Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Overview Report

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FOREWORD

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

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

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

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

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16. Abstract

The program described by this eight-volume report, a resource materials document type, identified the issues and risks associated with the potential design, development, and operation of an Automated Highway System (AHS), a highway system that utilizes limited access roadways and provides "hands off" driving. The AHS effort was conducted by a team formed and directed by the Calspan Advanced Technology Center. Primary Team members included Calspan, Parsons Brinckerhoff, Dunn Engineering Associates, and Princeton University. Supporting members of the team were BMW, New York State Thruway Authority, New York State Department of Transportation, Massachusetts Department of Transportation, the New Jersey Department of Transportation, Boston Research, Vitro Corporation, and Michael P. Walsh of Walsh Associates.

Calspan provided overall management and integration of the program and had lead responsibility for 5 of the 17 tasks. Parsons Brinckerhoff provided transportation planning and engineering expertise and had lead responsibility for 5 tasks. Dunn Engineering provided traffic engineering expertise and had lead responsibility on 2 tasks. Princeton supported the areas of transportation planning and automated control.

The 17 task reports (A through P plus Representative Systems Configurations) are organized into 8 volumes. This volume provides an overview of the program compiled by the program manager, Joseph A. Elias, who was supported by Habib Shamskhou of Parsons Brinckerhoff in the area of Representative Systems Configurations.

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VOLUME I — PRECURSOR SYSTEMS ANALYSES OF AUTOMATED HIGHWAY SYSTEMS OVERVIEW REPORT

1.0 EXECUTIVE SUMMARY

An Automated Highway System (AHS) utilizes limited access roadways and provides "hands off" driving through automated control. At this stage of the research, AHS is only a concept. The Precursor Systems Analysis (PSA) of Automated Highway Systems research effort was established to identify the most prominent issues and risks associated with the design, development, and operation of an Automated Highway System. The results of our PSA research are presented in this eight volume report. This volume (Volume I) provides introductory material and summarizes the entire research program. Volumes II through VIII contain all of the detailed analyses results.

The research effort was organized along the sixteen PSA individual task areas. An initial effort (outside of the sixteen) was performed that developed Representative System Configurations (RSCs). These RSCs were used as different conceptualizations of an AHS to provide a framework for our analyses.

Our approach to AHS analyses was broad-based. We emphasized breadth of scope rather than depth of analysis in any one design area. Nevertheless, our key findings are numerous and provide details into the design trade-offs required for AHS feasibility.

Our major conclusion is that there are no showstoppers for ultimate AHS implementation. But, broad-based design trade-offs still exist that effect cost, performance, and ultimately AHS salability. The market demand and potential are varied. It includes a number of different scenarios in terms of trip purpose, roadway configuration, vehicle types, level of service required, and impact on society as a whole. Details concerning the various trade-offs form the basis of our results.

Our purpose and scope of this overview volume is reflected in its organization. Section 2 contains the introductory information about the objects of the research and the approach taken to meet the objectives. Section 3 contains both high level discussions and detailed information about the RSCs and their significance to the research. Therefore, sections 2 and 3 are required reading for any other report sections within the eight volumes.

Section 4 begins the documentation of the summary results. It includes the executive summaries for all of the sixteen tasks areas. These executive summaries are extracted from Volumes II through VIII. The reader may pick and choose areas of interest and obtain summary information for their area of interest by reading selected portions of section 4. If more detailed results are desired, the reader is directed to the full set of results in the individual tasks report.

Section 5 is provided as a complete summary of the entire program. It is a condensed version of the individual task executive summaries, reorganized to provide a system view rather than a task analysis view. It can be read independently from section 4.

2.0 INTRODUCTION

The purpose of this final report is to present the Precursor Systems Analysis (PSA) of Automated Highway Systems (AHS) program results. The PSA of AHS program objective is to identify the most prominent issues and risks associated with the design, development, and operation of an Automated Highway System. By definition, an AHS is a highway system that utilizes limited access roadways (freeways) and provides "hands off" driving through automated control.

2.1 Summary Description of Activity Areas

The goals of an Automated Highway System implementation are to improve traffic flow, trip reliability, trip time, safety and driver comfort and convenience. The PSA program consists of high level analysis AHS concepts that will meet the AHS goals.

We organized this program into seventeen separate tasks. The seventeen tasks are listed in table 1.

Table 1. PSA of AHS Tasks

Task ID*	Task Description
—	Representative Systems Configuration
A	Urban and Rural Analyses
B	Automated Check-In
C	Automated Check-Out
D	Lateral and Longitudinal Control Analysis
E	Entry/Exit Implementation
F	Commercial and Transit Analysis
G	Comparable Systems Analysis
H & I**	Roadway Deployment and Non-AHS-Impact Analysis
J	Malfunction Management Analysis
K	Roadway Operations
L	Vehicle Operational Analysis
M	Alternative Propulsion Impact
N	AHS Safety Issues
O	Institutional and Societal Issues
P	Preliminary Cost/Benefit Factors Analysis

* The Task ID is a letter assigned to the activity area in the statement of work.
** The results of Tasks H and I are reported in the document as one task.

2.2 OVERALL APPROACH AND METHODOLOGY

Due to the high level nature of the analyses, the overall approach selected for AHS analysis, in accordance with the proper objective, as a simple systems engineering approach. Figure 1 describes the evaluation approach used on this study.

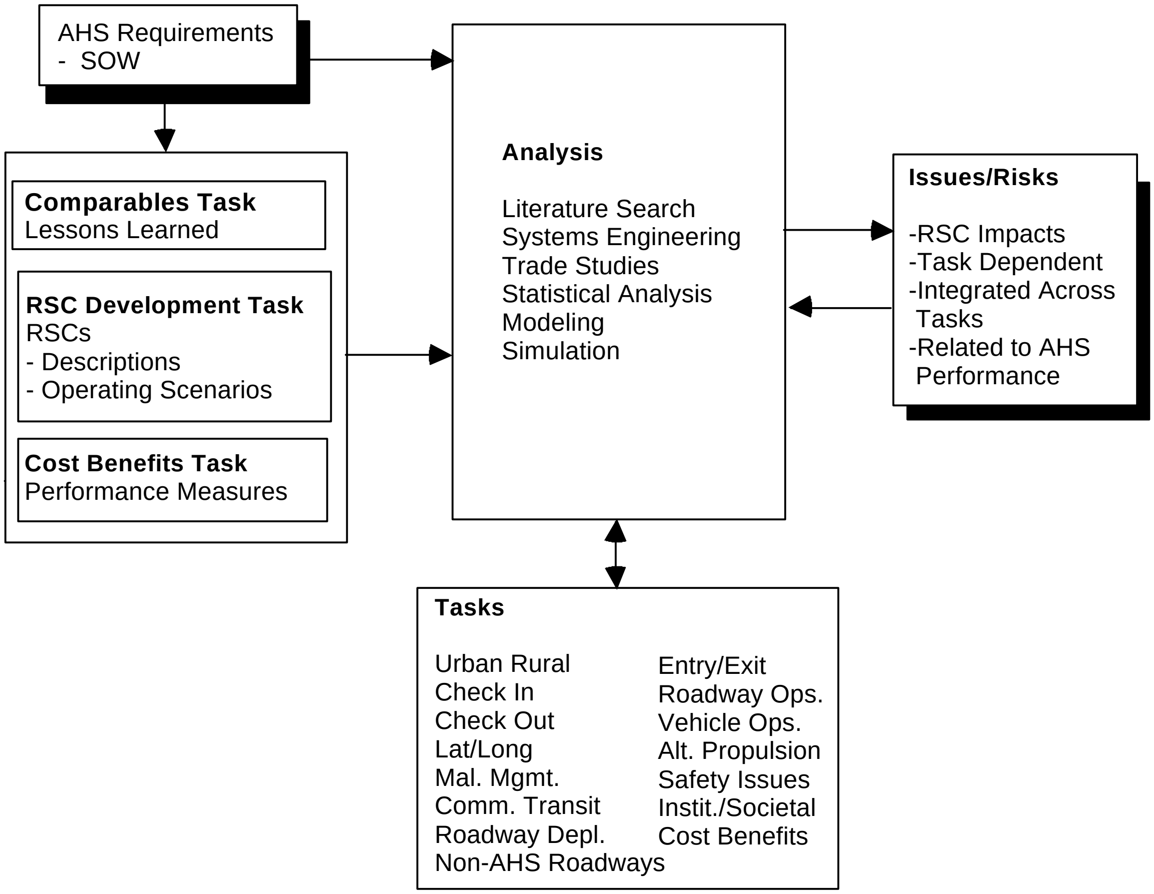

Figure 1. PSA of AHS Evaluation Approach Overview

There are three front end activities within this approach. They are: developing AHS Lessons Learned, specifying Representative System Configurations (RSCs), and developing AHS Performance Measures (measures of effectiveness). The AHS lessons learned are produced by the Comparable Systems task. The RSC Development task produces the RSC descriptions and the list of performance measures.

These three front-end efforts are very useful in providing a common framework for the remainder of the analysis. The Comparable Systems task provides lessons learned from both transportation and non-transportation systems. These systems have specific areas of applicability for AHS development.

The RSC descriptions provide an initial level of definition of an AHS that will meet the basic requirements. Our approach to RSC definition was to cover the spectrum of possibilities. This approach provided a framework for the remaining analysis. The issues and risks resulting from this approach will focus more on broad based design, development, deployment and operation aspects of AHS rather than a few system components/designs.

The list of performance measures presented in table 2 are an expanded list of those presented in the statement of work. The list contains six general categories of performance. In each of the six performance categories a number of specific measures are identified. The AHS is expected to perform better than the existing limited access highway system in each of the first four performance categories. Some of the measures are related to individual user benefits (e.g., trip time, stress amount, trip reliability/predictability, etc.), others are more societal in nature (e.g., level of emissions, noise, land use, incident impact, etc.) and others impact both (e.g., operating speed, number of accidents, etc.).

Table 2. AHS Performance Measures

Performance Area	**Performance Measure**
Safety	Number of Accidents Severity of Accidents • Property • Personal
Throughput	Lane Capacity Operating Speed Incident Impact Trip Time
User Comfort and Convenience	Stress Amount Effective Trip Range Trip Reliability Productive Use of Travel Time
Environmental	Fuel Consumption Emissions Noise Land Use
Deployability	User Penetration Evolutionary Deployability
Market Development	Auto Industry Impact Highway Industry Impact Associated Industry Impact

The fifth performance measure, deployability, has a critical impact on the future viability of AHS. AHS needs a definitive startup strategy, along with an incremental development strategy. The user penetration amount (based on the level of performance of the first three performance measures) will have a significant impact on the strategy for deploying the system both in geographical dimensions and functional capabilities.

Lastly, the AHS needs to be evaluated in terms of its economical impact on the United States industrial base. AHS may possibly be useful in sustaining the growth of the automobile industry and providing additional growth potential to the highway industry in terms of product development. Lastly, due to the dependence of AHS on electronics it could be instrumental in supporting the growth of the electronics industry.

Quantification of some of the performance measures is straightforward (e. g., capacity can be measured in vehicles per lane per mile, ability to attract users by % of vehicles equipped) but others are more obscure (e.g., productive use of travel time). More definitive measurement guidelines will evolve as the study continues.

The AHS requirements, along with the lessons learned, RSC definitions and performance measures are used during the analysis performed within the fifteen remaining Calspan tasks. The analysis areas cover a wide variety of advanced electronics technology, highway, vehicle, and transportation related research areas. The type of analysis that is performed varies over the task areas. However, most tasks start with a literature review within the specific research area. Systems engineering approaches are used throughout the analysis to develop potential solutions to AHS requirements and identify issues and risks.

Tradeoff analyses is the fundamental analytical approach to identifying AHS issues and risks. Many of the trade study results will be based on the expertise of the analysts, developed over many years of experience solving highway, transportation, and technology based problems. Others will utilize the literature review results and others will be based on hard data resulting from newly performed statistical analyses, analytical modeling, complex simulations, etc. For example, some of the safety analysis are being performed by using statistical samples from existing highway accident data. Also, models of various entry and exit strategies and highway geometry will be developed to quantify performance.

The end result of this study will be issues and risks. These issues and risks will identify possible impediments to AHS viability or to the overall effectiveness of a specific AHS concept. A standard format for documentation of issues and risks has been developed. The preliminary results in each of the task sections contains issues and risks in our standard table format. Integration of issues and risks across the entire program is being accomplished through a data base that cross references all issues and risks across all tasks and RSCs.

2.3 AHS DEFINITIONS AND GUIDING ASSUMPTIONS

The definitions and guiding assumptions used in this study were obtained from the SOW.

AHS DEFINITIONS

(a) AHS control. Some form of longitudinal position, headway, lateral position and/or sideway automatic control. One need not have all of these to have AHS control. A low level of control that may be of interest is headway control only.

(b) Manual control. Control of a non-AHS-instrumented vehicle or control of an AHS-instrumented vehicle or control of an AHS-instrumented vehicle with the AHS control inactive. (Standard cruise control or ABS braking would be considered a manual mode of control.)

(c) AHS-instrumented vehicle. A vehicle possessing features which allow AHS control

(d) Non-AHS-instrumented vehicle. A vehicle lacking features which allow AHS control.

(e) AHS-instrumented roadway. A roadway, roadway segment, or lane on which AHS control is allowed.

(f) Non-instrumented roadway. A roadway, roadway segment, or lane on which only manual control is allowed.

(g) Transition region. That part of an AHS-instrumented roadway on which normal transition between manual control and AHS control is accomplished (manual to AHS or AHS to manual).

(h) Freeway (AASHTO definition). A divided highway for through traffic that has full control of access. Entrances and exits provide minimum speed differential.

AHS BASELINE REQUIREMENTS/ASSUMPTIONS

1. Personal automobile class of performance and control qualities is assumed (other classes are studied as part of later deployment.)

2. Some from of AHS automatic vehicle control is possible when operating on o segments of the roadway.

3. Instrumented vehicles will be capable of manual control on non-instrumented roadways.

4. Vehicles under manual. control are not allowed on an instrumented roadway unless it is a transition region. Transition regions are not defined in the RFP but are a necessary subsystem in any representative system that considers cars that satisfy item 3 for part of a trip. It is also useful to define instrumented roadway as a potion of a freeway (e.g., a special lane as in (e) above).

5. A non-instrumented vehicle can be retrofitted to be an instrumented vehicle.

6. Instrumented roadways are freeways (using AASHTO definition of freeway)

7. AHS primary control will not rely on mechanical or physical contact techniques. (Such techniques are allowed as a backup if the primary system should degrade or fail.)

8. A highway system in which AHS is deployed shall be designed to the following requirements:

   (a) Safety, as measured by number and severity of collisions, shall be significantly better than that of today's freeways. Operation under AHS control shall be collision-free in the absence of malfunctions. Malfunction management that maximizes safety shall be part of the AHS design.

   (b) Throughput capacity of the roadway on which AHS is deployed as measured by the vehicles per hour per lane shall be significantly increased over today's freeways. It is understood that this increased throughput shall be sustainable by the entry an exit facilities of the AHS.

   (c) User comfort on the roadway on which AHS is deployed, as reflected by ride, strain on roadway users, and confidence, shall be increased over today's freeways. The designs involving manual and AHS driving on the same roadway shall not decrease the comfort of the manual user.

   (d) Environmental impact as measured by fossil fuel consumption and emissions *per vehicle mile* shall be reduced relative to today's highways. The underlining is significant if more vehicles use the highways were AHS is employed or speed is increased.

   (e) Operation shall be possible in all weather conditions for which manual operation is possible. This statement is somewhat stronger than stated in the RFP and is subject to further clarification in the studies.

   (f) Operation shall be practical — useful in the ordinary routine of business or pleasure.

   (g) The initial investment, maintenance, and operating costs shall be affordable for the user, the owner, an the operator.

   (h) Highways incorporating AHS shall be more desirable than manual highways. See item (c).

   (i) Operation shall be user-friendly by being straightforward, intuitive, and forgiving. A minimum of special instruction and training shall be required.

AHS COMPONENTS

The following AHS subsystems will be part of all AHS designs considered.

1. Driver
2. Instrumented vehicle (including control computer, if any)
3. Instrumented roadway (including control computer, if any)
4. Transition region on entry
5. Transition region on exit
6. Check-in subsystem
7. Check-out subsystem
8. Breakdown or emergency lane
9. Data links among vehicles and the infrastructure (to include vehicle-to-vehicle as a common option).
10. Entry to freeway (depends on system configuration)
11. Exit from freeway (depends on system configuration

2.4 SCOPE OF OVERVIEW REPORT

This overview report volume, Volume I if the eight volume set, contains the results of the entire study, presented in summary format. Section 3 contains both high level discussions and detailed information about the RSCs and their significance to the research. Therefore, section 3 is required reading for any other report sections within the eight volumes.

Section 4 begins the documentation of the summary results. It includes the executive summaries for all of the sixteen tasks areas. These executive summaries are extracted from Volumes II through VIII. The reader may pick and choose areas of interest and obtain summary information for their area of interest by reading selected portions of section 4. If more detailed results are desired, the reader is directed to the full set of results in the individual tasks report.

Section 5 is provided as a complete summary of the entire program. It is a condensed version of the individual task executive summaries, reorganized to provide a system view rather than a task analysis view. It can be read independently from section 4.

3.0 REPRESENTATIVE SYSTEMS CONFIGURATIONS (RSC)

The RSC descriptions provide an initial level of definition of an AHS that will meet the basic requirements. The Calspan approach to RSC definition is to cover the spectrum of possibilities, in as general a way as possible. This approach provides a framework for the remaining analysis that facilitates the generation of a comprehensive set of issues and risks.

The issues and risks resulting from this approach will focus more on broad based design, development, deployment and operation aspects of AHS rather than a few system components/designs. The detailed description of the RSCs resulting from this task are presented in section 3.2.

3.1 APPROACH

The Calspan Team RSC definition approach consists of defining generic candidate AHS designs in relation to these three dimensions: (1) the amount of dedicated ***roadway infrastructure*** required; (2) the ***degree of command, control, and communication*** required (i.e., centralized control over vehicle maneuvers); and (3) the ***types of vehicles*** to be served. Emphasis was placed on covering the extremes of the three AHS dimensions and reasonable mid-point values. RSCs to be included in the study were then selected through a process of elimination from all possible combinations among these dimensions. RSCs were eliminated if they were redundant in terms of supporting the study of AHS issues or if they were impractical from an implementation perspective. For example, an AHS with highly centralized control cannot be applied to an AHS configuration with a low level of infrastructure according to our definitions.

The infrastructure dimension for the RSC definitions ranges from an AHS in which existing freeways can serve AHS with minimal modification and change in use patterns, to one in which a roadway is completely dedicated to AHS use. A mid-range on this dimension defines an AHS configuration in which AHS traffic operates on specialized lanes similar to HOV lanes in operation today.

The degree of centralized control RSC dimension ranges from an AHS in which AHS vehicles operate independent from roadway-based control to one in which all decisions about vehicle speed, spacing, and lane maneuvers are made by a central control entity. In the mid-range, an AHS in which the responsibility for decision making is shared between drivers/vehicles and the roadway is also defined.

Finally, variations across ***the types of vehicles to be served*** by the AHS have been defined. These include an AHS that serves only single vehicle equivalents (SVEs) such as passenger cars and other equivalent commercial vehicles, as well as systems that also serve multiple vehicle equivalents (MVEs), i.e., vehicles that are larger in size and mass, such as busses and large trucks. The RSCs along this dimension include systems in which SVEs and MVEs are mixed as well as those in which they are segregated. One extreme of this dimension was defined to include vehicles which are electromagnetically powered by the roadway itself (RPEVs).

3.2 RSC DESCRIPTIONS

3.2.1 Basic Descriptions

Table 3 provides an overview of the selected RSCs. Possible RSCs that were not selected are also shown with the reason they were eliminated. Each of the three dimensions were defined in terms of levels. The Infrastructure dimension contains three levels (I1, I2, I3). The Command, Control and Communications dimension has three levels (C1, C2, C3), and the vehicle dimension has four levels (V1, V2, V3, V4). The columns of the table are the major characteristics used to differentiate among the various levels. The legend for the rows and columns of the table is presented below.

Legend for Rows in Table 3

Infrastructure (I)

I1. Existing highway with minor modifications

I2. Dedicated AHS lane(s) with access from existing freeway (similar to existing HOVs)

I3. New dedicated AHS lane(s) with limited access.

Table 3. Overview of Representative System Configurations

		Infrastructure			Command, Control, Communication							Vehicle Parameters				
RSC Config.		Highway	Entry/Exit to Freeway	Where Transition Occurs	Control Central-ization	Highway Role	Determine Speed	Determine Spacing	Cruise Lane Change Decisions	Lane Change Manuever	RSC No.	Vehicle Type	AHS Vehicles	Vehicle Mix Condition	Comments	PB No.
I1	C1	Existing	Conventional	Anywhere on Freeway Lanes	Low	Advisory	Driver/ Traffic	Driver/ Vehicle	Driver	Manual	1	V1	SVE	Manual SVEs and MVEs allowed		1
												V2			Violates infrastructure definition	10
											2	V3	SVE & MVE	Manual SVEs and MVEs allowed		19
	C2														Not practical, cannot control or communicate with non-AHS vehicles	2 11 20
	C3														Not practical, cannot control or communicate with non-AHS vehicles	3 12 21
I2	C1	Separate AHS Lane(s)	Conventional	AHS Lane(s)	Low	Advisory	Driver/ Traffic	Driver/ Vehicle	Driver	Mixed	3	V1	SVE	SVEs only		4
											4	V2	SVE & MVE	Seg. by type except for transn.		13
												V3			Issues considered in RSCs 3 & 4	22
	C2	Separate AHS Lane(s)	Conventional	Transition lane	Medium	Cmd. spd. & Spacing	Roadway	Roadway	Driver	Automated	5	V1	SVE	SVEs only		5
											6	V2	SVE & MVE	Seg. by type except for transn.		14
											7	V3	SVE & MVE	SVEs & MVEs fully mixed		23
	C3														Issues considered in RSC 12	6 15 24
I3	C1	Dedicated	Direct from Non-AHS Roads	Entrance Ramp	Low	Advisory	Driver/ Traffic	Driver/ Vehicle	Driver	Mixed	8	V1	SVE	SVEs only		7
												V2			Issues considered in RSCs 4 & 8	16
												V3			Issues considered in RSCs 2 & 8	25
	C2	Dedicated	Direct from Non-AHS Roads	Entrance Ramp	Medium	Cmd. spd. & Spacing	Roadway	Roadway	Driver	Automated	9	V1	SVE	SVEs only		8
											10	V2	SVE & MVE	Seg. by type except for transn.		17
											11	V3	SVE & MVE	SVEs & MVEs fully mixed		26
	C3	Dedicated	Direct from Non-AHS Roads	Entrance Ramp	High	Command all vehicle actions	Roadway	Roadway	Roadway	Automated	12	V1	SVEs	SVEs only		9
												V2			Issues considered in RSC 10 & 12	18
												V3			Issues considered in RSC 11 &12	27
											13	V4	Elect. SVEs	Electric SVEs only		28

Command, Control, and Communication (C)

C1. Low Centralization. Roadway provides advisories regarding speed, spacing, weather, incidents, congestion, etc. Driver determines speed, spacing, etc. within the constraints imposed by the vehicle computer and after considering roadway advisories. Inter-vehicle communication may be applied.

C2. Medium Centralization. Roadway commands speed and spacing by sector and advises of weather, incidents, congestion, etc. Roadway oversees traffic synchronization (access, egress, merge, de-merge) and reverses unfavorable demand/capacity trends by changing sector speed and spacing commands. Inter-vehicle communication will be required.

C3. High Centralization. Roadway controls traffic synchronization by commanding individual vehicles. Inter-vehicle communication will be required.

Vehicle (V)

V1. SVE (Single Vehicle Equivalents) — AHS vehicles limited to SVEs, those approximating the size and handling characteristics of passenger vehicles and small trucks.

V2. SVE and MVE (Multiple Vehicle Equivalents) segregated — AHS vehicles include both SVEs and MVEs segregated on separate lanes. MVEs are those vehicles whose size and handling characteristics approximate those of trucks and busses (and could fill multiple SVE slots).

V3. SVEs and MVEs mixed — AHS vehicles include both SVEs and MVEs mixed on the same AHS lane(s).

Legend for Columns in Table 3

This table has been structured according to the three dimensions which define the RSCs (i.e., infrastructure; command, control, and communication; and vehicle parameters). The columns, within each of the dimension categories, provide additional description with respect to important AHS parameters. The following are definitions of terms that may not be self explanatory.

Infrastructure (I)

Entry/Exit to Freeway — In general the part of the AHS design concerned with going to and from the surrounding non-AHS roads. More specifically, this is the entry to and exit from the freeway on which the AHS operation is placed as distinguished from entering and leaving the automated lane. Two possibilities are considered:

- ***Conventional.*** Entries and exits which are similar in design and configuration to today's freeway entries and exits. These involve mixing with manual traffic prior to automated operation.

- ***Direct from non-AHS roads.*** Entry/exit between non-AHS roads and AHS lanes without mixing with manual traffic.

Where Transition Occurs — The location where mode changes between manual and automated operation occurs. Four possibilities are noted in the table. These are self explanatory.

Command, Control, and Communication(C)

The entries in the columns under this area define the degree to which vehicle speed, spacing, lane changing, and entry/exit are determined by a central AHS component. The following definitions may not be self explanatory:

Speed — Velocity in a sector for each vehicle unless gap creation adjustments are required.

Spacing — Gap between vehicles unless multiple gaps are needed for vehicle access to the AHS lane.

Driver/Traffic — The term used in C1 to denote that drivers are able to decide desired speed subject to the speed of other vehicles in the AHS lane and roadway advisories.

Driver/Vehicle — The term used in C1 to denote that the driver could elect a greater than nominal gap. Normally, the vehicle would adjust its own safe gap based on speed (and perhaps road conditions).

Mixed — Denotes that lane changing from one AHS lane to another AHS lane would be accomplished manually with automated assistance. For example, the driver may change lanes by disengaging automated control and re-engaging when in the new lane (i.e., manual lane change) with highway assistance in creating needed gaps in adjacent lanes.

Vehicle (V)

The entries in this part of the table define the vehicle types allowed to engage in AHS operation and the permitted mixing among the vehicle types, and with manual traffic. The definitions of the vehicle types are given above. Other entries in this part of the table are self explanatory.

Figure 2 provides a graphical view of the selected RSCs against the three RSC dimensions. The various trade studies will be along the dimensions of the chart. For example, the effect of increasing the level of centralization from level one to level two to level three can be analyzed while keeping the infrastructure level constant. The

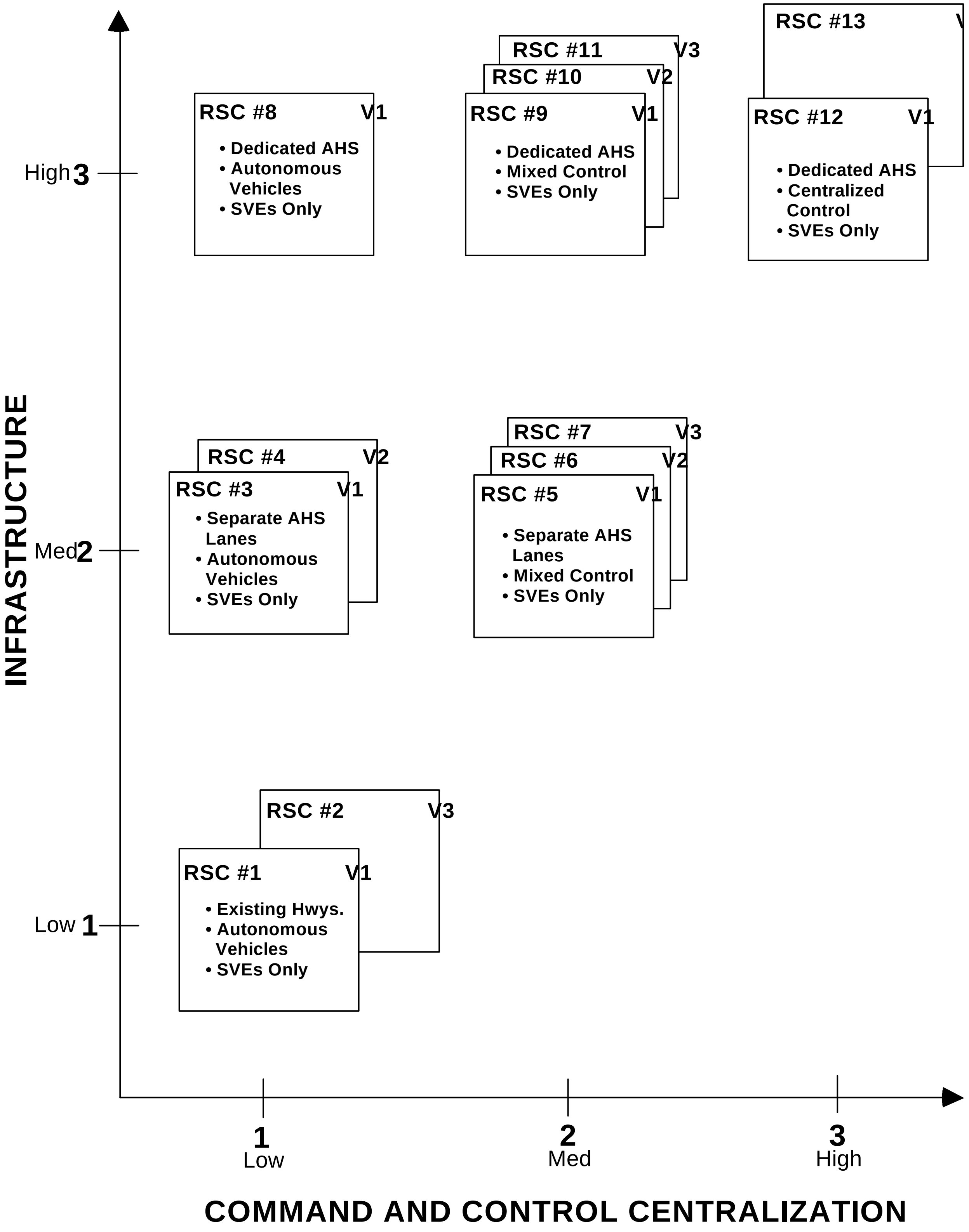

Figure 2. Graphical Representation of Representative System Configurations

extremes of the RSCs will be given particular attention (e.g., I1C1 versus I3C3 tradeoff).

Most of the analyses to be conducted during the PSA effort will focus on the six SVE RSCs. Tasks in which vehicle issues are important will apply the vehicle-specific RSC definitions.

3.2.2 EXPANDED RSC DESCRIPTIONS

Once the 13 RSCs were defined an effort was started to provide greater detail to the definitions. The expansion focused on the infrastructure, and command, control and communications centralization dimensions. This was accomplished by adding characteristics. The characterization is done in detail only for the six V1 RSCs. General comments concerning the variation along the vehicle dimension follow the "I" and "C" dimension discussions.

3.2.2.1 INFRASTRUCTURE DIMENSION

In table 3 we used the following characteristics to describe the infrastructure dimension: highway configuration (AHS lanes in relation to manual lanes), method for entry/exit to freeway, and location of transition to automated mode. We are adding these characteristics: ***requirement for barriers, requirement for a breakdown lane, and potential and need for multiple AHS lanes***. We will describe the characteristics as they relate to the six basic RSCs . A table summarizing our descriptions is included as table 4. A discussion of each infrastructure follows.

I3 (includes C1, C2, and C3)

Summary: All three I3 RSCs are dedicated AHS freeways. Freeway entry/exit and AHS access/egress is achieved by vehicles being driven from a non-AHS road to the AHS freeway entrance where hands-off systems engage. At the exit, systems disengage just prior to leaving the freeway area. In other "I" dimension RSCs, some manual driving occurs on entry/exit ramps and on cruise lanes. In the I3 dimension there need not be any high-speed manual driving required in normal operation. The variation across the "C" dimension does not have a significant impact on the characteristics described below. Therefore, the descriptions apply to all I3 configurations.

Barriers: The AHS could be entirely removed from other traffic. However, there are strong economic reasons to use the existing right-of-way. Therefore, a likely deployment is down the median of an existing manual freeway. Barriers will be needed to separate AHS from the manual freeway to prevent unauthorized access. Barriers within the AHS (multiple lane configurations) might be necessary to contain vehicles during incidents but malfunction management strategies should preclude their need.

