feasibility	Conclusion	x			x	

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