Table 4. Expanded RSC Characteristics: Infrastructure Dimension

	Infrastructure						
RSC Config.	Highway	Entry/Exit to Freeway	Where Transition Occurs	Barriers	Dedicated Breakdown Lane	Multiple AHS Lanes	RSC No.
I1 C1	Existing	Conventional	Anywhere on Freeway Lanes	Same as existing	Same as existing	Left Lane Only	1,2
I2 C1	Separate AHS Lane(s)	Conventional	Transition Lane(s)	Possible	Preferred	Dictated By Demand	3,4
I2 C2	Separate AHS Lane(s)	Conventional	Transition Lane(s)	Possible	Preferred	Dictated By Demand	5,6,7
I3 C1	Dedicated	Direct from Non-AHS Roads	Entrance Ramp	Required if adjacent to manual	Required	Dictated By Demand	8
I3 C2	Dedicated	Direct from Non-AHS Roads	Entrance Ramp	Required if adjacent to manual	Required	Dictated By Demand	9,10,11
I3 C3	Dedicated	Direct from Non-AHS Roads	Entrance Ramp	Required if adjacent to manual	Required	Dictated By Demand	12,13

Table 4. Expanded RSC Characteristics: Command, Control, Communication Dimension (continued)

	Command, Control, Communication															
	Command				Access/Egress/Cruise			Communications Links				Lane Keep.				
RSC Config.	Centralization	Highway Role	Determine Speed	Determine Spacing	Lane Change Decisions	Lane Change Maneuver	Headway Policy	RVR	VV	RV	Long. Control	Lateral Control	Check-In	Check-Out	Driver Role	RSC No.
I1 C1	Low	Advisory	Driver/ Traffic	Driver/ Vehicle	Driver	Manual	Safety Determined	No	Optional	Advisory	Vehicle Controlled	Vehicle Controlled	In-vehicle periodic	In-vehicle Periodic	Fully Engaged, Respond per MM Rules	1,2
I2 C1	Low	Command Speed	Roadway	Driver/ Vehicle	Driver/ Vehicle	Manual/ Automated	Safety Determined	No	Yes	Yes	Vehicle Controlled	Vehicle Controlled	In-vehicle periodic	In-vehicle Periodic	Monitor Status, Respond per MM Rules	3,4
I2 C2	Medium	Cmd. spd. & Spacing	Roadway	Roadway	Driver/ Vehicle	Automated	Safety Determined	No	Yes	Yes	Vehicle Controlled	Vehicle Controlled	In-vehicle periodic	In-vehicle Periodic	Monitor Status, Respond per MM Rules	5,6,7
I3 C1	Low	Command Speed	Roadway	Driver/ Vehicle	Driver/ Vehicle	Manual/ Automated	Safety Determined	No	Yes	Yes	Vehicle Controlled	Vehicle Controlled	In-vehicle periodic	In-vehicle Periodic	Monitor Status, Respond per MM Rules	8
I3 C2	Medium	Cmd. spd. & Spacing	Roadway	Roadway	Driver/ Vehicle	Automated	Safety Determined	No	Yes	Yes	Vehicle Controlled	Vehicle Controlled	In-vehicle periodic	In-vehicle Periodic	Monitor Status, Respond per MM Rules	9,10,11
I3 C3	High	Command all vehicle actions	Roadway	Roadway	Roadway	Automated	Safety Determined	Yes	Yes	Optional Advisory	Vehicle Controlled	Vehicle Controlled	In-vehicle periodic	In-vehicle Periodic	Monitor Status, Respond per MM Rules	12,13

Breakdown lane: Breakdown lanes are used to reduce the congestion and safety impact related to incidents. When cost is overwhelming, there can be sections of roadway without them. The high single lane flow capacities of a dedicated AHS provide greater justification for the existence of a breakdown lane. Even with vehicles much more reliable than today's, the statistics for the number of breakdowns per day in a five mile stretch of 4000 to 8000 vph flow are discouraging. If the breakdown lane can be used for cruising while the AHS lane is being maintained, additional justification for a breakdown lane exists. It, most likely, will also be used for service access. For these and other reasons, the baseline here will include a breakdown lane.

Multiple AHS lanes: If market penetration is high enough or special circumstances exist multiple AHS lanes can be used. Since I3 is a dedicated facility, with the associated costs of dedicated exit and entrance ramps, multiple lanes would increase capacity and thus reduce the average cost. However, if the requirement is to build the dedicated lane within the existing right-of-way, multiple lanes may not fit.

I2 (includes C1 and C2)

Summary: Both I2 RSCs have dedicated AHS lanes that are a part of an existing manual freeway. Vehicles enter and leave the freeway manually. The AHS lane(s) are accessed from a parallel lane that is entered and exited manually from the normal manual traffic lanes. This parallel lane (transition lane) may possibly be used by manual cruising traffic, if it is required by capacity needs. This concept includes continuous access/egress if barriers are not used. Early results suggest that transition could take anywhere from a few hundred feet to several thousand feet depending on speed and positioning scenario. Thus this concept does not readily fit the local traveler whose intention is to use the lane only a mile or so. Rather, the concept is that of an express lane where the use is five to six miles or more.

Barriers: Barriers would help keep manual cars from driving on the AHS lane, but would not prevent the manual driver from entering through the transition lane. They could also eliminate the spillover of an accident from the manual lane into the AHS lane. When the AHS lane flow is more like 2000 to 2500 vph in this RSC, due to an early low percent participation assumption, barriers are probably less desirable.

Breakdown lane: Same as I3 RSCs.

Multiple AHS lanes: Multiple AHS lanes, in an I2 RSC, require at least a four-lane configuration to allow manual lanes to have a slow and a passing lane. The AHS demand would have to exceed the single-lane AHS capacity (4000 to 6000 vph) to justify this configuration. Since the two manual lanes should not run at more than 1800 vph, the AHS participation would have to exceed 50 to 60 percent to justify multiple AHS lanes.

I1 (C1 only)

Summary: RSC I1C1 is a mix of manual and automated vehicles in the same lane on an existing freeway. Vehicles would enter and exit the freeway in the present manner and engage the automated mode when reaching cruise speed. Automated mode of travel would be restricted to the left lane. Automated vehicles would have the capability to cruise together.

Barriers: Use of barriers would be the same as for today's freeways.

Breakdown lane: Breakdown lanes would be present as they are on today's freeways.

Multiple AHS lanes: There are no dedicated AHS lanes (although AHS travel is restricted to the left lane). If demand was sufficient for multiple lanes an I2 or I3 configuration would be more effective.

3.2.2.2 Command, Control and Communications Centralization Dimension

In table 3, we used the following characteristics to describe the command, control and communications dimension: control centralization, highway role, speed determination, spacing determination, lane change decisions, and lane change maneuvers. We are now adding these "C" dimension characteristics: ***headway policy, communications links, longitudinal control, lane keeping lateral control, check-in; check-out; and driver role.*** We will describe the characteristics as they relate to the six basic RSCs in the following paragraphs. A table summarizing our descriptions is included as table 4.

The communication links component of the "C" dimension of RSCs will be described below in terms of three data links: the RV notation is used for roadway-to-vehicle communication; the VV notation is used for vehicle-to-vehicle communication and RVR for roadway-to-vehicle-to-roadway communication. The communications links provide a major source of discrimination among RSCs.

RSC I3C3

Summary: RSC I3C3 is a dedicated AHS freeway with all three data links: RVR, VV and RV. Coordination of vehicles (e. g., exit/entry, normal operations, and emergency operations) is, most likely, highly synchronized through roadway command. Cooperative vehicle control is accomplished using the VV link for monitoring safety parameters and as a back-up if the RVR link fails.

Headway policy: Headway can be short but not shorter than safety policy allows. Normal speed control will dictate that no touching will occur up to the level of braking that is defined as maximum for normal maneuvering. For coping with incidents, emergencies, etc. touching might be shown to be safe up to some delta velocity. For now, we can see that in theory, plenty of capacity is available (5500 vplph) even with gap sizes like 40 feet at speeds of 60 mph.

Roadway-to-Vehicle-to-Roadway (RVR) communication: This data link will command speed, spacing, lane change, and any other functions the centralized traffic manager might find useful. It could advise as to the feasibility of a request for AHS entry to keep demand within capacity. It could advise, or in some instances, command exit at other than the requested exit point to control demand. (Hopefully, this rarely happens since speed and spacing would be used to control flow into an entry/exit sector.) In short, this is traffic management at its highest level of intelligence and capability. No queues, no slow cruising, no adverse impact on non-AHS traffic. All the good things automation can give us. The road surface condition, weather, incident factors, navigation, etc. might also be on this link or on a third link (RV) from a system-wide agency.

Vehicle-to-Vehicle (VV) communication: A data link among vehicles is assumed. We envision a two-way link in each vehicle. Normally, vehicles would send messages to vehicles behind them and receive messages from vehicles that are in front of them to exchange accel/decel commands and/or actual sensor outputs. The roadway could monitor this link by positioning stations along the freeway.

Roadway-to-Vehicle (RV) communication: The road surface condition, weather, incident factors, navigation information, etc. might be on this link from a system-wide agency.

Longitudinal control: Some form of roadway commanded vehicle coordination is assumed. Vehicle-based headway control is needed. With no roadway input, the vehicle will maintain speed and spacing through onboard control loops (i.e., no data links inside the loops). If a point-follower concept is used, it is assumed that the vehicle based headway control can override it if necessary for safety reasons.

Lane Keeping Lateral Control: The center of the lane is tracked automatically. Lane changes are commanded by the roadway including access to and egress from the cruising lane(s).

Check-in: We will assume that the software that accomplishes check-in is vehicle-based since all the hardware and software being checked is vehicle-based. We will also assume that many of the checks will be continuous as the vehicle cruises. The driver should be alert enough to answer an “Are you okay?” query. This should be repeated often enough to verify capability. The result of a successful C3 check-in would be continued entry procedure (i.e., transition to automated driving). Lack of success would require the driver to lead the vehicle back to non-AHS roads or to parking. But even in C3, the roadway needs to do little computation. Just receipt of the “okay” bit should suffice. The roadway may also verify that a vehicle that fails check-in does not enter the AHS.

Check-out: We will assume that check-out will occur while the vehicle is moving along its normal path nearing an exit and will be vehicle based. It may also be applied periodically during normal AHS use. A breakdown area will be provided for vehicles/drivers that do not pass. The vehicle will park itself in the breakdown lane, or parking area, should it or its driver fail to pass the checks or the checkout protocol.

Driver role: In this RSC, the driver will: initiate (i.e., request) AHS engagement; maintain (or regain) manual control if check-in fails; monitor vehicle and AHS status; respond to malfunctions in accordance with malfunction rules; specify destination, and participate in required check-out procedures. This role assumes that the driver will be required to respond to malfunctions. One can argue that requiring continuous readiness to take over is unreasonable and defeats one of the AHS purposes. On the other hand, the system reliability implied by giving the driver no role seems beyond what is practical. Thus the role we assume is that of a person working at a desk but answering the phone and taking action, if necessary.

RSC I3C2

Summary: RSC I3C2 is a dedicated AHS freeway with a VV data link and a RV data link for commands. Vehicle coordination is accomplished using the VV link. Roadway will command speed and spacing by sector.

Headway policy: Same as I3C3

Roadway-to-Vehicle-to-Roadway communication: None.

Vehicle-to-vehicle communication: Same as I3C3 except the typical data rate would be higher than in I3C3 since the link (VV) would be used for entry/exit and lane change synchronization.

Roadway-to-Vehicle communication: The RV link provides commands on a sector basis. The road surface condition, weather, incident factors, navigation, etc. might also be on this link from a system-wide agency.

Longitudinal control: Longitudinal control will be performed by the vehicle using on-board sensors and control logic. Infrastructure based facilities (e.g., GPS, magnetic nails, etc.) may be used for reference.

Lane Keeping Lateral Control: The center of the lane is tracked automatically. The control logic for lane keeping is based in the vehicle.

Check-in: Same as I3C3

Check-out: Same as I3C3

Driver role: Same as I3C3 plus the driver will be required to provide AHS parameter inputs (e.g., lane change decisions) as shown in table 3.

RSC I3C1

Summary: RSC I3C1 is a dedicated AHS freeway with no RVR data link. It relies on the RV and VV links for all command functions, including sector speed and spacing, coordination of entry/exit and surface condition input. The roadway monitors the VV link for malfunction management and uses the RV link to send speed commands. The VV data link would be used to manage speed and spacing throughout the sector using the vehicle computer. The roadway could receive this data link and manage traffic by sector speed commands and perhaps metering entry traffic.

Headway policy: Same as I3C3/I3C2.

Roadway-to-Vehicle-to Roadway communication: There is no RVR data link in C1. There could be communication by having the roadway participate on the VV data link in addition to the RV link.

Vehicle-to-Vehicle communication: All coordination functions are performed using the VV data link as required. We envision a two-way link with transmitter and receiver in each vehicle. The roadway might be included like a stationary or a slow moving vehicle.

Examples of a VV Link are:

(a) A short-range broadcast on one frequency for the entire AHS with the digital frame multiplexed among parties within range and each time slice shared with parties out of range.

(b) A data link reception from the vehicle immediately ahead and transmission to the vehicle immediately behind. It must have a very short frame time and latency. This link must provide the capability to pass data even if the VV link is failed.

Roadway-to-Vehicle communication: This link provides speed command information. It may also provide information on road surface condition, weather, incident factors, navigation, etc.

Longitudinal control: Same as I3C2.

Lane Keeping Lateral Control: Same as I3C2.

Check-in: Similar to I3C3/I3C2. The result of a successful check-in in C1 would be continued entry procedure (i.e., transition to automated driving). Lack of success would return the vehicle back to manual control and the vehicle would be directed off the AHS.

Check-out: Same as I3C3/I3C2.

Driver role: Same as I3C2.

RSC I2C2

Summary: RSC I2C2 is a dedicated AHS lane on an existing manual freeway. Vehicle coordination and safety is accomplished by the VV link. The VR link commands speed and spacing.

Headway policy: Same as I3C3/I3C2/I3C1.

Roadway-to-Vehicle-to-Roadway communication: Same as I3C2.

Vehicle-to-Vehicle communication: Same as I3C2.

Vehicle-to-Roadway communication: Same as I3C2.

Longitudinal control: Same as I3C2.

Lane Keeping Lateral Control: Same as I3C2.

Check-in: Same as I3C2.

Check-out: Same as I3C2.

Driver role: The driver role is similar to I3C2. The driver will be assumed to be aware of events in the AHS and be prepared to cope with some malfunctions. Since access/egress is at cruising speed in I2C2 and manual vehicles can be in the adjacent lane with no barrier, the driver should have higher awareness and possible higher alertness during the automatic access and egress sequences.

RSC I2C1

Summary: RSC I2C1 is a dedicated AHS lane on an existing manual freeway with no RVR link. It relies on the VV link for vehicle coordination and safety. The roadway monitors the VV link for malfunction management and uses the RV link to command speed and send general messages.

Headway policy: Same as I3C3/I3C2/I3C1/I2C2.

Roadway-to-Vehicle-to-Roadway communication (RVR): Same as I3C1.

Vehicle-to-Vehicle communication: Same as I3C1.

Vehicle-to-Roadway communication: Same as I3C1.

Longitudinal control: Same as I3C1.

Lane Keeping Lateral Control: Same as I3C1.

Check-in: Same as I3C1.

Check-out: Same as I3C1.

Driver role: Same as I2C2.

RSC I1C1

Summary: RSC I1C1 is a mix of manual and automated vehicles in the same lane on an existing freeway. Operation is similar to present manual operation except that automated vehicles can also be used and can even form small caravans to take advantage of their smaller safety gap capability, if a VV link is provided. RSC I1C1 makes sense on a two- or three-lane freeway configurations. Grouped operation could involve contacting an adjacent automated vehicle ahead in the outside lane and requesting link-up.

Headway policy: Same as I3C3/I3C2/I3C1/I2C2/I2C1 except that the vehicle ahead must be a cooperating (i.e., via VV link) automated vehicle to use the shorter safety gap prescribed for AHS vehicles. Manual vehicles must maintain safe gaps.

Roadway-to-Vehicle-to-Roadway communication (RVR): Same as I3C1/I2C1.

Vehicle-to-Vehicle communication: Same as I3C1/I2C1.

Roadway-to-Vehicle-communication: This will be used to provide advisory information only (e.g., road conditions, navigation info, etc.).

Longitudinal control: This control system would use in-vehicle sensor and control logic and will hold speed with a minimum safety gap. Computer logic would properly adjust gap size depending on whether vehicle ahead is manual or cooperating AHS vehicle.

Lane Keeping Lateral Control: The lane centerline is tracked by vehicle-based mechanization and perhaps some passive roadway features. The mixing of manual traffic makes it natural to assume a driver biasing capability to provide a defensive driving feature (e.g., bias left when passing a truck in the adjacent right hand lane.

Check-in: Same I2C1 except that lack of success would simply prevent engagement of the automated mode. Manual operation in the lane would continue.

Check-out: Similar to other RSCs except that continuous driver alertness and readiness for manual input is an issue. If the alertness test is failed, the vehicle is slowed to a stop with flashers on.

Driver role: Same as I2C1 except that driver will be responsible for maintaining full awareness. The driver would function much like a driver in today's traffic except that attention would shift from gap, speed and lane holding to more awareness of the other vehicles in the vicinity and the overall traffic situation. The driver will be required to take over if the situation demands (e.g., road conditions change).

3.2.2.3 RSCs with Multiple Vehicle Equivalents (MVEs):

Summary: General comments are listed below for RSCs involving MVEs as shown in table 5. I3C2V2 also has a separate entry ramp for MVEs. Today's freeways were designed to fit MVEs geometrically. Therefore, I1C1V3, I2C2V3, I2C1V2 and I2C2V2 are appropriate RSCs to consider. Since today's tractor-trailers are too wide for a ten foot lane, the I3 concept requires more width of pavement or narrower trucks (a rollover issue) if MVEs are allowed.

3.2.2.3.1 Infrastructure Dimension

Barriers: Height and strength of barriers are an issue.

Breakdown lane: Same as SVEs.

Multiple AHS lanes: Multiple AHS lanes are required in V2 RSCs.

3.2.2.3.2 Command, Control, and Communication Centralization

Headway policy: Gap size must be large in front of an MVE for safety and comfort of an SVE ahead. Likewise, gap behind might need to be larger for comfort and visual consideration.

Table 5. RSCs that Include the MVE Condition

	C1	C2	C3
I3		V2, V3	
I2	V2	V2, V3	
I1	V3		

Longitudinal control: Since accelerations of SVEs need to be low for passenger comfort, the acceleration/deceleration command can be compatible with MVEs. Maximum deceleration capability will be less and will vary greatly with cargo load.

Lane Keeping Lateral Control: Lateral control might differ from SVE only control in detail but not in overall concept. There may be a need in all vehicles, but especially in heavy vehicles, to program a slight weaving motion to avoid grooving the pavement excessively.

Roadway-to-Vehicle-to-Roadway communication: Same as SVEs.

Vehicle-to-Vehicle communication: Same as SVEs.

Roadway-to-Vehicle communication: Same as SVEs.

Check-in: Same as SVEs.

Check-out: Same as SVEs.

Driver role: Could be the same as SVEs. However, driverless operation of MVEs, for example trucks, has economic appeal in the savings of a professional driver's wages. This advantage needs to be analyzed in relation to the cost of vehicle reliability and associated malfunction management strategies.

4.0 HIGHLIGHTS OF THE TECHNICAL DISCUSSIONS

4.1 Introduction

The RSCs, defined above, provide a system level view of potential AHS configurations. They have served as a key system integration element for each task's analysis. The level of definition of each RSC is quite general. In most cases, the detailed analysis performed in each task required further system design. Therefore, each task leader was required to develop assumptions about detailed design issues for the purposes of their analysis. These assumptions follow the overall RSC approach, then branch out along new system design paths.

These assumptions, in many cases, cover research topics involving more than one task. Our research approach has emphasized the integration of research across tasks, where appropriate. For example, the Roadway Deployment, Exit/Entry, and Impact of Non-AHS Roadways tasks are interrelated. The results of various AHS deployment strategies impact directly the non-AHS roadways. Therefore, these two tasks were performed as one task. Also, the roadway deployment study results are based on assumptions about the exit and entry strategy. These assumptions have been provided to Roadway Deployment as preliminary results from the entry/exit task. Therefore, most of the results in the individual reports, which are summarized below, demonstrate system wide views of the AHS. Clear statements of the assumptions used in the analysis are included with the results.

This section summarizes the efforts of each task by including the executive summaries from each task report. The task results are presented in the same organization as the volumes. A key element of the task results is the key findings, which are included in the executive summaries. The key findings in section 4 are labeled sequentially by the task area. They are displayed as a two letter task identifier followed by the sequence number. They appear after the key finding in parenthesis. The labels will be used in section 5 (Overall Cross-Cutting Conclusions and Observations) as cross-references to the originating task.

4.2 AHS Comparable Systems Analysis (Task G)

"Don't take all my experience as applicable today, but please, let's not relive history. Let's not mislead anyone as to what is reality; let's find that reality and go forward on that basis." — Najeeb Halaby
FAA Administrator
Head, Supersonic Transport (SST) Program

4.2.1 Introduction

The Automated Highway System is not the first large system that involved the introduction of new innovative technology, was intended for widespread public use, required coordination across Government and private industry, had potentially significant cultural and societal impact, and required large amounts of financial investment. Large innovative systems have come and gone. Some have been successful and changed society forever in fundamental and important ways (e.g., the automobile, computers). Many changed our world in small to moderate, yet important ways (e.g., ramp metering, electronic toll systems and traffic management systems). Others met with public and/or political resistance or technological and/or fiscal problems and ultimately failed (e.g., the supersonic transport—SST).

4.2.2 Task Objective

These analyses were completed to learn from the history of systems sharing common features with AHS. The objective was to identify and document relevant historical lessons for AHS planning and development. As recommended by Najeeb Halaby, the first FAA SST Program Manager, our goal was to define today's reality for AHS in an historical context, drawing from the lessons of past programs that share important features with AHS.

4.2.3 Technical Approach

The approach taken for this task maintained a high-level perspective. Brainstorming, review of literature, and personal contacts/interviews with experts were applied as appropriate. The effort proceeded with the following subtasks:

1. **Candidate Comparable System Selection** — A list of candidate comparable systems that could provide lessons learned for AHS was generated. These were identified through a brainstorming session held early in the program.

2. **Candidate Comparable Systems Prioritization** — Candidate comparable systems were prioritized and selected for high level study. This was accomplished using a nominal group technique supported by project task leaders.

3. **Comparable Systems Study Assignments** — Study action items were assigned. Based on their expertise, task personnel were assigned comparable systems to study.

4. **Comparable Systems Analysis** — Analyses were conducted. During this step, relevant literature was reviewed, domain experts were consulted, and lessons for AHS were identified.

5. **Internal Communication of Interim Results** — Intermediate results of the analyses were provided to other PSA of AHS Task Leaders based on relevance to their respective tasks. This was done via internal memorandum, draft interim results documentation, and informal personal contact.

6. **Integration of Final Results** — During this task, lessons learned based on the analysis of selected comparable systems were consolidated and integrated. Twenty high level conclusions were identified based on integration of the over 100 individual issues, risks, concerns, and recommendations resulting from the individual analyses.

7. **Documentation** — Conclusions were documented in a final report (this volume) and within the PSA of AHS issues database (ongoing).

4.2.4 Overall Conclusions/Key Findings

The results of the analyses are synthesized into 20 major conclusions. The following paragraphs describe each major conclusion and cite evidence from relevant comparable systems.

1. The public must perceive the overall benefits of AHS. (CS1)

   In order for a new technology to successfully replace an existing technology, the new system must offer clear and obvious advantages and benefits over the older system. If these benefits are not provided or evident, potential users will likely be unwilling to give up the pre-existing trusted system for the newer system, especially if the changeover involves significant costs (e.g., money to purchase the new system, time to learn new procedures, license fees). AHS design and deployment should proceed in ways that will make the benefits obvious to all potential users.

   Evidence for this conclusion comes from several of the comparable systems studied. For example, experience with HOV implementation indicates that, when drivers can see that HOV lanes are moving more people than non-HOV lanes, they are willing to accept the dedication of a lane for this purpose, even if they do not personally choose to use the HOV lane themselves. Similar experience has been found with the implementation of ramp meters. Toll road implementation also provides support for this conclusion. When toll roads were first implemented in this country, there was great concern whether people would pay to use them when conventional roads were available free. However, experience has shown that because toll roads significantly reduced travel time, they were very successful. Other comparable systems that support this conclusion include the streetcar, commercial flight, domestic appliances, and automated teller machines (ATMs).

2. The safety and reliability of AHS must be clearly demonstrated. (CS2)

Any new technology must be proven safe and reliable before the general public is willing to accept and use it. Evidence from the comparable systems studied has shown that even systems that have a reputation for good safety may face loss of users if a safety incident does occur. Systems that have a reputation of safety problems have had a very difficult time achieving public acceptance.

Evidence for this conclusion comes from the study of elevators, commercial flight, bank automated teller machines (ATMs), aircraft automation, and the Morgantown personal rapid transit system. Public concerns about health and safety have even been raised for electronic toll and traffic management (ETTM) systems. To illustrate, elevators have been around since the middle ages but, until after 1854, were limited to hauling freight because the public had serious concerns about their safety. In 1854, Elisha Otis dramatically demonstrated the safety of his "safety elevator" by having himself raised 40 feet in the air and having the elevator rope severed, demonstrating the effectiveness of the new elevator safety mechanism. From then on, elevators have been used to haul people (and, in fact, are the safest form of automated transportation in use today!). The ubiquitous use of elevators has changed the urban landscape forever.

On the negative side, when safety and reliability problems occur, acceptance of the systems involved is reduced. For example, when the Hindenburg crashed, the then thriving commercial dirigible industry completely collapsed. Similarly, when a demonstration intended to show that sonic booms from the SST would not disturb residents led to over 15,000 angry phone calls and over 5,000 damage claims, the program was severely damaged and never really recovered.

The success of AHS will require demonstration of safety and reliability before full implementation. People must believe that the system is as safe, or safer, than the traditional highway system. Further, public demonstrations of AHS that raise safety concerns may do more harm than good, and even prevent the system from ever being accepted. AHS developers should perform extensive testing before a prototype is demonstrated to the public.

3. Long-term and continuous financial support for AHS deployment must be secured. (CS3)

For the long-term success of AHS, it is important to ensure that funding for the project is sufficient and guaranteed. If the funding is not sufficient, it may be difficult to raise funds at a later date. If the funds are not guaranteed, they may be cut at any time, and battles for project financing will be ongoing. Further, funding needs to be specific to the goals of AHS, and pay-as-you-go financing is preferable to borrowing.

Evidence for this conclusion comes from study of the interstate highway system, automated guideway transit systems, the railroad (i.e., interurbans and maglev), and the SST. When interstate highway funding was first made available the scope of its intended use was defined in a general way and much of the money allocated was used to fund porkbarrel projects. Subsequent attempts at interstate highway legislation were unsuccessful, because of the very large amounts of borrowing required. The interstate highway was ultimately developed successfully, but on a pay-as-you-go basis. A small gasoline tax was levied and used to develop the interstate highway network over a long period of time.

4. Support from influential persons in Government and industry is important for large programs. (CS4)

   The success of many large-scale projects has been facilitated through the commitment of high ranking officials from Government or industry who were willing to work hard to ensure the success of the projects. AHS will benefit from such an individual (or group) to help secure the necessary financing and support, and to help maintain enthusiasm for the project during all stages of design and implementation.

   The importance of a strong proponent for large projects was evident in many of the systems studied during this program. Without one or more strong supporters, projects have often faced great difficulties. Those with strong and influential supporters have generally been more successful. For example, support from Senator Daniel Moynihan (D-NY) was a key factor in the recent formation of the Maglev Technical Advisory Committee and the National Maglev Institute, and in the ensuing interest in maglev development. Public confidence and interest in commercial flight were greatly bolstered when Franklin D. Roosevelt used an airplane to travel from New York to Chicago to accept the Democratic nomination for the presidency of the United States. Similar proponents of AHS would increase its potential for success.

5. Evolutionary development of AHS is recommended. (CS5)

   An evolutionary approach to the development and implementation of AHS is recommended, based on the experience of several large-scale public systems studied during this project. An evolutionary approach will provide for incremental development, allow safety and reliability to be demonstrated on a small scale before system-level integration is attempted, and provide a gradual approach to achieving public acceptance. This will also allow alternative technologies and design approaches to be compared prior to selection. Finally, U.S. industry will be more willing to invest in AHS if short-term profits are possible.

   Evidence for the advantages of an evolutionary AHS development approach was found in many of the comparable systems studied, including HOV lanes, the interstate highway system, automated guideway transit, air traffic control, the railroads, office automation, domestic appliances, and ATMs. For example, the evolutionary approach taken in the development of the interstate highway system made it possible to fund the effort on an incremental basis, while the immediate provision of benefits maintained public support. HOV lanes have also been successful, in part because they build on existing highways (i.e., they are an evolutionary improvement to the existing highway system). Alternatively, when large projects have been unable to use an evolutionary development approach, they have experienced problems. The Chunnel (the tunnel connecting England and France under the English Channel) is a good example.

Cost overruns have led to serious questions about its ability to compete with less expensive ferry service, and the lack of any demonstrated benefits (no one has used the Chunnel yet) has led to waning public support for the project.

6. AHS should be designed for integration within the overall transportation system in the United States and worldwide. (CS6)

   The AHS market should be defined in relation to other transportation forms. The AHS network and design should be developed based on this potential market. When AHS is included as an integral component of the U.S. transportation system, rather than as an independent competing mode, a realistic and stable user base will be encouraged, and the goals of the U.S. transportation system will be best served. AHS objectives should be developed on the basis of this integrated definition. Further, AHS components should be standardized for all AHS applications in the U.S. and worldwide and should be compatible with existing conventions. For example, AHS should be designed to be as compatible as possible with existing highway signs and procedures.

   Evidence for this conclusion was found in the study of several comparable systems, mostly from the transportation area. For example, the success of HOV treatments has been facilitated when integrated with park-and-ride lots and mass transit (e.g., preferred parking spaces reserved for HOVs). Experience in the planning of mass transit systems has also shown that realistic estimates of market size should be made in the context of the larger transportation system as a starting point. Transportation systems that have been developed without an integrated view have experienced problems. For example, the interstate highway system did not consider the effect of interstates on urban traffic patterns and the result has been excessive congestion in many areas; independently developed regional railroads resulted in a totally incompatible national rail network requiring extensive rework.

7. Cost and time estimates for developing AHS must be carefully and accurately determined. (CS7)

   Budget overruns and schedule slippage can lead to negative publicity, poor public acceptance, and reduced political support for the system. System design, testing, and implementation must remain within budgetary guidelines and time constraints for the project to ensure continued support. Cost and schedule "bad news" can reduce public acceptance of AHS, even when the shortfalls are due to estimation errors, rather than the more serious system problems. Also, it is important to plan for schedule and cost contingencies. Despite good planning, unforeseen problems are likely to emerge and require unplanned effort.

   For these reasons, AHS developers must carefully make realistic estimates concerning the amount of time the system will take to implement, and the amount of money it will cost to complete. Neither the financial backers nor the general public is pleased when a project requires sudden increases in financial support halfway through, or when the project takes significantly longer to complete than predicted. This is especially true for projects financed by public funds. Overly optimistic budget and schedule estimates look good at planning time but lead to almost certain failure, at least as measured against budget and schedule.

Evidence for this issue has been found in the study of several comparable systems, including the Morgantown Personal Rapid Transit (PRT) System, the Denver International Airport (DIA), the Chunnel, and the SST. The Morgantown PRT is a good example. The project was initially under-estimated in terms of both budget and schedule. When it became apparent that the project required significantly more time and money to complete, political pressure led to design and development shortcuts. These, in turn, led to system deficiencies and problems requiring rework. Even more extensive cost and schedule overruns resulted, leading to very poor public perception. The project took years to complete and support for other PRT projects was also jeopardized.

8. Consortiums of private and public agencies can facilitate AHS successful development. (CS8)

   A consortium approach to AHS development can help to ensure that the AHS system is successfully implemented. The consortium approach will allow the project to benefit from a wide range of expertise and perspectives, and to share the costs involved with implementation. Even more importantly, cooperation among the various industries and organizations interested in AHS will facilitate efficient and effective designs that can be supported by products and services developed independently, yet which must operate within a common infrastructure. The motivation for investment, participation in the consortium, and diligence in the task comes from the increased market share potential that results from design participation. Winners and losers are sorted out in the market place.

   A consortium approach to system development has been effective in many situations similar to AHS (i.e., large, market driven systems). Some examples studied during this task are commercial flight and ATMs. The airlines and associated Government agencies from all nations (except Russia) joined to form the International Air Transport Association (IATA) in 1944. They established international standards for safety, navigational controls, air maps, and even the setting of international air fares (Solberg, 1979), providing safer and more efficient international air travel . These accomplishments would not have been possible without this widespread cooperation. When New York City banks joined to develop the New York Cash Exchange (NYCE) system they were able to overcome the ATM market head start previously enjoyed by Citibank. Cooperative ventures between Government and private industry in Europe and Japan to develop IVHS technologies have also been successful. By contrast, the lack of cooperation among early U.S. railroad companies led to a national system of largely incompatible tracks.

9. Community outreach and public involvement will be important to AHS success. (CS9)

   It will be wise to keep the public educated and informed throughout the AHS planning, design, and development phases. AHS developers and supporters should make the public aware of the benefits of AHS, and immediately deal with any criticisms and/or concerns raised. AHS developers and promoters should also build coalitions with opposition groups (or at least be prepared to counter negative arguments). Environmental concerns will be important considerations. Public education and outreach, in addition to maintaining support for the program, will help attract users to the system, by allowing them to understand how the system works and the benefits it offers.

Also, our research has found that full public disclosure and education are important for avoiding liability problems. According to the U.S. legal system, definitions of a defective product and dangerous conditions are based on perceptions held by the general public. It is necessary to inform and educate the public about AHS operation and limitations in order to help mitigate legal challenges.

Evidence for this conclusion comes from our study of ramp metering, the interstate highway system, ETTMs, the automobile, commercial flight, the SST, and the planning of mass transit. For example, ramp metering projects have encountered public resistance in several locations, in one instance leading to litigation. Experience has shown that, by involving the affected communities during the planning process, these problems are greatly reduced.

10. AHS may produce significant changes in society that may be difficult to predict. (CS10)

    It is difficult to predict the effect that introducing AHS will have on the national highway system, and on society, in the United States. We have found that the introduction of new technology in the United States has often led to unforeseen effects. Research to explore the non-obvious affects of AHS should be undertaken as part of the AHS planning process (e.g., through focus groups and market research).

    Evidence for this conclusion comes from our study of automobile history, the railroads (primarily interurbans), the elevator, and office automation (primarily the typewriter). To take an example, the elevator had far reaching effects beyond simply moving people between floors more quickly and comfortably. They made it possible to build taller buildings. The result has been a completely new look to our urban centers. Even the rent structure for offices was reversed when elevators were put in use (higher floors received premium rents). An example where unforeseen consequences of technology led to a systems failure (at least for a while) is the typewriter. When first introduced and marketed, there was great resistance to the typewriter due to societal norms in effect dealing with penmanship and the social etiquette of letter writing. Letters typed with the typewriter seemed impersonal, and issues of authenticity were raised. The practice of signing otherwise typed letters adopted later helped overcome these concerns. It will be important to determine if AHS will have effects that could hinder its development and success.

11. Potential markets for AHS should not be overlooked. (CS11)

    The wider the potential market-base, the easier it will be to gain widespread acceptance of the new technology. This may also help to keep operating costs low. Limiting the potential market for AHS could exclude potential users, and result in poor public perception of AHS. That is, it could be seen as having limited usefulness and value, or being toys for the rich and powerful. To maximize the potential for AHS success, it is best to open up the system to as many categories of users as possible (e.g., consider commercial and consumer markets). This approach of seeking the broadest possible market is recommended on the basis of the study of several comparable systems

This conclusion is based on our study of the interstate highway system, ETTMs, the automobile, automated group transit systems, office automation (the typewriter), domestic appliances (the VCR and electricity itself), and ATMs. In all cases, success was facilitated by expanding the market to a wider user base. For example, early automobiles were very expensive and sold only to the wealthy. With the introduction of the Model-T, the average citizen became included in the potential market. The automobile's success was greatly increased. Similarly, the initially unsuccessful typewriter became a great overnight success when the business market was targeted.

12. A large return for AHS can be achieved with transit vehicles. (CS12)

    AHS when combined with transit and/or HOV treatments can provide very significant improvements to the people-moving capacity of our highways. These treatments are especially applicable to (and perhaps limited to) AHS applications in urban areas and along congested corridors. When considering the AHS goal of congestion mitigation, the potential of these treatments cannot be overlooked. For example, an AHS implemented in the Lincoln Tunnel Express Bus Lane could potentially provide people-moving capacity greatly exceeding that possible with heavy rail mass transit (although this would require expanded terminal capacity). Even HOV treatments on AHS could potentially provide service comparable to existing light rail systems.

13. AHS design insights and technology foundations can be found through the study of comparable systems. (CS13)

    No single comparable system was found (or expected) to provide guidance across all AHS design aspects. However, many comparable systems have been found that can provide insight and technology to support specific aspects of AHS development and implementation. In some cases, comparable systems can provide insight into public relations and social aspects of AHS development. In other cases, design approaches are recommended, or technology solutions suggested. This is the most general finding resulting from this task and relates to all comparable systems studied. It is recommended that the comparable systems studied during this task, as well as others, be considered during AHS design and implementation.

14. AHS will face liability issues. These should be anticipated and plans made to avoid or overcome legal challenges. (CS14)

    We live in a litigious society. It seems clear that AHS implementations will face legal challenges (like all other systems). These can stem from mismanufacture, defective design, failure to warn, and/or product/service misrepresentation.

AHS development should be managed in a way that minimizes legal vulnerability. Safety analyses will be required to support design decisions. It will be important to educate drivers about AHS capabilities, limitations, and safety procedures. Plans for updating AHS to avoid antiquated technology will need to be made, and AHS must be based on capable technology. Government standards and design redundancy can help reduce liability for private industry. Since legal foundations are built on precedents, legal issues left unaddressed will be decided in court.

Evidence supporting this recommendation is based on an analysis of the liability experience with cruise control, ABS brakes, and air bags in today's cars.

15. AHS should be designed with maintenance and system upgrade in mind. (CS15)

    AHS design must consider requirements for accomplishing system maintenance. This will include incident management, routine roadway maintenance such as snow removal, preventive maintenance and system inspection, and infrastructure repair. It must be possible to accomplish these functions without significant disruption of service.

    It should also be possible to accomplish system upgrades and expansion with only minimal disruptions of service. One design consideration related to system upgrades is that it should be possible to accommodate earlier AHS users after upgrades are accomplished.

    These recommendations are based on the study of several comparable systems including the automobile, automated group transit, air traffic control, elevators, and office automation. For example, the rapid development of and improvements to computer technology have been facilitated by the common practice of making changes downward compatible (e.g., designing new hardware to work with old software). This preserves and supports the development of the customer base.

16. Public acceptance will be critical for AHS success. (CS16)

    If we build it, will they come? And will they support its development? These are very important questions for AHS. Public demand for systems can drive the development and expansion of markets to worldwide levels. On the other hand, public opposition to systems can create serious obstacles to success. Issues of public acceptance for AHS will be very important.

    Many factors contribute to public acceptance. Important factors include cost relative to other transportation modes, convenience and ease of use, ability to match users' origins and destinations, obviousness of fail-safe features, and impact on pollution. It will be important to pay attention to public relations and privacy issues, and to the needs of special user groups (e.g., non-English speakers, handicapped). The perceived impact of AHS on job security can impact the acceptance for commercial AHS applications. Finally, even the general appearance of AHS can be a factor in AHS public acceptance. It will be important to consider and assess these issues throughout AHS development.

This recommendation is based on several comparable systems, including ETTMs, the automobile, aircraft automation, the bicycle railroad, commercial flight, office automation, and ATMs. For example, the employment of nurses as flight attendants during the early days of commercial flight helped to reduce the public's apprehension about flying, and helped facilitate the success of this market.

17. The degree of centralized control and human decision making can slow system response. (CS17)

    The degree of centralized control can slow system response time and reduce the ability to deal with local conditions. This could affect spacing and flow achievable. Highly centralized control approaches can create lags in the control system and make it difficult to deal with local conditions. The requirement for human decision making in the control loop is especially problematic and should be limited to global, non-time-critical-parameters. Finally, the requirement for driver assimilation and interpretation of messages can slow response. Commands sent to the driver should be clear and unambiguous. If a centralized control system is selected for AHS, it must be designed in a way that it does not create serious control lags.

    The evidence for this conclusion comes from study of the air traffic control (ATC) system. The ATC system is highly centralized. The speed, spacing, and flight path of aircraft are determined and controlled from the ground. Human air traffic controllers determine the desired aircraft flight parameters and issue voice commands to pilots, who make appropriate adjustments. This system is slow, cumbersome, and makes the ability to adjust to local conditions (e.g., weather) difficult. It leads to an inefficient use of airspace, because aircraft must be kept widely separated to allow for control system lags.

18. AHS exit efficiency will be critical for handling high AHS flow rates. (CS18)

    Bottlenecks can be created at popular exits if the exits cannot handle traffic demand. This could require closing an exit to avoid vehicles from backing-up onto the AHS lane(s). Approaches for mitigating this problem include proactive planning and the use of multiple parallel exits or buffer zones. Proactive planning could include placing, under system control, groups of exits in congested areas (e.g., near an activity center such as a stadium or CBD). Drivers desiring to exit could be assigned an exit by the system in a way that optimizes overall exit efficiency and flow. When there is room, an additional exit lane could be also added.

    This conclusion is based on the study of the ATC system and the management of finish chutes at foot races. ATC restricts aircraft take-off permission until landing slots are available. Foot race finishes handle the processing of large numbers of runners at race finishes without backing-up into the race by careful management of parallel finish chutes.

19. AHS marketability will be influenced by design and economic factors. (CS19)

AHS will be one of several options for travelers. Its design and pricing approach will affect its potential market base. Innovative approaches to AHS pricing and the sales approach used can increase the potential market achievable. For example, whether AHS systems must be purchased or leased will affect their price to consumers and impact their competitiveness within the transportation market. Also, the development of the AHS market can be facilitated by "piggybacking" on other markets (e.g., market to those using existing ETTM systems, offering commuter packages that include AHS and connecting mass transit passes). In planning for AHS marketing, it will also be important to consider prevailing economic conditions. If the AHS industry is characterized by significant competitive forces, this can facilitate development of innovative marketing approaches.

Several comparable systems form the base for this conclusion, including ETTM systems (the New York State E-Z Pass system), commercial flight, office automation, and domestic appliances.

20. There may be regions that favor AHS implementation over others. (CS20)

There may be regions in which geographic or traffic conditions favor AHS, while other areas may be less favorable. On the one hand, this will make it possible to select locations for AHS demonstration where AHS can provide significant benefits within the larger transportation system. It also will help guide the planning of AHS evolution and system expansion. On the other hand, it will be difficult to gain political support from legislators representing areas with little to gain from AHS. In fact, those areas where AHS is less applicable can be sources of opposition.

This conclusion is based on the study of the interurbans, and high speed trains. For example, interurbans were most applicable in areas were cities and suburbs were closely spaced and the terrain was relatively flat.

4.2.5 Recommendations For Further Work

The conclusions and recommendations described in this volume are based on the study of many comparable systems. The study was broad-based to identify sources of insight and technical foundations for AHS. Because the study considered many comparable systems, each was considered at a high level. More detailed information may be available. It is recommended that the results and data provided in this volume be used as a starting point for further investigation as appropriate. Specific literature and data sources included in the references, bibliography, and literature review sections should be consulted during AHS development and implementation. For example, when design decisions must be made, it might be valuable to contact persons involved in highly relevant studies and projects.

The conclusions presented in this volume may be more relevant to some aspects of AHS than others, and to some AHS design phases more than others. The conclusions presented should be applied as appropriate, considering the specific tasks at hand.

4.3 AHS ROADWAY ANALYSIS

The AHS roadway analysis consists of these three task report summaries: (1) Urban and Rural AHS Analysis (Task A), (2) AHS Roadway Deployment Analysis and Impact of AHS on Surrounding Non-AHS Roads (Tasks H and I), and (3) AHS Roadway Operation Analysis (Task K)

4.3.1 Urban and Rural AHS Analysis (Task A)

4.3.1.1 Task Objective and Approach

The target for Automated Highway System (AHS) deployment is our national freeways, the backbone for worker commuter, inter- and intracity travel and the major roadway choice of America. Freeways, pressured to carry more traffic, are experiencing crippling and prolonged congestion. The remedy for congested freeways is not to build more of them but to make them work more efficiently. AHS analysis is based on this premise.

Experienced transportation engineers recognize the fact that freeway problems are not the same for urban, suburban and rural environments. They were not built for the same purposes, were not engineered the same, and do not operate the same (AASHO *Blue Book*, 1954, *Red Book*, 1957). Rural freeways were built before urban freeways, with the primary purpose of connecting cities. Urban freeways were built to 80.5 km/hr (50 mph) design standards within tight right-of-way (ROW); rural freeways used 112.7 km/hr (70 mph) design standards with ample ROW. However, many freeways that were created as rural freeways are now surrounded with spreading suburbs, which generate significant traffic. This evolution from rural to suburban leaves only open country freeways to free flow. This freeway evolution to three different environments has gradually evolved over the half century existence of the interstate highway system.

AHS deployment may be easy to envision in a final form, where all vehicles and roadways are AHS equipped. This would be a complete replacement for the manual interstate highway system. If this is a potential long-term goal, then the near-term process is one of converting manual freeways to automated freeways, to begin the market driven process towards the final level of automation. Solving this near term deployment problem is the immediate challenge for AHS designers.

The urban and rural analysis task is the initial task, under the Precursor Systems Analysis (PSA) research effort, that concentrates on the roadway aspect of AHS. A very general analysis approach was adopted for this task. This general approach will provide the overall insights necessary for use in other task research. Each of the three interstate environments: urban, suburban, and rural were characterized in terms of the following five attributes: Trip Characteristics, Incident Impacts, Roadway Restraints, Potential Market, and Societal Impacts. These attributes were chosen because of their effectiveness in characterizing freeway environments and their relevance to AHS design.

4.3.1.2 Conclusions and Key Findings

The following are conclusions from the analysis performed under this task:

- The daily user of urban and suburban freeways wants travel time savings as a performance improvement. Acceptance of AHS equipment and traffic management costs will be based on the performance gain. A target goal for this savings is one minute per 1.61 kilometer travel (one mile), totaling at least ten minutes on the freeway portion of the trip. This objective can, most likely, be accomplished by providing preferential lane and exit/entry provisions for AHS users, since automated control can regulate speeds above the current congested level. (UR1)

- Major sources of urban and suburban freeway congestion are incidents (non-recurring), bottlenecks at entry/exit points (recurring), and scheduled maintenance (non-recurring). AHS vehicle instrumentation and Traffic Management (TM) are tools to eliminate congestion, provided poor roadway geometry is corrected. (UR2)

- Worker commuter users of urban and suburban freeways are effective targets for early deployment of AHS. These individual users have a vested interest in making AHS a success as they gain time, reliability, and safer trips. As a daily user, they should be willing to equip their vehicles and pay for the service. High Occupancy Vehicle (HOV) users and Transit are prime customers for AHS since they are currently part of the solution for urban and suburban congestion. (UR3)

- Optimize operational improvements on urban and suburban freeways along with introduction of AHS, as it a part of a Traffic Management (TM) package not a stand alone service. Traffic Management includes; surveillance and control systems, ramp metering, incident management, motorist information systems, HOV facilities, and low-cost geometric improvements. These TM techniques are required to supplement AHS full automation. (UR4)

- During early year deployments, AHS performance may not be ideal in terms of congestion relief, due to mix of manual and automated vehicles. Working with existing freeways to gain initial automation benefits, provides a wider and more immediately visible return than attempting to build new AHS guideways to serve a select few. (UR5)

- Understand and respect the social issues of AHS deployment. AHS deployment is not just a technical installation exercise to provide a service. Impacts on land use planning, air/noise pollution and public/political acceptance may be more important than solving mechanical/electronic/concrete problems. (UR6)

- Consider separated AHS lanes a high priority for suburban freeway deployment, provided equal provisions can be made for entry and exiting. A major infrastructure design issue for AHS deployment is solutions to the traffic mixing, weaving, entry and exit with non-AHS vehicles especially heavy trucks. (UR7)

- Assume that AHS on rural freeways will initially operate in mixed traffic lanes. When AHS use increases, and higher performance is needed, the minimum lane requirements appear to be one AHS lane and two general use lanes. This requirement will impact most of the dual two-lane freeways (outer suburban and rural). Although traffic volumes may show only a need for a single general (manual) lane, entrance/exit, passing, incidents plus operation during maintenance will probably require a minimum of two general lanes. (UR8)

- AHS can increase throughput during peak hours provided the supporting interchanges, feeder roads and city streets can accept this increase. At the proposed high flow rates, urban and suburban facilities now regularly fail. Only rural freeway feeders have the capacity required. (UR9)

- Research into AHS technology is important as this defines the "How". Equally important is research in the market to identify size and needs as this defines the "Customer". The "How" should be driven by the "Customers' Needs". (UR10)

- Envisioning AHS as a national system requires flexibility of design to accommodate urban, suburban, and rural needs. The urban, suburban, and rural environments cover a spectrum of needs. Therefore, a variety of configurations are required to meet each of the needs. Suburban would be more I3 driven and rural would be more I1 driven. (UR11)

4.3.2 AHS Roadway Deployment Analysis and Impact of AHS on Surrounding Non-AHS Roads (Tasks H and I)

Tasks H and I results are reported as a single summary because they were performed as one task, due to the high level of coupling between them.

4.3.2.1 Objective

The objectives of these tasks are the following:

- Identify the types of infrastructure configurations which should be deployed. Representative System Configuration (RSC) definitions are discussed in Volume I. Since RSC I1 requires no change to the infrastructure, the studies included RSCs I2 and I3.

- Identify examples of Automated Highway System (AHS) deployment in the context of real case studies and quantify the benefits of these deployment scenarios using measures of effectiveness such as speed, delay, and throughput.

- Assess the effect of AHS market penetration (MP) on traffic patterns for RSCs I2 and I3 based AHS deployments.

- Assess the effect of traffic pattern changes on non-AHS roadways resulting from AHS deployment.

4.3.2.2 Technical Approach

Approach

The objectives described above were accomplished as follows:

- AHS roadway design concepts for RSCs I2 and I3 were developed. A physical layout of an AHS system employing these concepts was developed for the Long Island Expressway (LIE).

- Four case studies were developed to assess the performance and potential benefits of AHS installation. These included one urban, two suburban, and one rural freeway. Traffic loading and AHS and general lane configurations were developed for each case study. The INTEGRATION traffic model was adapted for evaluation purposes, and the performance of each AHS design was evaluated relative to a baseline or no build case. The effects on nearby surface street intersections were evaluated in some cases.

- An existing TRANPLAN traffic model of Long Island was modified to determine the effect of AHS deployment on areawide traffic. AHS MP was used as a variable parameter for this study.

- The generalized traffic pattern changes on surface streets caused by the introduction of the AHS were identified. Conceptual changes in traffic assignment models resulting from the introduction of AHS use costs to the motorists were identified.

- Certain AHS control strategies require tight control of vehicles desiring to enter the AHS. One approach to achieving this merge is to release vehicles desiring AHS access from an entry queue at the appropriate instant and under automated control. A study was performed to determine the queue delays experienced by the motorist and the queue storage requirements.

Key Assumptions

Analyses were conducted by making certain assumptions about the AHS. These assumptions were used as constraints for the evaluation of a variety of AHS designs.

- The capacity of the AHS lane was assumed to be 5000 vehicles per hour (vehicles/hr) with a usable capacity of 4500 vehicles/hr.

- All AHS access and egress ramps were assumed to have a capacity of at least 1400 vehicles per hour (vehicles/hr).

- The AHS access transition lane requires approximately 2500 feet.

- The AHS egress transition lane requires approximately 1600 feet.

- For the RSC I3, all AHS ramps enter and exit from and to a service road and/or a general use lane and/or a separate ramp. This eliminates the weaving movements of AHS equipped vehicles that utilize the AHS lane. Therefore, the AHS ramps can be placed closer to the traditional on and off-ramps.

- For the RSC I2, the access points to the AHS lane were placed at least 2000-3000 feet from the preceding on-ramp. Also, the egress points from the AHS lane were placed at least 2000-3000 feet from the next off-ramp. These distances were assumed to adequately facilitate weaving movements required by AHS equipped vehicles that utilize the AHS lane.

4.3.2.3 Conclusions/Key Findings

Infrastructure Design

This study concentrated on AHS infrastructure designs which provide separate lanes for AHS and non-AHS vehicles. The separate facility provides an environment which maximizes the constant speed and headway keeping capabilities of AHS vehicles. To create separate facilities, RSCs, with respect to the infrastructure, were developed. The RSCs developed were termed I2 and I3. RSC I2 provides for entry and exit to and from the AHS facility directly from the general use lanes of an expressway mainline. With the I2 design, the AHS lane can be physically separated by a barrier, a striped separation a few feet wide, or by a continuous transition lane for the length of the AHS lane. The continuous transition lane option for the RSC I2 design would require increased right-of-way as compared with the barrier option. Ingress/egress for the AHS lane would be allowed at any point. Finally, for RSC I2, both the transition lane option and the striped separation option require an impracticable level of enforcement to ensure exclusion of non-AHS vehicles. RSC I3 is achieved by providing separate ingress and egress for the AHS facility. The RSC I3 design was developed by separating the general use lanes from the AHS lane using physical barriers and providing AHS access/egress ramps that link directly to service roads or ramps.

AHS Performance Evaluation

Evaluation of the implementation of an AHS facility in urban, suburban, and rural environments provided the following results:

- AHS deployments using RSCs I2 and I3 on congested urban and suburban freeways can significantly improve speed and travel time on these facilities. Travel time improvements of up to 38 percent were obtained for the cases studied. Significant travel time improvements on the rural facility were only obtained when the AHS cruise speed was increased to 80 mph from the 62 mph speed used for the other cases. (RD1)

- The selection of I2 or I3 AHS lane access techniques is best determined by the AHS access and egress volume requirements, by the general lane traffic of these locations, and by the level of service (LOS) on the general lanes. (RD2)

- AHS deployments using RSCs I2 and I3 on congested urban and suburban freeways may significantly increase facility capacity to respond to future year demand. Depending on the origin-destination (OD) requirements, the capacity of the remaining general lanes rather than the AHS lanes may limit capacity. (RD3)

- In areas which experience traffic congestion, such as Long Island, high levels of AHS utilization are obtained based on RSCs I2 and I3 type facilities at relatively low levels of AHS MP (15-25 percent). (RD4)

- In congestion prone areas, the AHS may generate significant changes in the utilization of parallel facilities located several miles away from the AHS. However, as market penetration increases, as was evident on Long Island, the attraction of the AHS facility to distant parallel roadways decreases, and total vehicle-miles traveled (VMT) in the study area decreases. (RD5)

- The need to access the AHS will, in many cases, cause saturation of surface street intersections. Geometric improvements and signal timing changes will be commonly required. (RD6)

- Certain AHS control strategies call for queuing vehicles at AHS entry points (auxiliary lanes in the I2 configuration and ramps in the I3 configuration). Properly managed AHS traffic maintains queue delays and queue lengths at acceptable values. (RD7)

- The attraction of the AHS facility in congestion prone areas results not only from increased capacity, but also, because of the facility's ability to sustain a constant comfortably high speed of 60 mph at increased volume. (RD8)

- An AHS facility on a congested urban or suburban freeway might tend to reduce the total travel time vehicle-hours in comparison to comparable non-AHS facilities, while satisfying the trip demand. This finding, however, must be tested further using a more precise modeling technique. (RD9)

4.3.2.4 Recommendations for Future Research

Roadway Configuration

A number of different design alternatives are possible for RSC I2. These include:

- Continuous transition lane and continuous entry/exit versus entry/exit at discrete locations.

- Provision and configuration of an AHS breakdown lane or shoulder.

- Physical barriers versus striping.

These alternatives have an important influence on the AHS physical design and right-of-way requirements. The selection of the alternatives is, however, largely dependent on safety issues, longitudinal control issues, and entry/exit issues. Although these issues are discussed under the separate tasks, their resolution is key to roadway design.

Modeling and Simulation

Existing models enable studies to be carried out at the following levels:

- Area Wide Level

- AHS Network Design Level

- Microscopic Level

This task utilized models at the first two levels.

Area Wide Level

This level is useful for establishing the “catchment area” for AHS and the effect on non-AHS roadways. The TRANPLAN model was used for this purpose in the study. These models are generally based on the use of trip generation and trip assignment on a daily average (or other average) basis. The model is generally developed on an area wide basis. The model does not provide for discrete placement of traffic controls; thus, it is most useful to establish general trip patterns, not to study detailed implementations. Limitations which were encountered included the following:

- It is not feasible to convert the daily model to a peak hour model. This strongly limits the ability of the model to generate trip demand and trip tables for the AHS Network Design which can be used during peak periods and various other periods.

- TRANPLAN has no current capability to model different AHS MP at different locations or at different distances from the AHS. The modeling effort for this study assumed a constant level of MP for the entire area.

- TRANPLAN has no capability to model trip based AHS user costs (tolls).

It is recommended that the investigation of a model which corrects these deficiencies be considered.

AHS Network Design Level

Case studies were conducted at this level by using the INTEGRATION model. This level is intended to model the AHS network (AHS roadways and non-AHS roadways which are significantly affected by AHS traffic). The intent is not to model on a microscopic basis but rather to establish the network traffic flows, identify flow problems, and obtain the performance characteristics for different design alternatives. INTEGRATION was designed for modeling highways. AHS lanes, ramps, and traffic flows were modeled by adapting the freeway and ramp flow characteristics to the approximate characteristics of the AHS, but this could only be accomplished imperfectly. AHS flow characteristics which could be adapted to the specific design would have been preferred.

Development of a Methodology to Determine AHS Entry and Exit Locations

The development of entry and exit locations for the three urban scenarios was performed by considering entry and exit volumes together with OD characteristics. With the possibility of using either RSC I2 or I3 access configurations, a large number of designs are possible. Several design combinations were heuristically developed for each case study, and the preferred approach was selected.

It is recommended that research be considered to develop a more structured methodology. Such a methodology might use a combination of data based and rule based techniques.

4.3.3 AHS Roadway Operation Analysis (Task K)

4.3.3.1 Overview

Successful deployment of an AHS requires examination of all operational scenarios and associated operational elements under which an AHS will be utilized. The promise and the nature of automated highways, which involve instrumentation through electronic means, requires consideration of applications completely different from those associated with the way we operate and maintain our existing highway systems. For example, a fully instrumented infrastructure is subject to a wider range of preventive maintenance repairs and supervisory control as compared to existing highways. Due to the fact that the representative system configurations (RSCs) vary in characteristics of infrastructure, communication, command and control, and vehicle type, the AHS roadway operational analysis is subject to a range of issues and impacts. Assuming the evolutionary deployment of AHS, there are no show stoppers or operational barriers with regard to AHS deployment.

4.3.3.2 Key Findings

Some of the key findings and considerations are as follow:

Current traffic management systems are primarily passive (and at best semi-automatic) and rely on macroscopic state variables such as density and speed to identify congestion and incidents. While traffic flow management requirements of an AHS would vary by RSC, configurations with central control will require a more discrete, microscopic orientation of traffic monitoring and management. The characteristics of traffic flow monitoring and management need to be examined and defined as AHS evolves. (RO1)

Although it is the promise of the AHS to reduce the occurrence of incidents, the impacts of any incident on AHS will be catastrophic with regard to traffic operation. Therefore AHS must improve incident detection and shorten incident response time. The impact of traffic congestion and delay on an AHS lane will be much greater than current impacts to the existing highway system. Therefore, the incident response time must be reduced in order to maintain current highway levels-of-service. (RO2)

For operation of an AHS, new or hybrid operating agencies and their organizational frameworks will need to be defined along with their potential operations responsibilities. The levels of association, coordination, and autonomy among the operations elements of existing highways, such as management, maintenance, police and emergency services need to be identified along with potential problems with existing arrangements of these operations elements. Each operating agency scenario and the operational impacts of a multi-jurisdictional framework need to be evaluated and studied. Evaluation criteria should include operations uniformity, effectiveness, and practicality of providing such service. (RO3)

Current levels of expertise and staffing available at existing operating agencies can not support the requirements necessary for an AHS. The areas of expertise required for operation and management of an AHS need to be evaluated. Survey and review of current practices of in-house versus contracted-out functions at state DOTs and highway authorities are essential to final deployment of AHS. (RO4)

AHS operations require preventive maintenance on a level similar to the airline industry. Existing levels of preventive maintenance performed by highway operating agencies, including operators of traffic management systems, will not satisfy the requirements of AHS. A target level of preventive maintenance for AHS needs to be defined through investigations of comparable systems. (RO5)

It is anticipated that the AHS will need policing and involve policing tactics different from those practiced today. Dependent upon the RSC, the level of policing, police functions, and tactics will vary. Current policing practices need to be examined, including the level of policing, functions and tactics applicable to deployment of an AHS. (RO6)

4.3.3.3 Recommendations For Future Research

Successful deployment of a fully-automated AHS is highly dependent on its reliability, efficiency and safety. In fact implementation of AHS concept will require careful and prudent planning, implementing, operation, maintenance, and mitigation efforts based on a clear understanding of the potential issues and potential problems. We believe in particular that further research is required in the following three areas: incident management techniques, maintenance requirements, and environmental monitoring.

4.4 AHS SYSTEMS ANALYSIS

The AHS systems analysis consists of these five task report summaries: (1) Automated Check-In (Task B), (2) Automated Check-Out (Task C), (3) Lateral and Longitudinal Control Analysis (Task D), (4) AHS Entry/Exit Implementation (Task J), (5) Vehicle Operations (Task L).

4.4.1 Automated Check-In (Task B)

4.4.1.1 Objective and Approach

The objectives of the check-in studies were to (1) develop a preliminary definition of the functions and subsystems that should be tested before the vehicle enters the AHS; (2) study methods of performing these tests; and (3) study how the check-in process might be performed for various Representative System Configurations (RSCs). The various systems/functions to be tested were grouped into two categories: one includes all normal vehicle-related items, such as oil pressure and engine coolant temperature; the other involves all AHS-related equipment, such as the steering or longitudinal control system. For each group, rather extensive lists of functions were identified and examined. The lists were reduced by combining functions into more systems and eliminating items that were very unlikely to cause a breakdown or present a serious safety hazard. For each item, we determined the criticality, measurability, and frequency of tests.

Check-in scenarios were postulated for various RSCs to outline where and how the check-in process would occur.

4.4.1.2 Conclusions/Key Findings

Three major key findings resulted from this study, as discussed below:

- Check-in tests should be performed on the fly. (CI1)

We believe all check-in tests can be made without stopping the vehicle. Status of all vehicle equipment can be tested with a series of dynamic tests. Upon receipt of a command to perform a check-in test, either generated by the roadside or by the vehicle computer, the various tests are performed. If certain tests determine that some vehicle equipment fails the test, the vehicle's computer would prevent the engagement of the automatic modes, and would also communicate to the roadside infrastructure that the vehicle is not fit to operate on the AHS.

- Actuators for steering, throttle, and brakes will require testing in a series of dynamic tests. (CI2)

In order to test for the proper operation of the various actuators, it is necessary to command the actuator to move and measure its response to the test command. These dynamic tests, which will cause a steering maneuver and changes in the vehicle's longitudinal acceleration, need not be a large or long-duration displacement. Steering tests can be a series of short pulses that may result in displacing the vehicle only a few inches. These tasks can be made on an out-ramp or in a transition lane.

- Vehicle testing will be performed continuously during AHS operation. (CI3)

The vehicle equipment test sensors and built-in test systems used during check-in will also be used as part of the malfunction management system to monitor vehicle health when engaged on the AHS. Tests of all the vehicle systems will be performed at various rates; e.g., the lateral control system will need to be monitored at a high rate. The check-in function can be considered a subset of the vehicle malfunction monitoring and management system.

With such an approach, the check-in/monitoring system must be tamper-proof, thereby preventing an unfit vehicle from operating on the AHS roadway.

4.4.1.3 Recommendations for Future Research

- Studies should continue to address how various monitoring instrumentation could be implemented for functions not currently monitored on vehicles, such as coolant and transmission fluid levels.

- A study should be conducted of the various actuator technologies that could be employed to provide steering control and brake operation. Both of these areas are safety-critical (particularly the steering), and will most likely require redundant components to provide the required extremely low probability of failure. This study should address reliability, cost, and ease of implementation.

- A system architecture study of the vehicle equipment monitoring system should be performed. Issues such as how the various sensors are monitored, built-in-test commanded and performed, and dynamic test executed need to be addressed. Outputs of this study would include a plan for how all the vehicle health monitoring, malfunction detection, and management would be integrated.

- Future studies and analysis of check-in should be combined with the malfunction management efforts into a single area. Check-in testing is a subsection of the larger area of malfunction detection and management.

4.4.2 Automated Check-Out (Task C)

4.4.2.1 Introduction

The check-out process is a critical component for ensuring AHS safety. It concerns the process of assuring safe transfer of control from the automated driving system to manual driving. Because the driver has been out of the driving loop during AHS operation, there is concern that the driver will not be ready or capable of assuming driving control and responsibility. Check-out is the procedure for transferring vehicle control to manual operation in a way that ensures driver readiness and capability, and tests the integrity of mechanical vehicle components needed for manual driving. The objective of this task is to identify and analyze issues associated with the design and implementation of a check-out process, within the context and structure of the AHS representative system configurations.

In order to complete this task, we have applied engineering analyses and small group brainstorming as the primary technical approaches. In addition, we have conducted a literature review, and have obtained inputs from other PSA tasks, as necessary. Our analysis has identified two distinct forms of the check-out process. The first, normal check-out, occurs at the end of an AHS trip. It is a routine process used to evaluate the driver's ability to retake manual control, when he/she has indicated a desire to exit the AHS. The second, emergency check-out, occurs during an automated trip, when a malfunction in the system is detected, requiring driver intervention. This type of check-out usually occurs with little forewarning.

4.4.2.2 Conclusions/Key Findings

The conclusions/key findings from this analysis are listed below. They are described in more detail in the discussion that follows.

- There are two types of check-out that must be considered: normal check-out and emergency check-out. (CO1)
- There are two parts to check-out: the testing of vehicle components, and testing for the driver's readiness to retake manual control. (CO2)
- During the process of transition from automated to manual driving, the driver must take control of the vehicle rather than having the vehicle give control back to the driver. (CO3)
- The check-out "test" should be an integrated part of the larger check-out process. (CO4)
- If check-out "tests" are required during the automated portion of the trip (for the purpose of maintaining an adequate level of vigilance), these "tests" should be meaningful and not artificial and extraneous. (CO5)
- The driver portion of the check-out process must account for the wide variability in capabilities within the driving population. (CO6)
- The requirements and approach for check-out are interdependent with the requirements for, and design of, AHS features and infrastructure. (CO7)

4.4.2.3 Approach

The transfer from automated vehicle control to manual control involves a mode switch. The relationship between the automated and manual systems of the vehicle that are involved in this mode switch are shown in figure 3. The objective of the check-out process is to ensure, when making this control transfer, that the linkages between the manual controls and vehicle actuators are functioning properly, and that the driver control logic is fully engaged and integrated within the dynamic driving situation.

It can be seen from this model that there are two aspects of the check-out process that must be considered. First, the integrity of the linkages between the vehicle actuators (e.g., the mechanical components that turn the wheels) and the driver's controls (e.g., steering wheel, pedals) must be verified before the automated control linkages can be safely disengaged. Second, driver readiness to assume control must be verified. Issues for accomplishing these requirements are described in this section and are summarized below.

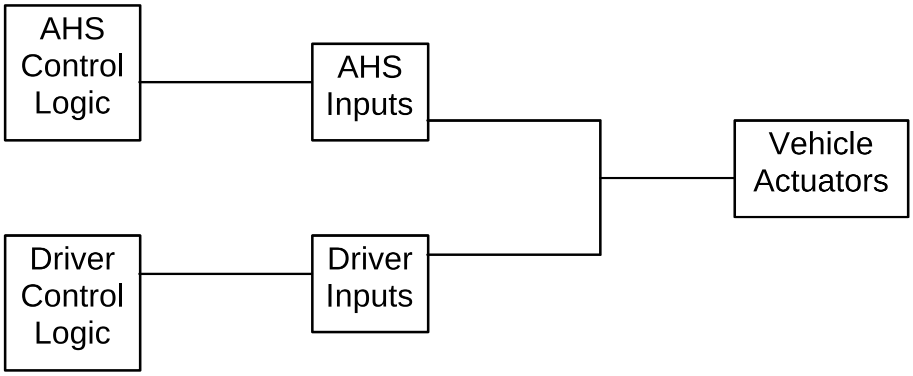

Figure 3. AHS Driver Check-Out Model

Assumptions

Several assumptions were made about the design of AHS to provide a common understanding for this analysis. These assumptions do not constrain the issues and conclusions defined, but rather provide a framework for their discussion. In most cases, if these assumptions are not correct, the design of the check-out process will be made easier. The assumptions and their impact on AHS check-out are summarized in table 6.

Given the assumption that drivers will have a malfunction management role during AHS operation (at least for initial AHS implementations), there will be a requirement for emergency check-out procedures. These will carry more demanding check-out time constraints than for normal check-out at AHS exits. Special check-out procedures will need to be applied to meet these more demanding requirements. It may be necessary to use less comprehensive tests, perhaps supplemented with an alarm to speed the alerting process. It may also be necessary to accept less certainty about full driver engagement in order to avoid a potentially more serious system failure condition. Both emergency and normal check-out procedures will need to be developed for AHS and both will need to be accomplished within available time budgets. The design of emergency check-out will require consideration of the underlying causal conditions and trade-offs between time available and the potential consequences if check-out is not accomplished quickly.

Table 6. AHS Assumptions Applied to Provide Context for the Check-Out Analysis

Assumption	Description	Implication for Check-Out
AHS cannot force drivers to obey all traffic laws.	AHS may help mitigate hazards associated with law breakers (e.g., vehicle inspection verified at check-in, minimal required driver capability verified at check-out). However, some risks from law breakers cannot be totally avoided (e.g., non-AHS-certified drivers using another driver's license). Potentially serious hazards resulting from law breakers will need to be addressed through enforcement or other means.	There are conditions that will reduce drivers' ability to safely exit the AHS that will not be tested directly during check-out (e.g., alcohol consumption). The check-out process will be applied to ensure that drivers have minimal capacity to safely transition to manual driving and drive safely. It will not be applied to ensure that all laws associated with safe driving are complied with.
Drivers will have a role during AHS operation requiring them to remain awake.	Because AHS is most likely to develop in an evolutionary fashion, we assume there will be a driver role during AHS operation (e.g., system monitoring, malfunction management), at least in early AHS implementations. This role will require driver wakefulness.	This assumption makes the check-out process more difficult to manage because there may be a requirement for check-out to be accomplished at any time, not just at exits. Further, since drivers will have a role in malfunction management, check-out under system failure conditions will need to be accomplished very quickly. It will be necessary to deal with sleepy (or sleeping) drivers, if this occurs.
Drivers will not be required to preselect destinations.	Most drivers will have a final destination in mind when entering the AHS. However, intermediate, unplanned stops may be required (especially on long trips) and some drivers may not be willing or able to pre-select exact exits (e.g., when traveling to unfamiliar cities).	In addition to ensuring safe transition to manual driving, the check-out process will need to be concerned with determining when the driver desires to exit the AHS (at least it makes sense to include this within the check-out procedures).
Drivers will be able to override the AHS and retake control (at least in initial AHS implementations such as RSC I1).	Since during initial AHS implementations we assume the driver will be required to serve in a system monitor role, there may be situations in which the driver determines that the AHS is not working properly and will need to take control.	The check-out design must consider the requirement for a driver initiated check-out process.
Drivers will have a "panic button" available for emergency AHS trip termination.	There may be situations in which the driver needs to immediately stop the vehicle (e.g., medical emergencies). Under these conditions, transition to manual control should not be undertaken. Nevertheless, AHS operation will be ended (e.g., the vehicle may be parked and help summoned).	Check-out design should recognize this manner of ending an AHS trip and consider driver interface issues (e.g., determining reason for ending the AHS operation).

Automation Guidelines/Implementations

Automated systems are becoming more and more commonplace today, and research into design approaches for optimal human oversight and intervention is being undertaken. Guidelines for the design of user interfaces to automated systems are emerging. These can provide guidance for the design of AHS, and particularly for AHS check-out related operations (e.g., maintaining awareness level to allow successful emergency check-out) . A few examples of these guidelines that may be applicable to AHS are given in table 7.

Table 7. Sample Automation Guidelines and Example AHS Implementations

General Automation Guideline	Example AHS Design Approaches
If automation reduces task demands to low levels, provide meaningful duties to maintain operator involvement and resistance to distraction.	• Remind drivers about approaching exits and request desires for continuing or exiting. • Provide information about system and trip status for driver review. • Provide access to on-line AHS training material.
If alarms have more than one mode or more than one condition that can cause the alarm, clearly indicate the mode or condition.	• Clearly indicate nature of AHS failure condition (especially if driver must respond)
When response time is not critical provide information to allow the validity of alarms to be established quickly and accurately.	• Present AHS status information in addition to alarm condition.
Provide training for operators working with automated equipment not only to ensure proper set-up and use, but to impart knowledge of operational concepts, malfunction procedures, and monitoring requirements.	• Make AHS operation extremely simple and/or provide training. Consider special licensing requirements.

Driver Readiness Issues

There is a large body of research dealing with how humans process information that can be applied to the design of an effective (driver) check-out procedure. This research deals with the way humans detect and discriminate stimuli, recognize and comprehend information and situations, make decisions, and select and execute responses. Knowledge of human strengths and limitations, within these activities, is necessary to design an effective check-out process. For example, a check-out process that focuses the driver's attention on the most critical information will help avoid selective attention and distraction problems. In addition, redundant cues can shorten and improve the process of developing driving situation awareness, (e.g., alert the driver about special road conditions). By careful human factors design, the driver readiness portion of the check-out process can be fine-tuned to perform in the most optimal fashion.

Human monitoring performance and associated vigilance decrement problems (reduction in level of alertness) have also been extensively studied. This research base can also be applied to AHS design of level of alertness and monitoring performance features. For example, knowledge of task duration has been found to affect the vigilance decrement. This can be applied to develop different approaches for maintaining vigilance on rural and urban AHS segments. One approach to ensure that the driver remains vigilant and alert is to test the driver periodically throughout the trip. However, these tests should be meaningful and related to the trip on the AHS. People generally do not respond well to meaningless tasks, and may perform poorly if they do not believe the test is important. For example, AHS could alert the driver that an exit is approaching, and could ask whether the driver desires to check-out. The act of responding to the system is an indication that the driver is awake and alert.

The driver check-out process must be designed to ensure that the driver is capable and engaged with respect to each important aspect of driving performance. Figure 4 shows a generalized model of the driving task including each important cognitive and control subtask. The check-out process must address each of these subtasks to keep the driver in-the-loop, ready, and capable of assuming driving responsibility.

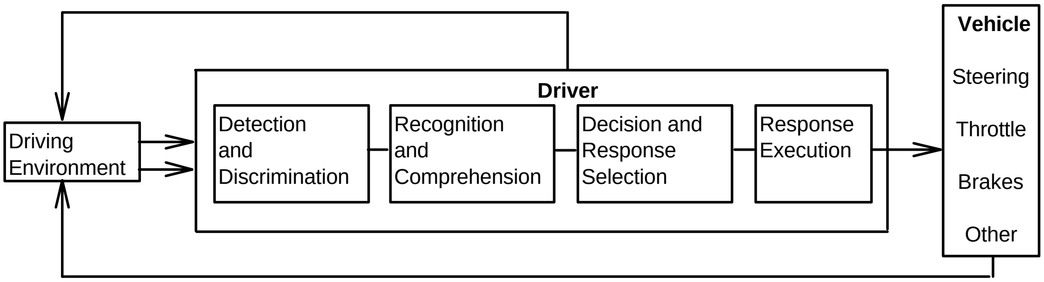

Figure 4. Information Processing Model

Given enough time, testing for driver capability and engagement with respect to the driving subtasks, shown in the information processing model (figure 4), would be straightforward. There are substantial research and tools available to support the measuring of human performance with respect to each of these activities. However, the practicality of implementing a driver assessment procedure within the check-out process must be considered. Drivers will not tolerate a system that requires a battery of tests each time the AHS is exited. Additionally, AHS flow requirements and infrastructure limitations dictate that the tests be accomplished quickly. Our AHS check-out challenge is to accomplish the goal of a comprehensive driver assessment within the worst-case time available. Further, this must be accomplished for AHS drivers varying in age, experience, and capability.

It would be most advantageous if the driver assessment procedure is accomplished within the process of transferring control from the automated driving system to manual driving. That is, the control transfer procedure should be designed to include steps that accomplish both transferring control to the driver, and assessing the driver's readiness to accept control. Table 8 shows each component of the driving task, as illustrated in figure 4, and identifies a general approach for assessing driver capability with respect to each. This is a very general model that needs to be further developed and tested during the next AHS program phase.

Table 8. A Generic Model of Driver Assessment within the Driving Control Transfer Process

Driving Subtask	Example Driver Assessment Approach
Detect and discriminate roadway stimuli	• The process of assuming vehicle control must ensure that the driver is attending to the roadway ahead. By placing the signal that the vehicle is ready to relinquish control in the forward field of view, the driver's focus can be properly directed. • The timing of vehicle ready signals should be determined on the basis of the time needed for worst-case drivers to gain a sufficient sense of dynamic roadway cues for an adequate level of situation awareness and pursuit-tracking performance (i.e., lane keeping).
Recognize and comprehend the driving situation	• The response to the vehicle ready signal can be simple yet one that requires recognition and comprehension. For example, require drivers to hit a button on the steering wheel that relates to correct vehicle speed or to a road sign ahead (could be a variable message sign showing a random number). • Special roadway condition information can be provided verbally during process (verbally so as not to compete with ongoing visual processes).
Demonstrate adequate decision and response capability	• Correct response to vehicle ready signal above provides evidence of adequate decision and response functioning.
Demonstrate correct response execution	• Driver must have hands on the wheel and feet on the pedal(s) (or the appropriate pedal). Driver may be required to initiate an appropriate steering wheel input (as determined by AHS sensors or just turn the wheel back and forth once) and tap the brake (as currently done for disengaging cruise control).

It must be emphasized that this is a very skeletal description of a possible driver readiness assessment process. The specifics of this procedure need to be determined and validated on the basis of further analysis and test. This generic example of a possible approach to meeting this requirement serves to demonstrate how the steps of driver readiness assessment can be embedded within the vehicle control transfer process in a way that is practical for AHS implementation.

One critical aspect of the driver readiness assessment process is that it never fails in determining that the driver is controlling the vehicle when automated control is relinquished. Our recommendation for meeting this important requirement is that the driver be required to **take control** rather than have the vehicle give up control. The driver should be required to initiate a positive action using the vehicle's manual controls to complete the control transfer process. This is very similar to the way drivers currently take control from today's cruise control. The check-out process must ensure continuous active control of the vehicle, and has important liability implications. This is an important conclusion of this task.

Vehicle Check-Out Issues

In addition to verifying that the driver is ready and actively controlling the vehicle, the integrity and proper functioning of the critical vehicle control mechanisms must be ensured. Most vehicle control functions operate under both automated and manual driving conditions, and, therefore can be assumed to be working. However, the manual links to safety-critical actuators must be verified. These include actuators for steering, braking, and throttle. Three possible approaches to AHS design relevant to these tests have been identified.

In the first design approach, the manual vehicle control system or the automated vehicle system can be connected at a time. One can be connected only when the other is disconnected. The approach to verifying manual control integrity with this design may be mechanical; e.g., a mechanical switch can be engaged when manual controls are "locked-in." Automated control links can only be allowed to disengage when the mechanical engage switch is engaged.

The second approach, requires software logic and control response testing. In this approach, both control modes remain connected to the vehicle actuators at all times. An electrical switch is used to control which mode is to be recognized by the actuators at any one time. The verification of control integrity must be done through control response testing, and the switch to manual control can only occur after the automated system has been disengaged.

In the third approach manual control is always engaged. All that is needed to disengage the automated system is to provide an input to the manual system. Thus, the vehicle actuators can accept commands from both control modes simultaneously. We do not recommend this approach, since a driver who accidentally provides an input to the manual control system (e.g., bumping the steering wheel) will interfere with the automated control system. This could lead to a potentially dangerous situation.

AHS/Highway Design Issues

There are also issues of AHS infrastructure design that have been identified during this task. It is assumed that the check-out process will be performed while the vehicle is traveling, at regular highway speed (as determined by the automated system). It may occur on the AHS or in the transition lane. Thus, during the time required to perform the check-out tests, the vehicle will cover quite a distance. In addition, it will be necessary to allow the driver to retake the check-out test upon failure on the first attempt. This further increases the distance traveled by the vehicle. For example, a vehicle traveling at 60 mph will travel 1/4 mile in the time necessary to conduct a 15-second test, and 1/2 mile in the time necessary to conduct two 15-second tests. It is necessary to initiate the check-out process far enough in advance for all of the check-out tests, and retesting if necessary, to be conducted prior to reaching the driver’s desired exit. The point where check-out must begin is determined by the speed of travel, the duration of the check-out test, and the maximum number of allowable retests. Roadway conditions may also affect where (and when) check-out is initiated. When the roadway is in less than optimal condition (e.g., rain, ice or snow), vehicles require a greater distance to decelerate, and may require additional time to perform the check-out process. Also, the check-out process may need to be modified in these situations, to reflect the increased difficulty of the driving task during non-optimal conditions.

The design of the check-out process may also affect the design of the entry/exit infrastructure, and may depend on how a check-out failure is handled by the system. AHS may either keep a driver on the system past the desired exit for further testing, or may park the vehicle at the desired exit. If a vehicle is allowed to continue to the next exit, it may be necessary to remerge that vehicle back into AHS traffic (if the vehicle had been pulled into the transition lane for check-out testing.) If a vehicle is to be parked, it may be necessary to construct parking lots at exits, or to merge the vehicle back into traffic until a breakdown lane can be reached. Obviously, it is undesirable for vehicles that fail the check-out process to interfere with the AHS traffic.

4.4.2.4 Recommendations For Future Work

Based on our analysis, it is not possible to specifically design an appropriate check-out process. Check-out is dependent on the design of many other AHS components, as well as the representative system configuration. However, based on our knowledge of what issues must be addressed during the check-out process, we can make the following recommendations for future work. First, additional study on the ability of a driver to retake manual control of his/her vehicle at high speeds and close headways is warranted. In addition, we recommend an experimental approach to the determination of the passing criteria for the check-out process. Individual variability, as well as the level of participation in the eventual AHS design, must both be taken into account. Finally, we stress the importance of designing the check-out process based on human factors considerations (e.g., information processing, vigilance, and interaction with automation), and in cooperation with other AHS design tasks (e.g., entry/exit, malfunction management, and lateral/longitudinal control).

4.4.3 Lateral and Longitudinal Control Analysis (Task D)

4.4.3.1 Introduction

The main emphasis of the Lateral and Longitudinal Control analysis was directed toward (1) a detailed review and study of the various technologies that may be utilized to provide sensors for lateral position measurement and longitudinal headway, and (2) a rather detailed digital simulation of a longitudinal control loop including the vehicle, engine, braking system, and control algorithms. To a lesser degree, consideration was given to communications associated with lateral and longitudinal control, obstacle detection, and a preliminary study of the cost trades between a system that employs an autonomous vehicle-follower longitudinal control and a point-follower system using an infrastructure base headway measurement system. Automatic lateral and longitudinal control is, of course, the heart of any AHS system. The studies conducted on this program barely scratch the surface of the automatic control problem. We do hope, however, that we have focused our efforts at some of the key design issues.

4.4.3.2 Approach

The following discussions briefly describe the various tasks performed.

Suggested Maneuvers

We very briefly looked at the various maneuvers that a vehicle will perform during travel on the AHS. These maneuvers include lane changing, closing a gap, and creating a gap. We defined some time/acceleration profiles for these maneuvers based upon ride comfort. This study was performed to give an insight into the time lines to perform these maneuvers. For instance, to close a gap of 60 feet requires approximately 12 to 13 seconds, if control is performed with throttle only (no braking).

Sensor Technology for Lateral and Longitudinal Control

A major effort was directed at the study of the sensor technology that might be applied to the problems of locating the lateral positions of a vehicle in a driving lane and the measurement of the headway between vehicles. For each of the technology areas, a review of the sensor technology was made along with a review of the work performed by other researchers.

Communication Considerations

Some preliminary communication studies were performed to address requirements , available technology, and possible communication structures. Because of the sheer numbers of vehicles in a given area, communication among vehicles, as well as with the infrastructure, require special techniques. One may want to consider operating frequencies in the absorption frequency bands (60 GHz) to limit the interference in other nearby regions. Some of the data to be passed between vehicles will require fairly high data rates, such as 20 Hertz to avoid data latency. The study examines transmitter power requirements, choice of frequencies, and network and link structures as well as multipath considerations.

Sensor Technology for Obstacle Detection

A brief study was performed into the various sensor technologies that may be employed to detect obstacles located on the AHS roadway, such as, mufflers, tail pipes, pieces of truck tires, and animals. Reliable detection of these obstacles with a low false alarm rate is extremely difficult. The most promising approach is to utilize two sensors, a passive optical system coupled with an active microwave radar. By comparing the data from the two sensors, one can eliminate shadow and flat items. The technology is by no means straightforward and may require a high resolution microwave radar.

Some Preliminary System Requirements for Lateral and Longitudinal Sensors

We have collected some preliminary requirements for the lateral and longitudinal sensors and control systems. It is too early in the AHS development to identify very many requirements or specifications; however, there are some general and a few specific values to suggest to AHS researchers.

We believe the automatic lateral and longitudinal control loops must be able to function in rather severe adverse weather, such as dense fog, heavy rain, and blizzard-like snow storms. Since the technology exists to provide an all weather operation, it makes little sense to pursue technology that exhibits the same limitations as the human. Lateral position sensor errors should be limited to approximately 5 to 7 cm (two to three inches) (1 sigma value) in order to hold lane tracking deviations to less than 15 cm (6 inches). We also believe that a measure of the coefficient of friction between the tire and the road surface will be required for both the lateral and longitudinal control loops. Headway gap, speed, and control loop gains must be adapted to the roadway conditions. Control loops that are designed for dry pavement will be completely unstable on an icy road.

Longitudinal Control Loop Digital Simulations

A rather detailed digital simulation of the longitudinal control loop was developed. This model included the vehicle, engine model, throttle control loop and a braking model. Provisions were made to allow a string of vehicles to operate in car-following mode. Tests were conducted with lead vehicle transients such as step accelerations and decelerations (including emergency braking). The simulation included modeling of headway radar sensor errors, both the headway gap distance and rate of change of the gap (differential velocity). Tradeoffs were made between loop bandwidths or gains vs. radar sensor errors. No effort was made to develop a lateral steering control loop. Because of limited program resources we focused on the longitudinal control loop, which is far more complex.

Recommended Sensor Technology

From a rather detailed study of the various sensor technologies, we have identified techniques that we judge as most promising and should be given special consideration.

Lateral guidance, in our view, can best be accomplished with magnetic markers such as the "nails" developed by the PATH program. The markers are low cost and very economical to install. Their greatest feature, however, is the ability to operate in all weather with very high reliability. The only drawbacks are that lane changing must be performed by dead reckoning between lanes. Also the range of control is limited to two feet or less from center line. Overhead induction wires can also be employed for lateral guidance, which will allow for lane change and a wider range of lateral control. The induction system is also all weather.

It appears that the measurement of headway gap can best be obtained from a millimeter wave radar which would allow for operation in fog, rain, and falling snow. Data link ranging using cooperative transceivers on the front and rear of each vehicle provides an all-weather approach but would only function if the vehicle ahead is also equipped. Since all vehicles must be AHS equipped, the system would not function on mixed traffic roadway that might be an early version of AHS.

Cost Trades Between a Vehicle Mounted Car-Follower Longitudinal Control System and an Infrastructure Based Point-Follower System

A preliminary cost trade study was made between a longitudinal control system that uses a vehicle-mounted headway measurement device operating in a vehicle-following mode as opposed to a system that uses roadway based sensors to measure the headway gaps between all vehicles. Each vehicle would be commanded to travel at a given speed, with periodic updates to each vehicle longitudinal control loop to maintain a given headway. For the assumptions made during the study (mainly that the roadway is located in a high population density where there is a very large number of vehicles per freeway mile), there are some total cost advantages to the infrastructure-based system, if the headway radar system costs more than $200 per vehicle.

4.4.3.3 Conclusion and Key Findings

During the course of the studies, several results became apparent. Because these results will have significant impact on further studies and research, we have referred to them as key findings. Each of these findings is discussed below:

- Sensors for lateral and longitudinal control must be capable of performing under severe adverse weather conditions. (LL1)

  An AHS system should be capable of operation during adverse weather such as very heavy rain, dense fog, and heavy falling snow. Many researchers are pursuing technologies that clearly will not function in severe weather. The argument that it is acceptable if it performs as well as a human does not make much sense to us. If, during severe weather, the lateral sensor can no longer locate the lateral position of the vehicle, or the headway sensor can no longer measure the headway, a serious safety condition exists. This is particularly true of lateral control. If a rain storm limits the performance of a headway sensor, other action can be taken, such as slowing (or stopping) all traffic. However, lateral guidance is required even if it is only used to steer the vehicle while a stopping maneuver is performed. During periods of severe weather, such as heavy rain or fog, the highway speed may be significantly reduced, provided that the sensors can continue to operate. To accommodate increased sensor errors, the gap spacing may be increased. Loss of lateral position information cannot be allowed to occur.

We must currently accept the limitations of the human sensors to function in severe weather, but we need not accept them for an AHS because sensor technology exists to provide for continued AHS operation in very dense fog, heavy rain storms, and blizzard conditions.

- Most promising lateral control technology involves magnetic markers or overhead wires. (LL2)

  Of the many techniques that various researchers have explored to provide lateral position information, the magnetic markers or "nails" appear to be the most attractive. They are inexpensive and of low cost to install in a roadway. They are passive (requiring no power), extremely durable, and will provide control in all weather conditions. Component failure will occur gracefully; i.e., if a given magnet should fail, vehicle operation can continue because one missing magnet will not affect performance.

  Lateral control based upon overhead wires that radiate signals, while more costly to install, also operates in all weather. The wires can also be used to provide a moving reference for point-follower type longitudinal control.

- Headway radars will be required to provide high azimuth angle resolution. (LL3)

  Headway radars used on an autonomous vehicle will be required to measure and locate the position of vehicles to determine the driving lane they occupy over ranges of approximately a few meters (feet) to 60 or 90 m (200 or 300 feet). Azimuth look or scan angles of ±45_ are likely to be required to confirm slots for lane change or merge/demerge. Because of the need to locate the vehicle in the azimuth plane, the headway radar will be required to have a beam width of one to two degrees, thus the radar sensor beam will need to scan in azimuth, either mechanically or electronically.

- Infrastructure-based systems may be cost effective. (LL4)

  An AHS system configuration which is based on the use of infrastructure-mounted sensors to obtain vehicle longitudinal position and to provide a portion of the longitudinal guidance signals and vehicle malfunction detection functions may have cost advantages over a system containing vehicle-based sensors which perform these functions. The component reliability of the infrastructure equipment can be made sufficiently high through redundancy so that component failure does not contribute significantly to the reliability of the overall system.

- Communication between vehicles may not be required for vehicles following at gaps of 0.5 seconds, even during emergency maneuvers. (LL5)

  Results of simulations show that communication of the acceleration of the lead vehicle(s) is not necessary for braking maneuvers. The simulated design separated the brake controller from the throttle or accelerator controller. The accelerator controller is designed to maintain vehicle headway during normal maneuvers, while the brake controller is designed to avoid collisions. Simulation shows that no collisions occurred even with the lead vehicle braking up to 1 g. The conditions were 0.5 seconds plus 1.5 m (5 feet) nominal gap, 97 kph (60 mph) speed, up to 15 following cars, and all cars had the capability of 1 g maximum braking. The reduction in headway as speed decreased to zero was more than enough to make up for distance lost because of sensing and braking dynamics. The acceleration of the preceding vehicle was estimated from the rate of change of the differential velocity. Up to 30 cm/sec (1 ft/sec) noise like errors on the speed measurements did not degrade the safety of the brake system. Speed and distance measurements were made at a 20 Hz rate, using an independent noise sample for each measurement. The minimum value for the gap to maintain safe braking has not been explored, but we expect it to be less than 3 m (10 feet). This finding is significant. Most researchers, ourselves included, have felt that each vehicle will need to pass its acceleration to following vehicles to prevent a collision during hard, emergency braking.

- There is a tradeoff between longitudinal maneuver errors and noise immunity. (LL6)

  In the design of a longitudinal controller for an AHS, there exists a classical tradeoff between tolerable maneuver errors and noise immunity. Typically, a longitudinal controller is designed to maintain a certain headway from the preceding vehicle. When the preceding vehicle changes speed, the following vehicle's control system will generate an acceleration command to maintain the headway. During the speed change, the headway error could range from a few centimeters to meters (inches to feet) depending on the maneuver. In our simulations, an increase in speed from 80 kmph (50 mph) (73.3 ft/sec) to 97 kph (60 mph) (88 ft/sec) at 0.1 g generated a 2 m (7 ft) distance error. The headway error gradually diminished to near zero ft/in about 25 seconds after the maneuver. If the bandwidth of the control system is increased, the headway errors can be reduced to less than 0.6 m (2 ft) with total recovery in less than 10 seconds. Although the tighter control seems more desirable, the effects of sensor errors in the system make a high bandwidth control system impractical. We believe that typical sensor errors for ranging and doppler devices are likely to be 0.3 m and 0.3 m/sec (1 ft and 1 ft/sec), respectively. When these errors are used in a high bandwidth simulation, throttle displacement is larger, causing accelerations of 0.6 m/sec/sec (±2 ft/sec/sec) during steady state cruising. The net result is an uncomfortable ride for the AHS user, not to mention reduced fuel economy. As the bandwidth of the control system is reduced, the ride may be more tolerable with accelerations for steady state cruising at 0.15 m (±0.5 ft/sec/sec). The net result is a tradeoff as shown below.

Control System	**Steady State Accelerations**	**Max Error**	**Recovery**
High Bandwidth	±0.6 m/sec/sec	±0.6 m	10 seconds
Low Bandwidth	±0.15 m/sec/sec	±2 m	25 seconds

In order to provide a high bandwidth control system providing rider comfort, improvements in the control system could be made. Improved decisions using Kalman filters or a different controller may provide lower errors and lower accelerations, but for each design a tradeoff between noise immunity and maneuver error must be made.

It should be recognized that the simulation used on this program did not assume that lead vehicles would communicate with following vehicles. The control system derived the lead vehicle acceleration from the differential velocity measurement which contains noise-like errors. If the leading vehicle passed its acceleration data to the following vehicle, a "cleaner" acceleration signal would be available. Thus, a high gain loop could have been used with better performance.

4.4.3.4 Areas For Future Research

The studies performed under this task have barely scratched the surface of the total problem of lateral and longitudinal control. Control of the steering, throttle, and brakes is, of course, the heart of an automatic highway system. From our studies, we have concluded that several areas need immediate study. These areas are discussed below.

- The longitudinal simulation effort begun on this task should be continued and expanded to include lateral control. Studies should be made with multiple vehicles in a car-follower mode to develop tradeoff data between sensor accuracy, performance, and ride comfort so that preliminary specifications can be developed for sensors and to evaluate various concepts for lane change, merge and demerge maneuvers.

- Promising sensor techniques for lateral position measurements and headway measurement should be developed and tested. Prototypes should be built and tested. In particular, the magnetic markers or nails developed on PATH program should be further developed and refined. The advantages of all weather, low cost, and high reliability make it a forerunner technique that should receive serious consideration.

- A detailed study, including simulations, should be made of the potential mutual interference problem of headway radars or lidars. These studies should consider the expected density of radars one would experience on a multiple lane, high density AHS roadway. Can the mutual interference be managed or is it a "show stopper"?

- Communication system concepts need to be defined and studied. These systems should consider the vehicle-to-vehicle and vehicle-to-roadway needs for lateral and longitudinal control, including lane-changing merge and demerge for an autonomous vehicle system, as well as for general information flow.

- Considerable effort should be given to an evaluation plan. How will the various IVHS equipment such as intelligent cruise control evolve into AHS? A road map is needed to determine how AHS can evolve and be implemented considering market penetration and minimal impact on existing traffic flow. While this study is not a lateral/longitudinal control issue by itself, it may heavily impact on the technology chosen for lateral and longitudinal control.

- Tests should be conducted with an instrumented vehicle to collect data on maneuver parameters such as longitudinal accelerations. The relationship between lateral and longitudinal accelerations and ride comfort need to be developed. Tests should be made with a closed-loop longitudinal control system. Noise-like errors should be introduced to cause various levels of vehicle accelerations that would be used to develop a relationship between accelerations and ride comfort.

- Tests should be conducted with a vehicle-mounted differential GPS system that employs carrier phase tracking and pseudolites to evaluate the potential for using GPS combined with stored map data to provide lateral and longitudinal control. These tests should be conducted in urban areas and in tunnels.

4.4.4 AHS Entry/Exit Implementation (Task J)

4.4.4.1 Introduction

Entry/exit is one of the major components of highway transportation service. Some might say it is the most important component since it ties directly to origin and destination (OD) pairs, as airline service is tied to city pairs and airport capacity.

Entry/exit capacity can dictate a freeway system capacity. As we increase the freeway cruise lane capacity, demand increase can overload the entry/exits. Local street volume in the vicinity will at some point reach capacity.

However, automation gives a new tool to deal with system overloads. The traffic controller can directly control sector speed and spacing. As we see in this chapter, the relationship between speed and "safe" capacity contains an optimum, much as manual traffic achieves today, only it is higher and peaks at a higher speed. The controller can choose to modify cruise speed, for increased capacity near an entrance region, to provide more space in the lane for a temporary increase in entry flow. Up to the capacity of the entry procedure, the need for queues or entry lane slowdowns can be eliminated.

Entry/exit concept definitions are closely tied to our RSC definitions. In I2, there is a shared or dedicated lane from the manual lanes to the AHS cruise lane. In I3, this transition lane is a dedicated lane and it can originate from a local street. In I2 the lane is not dedicated to AHS vehicles exclusively when participation[1] is not high enough to warrant. In I1 the cruise lane is not dedicated for the same reason.

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[1] "Participation" is defined as the automated cruising and accessing (or egressing) traffic flow ratioed to the total traffic flow. In general, this fraction could be higher than market penetration.

Because low participation is associated with the early years of AHS deployment, the RSCs and their corresponding entry/exit concepts have an evolutionary interpretation. Entry/exit is also tied to the RSC communication aspect. As discussed in this chapter, the entry/exit procedures we envision involve predominantly the vehicle/vehicle (VV) communications link and C1 concepts in I1, the roadside/vehicle (RV) communications link and the VV link in I3, and a less complex RV link in I2, with a fully utilized VV link.

We feel confident that we can achieve higher vehicle densities with automation. However, if this brings higher person-miles traveled by attracting more and longer personal trips, real increases in travel efficiency are questionable. If, through various measures, we can keep vehicle-miles traveled VMT unchanged and, in addition, the total flow in all cruising lanes is not changed, then maximum flows at entry/exits are not changed and existing ramps and local streets are not overloaded. The benefits to the individual user are shorter and more reliable trip time, assuming that cruising lane congestion was the problem in the first place. If, indeed, entry/exit capacity is a problem, it seems that, short of building more concrete infrastructure, aspects of Intelligent Transportation Systems (ITS) other than vehicle automation must be emphasized to solve congestion problems. There are concepts such as alternate routing and departure time specification, recognizing that everyone cannot use the same portion of concrete at the same time. This line of thinking leads us to examine rearrangement of flow from manual to automated in addition to producing high automated flows.

Finally, it seems reasonable to anticipate, with the increasing presence of automated vehicles, an "automation" mind set beginning to dominate all driver behavior. Perceiving automated vehicles to be a benefit to the manual vehicles in terms of decreased congestion and trip time, manual drivers would develop the cooperation and approval needed to share the road with automated drivers. In what follows, the entry/exit techniques can easily be foiled by irresponsible or uncooperative manual drivers. If our transportation systems and ourselves behave intelligently, we will all get to our destinations on time.

4.4.4.2 Objective

The objective is to identify and analyze design parameters of entry/exit which have major impact on generating, maintaining, and dissipating the flows desired in automated lanes.

4.4.4.3 Technical Objective

We looked at scenarios that assume an advanced traffic management system (ATMS) is in place. Since we do not necessarily increase VMT and vehicle flow rates, we do not overload the entry and exit ramps; neither do we overload the transition lanes. If a locality demands additional entry/exit flow at a particular ramp, we assume another ramp lane will be built and/or the city streets will be altered.

This assumption attributes stop-and-go driving to cruise lane undercapacity. Figure 5 below illustrates the benefit we hope to obtain. It plots cumulative traffic counts at A and B in a simple model of a freeway with rush hour traffic originating in Section A and leaving in Section B. Rush hour starts at about 6 a.m. because it takes an hour to get to Section B only 30 miles away. Using automation, the vehicles can move closer together and move smoothly at normal speed. The trip now takes 30 minutes and rush hour starts later. Note that the flows are the same. They occur later except at B where we assume the OD pairs have the same desired time at destination. Another way to look at it is to say that vehicles, sit in their garages a half hour longer instead of sitting on the freeway.

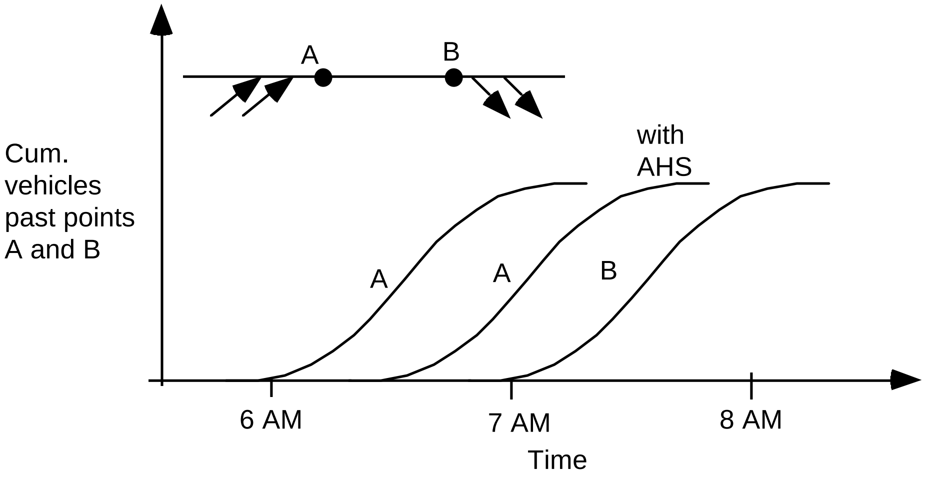

Figure 5. AHS Trip Time Benefits

Analyses show that we can get higher lane flow with AHS than with manual driving. Where the entry/exit capacity and the local streets can allow, this might be the choice of ATMS. Such an example is a bridge or tunnel bottleneck, where cruise and entry/exit capacity upstream and downstream are adequate, but traffic backs up from the bottleneck.

At given speed and weather conditions, how close can we space automated vehicles safely? The answer depends not only on cruise speed but also on entry/exit or ingress/egress to an AHS cruising stream. Our analysis provides a framework for determining how much space is available to add more vehicles. This analysis, used maximum braking distance, collision severity, maximum relative collision speed DV for elastic bumper behavior, deceleration system time delay, VV link time delay, the number of collisions and DVs of those collisions for a given deceleration of the vehicle ahead, the vehicle masses, and the vehicle lengths as input parameters in addition to speed.

Although not part of this task, we also consider that due to control limitations there will be a minimum allowed gap between vehicles for lane changes, mainly affecting the access maneuver.

Given a way to define the relationship of flow capacity (or vehicle density) and lane speed, we now proceed to the next step which is to define how we will utilize the empty space to add more vehicles to the stream. The concept of space distribution is introduced and we make the point that the merging of two flows with the spaces in one matching the vehicles in the other minimizes flow disturbances. Through a simple manual spacing strategy and a regular space distribution in the AHS lane approaching an ingress point, the final vernier adjustment is straightforward with minimal flow disturbance. Rudimentary flow analysis, with participation as a parameter, was undertaken. It leads to the definition of a reasonable boundary between the highest participation for which we still benefit by having manual vehicles in the AHS operating lane and the lowest participation appropriate for I2.

Topics related to I3 were studied. The concept of a dedicated entry ramp directly from the local streets allows a "collector" lane to be postulated that can run at high volume because it is automated. The final stage of this entry method is the merging of two automated streams at cruise velocity. This same high-speed merge appears in the interface of two AHS highways.

The use of space manipulation and entry vernier adjustments is shown to be rather primitive in I1C1, more sophisticated in I2C2, and highly refined in I3.

4.4.4.4 Conclusions and Key Findings

1. Entry/exits are key to AHS practicality since they dictate maximum flows throughout the system, are a big cost driver, and are a primary impact on the community. (EE1)

2. Participation is key to entry/exit design and indeed drives overall design. It is reasonable to estimate that participation will be significantly higher than market penetration. However, AHS entry/exits feasible for low participation are initially the most attractive. (EE2)

3. Entry/exit spacing is an important design criterion in the urban environment. Long Island Expressway data shows that the average OD pairing in that region involves only a few miles of freeway use. Yet, AHS conceptually is concerned with longer freeway segments. (EE3)

4. The different access/egress techniques associated with the different RSCs may well all find application on a single AHS because the specific design requirements of each freeway, street and traffic situation dictate the best technique. (EE4)

5. One of the highest infrastructure impacts assigned to entry/exit requirements is the merging of two AHS streams starting at right angles. This is due to the large radii required if speed is maintained and infrequent high-speed left lane exits in existing highway geometries. (EE5)

6. AHS traffic controllers, according to derived capacity-versus-speed estimates applicable to automated vehicles, will have the ability to provide a tradeoff between velocity and capacity to accommodate substantial volume variations. (EE6)

7. Single-lane access/egress <u>automated</u> flow is upper-bounded by single <u>manual</u> lane capacity. (EE7)

8. Single manual freeway lane capacity as defined by field data varies from 1800 vph at 60 mph (Level of Service C) to 2000 vph at 30 mph (Level of Service E). Below 30 mph the maximum flow decreases and the Level of Service is F (Reference 1). Field measurements higher than 2100 vph (over 15 minutes) have been recorded but at LOS F. (EE8)

9. Single automated lane capacity is 9600 vph at 52 mph based on detailed analysis of a moderate safety policy allowing a few minor collisions in rare instances. At speeds of 40 to 60 mph the capacity is maintained at 8800 vph and above. Outside of this speed range, capacity decreases rapidly but is maintained at 5500 vph and above for the speed range 28 to 80 mph. (EE9)

10. For the mishap scenario assumed, the probability of injury requiring hospitalization is twice as high at 60 mph with 3 foot gap as with 19 foot gap and there are 13 collisions at 60 mph as opposed to 2 collisions. The additional number of parties involved, much higher total property damage potential, and access/egress protocol complication lead us to favor the higher gap sizes. Grouping of vehicles to obtain the desired safety becomes unnecessary until the speed exceeds 60 to 70 mph. (EE10)

11. For the mishap scenario assumed, a slippery pavement reduces capacity to 5100 vph peak at 20 to 25 mph. This is an issue because today's manual speeds are typically higher and changing weather conditions require contingency traffic control. (EE11)

12. Using a less drastic mishap scenario increases the speed for maximum capacity but does not change the maximum significantly. (EE12)

13. Changing bumper/body design in the direction of greater energy absorption than assumed (5 mph bumper) does not change results significantly. More elasticity causes more problems at the smaller gap sizes. (EE13)

14. Heavy vehicles would require more space for equivalent safety. Adopting a no-collision policy requires about a factor of six at 60 mph. This translates to a large decrement in lane capacity for a small percentage of heavy vehicle flow. Hence, we conclude that design to accommodate heavy vehicles may be optimized if they are automated in an I1 concept sense (mixed manual and automated flow) but do not use the exclusive lanes of the I2 and I3 concepts except where the heavy vehicle percentage justifies a lane dedicated to those vehicles. (EE14)

15. The I1 concept (shared lane on a shared freeway with unmodified manual entry/exits) applies to early versions of AHS when participation will be low. It also applies to mature designs for four-lane interstates in rural areas giving manual vehicles a chance to pass. Access/egress is envisioned as manually performed using collision avoidance devices as aids. It can take place at any location at the driver's discretion. (EE15)

16. I1 benefits in terms of increased flow rates are predicted. However, the analysis is conservatively restricted to reduced trip time with no change in flow rate by equating speed to manual speed/flow conditions in the right lane. Benefits in I1 can be increased for a given participation by using communication to pair with another automated vehicle in the left lane. By not increasing overall flow, we can avoid any design change to entry/exits which would move away from the I1 concept of low infrastructure impact. (EE16)

17. Detailed analysis of I1 suggests that participation as low as five percent can increase a congested 4000 vph two-lane manual traffic from 30 to 40 mph. Fifteen percent can increase the speed to 55 to 58 mph. (EE17)

18. If the I1 concept is implemented on a six-lane freeway it can easily evolve into an I2 format where the left lane is exclusive. (EE18)

19. The I2 concept (exclusive left lane, shared or exclusive middle lane at access/egress points, manual right lane, unmodified manual entry/exits) allows synchronized access and quasi-synchronized egress. The I2 concept starts to make sense for participation higher than .45 and when flows at or higher than 6000 vph for each direction of a six-lane freeway can be serviced by existing manual entry/exits. (EE19)

20. Access in I2 could be synchronized by a simple timing system facilitated by space regularization in the automated lane. (EE20)

21. Manual vehicles in the transition lane need only hold the speed specified for the access/egress region but they must act cooperatively in doing so to avoid causing some automated vehicle to miss access or egress. The flow of manual vehicles in the middle lane must be limited by ATMS to about 1500 vph and preferably would be much lower. Operations in the middle lane can be modeled after the left lane in I1. (EE21)

22. In I2 with low acceleration/deceleration limits (for comfort and low emissions) and reasonable vehicle dynamics, analysis and simulation indicates access distance is about 1100 feet at 60 mph. Egress distance is about the same. With a 500 foot buffer between the total region is about 2700 feet at 60 mph. (EE22)

23. When I2 participation has grown to numbers that allow an exclusive transition lane, special entry/exit provisions can be justified to build flows in the cruise lane up to the 9000 vph range of an I3 concept. (EE23)

24. The I3 concept (exclusive cruise lane with exclusive transition or entry lane) allows maximum freedom to configure the entry/exit infrastructure and process and applies to conditions of very high participation. (EE24)

25. I3 allows the infrastructure to support a third kind of entry/exit – the cruise speed merge/demerge (the other two being access/egress from manual freeway lanes and from local streets). (EE25)

26. I3 access/egress from manual cruise lanes is similar to I2 without manual vehicles present. This would allow synchronization by manipulation of accessing vehicles rather than by creating gaps in the cruise lane at the proper places. (EE26)

27. I3 access from local streets allows safer low speed automation system engagement and disengagement. Once again, a timing procedures, in this application with a shaped acceleration profile, mechanized with a roadside data link and vehicle-to-vehicle link could be used with a closed-loop terminal guidance. The access distance is about 1100 feet for a cruise lane speed of 60 mph and it varies with speed in accordance with simple analysis of the access procedure up to 3300 feet at 120 mph. (EE27)

28. I3 egress distance is about the same as the access distance using maximum braking deceleration no greater than the acceleration used for access. Queue length at the local street must be added and it is site-specific. (EE28)

29. The new entry/exits designed for I3 should have curvature and possibly superelevation which limit side acceleration as a function of speed to comfortable values. This conclusion applies as to cruise speed merge/demerges as well as local street ramps. (EE29)

30. The I3 single-lane ramps would be limited to the 1200 to 1600 vph manual source flow capacity. To service greater demand, a collector lane can be used. Four single-ramp stages could build a flow of 4800 to 6400 vph for merging with the cruise lane (which must be running at a low v/c at the time) in a distance of roughly 6000 feet. (EE30)

31. The I3 access/egress process and particularly the cruise speed merge/demerge of large flows would require ATMS supervision and control to prevent system overloads. (EE31)

4.4.4.5 Recommendations

1. The relationship of collision velocity to injury severity at speeds less than 10 fps should be more fully defined for AHS-equipped vehicles as part of the lane capacity definition for access design.

2. Safety policy should be examined to define what would be acceptable to AHS designers, to users and to insurance companies. The role of a barrier between an automated lane and the manual lanes sharing the same roadbed in the I2 concept would be part of the mishap scenario definition as part of this policy. The presence of a barrier in the I2 concept allows access/egress only in specific places.

3. Access/egress operations and procedures should be tested, first through modeling and simulation but then on the test track to obtain reliable data.

4. The I1 concept is forecast to relieve a congested freeway with low participation. This prediction should be studied through simulation and then operationally tested.

5. The AHS/ATMS interface for access/egress regions and for entry/exits should be studied. The AHS potential benefit to ATMS on a regional basis using realistic conditions at these locations needs to be modeled as part of this study.

6. AHS operation in weather conditions affecting surface friction should be researched. Cruise speed, safety policy, lateral control, braking capability, speed for engagement and disengagement of automation, effects of grades and curves, presence of articulated vehicles, etc. all impact the entry/exit and access/egress operations.

7. The minimum space into which an automated vehicle can be safely maneuvered should be defined on the basis of realistic control capabilities and reasonable wind gusts, roadbed unevenness and other disturbances.

4.4.5 Vehicle Operations (Task L)

4.4.5.1 Overview

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

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

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

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

4.4.5.2 Key Findings

Numerous issues/risks were identified under this study. Some of the significant findings are addressed below.

Impact of Reliability (VO1)

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

Impact of Redundancy (VO2)

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

Impact of the AHS Scenarios (VO3)

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

AHS Evolution (VO4)

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

Deployment of the AHS Vehicle Components (VO5)

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

Software Cost (VO6)

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

Software Verification and Validation (VO7)

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

In-Vehicle Communications (VO8)

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

4.4.5.3 Recommendations for Future Research

Deployment of a fully-automated system will require a great deal of research and development on sensors, actuators, communication systems, control algorithms and so on.

However, at this stage of the study, we believe that in some areas of the vehicle operation more research is needed. These include:

- Determining the ultimate scenarios for deployment of AHS. This will facilitate development and deployment process of the promising technologies.
- For a higher reliability and safety, what AHS components need to be fully redundant or have backups with reduced performance: feasibility, cost, and reliability levels associated with each component should be discussed.
- On the issue of retrofitting, more investigation is needed to identify those elements of the AHS that can be retrofitted to the existing vehicles and also determine methods, costs, and reliability issues.
- What characteristics are needed to be included in communication protocols in order to deal with message prioritization in a high speed network.

4.5 AHS MALFUNCTION MANAGEMENT AND SAFETY ANALYSIS

The AHS malfunction management and safety analysis consists of these two task report summaries: (1) Malfunction Management and Analysis (Task E), and (2) AHS Safety Issues (Task N).

4.5.1 Malfunction Management and Analysis (Task E)

4.5.1.1 Introduction

This analysis area examines the role of malfunctions in the reliability of an AHS. Although various safety judgments are needed in this chapter, safety is primarily addressed in Chapter 2. Malfunctions can occur in any of the five physical components—the vehicle, the roadway, the driver, the payload and the environment. We concentrate on the vehicle since the other four components, for a variety of reasons, are less important at this stage of AHS development. Of the 21 function considered at the vehicle operations mini-conference, we consider primarily the three normal cruising functions—gap regulation, lane tracking, and space regulation.

4.5.1.2 Task Objective

The task objective was to define, in the most inclusive way possible, the physical subsystems of an AHS, then consider what design precepts might be applied to achieve reliability goals. From these precepts and present-day achievable failure rates for comparable systems, we seek a conclusion regarding achievable AHS vehicle failure rates. We also desire an analysis framework which can be used by future researchers to obtain specific results for various specific physical designs and protocols.

4.5.1.3 Technical Approach

Today's vehicles pull to a freeway shoulder because of malfunctions at the rate of one per 1,000 veh-hrs. This figure is justified by examining three highway data sources and by vehicle manufacturer's and fleet operators' data. Many of these failures are avoidable by better maintenance, inspections, onboard monitoring and operating procedures. The result of this study is the conjecture that the AHS basic vehicle failure rate could be improved by a factor of two or one per 2000 veh-hrs.

Create an AHS vehicle automation system reliability budget of one per 2000 veh-hrs. This results in a total vehicle failure rate of one per 1000 hours or the same as today's vehicles. If we can achieve this level of automation reliability, the public should accept the reliability of these vehicles as it does today's manual vehicles. The key questions are: 1) Can we achieve this level of reliability, 2) are the initial and lifetime maintenance costs acceptable for this reliability, 3) can we design AHSs that provide safe failure modes when failures occur.

Data from Government and industry sources were obtained from publications and telephone conversations. A table of MTBFs for twelve generic components was constructed. Six of these are components located in each vehicle.

A Strawman design is proposed and analyzed to yield composite AHS reliability numbers. Other designs are suggested to get a feel for the range of failure probabilities obtained. It is shown that the roadside reliability would play a minor role simply based on the number of vehicle-borne components versus the roadside components.

4.5.1.4 Conclusions

1. User data and analysis show that an automation failure rate of one per 2000 veh. hrs. is feasible. (MM1)

2. The full answer to the cost question, both acquisition and lifetime maintenance, must remain uncertain until specific designs are considered, but we are optimistic, (MM2)
3. The key issues in the approach to the question of safety are the use of redundancy in vehicle equipment, and the use of a breakdown lane, entry/exit protocol, and handling communication failures. Our study suggests design approaches to deal with these issues. (MM3)

4. Barriers in the I2 scenario would reduce the probability of vehicles and other objects from moving into the AHS lane from the manual lanes. The ability of an automated vehicle to cope with such objects is problematical, making consideration of barrier use part of this malfunction management. (MM4)

5. Driver role in malfunction management remains a controversy. We examined two driver roles—one where the driver is continually alert to the vehicle's behavior and progress throughout the trip and one where the driver can turn attention to unrelated activities but can expeditiously tend to systems alerts and advisories. These two roles both find application depending on the proximity of manually-operated vehicles as dictated by RSC definition. (MM5)

4.5.1.5 Recommendations

1. Preliminary subsystem design studies should be performed and integrated into an overall system design containing life cycle cost/reliability tradeoffs.

2. Redundant subsystems should be considered to obtain reliability goals with the following design questions addressed.

   - (a) Use of dissimilar technologies as part of the redundancy
   - (b) Failure detection availability
   - (c) Failure identification technique
   - (d) Transition without dynamic disturbance
   - (e) Common mode failures

3. The driver role in malfunction management should be studied in simulations and field tests.

4. A target basic vehicle locomotion MTBF should be established by standards organizations and vehicle manufacturers.

5. Further study is needed to resolve the issues of

   - (a) a continuous breakdown lane
   - (b) malfunctions during access and egress functions
   - (c) management of communication failures

6. Realistic affordable methods for managing the problem posed by an object in the lane must be developed. This study should consider the role of barriers in the AHS designs placing an automated lane contiguous to those used by manual traffic.

7. A related study should address the legal implications of enforcing traffic laws addressing obstruction of AHS traffic. Such violators should be easily detectable and therefore easy to fine or at least bring to trial. The delay caused in the AHS lane is, in worst case, equivalent to stopping three or more lanes of today's congested manual traffic. There appears to be no method short of a physical gate or severe legal consequence to prevent intended or negligent obstruction.

4.5.2 AHS Safety Issues (Task N)

4.5.2.1 Introduction And Technical Approach

The safety objective for an AHS is to design a driving environment that is collision-free under normal operating conditions. This task requires the identification of the issues involved in achieving a collision-free environment, and the risks associated with failure to meet this objective. Our analysis approach is based on the AHS concept as a major enhancement to the existing roadway system. Therefore, the experience acquired, lessons learned, and insights gained during the last 40 years of interstate highway operations is a benefit to the AHS concept analysis. This experience, coupled with our knowledge of vehicle and roadway safety is used to provide design guidelines for an AHS. Lastly, we interpreted the accident analysis results as a means of defining the potential AHS benefits.

Our technical approach was to focus on specific system features and driver functions associated with the Representative Systems Configurations (RSCs). The six general RSCs, independent of vehicle type, were used. From this perspective, two questions were answered. The first question, “What could go wrong?”, was addressed by a Fault Hazard Analysis (FHA) of AHS operations for each general RSC. The second question, “If something does go wrong, what are the consequences?" was answered using statistical accident data bases. The assumptions for this analysis are addressed below.

4.5.2.2 Key Findings / Conclusions

AHS Fault Hazard Analysis (What could go wrong?)

The fault hazard analysis of AHS operations addressed: (1) potential system failures or degradations, (2) their local and system-wide effects on the AHS, and (3) their criticality prior to any mitigating strategy. The analysis represented the individual phases of AHS operation as a time sequence of events for the six general RSCs. The main conclusions, after examining system impacts resulting from failure of AHS components, stress the need for system reliability and redundancy for a safe and successful AHS.

The key findings/conclusions stemming from the fault hazard analysis emphasize the primary issues to be addressed for safe driving on an AHS:

- Automated vehicles must have redundant steering and braking systems. The consequences of loss of vehicle control emphasize the need for complete control at all times. Graceful degradation from an automated mode is dependent on the integrity of the basic system, and in particular, the vehicle controllers. (SI1)

- The question of a human driver as a participant in automated vehicle control is controversial, particularly as a malfunction management tool. As part of the fault hazard analysis, two driver roles were identified:

    - Role 1: Brain On, Hands and Feet Off
    - Role 2: Brain Off, Hands and Feet Off

  Role 1, "Brain On, Hands and Feet Off", was assumed for assessment of local and system effects of component failures. Both roles require further investigation. Role 1 does not allow the driver to completely relax, but it maintains a very capable and intelligent system component that would be extremely expensive to replace. Role 2 permits the driver to be completely detached from the system. This mode eliminates the concept of manual backup, increases the requirements for malfunction management, and raises concern for AHS exit policies. (SI2)

- The object/animal in the roadway problem may remain a constant between today's interstates and an AHS. The magnitude of this problem is unclearly defined. Accident statistics indicate the number of times a vehicle strikes an object or animal in the roadway, not the number of times a driver successfully maneuvers around an obstacle and still maintains control of the vehicle. The cost of preventing these elements from entering the AHS emphasizes the need for detection devices. However, even if it is possible to detect an obstacle that truly needs to be avoided, the longitudinal and lateral control systems must be capable of diverting the stream of vehicles, and they must have the room to maneuver the vehicles safely around the obstacle. (SI3)

- The general RSCs were not developed as evolutionary configurations, although they can be viewed as an evolving progression from I1C1 to I3C3. However, the consequences of faults and hazards at the higher levels of automation emphasize the benefits of an evolutionary approach to an AHS. These benefits will be derived in the form of costs, implementation, and ability to gracefully degrade to lower levels of command and control as the more sophisticated designs are developed and implemented. Evolutionary designs may also turn out to be the configuration of choice for specific locations, such as rural areas, where the cost of building separate automated roadways is impractical and there is less demand for increased capacity. (SI4)

AHS Crash Analysis (If something does go wrong, what are the consequences?)

The second phase of the safety task answered the question: if something does go wrong, what are the consequences. This second phase was addressed using accident data bases and served two objectives: raise AHS safety issues and risks for AHS design considerations and estimate potential AHS benefits. The highlights of the crash analysis are discussed in this section, and the potential AHS benefits are quantified in the following section.

Crash Analysis for Design Guidelines

The goal of the AHS, under normal operating conditions, is a collision-free driving environment. This goal is based on assumptions of full automation and fail-safe malfunction management under any and all circumstances. To investigate the consequences of deviations from these assumptions, specific crash types were analyzed. The deviations appear in the form of mixed manual and automated vehicles for the I1C1 RSC and the transition lanes of the I2C1 and I2C2 RSCs. Deviations may also appear as holes in the mitigating strategies prescribed by malfunction management for any RSC or as degradations from safe designs due to cost, implementation or increased capacity tradeoffs.

Crash types similar to those on today’s interstates will probably become the crash types that occur on an AHS under non-normal operating conditions. The causal factors will be AHS unique, the number of vehicles involved will probably be greater, and the distribution of crash types will vary from today’s interstate accident picture. The emphasis must be on fail-safe designs that will be geared to the lowest injury-producing crash types. (SI5)

Data from the Fatal Accident Reporting System (FARS) were used to rank crash types according to risk of a fatal injury. Table 9 lists the individual crash types in order of decreasing likelihood of producing fatal injuries. The most common crash type to result in a fatal injury is the “not a collision with a motor vehicle in transport”. The collisions that do not involve another motor vehicle in transport consist of single vehicle accidents that are rollovers, barrier related, roadside departures or involve an object or animal in the roadway. Head-On and Sideswipe Opposite Direction are extremely low frequency events on interstates. (SI6)

Rear-end crashes were analyzed in detail since they are likely to be the most frequently occurring AHS crash type. The Crashworthiness Data System's (CDS) algorithms (PCCRASH) to estimate ΔVs for vehicles involved in a collision apply to rear-end crashes. The primary measure of collision impact severity is ΔV, defined as the change in a vehicle's velocity, taking into account vehicle mass.

Table 9. Ranking by Occurrence of Fatalities on Interstates

Crash Type	# Fatal Injuries	% of Total
Not Collision with a Motor Vehicle in Transport	612	54.1%
Head-On	199	17.6%
Rear-End	165	14.6%
Angle	111	9.8%
Sideswipe, Same Direction	34	3.0%
Sideswipe, Opposite Direction	7	0.6%
Total	1131	100.0%

Occupant injury levels and vehicle damage severities were expressed as a function of ΔV. This analysis was performed to estimate "tolerable" ΔVs for collisions on an AHS. Once tolerable ΔVs are obtained, safe headways for travel speeds based on maximum deceleration of a lead vehicle involved in a crash can be calculated. (SI7)

Figure 6 shows the highest level of medical treatment for striking vehicle occupants as a function of ΔV. Vehicle occupants suffered injuries requiring transportation to a medical facility where they were treated and released from crashes in the 6 to 10 mph ΔV range. Injuries requiring hospitalization resulted from crashes in the 11 to 15 mph ΔV range. This not only implies the seriousness of the incident in terms of occupant injury, but also indicates the amount of time necessary to clear the accident scene, and its influence on the perceived safety of the AHS. (SI8)

Barrier-related crashes represent another potential AHS crash type, particularly for the I2C1 and I2C2 RSCs, where automated lanes and manual lanes may be separated by barriers. CDS data show that left roadside departures account for approximately 78 percent of barrier crashes that occur on roadways with speed limits greater than 50 mph. This finding strongly supports the use of barriers on the AHS since, without a barrier between automated and manual lanes, left roadside departure vehicles from the manual lanes will intrude into the AHS. (SI9)

The likelihood of a lane-blocking incident on an AHS under normal operating conditions may be viewed as the possibility of a crash with an object or animal in the roadway. Automation is capable of creating a “smart driver” that knows the state of the vehicle, and the limits of the vehicle’s handling capabilities for road and weather conditions, but automation cannot control objects or animals. Therefore, automation must deal with them, particularly on the long stretches of suburban and rural highways where the problem is most significant. (SI10)

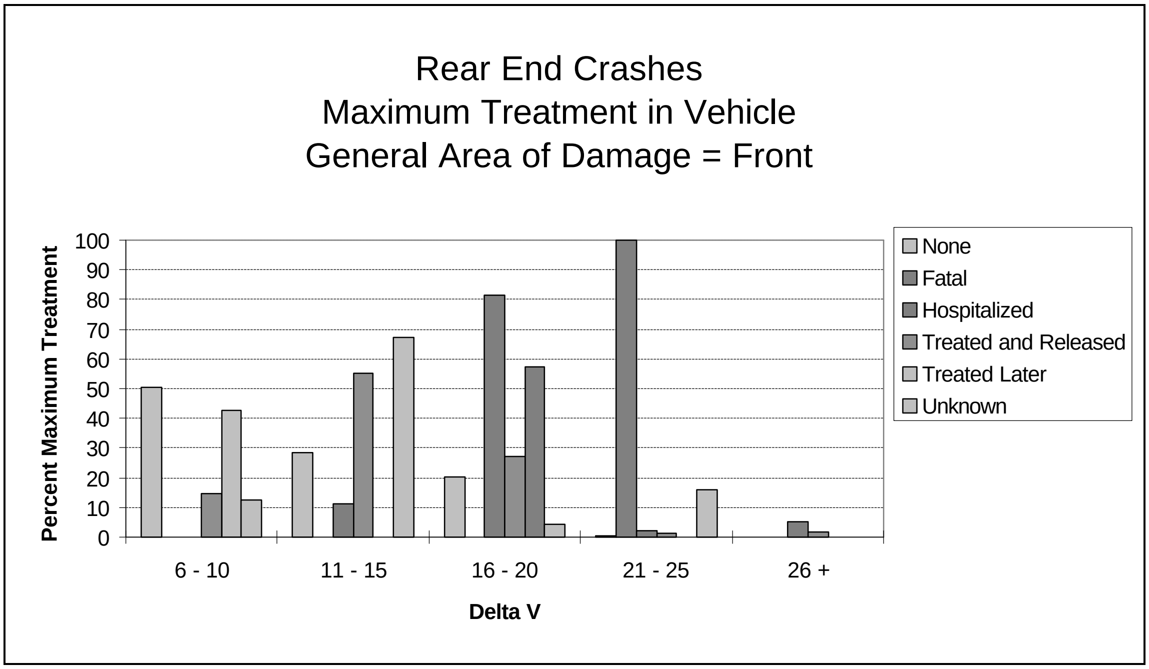

Figure 6. Medical Treatment in Vehicle by ΔV

Table 10 shows the likelihood of a lane-blocking incident on an AHS under normal operating conditions. Crashes involving objects or animals represent 5.2 percent of all interstates crashes. Given the 490,336 million vehicle miles of travel on US interstates, this equates to a rate of 0.03 incidents per million vehicle miles traveled. Additional events, under non-normal operating conditions, that may lead to "AHS roadway obstacles" or lane-blocking incidents are: (SI11)

- Loss of lateral control
- Offset rear-end crashes
- Rear-end crashes on low traction surfaces (perhaps due to fluid spills)
- Lane/change merge crashes
- Crashes related to driver impairments

Table 10. Likelihood of Lane-Blocking Incident on an AHS

Interstate Object / Animal Rate of Vehicle Collisions per Million VMT			
Location	**Urban**	**Suburban**	**Rural**
Number of Incidents	1,678	7,496	5,802
VMT (million miles)	190,217	95,108	205,011
Rate	0.01	0.08	0.03

AHS Benefits Analysis

The goal of the AHS, under normal operating conditions, is a collision-free driving environment. This assumes full automation and fail-safe malfunction management under any and all circumstances. Based on these assumptions, existing studies on accident causal factor analysis provide a quantification of benefits from an AHS. Estimates of the improved accident picture for an AHS are treated separately for each crash type, where data are available. An assessment of the overall safety benefits derived from an AHS is presented as a range of percent reduction in crash frequencies in table 11.

The lower limit is based on General Estimates System (GES) data where a vehicle defect, driver impairment, or inclement weather may have contributed to the crash. Only police-reported information is included in this estimate; there is no assessment of crash cause. This analysis resulted in a 31 percent improvement for all locations combined (table 11). (SI8)

The upper estimate of AHS safety improvement is based on data derived from a causal factor analysis of rear-end crashes (Knipling, 1993) and the Indiana Tri-Level study (Treat, 1979). This estimate is based on an assumption that the combination of automated control and vehicle system monitoring/inspection has the potential to remove human and vehicular factors and most (80 percent) of the environmental factors. This approach yields an 85 percent reduction in vehicle collisions. The data, which pertain to crashes on all roadways, are not limited to interstates.

Table 11. Percent of Interstate Collisions where Vehicle Defects, Driver Impairment, and Inclement Weather are Involved

Percent of All Interstate Collisions by Location			
	Location		
Factor which may have contributed to cause of crash:	**Urban**	**Suburban**	**Rural**
Vehicle Defects, Driver Impairments	28,316 (11.2%)	23,191 (12.7%)	18,033 (26.6%)
Vehicle Defects, Driver Impairments, Inclement Weather	65,707 (26.0%)	59,198 (32.5%)	30,986 (45.7%)
Number of Interstate Vehicle-Collisions	252,362	182,028	67,733

*Vehicle-Collisions refer to the total number of vehicles involved in an accident as opposed to the number of accidents that may involve more than one vehicle.

Causal factor results from the Indiana Tri-Level Study are based on 420 in-depth investigated accidents where a “certain” rating was applied to the causal factor. A “certain” rating is applied when there is absolutely no doubt as to a factor’s role, and is considered analogous to a 95 percent confidence level. “Certain” cause of the accident means that, assuming all else remains unchanged, there is no doubt that if the deficient factor had been removed or corrected, the accident would not have occurred.

The data in table 12 show the rate of vehicle collisions per million VMT for today’s interstates and estimates of the AHS rate when full automation is assumed. The range of improvement is shown to be 31 to 85 percent. These estimates are based on reductions in collisions; they do not include a factor for increased collision potential due to higher speeds and shorter headways. Collision numbers are from the 1992 General Estimates Systems

(GES). They are nationally representative estimates of police-reported interstate accidents by location. Vehicle collision rates are based on VMT on interstates, FARS, 1991.

Table 12. AHS Safety Improvements

Interstate and AHS Rate of Vehicle Collisions per Million VMT			
Location	**Urban**	**Suburban**	**Rural**
Vehicle-Collisions*	252,362	182,028	67,733
VMT (million miles)	190,217	95,108	205,011
Interstate Rate	1.33	1.91	0.33
Percent Improvement	26.0 - 85.0	32.5 - 85.0	45.7 - 85.0
AHS Rate	0.2 - 0.98	0.29 - 1.29	0.05 - 0.18

*Vehicle-Collisions refer to the total number of vehicles involved in an accident as opposed to the number of accidents that may involve more than one vehicle.

4.5.2.3 AHS Safety Recommendations For Future Research

After answering the "What could go wrong?" and "If it does go wrong, what are the consequences?" questions, the safety issues and risk associated with AHS operations became apparent. Many of the issues are the result of tradeoffs that will have to be decided during the AHS design phase. The support arguments for the tradeoffs are the risks. Major concerns that require future research are listed below.

The two driver roles of "brain on, hands and feet on" and "brain off, hands and feet off" identified during the fault hazard analysis must be investigated, although perhaps not as a black and white issue. In situations, such as a malfunctioning vehicle departing the roadway, time may be available to alert the driver and assume manual control. In situations where reaction time is short and speeds are high, manual backup may be totally impractical. An evaluation of the limits of driver capabilities will be required to resolve this issue.

The object/animal in the roadway is a thorn in the side of the AHS. The tradeoffs in cost and practicality of excluding these elements from the AHS environment versus detection and avoidance need to be addressed.

The levels of maintenance and inspection will be regulated to be high for AHS-equipped vehicles. Vehicle system monitoring will increase awareness of needed repairs. Public willingness must be evaluated to determine where the attraction of an automated system falls off as a function of the demands placed on automated vehicle owners.

The relationship of ΔV to injury levels and vehicle damage led to the recommendation that ΔVs for rear-end crashes should be limited to 10 mph. This 10 mph limit will minimize the consequences in an unmitigated malfunction scenario. If the system is not able to ensure straight front-to-back rear-end crashes and potential exits for offset rear-end crashes, this recommendation is lowered to ΔVs in the 5 mph range. The lower number is suggested to prevent a vehicle spinning off from a primary crash into a more severe crash type with a barrier or a vehicle in an adjacent lane. The use of anti-lock braking systems will also reduce the likelihood of vehicle rotation under maximum deceleration.

Review of current barrier design standards is warranted in light of AHS applications. The AHS operating environment may have vehicles traveling at speeds greater than those considered for present-day barriers. Also, in the event of a malfunction, multiple collisions are more likely to result than on today's highways. The role of barriers may increase on an AHS, and the new requirements must be identified and incorporated into practice.

Many crash types related to driver impairments, in particular drowsy drivers, will be eliminated by an AHS. However, crashes involving intoxicated drivers is not one of them. Intoxicated drivers are not permitted on the AHS, and if they are already on, getting them off is a problem. An AHS is meant to create a collision free driving environment. This is an AHS safety issue that requires further consideration.

Causal factor analysis specific to interstate highway crash types should be conducted to focus design strategies and quantification of benefits. Also, algorithms to estimated ΔVs for multiple rear-end collisions and other crash types should be developed.

The results of this study are based on general RSC concepts. A distinct possibility is that the automated highway will take form through an evolutionary process starting at the low end of the infrastructure/command and control implementations and gradually develop into a separate infrastructure with full roadway and vehicle control. Urban configurations may be quite different from rural configurations. The range of configurations that are selected for implementation will have specific safety implications that will require detailed analyses of the selected scenarios.

4.6 AHS ALTERNATIVE PROPULSION SYSTEM IMPACT (TASK M)

4.6.1 Approach

The objective of this task was to evaluate the effect of alternative propulsion vehicles (APVs) on the Automated Highway System (AHS). This entailed research and literature reviews, in-house knowledge and interviews with experts in applicable fields. Background information on APVs were gathered to gain a understanding of the technology issues and problems facing APVs.

An alternative propulsion vehicle does not rely on a internal combustion (IC) engine as its primary power source. Three types of vehicles were evaluated in this task. They are:

Electric vehicles (EVs) - All power is supplied by rechargeable onboard batteries.

Hybrid vehicles - There are two types of hybrids, series and parallel.
  Series: A combustion engine is used to charge the vehicle batteries directly.
  Parallel: The combustion engine can be used to either charge the batteries or to directly power the vehicle.

Roadway powered electric vehicles (RPEVs) - RPEVs are electric vehicles that can be charged dynamically while moving, receiving power through induction from a powered roadway.

All of these APVs are similar in that they have batteries and electric motors. The differences lie in how power is supplied to their batteries.

Electric vehicles are moving from technology demonstrators, of the 1970s and 1980s, to consumer vehicles that will be produced within the next ten years. Our EV research consisted of battery technology, performance parameters, use, and emissions. Hybrid vehicles may be the transition vehicles between today's conventional and electric vehicles. Several different types of hybrid vehicles were researched, along with their advantages and disadvantages for AHS use. Roadway powered electric vehicles are a derivative of EVs. They can be used to extend the range of EVs for AHS travel. We have analyzed the use of RPEVs, along with problems and advantages of an RPEV system. This task describes the relationship that APVs will have with their environment, the AHS, and their interaction with other vehicles.

The technical approach used assumptions based on our estimates for APV influence in the near-term vehicle population. We assumed that APVs may only reach the levels stated in California Air Resources Board (CARB) regulations. Estimates of battery storage capacity are stated within the calculations that they are used in. No breakthrough battery that increases range by a factor of two or three times is likely. More details concerning assumptions are provided in the individual examples cited. We believe our assumptions are real world, moderate in nature; unlike many inaccurate assumptions made about APVs in previous years. The APV goals of range, performance, refueling, and consumer acceptance have not been met.

4.6.2 Conclusions/Key Findings

The current and future generation of alternative propulsion vehicles (APVs) researched suffer decreased performance compared to most conventional spark ignition (SI) vehicles. These deficits encompass all aspects of vehicle performance, from acceleration and braking to vehicle range. The performance deficiencies, most notable in vehicle acceleration, result from the lack of an adequate power storage media for electricity. Current designs compromise vehicle performance for range, with battery technology the limiting factor. The present-generation batteries store only limited, and inadequate, amounts of electric charge. The range deficiency is the major drawback for APV market potential. This feature inhibits the manufacture of APVs with range and performance comparable to conventional vehicles. Therefore, because of interstate travel, AHS effectiveness will be reduced if APV battery technology is not improved. (AP1)

The current and near-future APVs may encounter problems on the AHS, depending upon the system’s speed limit. Although many APV designs are capable of speeds in excess of the current national speed limit, these vehicles are electronically limited to speeds in the range of 110 to 130 kmh (68 to 81 mph) to maintain battery charge. The operating speed limit will be critical to APV impact on the AHS. (AP2)

The acceleration performance of most APVs are within the range of current economy class vehicles and light trucks. These values are acceptable for the acceleration and deceleration lanes of current highways under American Association of State Highway and Transportation Officials (AASHTO) guidelines. No modifications are required of the road infrastructure to incorporate APVs. (AP3)

At present, a large proportion of APVs are conventional SI vehicles that have been converted to APV use. These vehicle conversions result in substantially higher design weights. This factor, along with low rolling resistance tires and a modified weight distribution, can seriously impair vehicle dynamics. Without changes to vehicle braking systems, APV braking distances are significantly longer than the original vehicle. This will cause problems for AHS platooning and emergency maneuvers. Ground-up electric vehicle designs do not suffer from these braking difficulties; at present, only one vehicle, the GM Impact, falls into this “purpose-built” category. The limited number of purpose-built vehicles illustrates the high costs involved in vehicle development. For the near-future, the APV fleet will consist predominantly of converted SI vehicles, and have a negative effect on performance. (AP4)

Vehicle range is the biggest handicap facing alternative propulsion vehicles today. Electric vehicle (EV) range is dependent on the battery storage system utilized. The only certainty of battery technology is that it is uncertain; it is difficult to extrapolate into the future. In the 1960s, researchers were predicting that electric vehicles would be commonplace in the seventies. This prediction was repeated in the seventies. Because current battery technologies do not provide APVs with range and performance comparable to SI vehicles, this prediction has not yet come to fruition. Research is making evolutionary progress in battery technology with no “revolutionary” breakthroughs on the horizon. The pace of battery system development will presage the closing of the performance and range gap of APVs to SI vehicles. Because of these trends, battery-powered electric vehicles will not have AHS interstate travel range. (AP5)

As with battery technology, electric vehicle recharging is advancing at a slow pace. Newer, quicker ways of vehicle charging need to be developed for consumer acceptance to rise. Goals for recharging of vehicles need to be in minutes, not hours, as is currently the case. Without the installation of special charging equipment, home electric vehicle recharging cannot be performed in one to three hours. Older homes may not have the capacity to use this equipment without a complete rewiring. For apartment dwellers, the problem is magnified. The specialized charging equipment will initially require charging stations similar to gas stations to allow quick-charge of these vehicles. Electric vehicle quick-charging will have to be performed at recharging stations, possibly co-located with gas stations or AHS service areas. (AP6)

If the future holds a breakthrough battery, the interim solution may be hybrid vehicles, due to their increased range capabilities and reduced emissions. Of the two types of hybrid vehicles, series and parallel, series hybrids hold the most promise since they are less complex, produce fewer emissions per distance traveled, and operate as zero emission vehicles (ZEVs) for a greater portion of their driving cycle. With the use of a small onboard SI engine, hybrids have greatly extended range capabilities as compared to EVs, and therefore provide promise as AHS vehicles. (AP7)

Decreased emissions is a major goal of future transportation systems. However, APVs must represent a large share of the vehicle population, or the benefits will be insignificant. Regionally, the reduction in emissions depends directly on the different types of fuel used (the generation mix) to generate electric power. A vehicle’s emissions may one day be a selling point similar to present-day features like styling, safety equipment (anti-lock brakes, airbags) and fuel consumption. APVs, especially electric vehicles, will have the lowest emissions of all vehicles. The major manufacturers’ disdain for APVs is similar to their general attitude toward small cars, catalytic converters and airbags in earlier years. (AP8)

Vehicle reliability will be equal to or greater than conventional SI vehicles, and electric motor reliability may be much greater. Depending on the type of APV, the need for instrumentation monitoring may decrease because of the less complex overall system. The only specialized training needed is training for AHS operation, which may be identical for all vehicles. Overall, APVs will be easier to use (less complex, no transmission, less maintenance) than comparable SI vehicles. (AP9)

Fleet use is the first and best use for APVs. Even with the limited present range (approximately 100 miles), APVs can be used as many types of delivery vehicles. Initially, APVs will be developed for fleet use, independent of the AHS. With further development, they may be suitable for AHS operation. Our findings, on daily miles driven, match other surveys. The majority of fleet vehicles travel less than 70 miles per day, which is within the range of present APVs. In this regard, electric vehicles can safely operate on the AHS, but they will have limited range. Initially, EVs will be best suited for inner city travel and not for intra city or cross-country travel. (AP10)

The use of roadway power as a range extender for EVs complements electric vehicle driveability. Roadway powered electric vehicles (RPEVs) will initially be used in transit/commercial applications where the vehicle routes are always the same. Initially, RPEV deployment will consist of public transportation operations. Roadway power presents a practical solution for eliminating emissions in densely populated areas. RPEVs are ideally suited for bus routes, shuttle services, airport shuttles, and use in pollution sensitive areas. RPEVs can play a significant role in transit applications if EV range does not improve. A battery breakthrough could render commuter RPEVs obsolete, while transit RPEVs would be modified to electric-electric vehicles. With battery advancements, RPEV status may change. Transit station recharging could be eliminated if an APV is able to recharge quickly for a entire day’s use. RPEVs are still in the experimental stage but the technology is available, mature, and appropriate for present day systems. RPEVs for transit use are a deployable system. Rubber-tired RPEVs would make an excellent replacement for diesel buses, trams, and trolleys. (AP11)

RPEVs can be operated on the AHS with minimal effect. The electro magnetic field (EMF) emitted by RPEVs is equivalent to household appliances or less. This is acceptable at the present known standards. No interference should occur with non-RPEVs operating on or near a powered RPEV roadway or vehicle. There does not appear to be a problem with EMF emissions from RPEV induction. But, RPEV EMF needs additional study due to the potentially serious consequences of EMF in general. The RPEV induction system is a likely candidate to be used for EV recharging, as it eliminates plugs and cables and is passive to use. If use of RPEVs is widespread in the future, it will tax power resources in New York State beginning around the year 2011. (AP12)

The inductive coupling required in the RPEV/AHS lane could act as a lateral guidance system available to all vehicles. Many EV designs are adapting “fly-by-wire” steering to reduce weight in the vehicle. Inductive lateral guidance systems have already been adopted and proved effective. (AP13)

The emissions reductions achieved using an RPEV-based AHS would be much larger than those of a non-RPEV AHS. This is an attractive alternative which promotes compliance with the 1990 Clean Air Act. (AP14)

Accidents related to APV technology on the AHS will not be a major concern. Battery safety has improved such that battery spills will cause no great threat or harm to the environment and can be safely dealt with by trained emergency crews. Use of APVs will be a stimulant to the businesses created to manufacture, design, and develop these vehicles. Considerable expertise in APVs lies not only in major auto manufacturers, but in vehicle converters and small businesses. APVs are efficient in their conversion of energy to propulsive power, are as safe as a conventional vehicle, and less harmful to the environment. (AP15)

The top design issues jointly affecting APVs and AHS are:

Range/charging - If current battery and charging technology are not improved by the time of AHS implementation, APVs will experience reduced AHS capabilities. Limited vehicle range can impair AHS interstate travel.

Top speed - Future APV designs must be capable of matching AHS design speeds. Limited top speed can negatively impact AHS throughput and increase travel time.

Fleet/Transit use - To meet CARB mandated sales goals, designers have focused on APVs for fleet use. This feature will facilitate AHS equipment implementation.

RPEV lane design - If RPEVs are used on the AHS, overall lane design must be standardized and power, billing, and EMF issues resolved. RPEV lanes can provide lateral guidance to all vehicles using the RPEV/AHS road. (AP16)

The major limitation is the range issue. The use of hybrid vehicles, which can extend the range of APVs, transitions the use of all the different types of APVs on the AHS. The differences in performance characteristics (acceleration, braking, and handling) between APVs and SI vehicles is decreasing and may be eliminated by the time AHS is implemented. (AP17)

4.6.3 Recommendations For Further Research

Further research is recommended in the following areas:

- Advancing battery technology is the most pressing problem affecting alternative propulsion vehicles and their use on the AHS.
- Quick (less than ten minutes), safe recharging must be developed simultaneously along with advancements in battery technology.
- APV safety research and testing is lacking; this issue needs further investigation before AHS implementation.
- Further study is needed on long range (20 to 50 years) electric power requirements of electric vehicles and RPEVs, and the projected generating capacity, generation mix, and emissions at that time.
- Hybrid vehicles, especially series hybrids, as extended range APVs, may bridge the gap between internal combustion and electric vehicle performance. Hybrid vehicles may resolve APVs AHS performance limitations.
- Roadway powered electric vehicles (RPEVs) are the least researched APV technology. RPEVs may provide EVs with the range and performance capabilities necessary for AHS.
- The effects of weather (snow, ice) on powered roadways and the AHS are unknown. Safety impacts must be assessed.
- Lateral and longitudinal guidance of RPEVs on the powered roadway/AHS. RPEV lanes can provide measures of vehicle lateral control.
- Alternative energy storage systems (mechanical batteries, ultracapacitors, fuel cells) may overcome current-generation APV range and performance limitations. These systems could provide APVs with adequate AHS performance.

- Any adverse electro magnetic field (EMF) effects of RPEVs on humans and AHS/equipment need to be addressed.
- APV research is advancing rapidly; further study of both domestic and foreign APV advancements is needed. With technological advancements, the APV performance limitations discussed may be remedied.

4.7 COMMERCIAL AND TRANSIT AHS ANALYSIS (TASK F)

This task was performed in two parts, Part I and Part II, as a parallel effort. The study for Part I was performed by Parsons Brinckerhoff. The study for Part II was performed by Princeton University.

4.7.1 Commercial and Transit AHS Analysis, Part I

4.7.1.1 General

If the implementation of AHS can result in improved highway travel time reliability, reduced delays, and lower accident rates for commercial vehicles as well as increased attractiveness of public transit for intercity as well as intra-urban travel, the potential benefits will also be accrued by passenger vehicle drivers and occupants who share these highway corridors.

4.7.1.2 Commercial Vehicles

This brief overview of the trucking industry has revealed its enormous contribution to the nation's economy, employment, and productivity. Its diverse types of companies, commodities carried, vehicle types, haul lengths, labor concerns, competitive pressures, and government regulations indicate that the AHS program will need to address multiple trucking industry as well as competing mode issues and concerns. The basic question will be "what's in it for us?" Issues of primary concern to the trucking industry include environmental regulations, safety and health, taxes, labor and emerging technologies.

As the tractor-trailer combination truck appears to be the "workhorse" of the trucking industry, it must be decided whether this vehicle type should be the design standard for deployment and control. The integration of mixed and separate commercial vehicles within the traffic stream must also be considered. We have performed analyses that illustrate implications of trucks on the traffic stream for both rural and urban scenarios. If commercial vehicles are to be included, should all types, sizes, weights, and combinations be permitted, or should the AHS lane or lanes only allow smaller single unit trucks with dynamic characteristics similar to passenger vehicles?

While heavier and longer vehicles are viewed as needed by the trucking industry, what place do they have, if any, on the initial and subsequent AHSs that will be developed and constructed over the next decades? What, if any should the truck type and size restriction be? What are the cost implications for pavements and bridges? Should AHSs be designed only for passenger vehicles, vans, buses, and single unit trucks with a weight limit of 10,000 lbs, allowing the other commercial vehicles to remain on separate but non - instrumented sections of the Interstate System in both urban and rural areas? Or, should longer and heavier trucks be allowed, as is being lobbied for by the trucking industry. In theory, AHS will permit the drivers' tasks to be automated except for ingress and egress, and the risk of truck driver and / or passenger vehicle driver error leading to accidents will largely be eliminated.

The control and maintenance requirements needed for longer combination vehicles (LCVs), if they are permitted, need careful evaluation, in view of the greater accident potential of these commercial vehicles. The industry is, judging from the accident rate reductions achieved over the past decade, focusing on safety and proud of its accomplishments. It should, accordingly, be participating in the AHS efforts, to lend its expertise and experience in those vehicle and driver-related areas which will produce the most benefits in the early phases.

4.7.1.3 Transit

AHS must be seen by the Local/Express Bus and Intercity transit industries as a cost effective, significant means to maintain current patronage and encourage new ridership.

The transit industry will need to demonstrate to the American public reasons for becoming competitive with personal autos. If AHS can provide the transit industry with the technology, service, reliability, frequency, direct routing (minimal transfers), at competitive costs with personal auto, there will be a demand for it. Contrary to the trends experienced over the last few decades, the emphasis in urban and suburban transportation is towards increased transit use, particularly based upon new federal legislation mandating change in travel habits by the public. The success of these new programs in accomplishing their goals will depend on transit's ability to provide more reliable, safe, and efficient transportation.

With AHS lanes or roadways available in high density travel corridors, buses, vans and qualifying high-occupancy vehicles will be afforded the opportunity to consistently meet on-time performance standards and schedules. Improved reliability and travel time will enhance customer service and attract 'choice' users from other modes.

AHS offers improved service and safety by reducing the potential for driver-related accidents. Removing the driver from the continuous operation of the vehicle and providing guidance and warning systems will enhance the performance of bus transit service on AHS facilities in high travel demand corridors. Continuous, predictable reliable service and well-maintained vehicles will eliminate excessive acceleration and deceleration rates which also cause numerous passenger injuries. The required increased maintenance practices would enhance vehicle operations and improve service reliability and safety.

Similar to the advantages of busways, buses and HOVs on AHS would include the following cost and service advantages:

1. Relatively low initial construction is required; i.e. convert existing HOV lanes to AHS, use existing central bus terminals, and expand as bus demand increases.

2. AHS transit lanes can be utilized by trucks during non-rush hour periods of the day.

3. Dual service buses provide manually driven feeder service, non-transfer trunk line AHS service, and downtown manually driven distribution service.

Expected time savings for HOVs can range from 0.5 to 2.0 minutes/mile. Carpooling has increased on HOV lanes in some cases up to 100 percent, and transit ridership has increased between 10 and 20 percent. The technology inherent to AHS would allow greater travel time savings and, potentially, higher ridership. In general, HOV lanes have shown good ridership growth and proven congestion mitigation. As travel demand grows and peak period capacity requirements outstrip available HOV lane capacity, AHS offers the next solution, with at least a doubling of vehicle carrying capability, and much greater multiples of person carrying capacity.

Improvements in the design of transit vehicles, and introduction of user-friendly transit information systems through IVHS programs, as well as additional government support through the mandates of the Clean Air Act Amendments and incentives introduced in ISTEA legislation, will lead to transit's evolution to a much more attractive alternative than it has been in the past. AHS offers the potential to make transit even more reliable, safer, and less time consuming. In light of the current legislation and support of transit by government policy to move people more efficiently, transit can be an integral, if not leading, component of initial AHS systems. Incorporation of transit into an AHS would allow transit agencies and their passengers to reap significant benefits, provided that the implementation and operating cost changes over existing conditions are viewed as worthwhile in terms of the benefits achieved. These potential benefits to the transit industry and its passengers Include:

- Increased ridership due to better customer service
- Reduced travel time: ability to compete with other, faster, modes of transportation
- Improved safety, reduced insurance costs, fewer third party claims from injuries sustained on-board buses, reduced fuel, energy consumption reduced bus down-time
- Reduced labor costs due to vehicle productivity increases
- Contribution to environmental goals of the CAAA, ISTEA.

Incorporation of AHS technologies into an existing High Occupancy Vehicle (HOV) lane or roadway would provide a cost effective transition from existing infrastructure. Transit vehicles and high occupancy vehicles would be among the first to benefit from AHS.

4.7.1.4 Case Studies

From the analyses conducted for the Long Island Expressway, the New York State Thruway, and the New Jersey Turnpike, it is evident that each type of interstate highway, urban or rural, exhibits varying capabilities for incorporating AHS technology.

From the analyses, based on the stated assumptions, it appears that the most efficient travel will occur with passenger vehicles in separate AHS lanes, as well as all commercial and transit vehicles in separate AHS lanes. (CT1)

AHS technology would be theoretically viable to alleviate congestion. The findings in the analyses for the LIE indicate that Option A for Scenario #4, with an ultimate capacity of 8,900 pcph, would be most beneficial for people-moving efficiency. These options also exhibit favorable average vehicle occupancies for compliance with the CAAA/ECO Program goals. Along the east Spur of the New Jersey Turnpike Option A for Scenarios #1 and #4, with an ultimate capacity of 8,900 pcph, prove to be the most efficient. Option A for Scenarios #1 and #4 for the combined section of the Turnpike would also be relatively efficient in people-moving efficiency. These options would require carpools 2+ persons and aid in the effort to achieve the CAAA/ECO Program goals. (CT2)

"No Build" conditions in 2024 on the New York State Thruway would not require excess capacity. An AHS could be implemented in this corridor for reasons of safety and efficiency. Option A, with one (1) AHS lane and two (2) GULs, would be the most effective option. None of the Scenarios/Options would meet CAAA/ECO Program goals. (CT3)

4.7.2 Commercial and Transit AHS Analysis, Part II

4.7.2.1 Introduction

This analysis focuses on how commercial and mass transit versions, as opposed to privately-owned, single-vehicle-equivalent (SVE) versions, of AHS can serve the commercial segments of the nation's transportation demand.

The analyses are user-oriented. They focus on the user (shippers and transit riders) demand for transportation. They seek to determine the extent to which those user needs are met by the services offered by public or private commercial operators of the various representative system configurations (RSC) of AHS. These analyses identify which AHS technologies have the best chance of providing user benefits to transportation providers (carriers, operators) and market-competitive services that will be purchased by transportation users (shippers, riders).

The analyses use various data bases that explicitly represent the existing spatial and temporal characteristics of commercial and transit transportation markets. It is these fundamental characteristics that AHS must serve competitively if AHS is to achieve a significant market penetration.

Separate analyses are carried out for each of the following commercial an transit market segments:

Inter-city Commercial Freight Traffic
Intra-city Commercial Freight Traffic
Commercial For-hire Inter-city Passenger Transport, and
AHS - based Urban Transit

Identified in each market segment were the fundamental market characteristics that could be better served with an AHS as compared to conventional technology. For example, the demand for inter-city freight transportation is widely distributed geographically. There exist no major corridor that serves even just a few origins and destinations. In general each stretch of road serves a large watershed of widely dispersed origins and destinations. For this reason, the initial stages of an infrastructure-based AHS is relegated to being able to serve only a short stretch of most shipments that travel over that segment. On the other hand, a vehicle-based AHS that can be used ubiquitously across the conventional highway infrastructure can serve essentially the entire trip length of all shipments served by even the first truck so equipped. Thus, a vehicle-based-RSC AHS has an enormous advantage in the initial stages of implementation.

For each of the market segments, the full array of AHS Representative System Configurations were analyzed to determine the extent to which they could effectively serve these markets. For those that were deemed to have the potential of achieving a significant market penetration an attempt was made at establishing some fundamental market parameters and potential market size. The perspective taken was to assume that the RSCs were operated by private or public entities that would offer to transport freight or passengers for a fee. The analyses were conservative in that they focused on only AHS's opportunities to serve existing demand. No attempt was made to try to forecast the growth or changes in demand that may be stimulated by the availability of the superior transportation services offered by AHS.

4.7.2.2 Conclusions and Key Findings

The analyses reached the following conclusions and findings:

For Commercial AHS Service of Inter-city Freight:

- The commercial freight inter-city market has most of its driving cycle on rural, uncongested interstate highways. (CT4)
- Class 8 trucks, on average, log more than 125,000 miles per year of travel, of which 100,000 is on the interstate highway system. (CT5)
- The market for class 8 trucks (over 33,000 pounds) is approximately 2 million per year. (CT6)
- Motor carriers have aggressively bought new technology that provides improved safety, comfort and convenience for the driver and advanced communication systems that improve the management of the truck fleet. (CT7)
- A vehicle-borne, infrastructure-free RSC 2-type system that would be usable on much of the nations interstate and expressway highway system without any infrastructure improvement would be extremely attractive to motor carriers (and the inter-city bus industry). A good price point for these systems would be a capital outlay of about $5,000 , and a maintenance cost of less than $500 per year. At this level this adds about one cent per mile to a truck's operating costs. (CT8)
- At a 50% market penetration of new sales, there is a $250 million annual market for a $5,000 vehicle-borne RSC-2 type system that is installed as optional equipment on new class-8 trucks. Conversions of existing trucks increases proportionately the size of this market. (CT9)
- An infrastructure-based, RSC 8-12-type AHS has a clear evolutionary path starting with dense 1,200 mile corridor along I-80 between Chicago and Salt Lake City. Each mile of such a system could serve as many as 1.8 million truck movements per year if the economics are right. Because such a system would serve only a small portion of the driving cycle of most trucks using the system, the on-vehicle hardware costs can't be amortized over as many miles as an RSC 2, infrastructure-free system. It will be paramount to keep the on-vehicle costs extremely low so as not to stifle market entry by those trucks that could otherwise use the system. (CT10)
- Future evolutions of an RSC 10-11-type AHS could grow to an 11,000 mile system that could serve roughly 50% of the current truck-served, inter-city freight market. (CT11)
- Even by assuming a 100% market penetration, the 11,000 mile RSC 8-12-type AHS would only generate toll revenues of $110,000 per route mile at toll rates of $.10 per mile. This level of tolls can service the capital debt of about $1 million per

mile. It is unlikely that motor carriers would be willing to pay AHS tolls that are much greater than $.10 per mile. (CT12)

- A driverless, SVE, RSC-8/9-type, Phase 3 AHS concept could serve a substantial amount of LTL demand. If toll charges are limited to approximately $.10 per vehicle mile, then, LTL demand patterns, shipment size, vehicle costs and existing freight rates suggest that each mile of such a system could serve as many as 600,000 of these shipments per year. Assuming a 50% market penetration, traffic densities on a Phase 3 network could generate toll revenues of about $30,000 per route-mile per year. (CT13)
- Comparing the basic economics of the market for a driverless, RSC-2-type AHS with an infrastructure-intensive RSC 10-11-type AHS suggests that an RSC 2-type system is much more attractive to the inter-city freight industry. It's on-board costs can deliver benefits over much more of the driving cycle, the system has a much lower cost of entry (infrastructure does not have to be built), and even a mature RSC 10-11-type AHS does not serve enough volume, even at a large toll ($.10/mile) to service the cost of the infrastructure. This finding suggests that R&D investment focused on reducing the cost of reliable vehicle-borne, infrastructure-free RSC-2 type systems is the best way to have AHS successfully serve the inter-city freight market. (CT14)

For Commercial AHS Service of Intracity Freight:

- Intra-city freight and the collection and distribution of inter-city freight are extremely difficult to serve with automation. The small shipment size and the multiple stop character of the operation are not conducive to automation. (CT15)
- As with inter-city commercial bus operation, the driver performs more functions than simply driving the truck. The driver is the service interface with the customer. (CT16)
- The geographic diffusivity of this traffic is such that much of the intra-city goods movement driving cycle takes place on road segments that are not compatible with an RSC-2 type AHS. Because each vehicle logs relative low annual mileage vehicle-borne AHS hardware can be amortized only over those few miles. An infrastructure-intensive RSC 8-12-type AHS serve even less of the driving cycle. (CT17)
- AHS does not seem to be particularly attractive to this market. (CT18)

For Commercial AHS Service of the Inter-city Passenger Market:

- The commercial inter-city market is small in comparison with the inter-city passenger market served by the private automobile. (CT19)
- The only likely short term commercial inter-city passenger market for AHS is that of inter-city bus. This is a very small market. Only 1,000 new inter-city buses are sold each year. However, the driving cycle of an inter-city bus is similar to that of an inter-city truck. Thus, it could provide a good secondary market for an RSC 2-type AHS that was designed to serve the inter-city freight market. (CT20)
- The bus market is less conducive to a driverless AHS because the driver provides substantial benefits other than driving. (CT21)
- An infrastructure intensive AHS has better opportunities than commercial freight to serve geographically contained sub-markets, because commercial buses can be

managed to operate in constrained corridors. Such a system could better serve geographic segments of the automobile market because the driving cycle of a particular automobile is much more geographically constrained than that of an inter-city truck. (CT22)

- The large inter-city market is served by the private automobile. Unfortunately, on average, the private automobile travels too few miles on inter-city expressways to justify spending even a modest amount for an RSC 1/2 type system. However, there may exist some significant sub-markets, such as traveling salesmen, that could easily justify investment in an RSC 1/2 type system. Such systems also become more attractive if they could be used for the daily commute portion of the automobile's driving cycle. (CT23)

For Commercial AHS Service of the For-hire, Intra-city Passenger Market (Transit):

Three major AHS technologies were analyzed for potential service of intra-city passenger traffic: automation of conventional mass transit, dual-mode transit and guideway-captive small vehicle automated guideway transit. For conventional transit, automation of the exclusive bus lane leading to the Lincoln Tunnel served as a case study. For dual-mode and analysis was performed that assessed the service potential of an state-wide dual-mode system in New Jersey. The following conclusions were reached:

Conventional Mass Transit-Automation of the Lincoln Tunnel - I-495 Exclusive Bus Lane:

- This system has the enormous people moving capacity of over 30,000 people per hour. (CT24)
- Technology requirement are relatively modest. (CT25)
- Infrastructure requirements are very modest. (CT26)
- Such a system is potentially the best candidate for an early successful implementation. (CT27)

Dual-mode "Mini-bus" System for New Jersey.

- This analysis shows that a relatively small 538 mile dual-mode AHS network could serve more than 70% of NJ's work trips that are currently taken by auto and are greater than 5 miles in length. This is a very strong finding. It needs to be moderated somewhat because we only analyzed ability to serve. We did not attempt to determine how many of those trips would likely divert to a dual-mode system if such a system were to be built and the service offered. (CT28)
- This analysis does highlight the fact that many work trips are close by in origin, destination and time. A service that would easily enable dynamic ride-sharing through the use of automation has a large market potential. It can attain enormously high average occupancy levels that can reach 4.5 passengers per vehicle in the peak period. (CT29)
- Because NJ's work trip patterns are thought to be similar to those that exist in many metropolitan areas, the dual-mode concept may have wide applicability. (CT30)

Analysis of Driverless AHS Transit Opportunities:

- In summary, driverless AHS systems would require an exclusive AHSway as envisioned in RSC 9-12. (CT31)
- The driverless feature is not attractive to providers of inter-city passenger transportation and intra city freight transportation because the driver provides substantial services beyond those of "driving" that can not otherwise be automated. (CT32)
- On the other hand, inter city freight and intra-city passengers can do without a driver, if the difficulties of access can be dealt with. In these situations, a driverless AHS may gain a significant cost advantage while providing comparable user service. (CT33)

Conclusions for the Transit Market:

- Urban transit, that is, for-hire, intra-city passenger transportation is only a small fraction of intra-city person transportation which is dominated by the private automobile. Nationally, transit serves only 3% of intra-city person trips. (CT34)
- Only the express bus sub-market of transit is conducive to the early stages of AHS. A particularly attractive example of such a system is the exclusive counter-flow bus lane leading to the Lincoln Tunnel. This is the busiest bus corridor in the US. (CT35)
- There are several fundamental characteristics that make the Lincoln Tunnel XBL a particularly good application for AHS. First, there is a monumental problem on the horizon if a substantial capacity improvement is need in this facility. There is no place to put another access lane and the cost of boring another tube is enormous. Thus, capacity through automation would surely be the most cost effective solution. Even without need for capacity improvement, automation would smooth out the flow of buses and improve the travel time reliability of the buses. The application is on a very short corridor, less than five (5) miles, and the same busses use the facilities repeatedly. The institutional challenges are "minimal". All buses are the property of NJDOT and were purchased with PANYNJ money. NJDOT and PANYNJ have authority over all operations and construction in the corridor. For these major reasons, this is an excellent candidate "early winner" for AHS. (CT36)
- A Dual-mode service over a 750 mile NJ AHS network could provide auto-like service 780,759 passengers (71 %) out of NJ's 1,116,985 daily auto-based work trips that are greater than 5 miles in length. A $.10 per passenger mile fare would generate annual revenues of about $800 million. It may well be that fares would need to be more like $.20 -$.25 per mile for such a system to begin to contribute to the debt service payments for the AHSway. (CT37)
- The average vehicle occupancy is 4.68 passengers per dual-mode vehicle. This is an enormous average vehicle occupancy, especially when compared with that of the current automobile's value of 1.1 for work trips. Because of this high average vehicle occupancy, the densest link on the network needs to serve a maximum of only 2,000 vehicles per hour. (CT38)
- Dual-mode is an interesting transit concept for a mature AHS. It needs to have access to a rather extensive network of AHSways in order to serve a significant portion of urban/suburban travel demand. (CT39)

- A driverless AHS transit application could piggy-back onto the economies of scale associated with private vehicle development and the AHSway construction. (CT40)
- A driverless AHS transit system could serve metropolitan trip demand nearly as well as dual-mode without the need of drivers and with less confusion in the collection and distribution. This concept make more sense as the size of the network of AHSways grows, thus, reducing the access problem. (CT41)

4.8 AHS INSTITUTIONAL, SOCIETAL, AND COST BENEFIT ANALYSIS

The AHS institutional, societal, and cost benefit analysis consists of these two task report summaries: (1) Institutional and Societal Issues (Task O), and (2) Preliminary Costs/Benefit Factors Analysis (Task P).

4.8.1 Institutional and Societal Issues (Task O)

4.8.1.1 Objective and Approach

The objective of this task has been to document the panoply of institutional and societal issues and risks — the so-called "non-technical" issues — that confront the effort to deploy Automated Highway Systems (AHS). [*Note: One of the recurrent recommendations during the course of the Institutional and Societal Issues Precursor System Analyses (PSA) has been that AHS be renamed, perhaps to Automated Transportation Systems. In recent months, IVHS America has begun to use the term Automated Vehicle Operations (AVO). With misgivings about perpetuating the term, but for consistency with the official title of the PSA effort and the other volumes of this Final Report, AHS is used in this chapter.*]

The methodology involved a multi-stage process beginning (and continuing throughout the effort) with a review of all available literature regarding the subject of automated vehicles and highways and regarding Intelligent Transportation Systems (ITS), formerly called Intelligent Vehicle Highway Systems (IVHS). The initial research lead to a categorization of AHS-specific issues and risks that was later modified to conform with commonly accepted categories being used by the ITS community. Additional institutional and societal issues identified in the course of the more technologically-based tasks and arising from discussions within the PSA effort were added over time. As anticipated at the outset of our effort, the findings of Task G regarding comparable systems were particularly valuable.

Issues were defined and redefined as work continued throughout the year on related ITS issues. Another important aspect of this task was to examine which institutional issues arise in connection with the different Representative System Configurations (RSCs). It became apparent early on in this effort that institutional and societal issues vary enormously depending on which RSC is deployed.

The confluence of some early conclusions regarding technological, societal and funding issues resulted in the finding in early March 1994 that AHS deployments ought to be phased-in, beginning with those RSCs that are less infrastructure intensive and less central command and control dependent.

Following the Interim Results Workshop in April 1994, we identified certain key issues that called for more in-depth analysis and that were not yet being examined in such depth by others involved in the PSA effort. The subsequent research in these areas — air quality, political structure (in certain geographic areas), land use, and social equity — is a particular highlight of this Final Report.

4.8.1.2 Key Findings

1. Perhaps, the most important finding of this task is that there are ***likely to be no insurmountable institutional and societal barriers — show stoppers — to the evolutionary deployment of AHS.*** This does not mean that surmounting some barriers will necessarily be easy. There is much to do before AHS deployments — beyond initial test sites — is feasible. (IS1)

This finding itself rests on two of the earliest conclusions of this research effort:

2. ***Institutional and societal issues and risks vary enormously depending on the RSC to be deployed***; and an important conclusion that seemed a bit daring when we first stated it early in the year, but which came be accepted with a surprising near-unanimity as of the conclusion of the April 1994 Interim Results Workshop, that (IS2)

3. Based on an analysis of the history of the introduction and acceptance of comparable, earlier technologies; the likely availability of funding, and the need to resolve <u>some</u> institutional and societal barriers incrementally as part of the process of deploying ITS technologies — even before AHS — ***AHS must develop evolutionarily from less infrastructure and outside-the-driver command and control technologies to more infrastructure dependent/greater outside command and control technologies***. (IS3)

Additional findings include:

4. Beyond confirming early (pre-PSA) predictions that AHS would be expected to provide air quality benefits — based on the assumption that carbon monoxide would be reduced simply because vehicles would move more consistently at higher speeds — ***it is likely that AHS will provide air quality benefits not only by reducing CO emissions, but also by reducing <u>both</u> the hydrocarbons and nitrogen oxides that create the more serious air quality problem of ground-level ozone***. (IS4)

5. ***Many institutional/societal issues that arise in connection with AHS are not unique to AHS, but rather, related to any plans to build roads today or in the future***. The AHS effort cannot be expected to address, let alone resolve, all of these larger societal and historical issues. On the other hand, these issues can become barriers to the deployment of AHS. And to the extent that AHS may accentuate the effects of how some of these issues are perceived, for example, urban sprawl, the AHS effort must be aware of its place in this larger context of institutional and societal issues and be prepared to address such issues in its deployments. (IS5)

6. ***The awareness that AHS is likely to evolve evolutionarily from ITS technologies and that the ITS effort is addressing many of the same institutional and societal issues does not mean that all of these issues will be resolved through the ITS deployment process prior to the time when it***

is technologically feasible to deploy AHS. Nor can the AHS effort expect that even those institutional and societal issues that are "resolved" in the process of deploying ITS will necessarily simply "go away" for AHS. Moreover, there are institutional and societal issues that are likely to arise specifically with AHS, as opposed to ITS, technologies. (IS6)

7. ***If the AHS technology is not generally available at modest cost, there are important equity issues involved in reserving or constructing a lane for the use of relatively wealthy private vehicle owners***. (IS7)

8. The AHS effort must play "catch-up" with the long-term state and regional transportation planning already well underway in response to previous state and federal mandates and the more recent 1990 amendments to the Clean Air Act and 1991 Intermodal Surface Transportation Efficiency Act (ISTEA). ***Transportation plans for the next 20 years in congested areas in many cases are looking to rail projects to address many of the same transportation issues that an AHS might conceivably address***. (IS8)

9. Application of the technology to a mode of transportation that serves moderate-income commuters in an existing, heavily used corridor under the institutional jurisdiction of relatively few actors provides the kind of setting that could allow an early AHS success. AHS proponents must focus on both short-term and long-term opportunities by being aware that it is the institutional and societal milieu that determines if, when and where new technologies such as AHS will be deployed and being prepared to: (IS9)

   Maximize the use or imminent improvement of existing facilities to demonstrate the benefits of AHS, even, or perhaps particularly, when the technology is used exclusively for non-personal vehicles, and that <u>such an early win opportunity may be represented by the desirability of automating the existing Lincoln Tunnel exclusive bus lane in New Jersey</u>, and
   Support the development of non-AHS facilities where there may be a good opportunity for later conversion to automation.

4.8.1.3 Recommendations for Future Research

Recommendations for further research during the next, consortium phase of the AHS effort are summarized below:

1. Tort and product liability — further research into the most viable of the several potential approaches for addressing this issue.

2. The extent to which AHS will induce demand for additional trips and for trips by low-occupancy vehicles that might otherwise be made by public transportation, and the extent to which AHS will encourage trips of greater distance — increased VMT — to take advantage of time savings.

3. Further research into how the issues of public acceptance and education might guide how any initial test deployments are structured, how their expectations are defined, and how their results are interpreted and disseminated.

4. The amount of revenue that might be raised with each type of funding source for AHS, the reliability and cyclical variability of revenues from each, and the political/institutional implications of each.

5. Additional research into those potential applications of AHS technology that would be of particular interest to previously-identified potential stakeholder groups, and particular research into how AHS might be used to improve local control of traffic and improve community livability.

4.8.2 Preliminary Costs/Benefit Factors Analysis (Task P)

4.8.2.1 Overview

Formulating the expected costs and benefits of an automated highway system requires the use of a conceptual framework for determining types of costs and benefits, measures of cost and benefits, and an understanding of the uncertainty involved in the range of estimates derived as a result of the framework. We have developed an analytical matrix that accomplishes this task. We have also evaluated the major factors affecting the incremental costs of an AHS system, from initial research, to early deployment, through ongoing operations. Similarly, we have identified the most important benefit measures to be travel time savings, from the point of view of AHS road users themselves; accident avoidance and congestion avoidance benefits, from the societal point of view; and traffic throughput from the road operator's point of view. In addition, there are significant construction and ongoing operations and maintenance benefits to be gained as a result of secondary or "multiplier" effects of spending resources in deploying such systems regionally, or even nationally. Other benefits, such as productivity improvements at the workplace, will have to be an area for further research. It is conceivable that these may be significant, but quantifying such benefits, when little is known or predicted about the share of (say) commuting trips that are taken on AHS roadways the produce travel time savings or other user comforts/conveniences, is difficult if at all possible.

On the cost side, AHS roadways will incur substantial infrastructure construction, operating and maintenance costs. In addition, there are the costs of on-board electronics, as well as the added costs of the system infrastructure. A proper evaluation of AHS systems will thus have to consider these cost components.

We also examined traffic data for several actual roadways that could implement candidate AHS systems. Considering estimates of both benefits and incremental costs for these actual roadway scenarios, we found that, on the whole, AHS roadways do not produce sufficient economic gains to outweigh potential costs. Only in one of our roadway scenarios did we find that AHS roadways would pass a numerical cost-benefit test. However, we cautioned against over-interpreting these results. Our estimated performance gains were just that: estimated. Our cost estimates could be subject to wide variation when real systems would be actually deployed. But this exercise provided us with some useful insights into some of the more prominent relationships between benefits and costs when considering AHS.

Our research focused on the major benefit and cost factors that should enter into proper evaluations of candidate AHS systems. We first defined the economic rationale behind cost-benefit analysis. The strongest principle of a sound investment in a project is its internal rate of return, which is the discounted present value of its projected income stream net of its initial investment and all other costs to be incurred during its projected lifetime. A project with a projected rate of return that is both large and positive is indeed a project that should be undertaken. Alternatively, we reviewed the net present value appraisal method. A project should be undertaken if its net present value, or its net discounted stream of future income minus costs, is positive. For example, we found that travel time savings will accrue to some roadway users after implementing an AHS system. These savings, expressed in dollars, constitute one component of the annual stream of expected benefits. On the other hand, annual periodic payments need to be made for the upkeep of the roadway, to take another example. These payments are counted in the future stream of costs. (CB1)

Following our discussion of cost-benefit principles, we discussed the importance of considering cost-benefit analysis for the policy context. There will be many goals expected from future AHS systems. Roadway operators will be concerned with performance gains, such as increased vehicular throughput and gains in operational efficiency, particularly in inclement conditions. Users will be concerned with increases in comfort and convenience and reductions in operating costs, delay and congestion, as well as better schedule reliability. To society as a whole, AHS roadways will have to deal with the roadway safety issue, with traffic congestion, with better personal mobility, with trip and schedule reliability, and so on. Concurrent with such benefit categories, AHS roadways will have to accomplish such gains while keeping deployment, operation, maintenance and renewal costs to a minimum. The importance of cost-benefit analysis, then, in this policy context, is to outline these categories of expected system benefits and costs so that AHS can be evaluated effectively, or even tailored so that it can achieve the maximum gain for the least amount of cost in general. (CB2)

Our next objective was to ensure that we could capture the major components of system benefits and costs. To do this, we researched several possible evolutionary deployment scenarios for representative AHS roadways. At each step in the evolutionary process, the costs of deploying systems would generally increase, with often either a corresponding or a less than corresponding increase in expected benefits. We took care in distinguishing between performance gains themselves, and the perceived value to users or others of such gains. We included at first all of the major components of benefits and costs, and then judged several distinct components to be more than significant than the others using currently accepted standards of evaluation.

In particular, we judged travel time savings, accident cost savings, and the secondary economic effects of ongoing operations and maintenance activities on societal output and employment to be among the most important categories of economic benefits that are the most easily quantifiable. Other benefit measures, such as general increases in workplace productivity or better schedule reliability are certainly important, but do not readily lend themselves to reasonable quantification. On the cost side, we found that the major component of system costs is the actual construction cost of the AHS roadway. Other important costs include system infrastructure costs, vehicle electronic costs, and the costs of ongoing operations and maintenance. (CB3)

To apply our general principles, we then considered four candidate real roadways where deploying some form of AHS would be possible and even desirable. We looked at New York's Long Island Expressway and the New York State Thruway, Baltimore's section of Interstate 495 and Boston's Interstate 93. Our analysis of these roadways suggested that, at least conceptually, AHS deployment would pass a numerical cost-benefit test on only one roadway scenario, New York's Long Island Expressway, a particularly congested roadway with parked peak hours of congestion, and a roadway with significant commercial vehicle access as well as transit (bus) use. However, that is not to suggest that AHS as currently configured does not make economic sense anywhere else. There are several reasons for this. One, our current evaluation methods are relatively crude, and cannot capture the major societal effects of general improvements in living standards or in workplace productivity as a result of reducing the stress, fatigue and accidents involved with major commuting patterns. Two, our analysis is preliminary and is entirely limited by the many assumptions used in our traffic analysis, cost estimates, and roadway deployment scenarios. It is entirely possible that as we refine our work in these and other areas, we will derive performance gains that are much more substantive. Three, there are too many uncertainties with regards to the possible makeup of future AHS systems that concluding at this stage that AHS has only limited economic applicability would be too premature. Clearly, AHS displays a considerable amount of promise with regards to potential economic gain, and this needs to be carefully developed further. Particularly since AHS will undoubtedly involve a significant commitment of public resources, its justification will hinge on the ability to develop and achieve such gains. (CB4)

4.8.2.2 Recommendations for Future Research

The most critical path for future research on the costs and benefit factors in evaluating proposed AHS systems is to investigate, develop and refine work on its performance gains as well as its incremental cost components. The state of the art in traffic engineering needs to be brought to bear on systems that have yet to see operational testing. Much needs to be accomplished in the area of on-board system configurations to enable some form of costing analysis to be done with greater precision than is currently achievable. Much more detailed research needs to be accomplished on the safety improvements promised by AHS. Stakeholders in the systems community need to be better integrated in systems definition to enable more accurate market definition, as well as to achieve a better sense of the ultimate consumer cost parameters. This is perhaps the most fertile area for future research, since cost-benefit analysis of tomorrow's AHS roadways depends crucially on the quality of the inputs from work on roadway deployment and operations, safety analysis, roadway configurations and systems infrastructure, and so on.

5.0 OVERALL CROSS-CUTTING CONCLUSIONS AND OBSERVATIONS

5.1 INTRODUCTION

Section 3 of this volume, and volumes II through VIII, document the activities and results of the seventeen tasks (RSC Task and Tasks A-P) that comprised this study. A summary of each of the sixteen primary tasks (Tasks A-P) is provided in section 4 above. The purpose of this section is to extend beyond the individual task boundaries, that typifies the rest of this report, and describe the results in a more cohesive manner.

Since this research effort was performed over the short period of one year, most all tasks were performed simultaneously. Therefore, the specific research activities were encapsulated, to some degree. However, efforts were made to provide some integration across the entire program. The RSC definitions (performed in the RSC Task and reported in section 3) were the primary multi-task integration approach. Other more limited approaches were applied to smaller task groupings. For example, the comparable systems task provided lessons learned as input to the institutional and societal task. Also, the exit and entry task supplied measurements of merge distance requirements to the roadway deployment task. As a last example, the cost benefits task received cost and benefits estimates from the safety task, the roadway deployment task, the lateral and longitudinal guidance task. These are only three of the many examples of synthesis that took place across the study. Therefore, the conclusions and key findings in the individual tasks reports, presented in section 4 above, already identify a number of cross-cutting conclusions. The cross-cutting conclusions in this section represent the major findings, but more importantly, are organized in a manner that consolidates the results.

The key findings, presented for each task in section 4, were labeled sequentially within the task area. They were displayed as a two letter task identifier followed by the sequence number. They appear after each key finding, in parenthesis. Where applicable, these labels will appear in the key findings in this synthesis section to facilitate cross-referencing to the originating task.

One major difficulty in effectively synthesizing the task results is the extent to which the individual tasks are based on common assumptions. The definitions of the RSCs provide one level of common assumptions; however, it is possible that some task conclusions arise from different and possibly contradictory assumptions. Therefore, we have been careful to only combine conclusions that come from similar assumptions.

It is important to state at this time five major themes associated with our study approach. They are:

1. The AHS analysis was performed with a priority towards **breadth of research** rather than depth of research. For example, the comparable systems task, the lateral and longitudinal guidance task, the institutional and societal task, and others all were very broad in scope.

2. A **conservative approach to safety** impacted most all design analysis. For example, the costing of the infrastructure included the cost of a breakdown lane for malfunction management purposes.

3. **Detailed infrastructure analysis** was performed. Since the infrastructure is such a costly component, the costing exercise utilized actual scale drawings of the roadway design to provide greater accuracy.

4. **Travel time benefits for four representative roadway scenarios** were carefully calculated. Most benefits models are driven by time reduction calculations. Therefore, the INTEGRATION model was exercised to supply estimates of travel time savings.

5. A comprehensive study was performed of the **market potential of commercial and transit applications of AHS**.

The organization of the remainder of this section illustrates our synthesis approach. The following four sections (sections 5.2 - 5.5) describe the overall results. They are organized into the following four topics: (1) AHS Configuration and Deployment, (2) Technical System, (3) Benefits and Costs, and (4) Institutional and Societal System Impacts. These topics were chosen to represent a high level systems view of AHS design, implementation, and operation issues. They are the researchers own choice and are not the only system level view available. However, they are a convenient structure to frame the major conclusions. The major element of the synthesis approach was to organize, analyze, and combine the individual task key findings into this new structure.

Section 5.6 presents a summary of the major recommendations for future work. These recommendations are also organized into the four topics.

5.2 AHS CONFIGURATIONS AND DEPLOYMENT

What will the AHS look like when it is implemented? Whom will it serve? How will it start and grow? These are the standard questions asked about an automated highway system. They were asked at the beginning of the study and remain open as we present our results. However, we do offer findings that narrow the view somewhat.

Our work in the RSC Definition Task started answering these questions. Our RSC definitions provided a broad view of the range of AHS possibilities. The detailed RSC definitions are provided in section 3, of this volume, and are referenced throughout the report. The three RSC dimensions, and their associated levels (I1, I2, I3, C1, C2, C3, V1, V2, V3, V4), were originally chosen to provide a framework for AHS trade-off analysis. Early on it seemed that this framework would facilitate the choice of an optimum AHS configuration. As the research progressed, it turned out that the definitions were better suited for analyzing the capability of AHS to fit a particular deployment strategy or serve a market niche. We will discuss these deployment results and market demand results in sections 5.2.2 and 5.2.3, respectively.

However, before we move on to the deployment and market potential results, it is useful to state a few general conclusions about the 13 RSCs. These conclusions are an outgrowth of various task results.

5.2.1 General RSC Conclusions

5.2.1.1 RSC Dimensions

As described in section 3 of this volume, the RSC definition approach consisted of defining generic candidate AHS designs in relation to these three dimensions: (1) the amount of dedicated ***roadway infrastructure*** **(I dimension)** required; (2) the ***degree of command, control, and communication*** **centralization (C dimension)** required (i.e., centralized control over vehicle maneuvers); and (3) the ***types of vehicles*** **(V dimension)** to be served. Emphasis was placed on covering the extremes of the three AHS dimensions as well as reasonable mid-point values. Specific RSCs, to be included in the study, were then selected through a process of elimination from all possible combinations among these dimensions. RSCs were eliminated if they were thought to be redundant for studying AHS issues or if they were impractical from an implementation perspective. For example, an AHS with highly centralized control cannot be effectively applied to an AHS configuration with a low level of infrastructure, according to our definitions.

Some general key findings resulting from the use of this RSC approach are:

- The three dimensions (I, C, and V) provided a comprehensive framework for analyzing the system concepts. The levels of each dimension were also well chosen and covered the system extremes.

- Although the RSCs provided a comprehensive framework for system analysis, they did not provide a full set of detailed concepts for analysis. Some specific approaches to AHS implementation were not covered in detail due to early prioritization requirements. For example, a major theme of our analysis was to take a conservative approach to the safety aspects of the system. This lead us to emphasize the need for barriers to separate AHS lanes from general use (manual) lanes. It also lead us to the requirement for a breakdown lane as a malfunction management tool. Once these system design approaches were identified, they, to some degree, limited the design analysis. It is important to emphasize that these choices were made based on very preliminary results, were dictated by the resources available for the remainder of the study, and provided consistency with our overall theme of a conservative safety policy. In no way are they the product of detailed analytical activities.

- The study heavily emphasized the infrastructure dimension more than the C and V dimensions. It also concentrated on AHS infrastructure designs which provide separate lanes for AHS and non-AHS vehicles (I2 and I3). A separate AHS facility provides an environment which maximizes the constant speed and headway keeping capabilities of AHS vehicles which in turn is a major system benefit.

5.2.1.2 Interaction of I and C Dimensions

The analysis concluded that the I and C dimensions are more strongly coupled than originally thought. The relationship between higher levels of infrastructure and higher levels of command, control, and communication centralization is strong. In general, RSCs that have infrastructure levels 2 and 3 require C levels greater than 1. Therefore, the I2C1 and I3C1 RSCs received little attention in this study. There are two fundamental principles that drive this conclusion: (1) the dedicated lanes of the I2 and I3 configurations provide the facility for greater control of speed, spacing and lane changes, and (2) the more the system controls these AHS functions the more traffic benefits occur. Also, a new RSC, I2C3, received some attention due to the perceived benefits of centralized command and control (C3) for vehicles traveling on separate AHS lanes accessed through the general use lanes (I2).

As part of our study we proposed specific definitions of the three levels of the I dimension and the C dimension. In general, the I dimension levels are quite specific and most likely universal in nature. The only major area of uncertainty involves the use of barriers within the I2 configuration rather than continuous transition lanes. However, the discrete definition of the C dimension is much more difficult. The approach taken within this study is based on coupling the level of command, control and communication to the type of communications links available to provide the necessary information flow. Our approach is probably unique. Although we feel it is a viable approach, it was not as easily applied across all task efforts as the infrastructure dimension levels. More front end analysis of the C dimension concepts would have been beneficial, if time permitted.

5.2.1.3 V Dimension

The intent of using the vehicle (V) dimension as an RSC descriptor was to provide a universal framework to analyze the various vehicle mix alternatives. Although, the AHS emulates the current interstate, which serves all vehicle types, the AHS market for commercial, transit, and personal vehicle use are not the same. Therefore, separate RSCs were provided for performing the various market analyses.

It also was also not clear how the automation requirements would impact the larger commercial and transit vehicle types. The automation concerns were studied, at a low level, in some of the technology related tasks and fed to the Commercial and Transit task. They offer some additional system design constraints but were not considered insurmountable.

However, the major impact of the various V dimension configurations appears to be their infrastructure impact. The V2 level calls for lane separation of the larger commercial and transit vehicles from the smaller commercial and transit vehicles and passenger vehicles. This approach has significant cost and deployment implications that were briefly addressed. They certainly require significantly more research.

5.2.2 Deployment Strategy

The deployment strategy analysis consisted of three separate parts. Initially, the various RSCs were analyzed for applicability to generalized deployment scenarios that cover the full spectrum of AHS applicable roadway environments (i.e., urban, suburban, and rural). The results of this general analysis were then used to guide studies of specific roadway deployments, with both SVE-only and mixed SVE and MVE AHS use. A third area of analysis then focused on the issues associated with the evolutionary aspects of deployment.

5.2.2.1 Urban, Rural, and Suburban Environment Analysis

The target for Automated Highway System (AHS) deployment is our national freeways, the backbone for worker commuter, inter- and inter-city travel and the major roadway choice of America. Freeways, pressured to carry more traffic, are experiencing crippling and prolonged congestion. The remedy for congested freeways is not to build more of them but to make them work more efficiently. AHS analysis is based on this premise.

Experienced transportation engineers recognize the fact that freeway problems are not the same for urban, suburban and rural environments. They were not built for the same purposes, were not engineered the same, and do not operate the same. Therefore, the three environments provide different market potential, different design problems, and different operational considerations.

We began this discussion by addressing the issues of AHS configuration. Our RSCs were analyzed against the market potential, design characteristics, and operational aspects of these three environments. Our **major conclusion** in this area is:

- Envisioning AHS as a national system requires flexibility of design to accommodate urban, suburban, and rural needs. The urban, suburban, and rural environments cover a spectrum of needs. Therefore, a variety of configurations are required to meet each of the needs. Suburban would be more I3 driven and rural would be more I1 driven. As discussed above, the I1 configuration would be more compatible with C1 control. The I2, I3 or mixed I2/I3 configurations would be more appropriate with C2 or C3 control. (UR11)

This study centered around deployments in the northeast US. Within this region, sufficient roadway diversity exists to support the requirement for a flexible implementation strategy.

Other major infrastructure related conclusions involve (1) minimum AHS and general use lane requirements, (2) use of manual lanes for access to the AHS lanes, and (3) the impact of increased throughput on surrounding roads.

The key findings in these areas are:

- If one assumes that rural AHS will initially operate in mixed traffic lanes, when AHS use increases, and higher throughput performance is required, the minimum lane requirements appear to be one AHS lane and two general use lanes. This requirement will impact most of the dual two-lane freeways (outer suburban and rural). Although traffic volumes may show only a need for a single general (manual) lane, entrance/exit, passing, incidents and operation during maintenance will probably require a minimum of two general lanes. This step in the evolutionary process is the most costly and the greatest risk to evolutionary advances of AHS. More detailed discussions about evolution of AHS is presented in section 5.2.2.4. (UR8)

- Suburban freeway deployment is a prime candidate for initial implementation of separate AHS, since the increased throughput is required and the right-of-way may be available. However, equal provisions need to be made for entry and exiting. A major infrastructure design issue for AHS deployment is finding solutions to the traffic mixing, weaving, entry and exit with non-AHS vehicles especially heavy trucks. (UR7)

- One of the highest infrastructure impacts assigned to entry/exit requirements is the merging of two AHS streams starting at right angles. This is due to the large radii required if speed is maintained, and the lack of such a requirement in today's highway geometries. (EE5)

- Infrastructure design issues, including exit and entry location and techniques, are not easily generalized. The four separate freeway case studies concluded that the placement of entries and exits significantly impact the traffic flow. Depending on the origin-destination (OD) requirements, the capacity of the remaining general lanes rather than the AHS lanes may limit overall capacity. Likewise, the specific street and traffic situations dictate requirements on exit and entry techniques. (RD3, EE3, EE4)

- AHS can increase throughput during peak hours provided the supporting interchanges, feeder roads and city streets can accept this increase. At the proposed high flow rates, urban and suburban facilities now regularly fail. Only rural freeway feeders have the capacity required. (UR9)

- Heavy vehicles would require more space for equivalent safety. Adopting a no-collision policy requires about a factor of six at 60 mph. This translates to a large decrement in lane capacity for a small percentage of heavy vehicle flow. Hence, we conclude that design to accommodate heavy vehicles may be optimized if they are automated in an I1 concept sense (mixed manual and automated flow) but do not use the exclusive lanes of the I2 and I3 concepts except where the heavy vehicle percentage justifies a lane dedicated to those vehicles. (EE14)

- The new entry/exits designed for I3 should have curvature and possibly superelevation which limit side acceleration as a function of speed to comfortable values. This conclusion applies as to cruise speed merge/demerges as well as local street ramps. (EE29)

- The I3 single-lane ramps would be limited to the 1200 to 1600 vph manual source flow capacity. To service greater demand, a collector lane can be used. Four single-ramp stages could build a flow of 4800 to 6400 vph for merging with the cruise lane (which must be running at a low v/c at the time) in a distance of roughly 6000 feet. (EE30)

5.2.2.2 Specific Deployment Case Studies

Four case studies were developed to assess the performance and potential benefits of AHS within these representative roadways. The four scenarios included one urban, two suburban, and one rural freeway. Traffic loading for AHS and general lane configurations were developed for each case study. The INTEGRATION traffic model was adapted for AHS evaluation purposes, and the performance of each AHS design was evaluated relative to a baseline or no build case. The effects on nearby surface street intersections were evaluated in some cases.

Two of the objectives of the deployment case studies were:

1. Identify examples of Automated Highway System (AHS) deployment in the context of real case studies and quantify the benefits of these deployment scenarios using measures of effectiveness such as speed, delay, and throughput.

2. Assess the effect of AHS market penetration (MP) on traffic patterns for RSCs I2 and I3 based AHS deployments.

5.2.2.2.1 Urban and Suburban Case Studies

Three of the studies were performed using roadways that are characterized as either urban or suburban. They are segments of: the Maryland Beltway (I495) near Washington DC, the Long Island Expressway (I495), and the Southeast Expressway in Boston (I93). Five conclusions from these studies are:

- RSCs I2 and I3 deployments on congested urban and suburban freeways can significantly improve speed and travel time on these facilities. Travel time improvements of up to 38 percent were obtained for the cases studied. (RD1)

- The selection of I2 or I3 AHS lane access techniques is best determined by the AHS access and egress volume requirements, by the general lane traffic of these locations, and by the level of service (LOS) on the general lanes. (RD2)

- In areas which experience high levels of traffic congestion, such as Long Island, high levels of AHS utilization are obtained based on RSCs I2 and I3 type facilities at relatively low levels of AHS Market Penetration (15-25 percent). (RD4)

- In congestion prone areas, the AHS may generate significant changes in the utilization of parallel facilities located several miles away from the AHS. However, as market penetration increases, as was evident on Long Island, the attraction of the AHS facility to distant parallel roadways decreases, and total vehicle-miles traveled (VMT) in the study area decreases. (RD5)

- The need to access the AHS will, in many cases, cause saturation of surface street intersections. Geometric improvements and signal timing changes will be commonly required. (RD6)

5.2.2.2.2 Rural Case Study

The rural case study was for a segment of the New York State Thruway (I87) north of New York City.

One conclusion from this study is:

- Significant travel time improvements on the rural facility were only obtained when the AHS cruise speed was increased to 80 mph from the 62 mph speed used for the urban and suburban case because the roadway runs at the speed limit with no recurring delay. (RD1)

5.2.2.2.3 Commercial and Transit Case Studies

The deployment results presented above are based on only passenger vehicle types. The assumptions used vehicle headways, and associated capacities, that were based on passenger vehicle characteristics. Three separate case studies were used to study the effects of mixing commercial and transit vehicles with passenger vehicles. These case studies were for the Long Island Expressway, the New York State Thruway, and the New Jersey Turnpike. The results indicated that each type of interstate highway, urban or rural, exhibited varying capabilities for incorporating AHS technology over a mix of vehicle types.

Four of the more significant conclusions are:

1. The most efficient travel occurs with passenger vehicles and large commercial and transit vehicles separated, either both in AHS lanes or one type in AHS lanes and the other in the manual lanes. (CT1)

2. AHS technology is viable to alleviate congestion. The findings for the LIE indicate that an exclusive AHS lane for all commercial and transit vehicles and all passenger cars distributed evenly between two general use lanes, with an ultimate capacity of 8,900 pcph, would be the most beneficial case for people-moving efficiency. These options also exhibit favorable average vehicle occupancies for compliance with the CAAA/ECO Program goals. (CT2)

3. Along the east spur of the New Jersey Turnpike an exclusive AHS lane for only passenger vehicles and two general use lanes for all vehicle types or an exclusive AHS lane for all commercial and transit vehicles and all passenger cars distributed evenly between two general use lanes, with ultimate capacities of 8,900 pcph, prove to be the most efficient. These options for the combined section of the Turnpike would also be relatively efficient in people-moving efficiency. These options would require carpools of two or more persons and aid in the effort to achieve the CAAA/ECO Program goals. (CT2)

4. “No Build” conditions in 2024 on the New York State Thruway would not require excess capacity. An AHS could be implemented in this corridor for reasons of safety and efficiency. One AHS lane and two general use lanes would be the most effective option. None of the Scenarios/Options would meet CAAA/ECO Program goals. (CT3)

5.2.2.3 Evolution versus Revolution

The results presented to this point have been constructed from studies that make specific assumptions about the time period, and corresponding environment, of the implementation. Many of the time periods were significantly advanced and require a number of events to occur for the scenario to be plausible. For example, many of the roadway deployment scenarios for the I2 and I3 configurations assume that the infrastructure was constructed without analyzing the affect of the construction. Similarly, the number of vehicles assigned to the new AHS lanes are required to have bought and tested the vehicle based equipment required for use of the system.

However, these assumptions cannot just be taken for granted. The question continually surfaces as to the extent, cost and associated benefits of the initial implementation.

Simply stated, the question is one of evolutionary deployment versus revolutionary deployment. The evolutionary approach would entail simpler, less costly systems that provide compatible benefits. It would then grow incrementally, with appropriately scaled costs and benefits, to a more complete system. Each stage would be driven by the market. The revolutionary approach is much different from this strategy. It is driven by the need to implement a complete system in order to generate sufficient benefits to outweigh the costs. The assumption is that the market will not drive the incremental growth; it needs to be orchestrated in one collective effort.

Our study addressed this subject from a number of viewpoints. **We believe that it is a critical area of research**. We are more led to the concept of evolutionary deployment; but we are aware that more analysis is required in the area of system definition, along with the associated cost and benefits, in order to resolve the issue. A discussion based on RSC evolution follows.

The realization of a high-capacity AHS is much more likely to be achieved if the technology evolves in an orderly evolutionary process that has commercially successful stages at the lower RSC levels. A journey of 1,000 miles requires successful 1st, 2nd, 3rd, etc. steps. In the end it will be the market place that will pull the technology through the evolutionary stages. Thus, we need to pay attention to the marketplace and pay as much, if not more, attention on the lower RSCs, while keeping an eye on the higher RSCs to ensure that we are guiding the technology to its desired end.

While the lower RSCs don't deliver the broader social benefits of higher capacity and lower congestion, they do deliver, independent of market penetration, the user benefits of comfort, convenience and safety. For example, in RSC I1C1, even the first AHS vehicle will deliver to its driver all the comfort benefits of automated steering and the safety benefits of intelligent cruise control. Because the lower RSCs deliver benefits derived from individual purchase decisions, they have an opportunity to be market driven. On the other hand the higher RSCs can begin to deliver the congestion relief benefits only after a large segment of the market has committed itself to AHS. This leads to a "catch-22" situation with the benefits not achievable until everyone buys and each individual won't invest before the congestion benefit is a reality. Nobody can justify going first, or even second. In this case, valid justification doesn't emerge until the market penetration is extremely large. Only in niche markets, like the Lincoln Tunnel express bus market, where a few decision makers control the market, could one hope to generate enough market penetration to trigger the congestion relief benefit. These fundamental market forces strongly recommend that an orderly evolutionary process be adopted.

Within our cost and benefits analysis we proposed an evolutionary deployment scenario that involves four stages of development. The arguments for this four stage approach are more qualitative than quantitative, yet they provide some level of detail to this important area of study. It begins with a baseline system of intelligent cruise control and advisories and progresses to a stage one AHS. This AHS first stage system adds lateral control and speed commands to provide full automation. It still utilizes the general use lanes but has left lane priority. The next stage begins separated lane utilization with both speed and spacing fully automated. Lastly, all vehicle maneuvers, such as lane change, are automated. Each stage has an associated estimated level of participation required for viability.

Other conclusions leading towards the recommendation for an evolutionary deployment strategy are:

- During early year deployments, AHS performance may not be ideal in terms of congestion relief, due to mix of manual and automated vehicles. However, working with existing freeways to gain initial automation benefits, provides a wider and more immediately visible return than attempting to build new AHS guideways to serve a select few. (UR5)

- An evolutionary approach to the development and implementation of AHS is recommended, based on the experience of several large-scale public systems studied during this project. An evolutionary approach will provide for incremental development, allow safety and reliability to be demonstrated on a small scale before system-level integration is attempted, and provide a gradual approach to achieving public acceptance. This will also allow alternative technologies and design approaches to be compared prior to selection. Finally, US industry will be more willing to invest in AHS if short-term profits are possible. (CS5)

- Evidence for the advantages of an evolutionary AHS development approach was found in many of the comparable systems studied, including HOV lanes, the interstate highway system, automated guideway transit, air traffic control, the railroads, office automation, domestic appliances, and ATMs. For example, the evolutionary approach taken in the development of the interstate highway system made it possible to fund the effort on an incremental basis, while the immediate provision of benefits maintained public support. HOV lanes have also been successful, in part because they build on existing highways (i.e., they are an evolutionary improvement to the existing highway system). (CS5)

- Arguments against the revolutionary approach include the recent experience of the English Chunnel (the tunnel connecting England and France under the English Channel). Cost overruns have led to serious questions about its ability to compete with less expensive ferry service, and the lack of any demonstrated benefits has led to waning public support for the project. (CS5)

- The consequences of faults and hazards at the higher levels of automation emphasize the benefits of an evolutionary approach to an AHS. These benefits will be derived in the form of costs, implementation, and ability to gracefully degrade to lower levels of command and control as the more sophisticated designs are developed and implemented. Evolutionary designs may also turn out to be the configuration of choice for specific locations, such as rural areas, where the cost of building separate automated roadways is impractical and there is less demand for increased capacity. (SI4)

5.2.2.4 AHS Operations

Deployment strategies must include operational issues along with the more visible design and development issues. The long term viability of the system depends heavily on the effectiveness of systems operation, which is highly focused on organizations and procedures.

Some of our key findings in the area of AHS operations follow:

- For operation of an AHS, new or hybrid operating agencies and their organizational frameworks will need to be defined along with their potential operations responsibilities. The levels of association, coordination, and autonomy among the operations elements of existing highways, such as management, maintenance, police and emergency services need to be identified along with potential problems with existing arrangements of these operations elements. Each operating agency scenario and the operational impacts of a multi-jurisdictional framework need to be evaluated and studied. Evaluation criteria should include operations uniformity, effectiveness, and practicality of providing such service. (RO3)

- Current levels of expertise and staffing available at existing operating agencies can not support the requirements necessary for an AHS. The areas of expertise required for operation and management of an AHS need to be evaluated. Survey and review of current practices of in-house versus contracted-out functions at state DOTs and highway authorities are essential to final deployment of AHS. (RO4)

- AHS operations require preventive maintenance on a level similar to the airline industry. Existing levels of preventive maintenance performed by highway operating agencies, including operators of traffic management systems, will not satisfy the requirements of AHS. A target level of preventive maintenance for AHS needs to be defined through investigations of comparable systems. (RO5)

- It is anticipated that the AHS will need policing and involve policing tactics different from those practiced today. Dependent upon the RSC, the level of policing, police functions, and tactics will vary. Current policing practices need to be examined, including the level of policing, functions and tactics applicable to deployment of an AHS. (RO6)

- AHS should be designed with system upgrades in mind. System upgrades and expansion need to be accomplished with only minimal disruptions of service. System upgrades should accommodate earlier AHS users after it is upgraded. (CS15)

5.2.3 Market Potential

The specific AHS system configurations and the various deployment strategies should be driven by the market need. **That is a clear result of this study and a mandate for any follow-on program**. The market has many facets however and all need to be included. It includes the public and private system operators, who are responsible for building, operating and maintaining the roadways that serve potential AHS customers. It also includes the various private vehicle operators that use the roadways for work commutes, inter-city business travel, vacation travel, etc. It includes the private and public commercial and transit industry. It also covers the various manufacturing elements of the system; vehicle manufactures, roadway electronics, etc. that will be driven to find cost effective methods to supply products.

Our study offers a broad base of results as to the potential of enticing these various elements of the market to invest in the future of an AHS. We have organized our findings into (1) the overall market potential of the system and (2) the market strategies that are required to demonstrate the potential.

5.2.3.1 Overall Market Potential

Our research into overall market potential of the system focused more on the quantifiable traffic related benefits of the system rather than the more subtle benefits of user comfort and convenience and increased productivity.

Our key findings in this area follow:

- Research into AHS technology is important as this defines the "How". Equally important is research in the market to identify size and needs as this defines the "Customer". The "How" should be driven by the "Customers' Needs". (UR10)

- The daily user of urban and suburban freeways wants travel time savings as a performance improvement. Acceptance of AHS equipment and traffic management costs will be based on the performance gain. A target goal for this savings is one minute per travel mile; totaling at least ten minutes on the freeway portion of the trip. This objective can, most likely, be accomplished by providing preferential lane and exit/entry provisions for AHS users, since automated control can regulate speeds above the current congested level. (UR1)

- Worker commuter users of urban and suburban freeways are effective targets for early deployment of AHS. These individual users have a vested interest in making AHS a success as they gain time, reliability, and safer trips. As a daily user, they should be willing to equip their vehicles and pay for the service. High Occupancy Vehicle (HOV) users and Transit providers are prime customers for AHS since they are currently part of the solution for urban and suburban congestion. (UR3)

- In areas which experience significant traffic congestion, such as Long Island, high levels of AHS utilization are obtained based on RSCs I2 and I3 type facilities at relatively low levels of AHS Market Penetration (15-25 percent). (RD4)

- A large AHS benefit can be achieved with transit vehicles. (CS12)

  AHS when combined with transit and/or HOV treatments can provide very significant improvements to the people-moving capacity of our highways. These treatments are especially applicable to (and perhaps limited to) AHS applications in urban areas and along congested corridors. When considering the AHS goal of congestion mitigation, the potential of these treatments cannot be overlooked. For example, an AHS implemented in the Lincoln Tunnel Express Bus Lane could potentially provide people-moving capacity greatly exceeding that possible with heavy rail mass transit (although this would require expanded terminal capacity). Even HOV treatments on AHS could potentially provide service comparable to existing light rail systems.

5.2.3.2 Market Potential Strategy

The market is not solely driven by quantifiable benefits. It requires comprehensive and effective strategies to showcase or demonstrate the benefits. **These strategies are probably more important than the benefits themselves**. Our key findings indicate the need for these strategies and suggest targets for the strategies. They do not provide detailed approaches. Some of the conclusions in this area are reinforced within the institutional and societal results that will be summarized in section 5.5. The primary source for these findings is the comparable systems study.

The key findings are:

- Public acceptance will be critical for AHS success. (CS16)

  If we build it, will they come? And will they support its development? These are very important questions for AHS. Public demand for systems can drive the development and expansion of markets to worldwide levels. On the other hand, public opposition to systems can create serious obstacles to success. Issues of public acceptance for AHS will be very important.

  Many factors contribute to public acceptance. Important factors include cost relative to other transportation modes, convenience and ease of use, ability to match users' origins and destinations, obviousness of fail-safe features, and impact on pollution. It will be important to pay attention to public relations and privacy issues, and to the needs of special user groups (e.g., non-English speakers, handicapped). The perceived impact of AHS on job security can impact the acceptance for commercial AHS applications. Finally, even the general appearance of AHS can be a factor in AHS public acceptance. It will be important to consider and assess these issues throughout AHS development.

  This recommendation is based on several comparable systems, including ETTMs, the automobile, aircraft automation, the bicycle railroad, commercial flight, office automation, and ATMs. For example, the employment of nurses as flight attendants during the early days of commercial flight helped to reduce the public's apprehension about flying, and helped facilitate the success of this market.

- The public must perceive the overall benefits of AHS. (CS1)

  In order for a new technology to successfully replace an existing technology, the new system must offer clear and obvious advantages and benefits over the older system. If these benefits are not provided or evident, potential users will likely be unwilling to give up the pre-existing trusted system for the newer system, especially if the changeover involves significant costs (e.g., money to purchase the new system, time to learn new procedures, license fees). AHS design and deployment should proceed in ways that will make the benefits obvious to all potential users.

  Evidence for this conclusion comes from several of the comparable systems studied. For example, experience with HOV implementation indicates that, when drivers can see that HOV lanes are moving more people than non-HOV lanes, they are willing to accept the dedication of a lane for this purpose, even if they do not personally choose to use the HOV lane themselves. Similar experience has been found with the implementation of ramp meters. Toll road implementation also provides support for this conclusion. When toll roads were first implemented in this country, there was great concern whether people would pay to use them when conventional roads were available free. However, experience has shown that because toll roads significantly reduced travel time, they were very successful. Other comparable systems that support this conclusion include the streetcar, commercial flight, domestic appliances, and automated teller machines (ATMs).

- Community outreach and public involvement will be important to AHS success. (CS9)

  It will be wise to keep the public educated and informed throughout the AHS planning, design, and development phases. AHS developers and supporters should make the public aware of the benefits of AHS, and immediately deal with any criticisms and/or concerns raised. AHS developers and promoters should also build coalitions with opposition groups (or at least be prepared to counter negative arguments). Environmental concerns will be important considerations. Public education and outreach, in addition to maintaining support for the program, will help attract users to the system, by allowing them to understand how the system works and the benefits it offers.

  Also, our research has found that full public disclosure and education are important for avoiding liability problems. According to the US legal system, definitions of a defective product and dangerous conditions are based on perceptions held by the general public. It is necessary to inform and educate the public about AHS operation and limitations in order to help mitigate legal challenges.

  Evidence for this conclusion comes from our study of ramp metering, the interstate highway system, ETTMs, the automobile, commercial flight, the SST, and the planning of mass transit. For example, ramp metering projects have encountered public resistance in several locations, in one instance leading to litigation. Experience has shown that, by involving the affected communities during the planning process, these problems are greatly reduced.

- AHS should be designed for integration within the overall transportation system in the United States and worldwide. (CS6)

  The AHS market should be defined in relation to other transportation forms. The AHS network and design should be developed based on this potential market. When AHS is included as an integral component of the US transportation system, rather than as an independent competing mode, a realistic and stable user base will be encouraged, and the goals of the US transportation system will be best served. AHS objectives should be developed on the basis of this integrated definition. Further, AHS components should be standardized for all AHS applications in the US and worldwide and should be compatible with existing conventions. For example, AHS should be designed to be as compatible as possible with existing highway signs and procedures.

Evidence for this conclusion was found in the study of several comparable systems, mostly from the transportation area. For example, the success of HOV treatments has been facilitated when integrated with park-and-ride lots and mass transit (e.g., preferred parking spaces reserved for HOVs). Experience in the planning of mass transit systems has also shown that realistic estimates of market size should be made in the context of the larger transportation system as a starting point. Transportation systems that have been developed without an integrated view have experienced problems. For example, the interstate highway system did not consider the effect of interstates on urban traffic patterns and the result has been excessive congestion in many areas; independently developed regional railroads resulted in a totally incompatible national rail network requiring extensive rework.

- AHS may produce significant changes in society that may be difficult to predict. (CS10)

  It is difficult to predict the effect that introducing AHS will have on the national highway system, and on society, in the United States. We have found that the introduction of new technology in the United States has often led to unforeseen effects. Research to explore the non-obvious affects of AHS should be undertaken as part of the AHS planning process (e.g., through focus groups and market research).

  Evidence for this conclusion comes from our study of automobile history, the railroads (primarily inter-urban), the elevator, and office automation (primarily the typewriter). To take an example, the elevator had far reaching effects beyond simply moving people between floors more quickly and comfortably. They made it possible to build taller buildings. The result has been a completely new look to our urban centers. Even the rent structure for offices was reversed when elevators were put in use (higher floors received premium rents). An example where unforeseen consequences of technology led to a systems failure (at least for a while) is the typewriter. When first introduced and marketed, there was great resistance to the typewriter due to societal norms in effect dealing with penmanship and the social etiquette of letter writing. Letters typed with the typewriter seemed impersonal, and issues of authenticity were raised. The practice of signing otherwise typed letters adopted later helped overcome these concerns. It will be important to determine if AHS will have effects that could hinder its development and success.

- Potential markets for AHS should not be overlooked. (CS11)

  The wider the potential market-base, the easier it will be to gain widespread acceptance of the new technology. This may also help to keep operating costs low. Limiting the potential market for AHS could exclude potential users, and result in poor public perception of AHS. That is, it could be seen as having limited usefulness and value, or being toys for the rich and powerful. To maximize the potential for AHS success, it is best to open up the system to as many categories of users as possible (e.g., consider commercial and consumer markets). This approach of seeking the broadest possible market is recommended on the basis of the study of several comparable systems

This conclusion is based on our study of the interstate highway system, ETTMs, the automobile, automated group transit systems, office automation (the typewriter), domestic appliances (the VCR and electricity itself), and ATMs. In all cases, success was facilitated by expanding the market to a wider user base. For example, early automobiles were very expensive and sold only to the wealthy. With the introduction of the Model-T, the average citizen became included in the potential market. The automobile's success was greatly increased. Similarly, the initially unsuccessful typewriter became a great overnight success when the business market was targeted.

- AHS marketability will be influenced by design and economic factors. (CS19)

  AHS will be one of several options for travelers. Its design and pricing approach will affect its potential market base. Innovative approaches to AHS pricing and the sales approach used can increase the potential market achievable. For example, whether AHS systems must be purchased or leased will affect their price to consumers and impact their competitiveness within the transportation market. Also, the development of the AHS market can be facilitated by "piggybacking" on other markets (e.g., market to those using existing ETTM systems, offering commuter packages that include AHS and connecting mass transit passes). In planning for AHS marketing, it will also be important to consider prevailing economic conditions. If the AHS industry is characterized by significant competitive forces, this can facilitate development of innovative marketing approaches.

  Several comparable systems form the base for this conclusion, including ETTM systems (the New York State E-Z Pass system), commercial flight, office automation, and domestic appliances.

- There may be regions that favor AHS implementation over others. (CS20)

  There may be regions in which geographic or traffic conditions favor AHS, while other areas may be less favorable. On the one hand, this will make it possible to select locations for AHS demonstration where AHS can provide significant benefits within the larger transportation system. It also will help guide the planning of AHS evolution and system expansion. On the other hand, it will be difficult to gain political support from legislators representing areas with little to gain from AHS. In fact, those areas where AHS is less applicable can be sources of opposition.

  This conclusion is based on the study of the inter-urban, and high speed trains. For example, inter-urban were most applicable in areas were cities and suburbs were closely spaced and the terrain was relatively flat.

5.3 TECHNICAL ASPECTS

The RSCs are generalized approaches to specific AHS technology implementations. They served a useful purpose for supporting the generalized deployment studies, reported in section 5.2 above. However, all of the analysis assumed: (1) the technology was available to safely and reliably deliver the level of automation required by the market, and (2) the system design appropriately accounted for driver capabilities. This section reports on our research findings relating to these two broad assumptions.

It is organized into three major subsections. The first subsection, entitled Automation Capability, covers the areas of automated control, driver role, and safety, reliability, and malfunction management. The next subsection covers the more global automation issue of traffic management. Lastly, a subsection is included that reports on AHS vehicle propulsion system alternatives to the conventional spark ignition (SI) engine.

5.3.1 Automation Capability

Automation of manual operations has been an ever increasing element of our society over the last few decades. A few examples are unmanned elevators, robots for manufacturing, aircraft automation, and ATMs. The surface transportation industry's experience with automation is not as extensive as other aspects of society. It is mostly relegated to transit vehicles operating on fixed guideways. **Therefore, the automation of rubber tired vehicles using interstate highways is a very significant and challenging technology initiative.**

Our comparable systems study researched a full set of comparable systems in regards to automated technology. A major conclusion of this research is that no one system is entirely comparable. This fully supports the need for research in the various underlying technologies to determine the technology related design issues and risks.

5.3.1.1 Control

This section reports our results relating to the speed, spacing, and lane keeping within an AHS lane, and entry maneuvers to an AHS lane and exit maneuvers from an AHS lane.

5.3.1.1.1 Speed, Spacing and Lane Keeping

Automatic lateral and longitudinal control is the means by which AHS vehicles maintain speed, spacing and lane keeping. Many believe that it is the core technology associated with AHS implementation. Studies in lateral and longitudinal control have been performed over many years and experimental systems exist. However, the studies conducted on this program were focused on broad design issues and barely scratch the surface of the automatic control problem. We do believe, however, that our efforts were focused on some of the key design issues.

We studied the sensor technology that could be applied, as well as the research/experiments that had been performed. We also studied longitudinal control problems utilizing a simulator developed on this program; particularly the effects of sensor errors and emergency braking with a string of vehicles. The communication needs and associated concepts were considered. Finally, a preliminary cost trade was performed between a system that utilized a headway sensor in a car following mode and a system that used an infrastructure base headway measurement and operated in a point following concept.

Our key findings are:

- The most promising lateral control technology involves magnetic markers or overhead wires. (LL2)

Of the many techniques that various researchers have explored to provide lateral position information, the magnetic markers or "nails" appear to be the most attractive. They are inexpensive and of low cost to install in a roadway. They are passive (requiring no power), extremely durable, and will provide control in all weather conditions. Component failure will occur gracefully; i.e., if a given magnet should fail, vehicle operation can continue because one missing magnet will not affect performance.

Lateral control based upon overhead wires that radiate signals, while more costly to install, also operates in all weather. The wires can also be used to provide a moving reference for point-follower type longitudinal control.

- Headway radars will be required to provide high azimuth angle resolution. (LL3)

  Headway radars used on an autonomous vehicle will be required to measure and locate the position of vehicles to determine the driving lane they occupy over ranges of approximately a few meters (feet) to 60 or 90 m (200 or 300 feet). Azimuth look or scan angles of ±45° are likely to be required to confirm slots for lane change or merge/demerge. Because of the need to locate the vehicle in the azimuth plane, the headway radar will be required to have a beam width of one to two degrees, thus the radar sensor beam will need to scan in azimuth, either mechanically or electronically.

- Infrastructure-based systems may be cost effective. (LL4)

  An AHS system configuration which is based on the use of infrastructure-mounted sensors to obtain vehicle longitudinal position and to provide a portion of the longitudinal guidance signals and vehicle malfunction detection functions may have cost advantages over a system containing vehicle-based sensors which perform these functions. The component reliability of the infrastructure equipment can be made sufficiently high through redundancy so that component failure does not contribute significantly to the reliability of the overall system.

- There is a tradeoff between longitudinal maneuver errors and noise immunity. (LL6)

  In the design of a longitudinal controller for an AHS, there exists a classical tradeoff between tolerable maneuver errors and noise immunity. Typically, a longitudinal controller is designed to maintain a certain headway from the preceding vehicle. When the preceding vehicle changes speed, the following vehicle's control system will generate an acceleration command to maintain the headway. During the speed change, the headway error could range from a few centimeters to meters (inches to feet) depending on the maneuver. In our simulations, an increase in speed from 80 kmph (50 mph) (73.3 ft/sec) to 97 kph (60 mph) (88 ft/sec) at 0.1 g generated a 2 m (7 ft) distance error. The headway error gradually diminished to near zero ft/in about 25 seconds after the maneuver. If the bandwidth of the control system is increased, the headway errors can be reduced to less than 0.6 m (2 ft) with total recovery in less than 10 seconds. Although the tighter control seems more desirable, the effects of sensor errors in the system make a high bandwidth control system impractical. We believe that typical sensor errors for ranging and doppler devices are likely to be 0.3 m and 0.3 m/sec (1 ft and 1 ft/sec), respectively. When these errors are used in a high bandwidth simulation, throttle displacement is larger, causing accelerations of 0.6 m/sec/sec (±2 ft/sec/sec) during steady state cruising. The net result is an uncomfortable ride for the AHS user, not to mention reduced fuel economy. As the bandwidth of the control system is reduced, the ride may be more tolerable with accelerations for steady state cruising at 0.15 m (±0.5 ft/sec/sec). The net result is a tradeoff as shown below.

Control System	**Steady State Accelerations**	**Max Error**	**Recovery**
High Bandwidth	±0.6 m/sec/sec	±0.6 m	10 seconds
Low Bandwidth	±0.15 m/sec/sec	±2 m	25 seconds

In order to provide a high bandwidth control system providing rider comfort, improvements in the control system could be made. Improved decisions using Kalman filters or a different controller may provide lower errors and lower accelerations, but for each design a tradeoff between noise immunity and maneuver error must be made.

It should be recognized that the simulation used on this program did not assume that lead vehicles would communicate with following vehicles. The control system derived the lead vehicle acceleration from the differential velocity measurement which contains noise-like errors. If the leading vehicle passed its acceleration data to the following vehicle, a "cleaner" acceleration signal would be available. Thus, a high gain loop could have been used with better performance.

- Sensors for lateral and longitudinal control must be capable of performing under severe adverse weather conditions. (LL1)

An AHS system should be capable of operation during adverse weather such as very heavy rain, dense fog, and heavy falling snow. Many researchers are pursuing technologies that clearly will not function in severe weather. The argument that it is acceptable if it performs as well as a human does not make much sense to us. If, during severe weather, the lateral sensor can no longer locate the lateral position of the vehicle, or the headway sensor can no longer measure the headway, a serious safety condition exists. This is particularly true of lateral control. If a rain storm limits the performance of a headway sensor, other action can be taken, such as slowing (or stopping) all traffic. However, lateral guidance is required even if it is only used to steer the vehicle while a stopping maneuver is performed. During periods of severe weather, such as heavy rain or fog, the highway speed may be significantly reduced, provided that the sensors can continue to operate. To accommodate increased sensor errors, the gap spacing may be increased. Loss of lateral position information cannot be allowed to occur.

We must currently accept the limitations of the human sensors to function in severe weather, but we need not accept them for an AHS because sensor technology exists to provide for continued AHS operation in very dense fog, heavy rain storms, and blizzard conditions.

- Communication between vehicles may not be required for vehicles following at gaps of 0.5 seconds, even during emergency maneuvers. (LL5)

  Results of simulations show that communication of the acceleration of the lead vehicle(s) is not necessary for braking maneuvers. The simulated design separated the brake controller from the throttle or accelerator controller. The accelerator controller is designed to maintain vehicle headway during normal maneuvers, while the brake controller is designed to avoid collisions. Simulation shows that no collisions occurred even with the lead vehicle braking up to 1 g. The conditions were 0.5 seconds plus 1.5 m (5 feet) nominal gap, 97 kph (60 mph) speed, up to 15 following cars, and all cars had the capability of 1 g maximum braking. The reduction in headway as speed decreased to zero was more than enough to make up for distance lost because of sensing and braking dynamics. The acceleration of the preceding vehicle was estimated from the rate of change of the differential velocity. Up to 30 cm/sec (1 ft/sec) noise like errors on the speed measurements did not degrade the safety of the brake system. Speed and distance measurements were made at a 20 Hz rate, using an independent noise sample for each measurement. The minimum value for the gap to maintain safe braking has not been explored, but we expect it to be less than 3 m (10 feet). This finding is significant. Most researchers, ourselves included, have felt that each vehicle will need to pass its acceleration to following vehicles to prevent a collision during hard, emergency braking.

5.3.1.1.2 Entry and Exit Maneuvers

Entry and exit concept definitions are closely tied to our RSC definitions. In I2, there can be a dedicated lane from the manual or general use lanes to the AHS lanes. In I3, this dedicated lane can originate from a local street or from another AHS lane. In the I1 configuration, with low participation (the fraction intending to be automated at the access point), the lane is not dedicated to AHS vehicles exclusively.

Entry and exit concept definitions are also tied to the various communication aspects of RSCs. We envision involving the vehicle/vehicle (VV) communications link and C1 concepts in I1; the roadside/vehicle (RV) communications link and the VV link in I3; and a less complex RV link in I2, with a fully utilized VV link.

Some other key findings are:

- Entry and exit techniques are key to the derivation of traffic flow related benefits since they dictate maximum flows throughout the system. (EE1)

- AHS traffic controllers, according to derived capacity-versus-speed estimates applicable to automated vehicles, will have the ability to provide a tradeoff between velocity and capacity to accommodate substantial volume variations.

- I1 benefits in terms of increased flow rates are predicted. However, the analysis is conservatively restricted to reduced trip time with no change in flow rate by equating speed to manual speed/flow conditions in the right lane. Benefits in I1 can be increased for a given participation by using communication to pair with another automated vehicle in the left lane. By not increasing overall flow, we can avoid any design change to entry/exits which would move away from the I1 concept of low infrastructure impact. (EE16)

- Detailed analysis of I1 suggests that participation as low as five percent can increase a congested 4000 vph two-lane manual traffic from 30 to 40 mph. Fifteen percent can increase the speed to 55 to 58 mph. (EE17)
- Access in I2 could be synchronized by a simple timing system facilitated by space regularization in the automated lane. (EE20)
- I3 access from local streets allows safer low speed automation system engagement and disengagement. Once again, a timing procedure, in this application with a shaped acceleration profile, mechanized with a roadside data link and vehicle-to-vehicle link could be used with a closed-loop terminal guidance. The access distance is about 1100 feet for a cruise lane speed of 60 mph and it varies with speed in accordance with simple analysis of the access procedure up to 3300 feet at 120 mph. (EE27)
- The check-out “test”, associated with exit from the AHS lane, should be an integrated part of the larger check-out process that has the driver take control of the system rather than the system give control to the driver. (CO4)

5.3.1.2 Driver Role

The automation capabilities, described above, are a replacement for some of the functions performed by the manual driver. However, the manual driver is a very significant component of the existing interstate transportation system. He or she performs a variety of tasks that are critical to the safe operation, trip reliability, and overall system performance. He or she will have a new role in the AHS. By definition it will be less time consuming but it will still require retention of some of the old skills and, importantly, development of new skills.

The role of the driver is directly related to the RSC implemented. For example, in the I1C1 RSC, the driver may be required to perform the lane change maneuver rather than having it performed by the system. Other driver functions associated with this RSC are: (1) setting speed and spacing requirements based on roadway advisories, (2) indicating to the system that a lane change is necessary, (3) monitoring vehicle status, and (4) taking control of the vehicle when directed. The lane keeping and headway function are so monotonous and boring, especially on long trips, that a driver can accumulate substantial benefits from a system that alleviates those ills. Consequently, a user-oriented, market-driven view of these systems strongly suggests that systems should be designed to let the driver perform the more chronologically-challenging, rarely-needed tasks. Another substantial benefit associated with keeping the driver as an active part of the AHS functions is the retention of liability to the driver.

We have made substantial arguments for AHS benefits within the I1 scenario. In this scenario, manual vehicles are mixed with automated vehicles. Therefore, questions arise as to the nature of the manual driver role. It seems reasonable to anticipate, with the increasing presence of automated vehicles, an "automation" mind set would begin to dominate all driver behavior. Perceiving automated vehicles to be a benefit to the manual vehicles in terms of decreased congestion and trip time, automated travelers would help develop the cooperation and approval needed from manual drivers to effectively share the roadway. Many of the automated features of AHS vehicles, driving on mixed roadways, can easily be foiled by irresponsible or uncooperative manual drivers. Thus, just as exists today, there must be recognition that if we behave intelligently, our transportation systems will be more useful to everyone. Interstate driving was an acquired skill over the last four decades. It is assumed that AHS related driving, for both automatic and manual operation will also be an acquired skill.

In higher level RSCs, the driver is replaced by increased levels of automation thus increasing the requirements for reliability and malfunction management. In the C3 RSCs, the driver is only responsible for monitoring the system to ensure that he or she is available to perform an unanticipated task. However, the one function that is universal across all RSCs is the check-out related tasks of regaining control of the vehicle. This task has significant driver role implementations.

Some key driver-role related findings in the check-out area are:

- During the process of transition from automated to manual driving, the driver must take control of the vehicle rather than having the vehicle give control back to the driver. (CO3)

- The check-out “test” should be an integrated part of the larger check-out process. (CO4)

- If check-out “tests” are required during the automated portion of the trip (for the purpose of maintaining an adequate level of vigilance), these “tests” should be meaningful and not artificial and extraneous. (CO5)

- The driver portion of the check-out process must account for the wide variability in capabilities within the driving population. (CO6)

One, often discussed, driver role associated with AHS travel is “Brain Off as well as Hands and Feet Off”. This is in contrast to a “Brain On, Hands and Feet Off” role. We studied both roles as part of our fault hazard analysis work in the safety and malfunction management tasks. Both roles require further investigation but our preliminary conclusions are:

- Not allowing the driver to completely relax maintains a very capable and intelligent system component that would be extremely expensive to replace. (SI2)

- Allowing the driver to be completely detached from the system eliminates the concept of manual backup, increases the requirements for malfunction management, and raises concern for AHS exit policies. (SI2)

5.3.1.3 Reliability, Malfunction Management and Safety

The reliability, safety and malfunction management aspects of the system are critical to the AHS market driven strategy. These characteristics are not products of the system design. They are drivers of the design. Therefore, a number of issues relating to reliability, safety, and malfunction management need to be addressed as the AHS system design moves forward.

One comparable systems study conclusion clearly states the compelling case for designing a safe and reliable AHS system.

- The safety and reliability of AHS must be clearly demonstrated. (CS2)

  Any new technology must be proven safe and reliable before the general public is willing to accept and use it. Evidence from the comparable systems studied has shown that even systems that have a reputation for good safety may face loss of users if a safety incident does occur. Systems that have a reputation of safety problems have had a very difficult time achieving public acceptance.

  Evidence for this conclusion comes from the study of elevators, commercial flight, bank automated teller machines (ATMs), aircraft automation, and the Morgantown personal rapid transit system. Public concerns about health and safety have even been raised for electronic toll and traffic management (ETTM) systems.

  On the negative side, when safety and reliability problems occur, acceptance of the systems involved is reduced. For example, when the Hindenburg crashed, the then thriving commercial dirigible industry completely collapsed. Similarly, when a demonstration intended to show that sonic booms from the SST would not disturb residents led to over 15,000 angry phone calls and over 5,000 damage claims, the program was severely damaged and never really recovered.

  The success of AHS will require demonstration of safety and reliability before full implementation. People must believe that the system is as safe, or safer, than the traditional highway system. Further, public demonstrations of AHS that raise safety concerns may do more harm than good, and even prevent the system from ever being accepted. AHS developers should perform extensive testing before a prototype is demonstrated to the public.

5.3.1.3.1 Reliability and Malfunction Management

What are the key design issues that will provide acceptable levels of safety and reliability? One key design aspect is the effective use of a check-in test. As part of our check-in study scenarios were postulated for various RSCs to outline where and how the check-in process would occur.

Three key findings resulted from this check-in study are:

- Check-in tests should be performed on the fly. (CI1)

We believe all check-in tests can be made without stopping the vehicle. Status of all vehicle equipment can be tested with a series of dynamic tests. Upon receipt of a command to perform a check-in test, either generated by the roadside or by the vehicle computer, the various tests are performed. If certain tests determine that some vehicle equipment fails the test, the vehicle's computer would prevent the engagement of the automatic modes, and would also communicate to the roadside infrastructure that the vehicle is not fit to operate on the AHS.

- Actuators for steering, throttle, and brakes will require testing in a series of dynamic tests. (CI2)

  In order to test for the proper operation of the various actuators, it is necessary to command the actuator to move and measure its response to the test command. These dynamic tests, which will cause a steering maneuver and changes in the vehicle's longitudinal acceleration, need not be a large or long-duration displacement. Steering tests can be a series of short pulses that may result in displacing the vehicle only a few inches. These tasks can be made on an on-ramp or in a transition lane.

- Vehicle testing will be performed continuously during AHS operation. (CI3)

  The vehicle equipment test sensors and built-in test systems used during check-in will also be used as part of the malfunction management system to monitor vehicle health when engaged on the AHS. Tests of all the vehicle systems will be performed at various rates; e.g., the lateral control system will need to be monitored at a high rate. The check-in function can be considered a subset of the vehicle malfunction monitoring and management system.

The check-in process, along with periodic off-road inspections, will assist in the detection of possible malfunctions. However, other reliability approaches are required. Component redundancy is a primary method. Design decisions are based on failure rate targets and component criticality determinations.

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

Other key findings in the area of system reliability and malfunction management are:

1. User data and analysis show that an automation failure rate of one per 2000 veh. hrs. is feasible. This would provide acceptable levels of service for an AHS. (MM1)

2. The full answer to the cost impacts associated with delivering a specific failure rate performance, both acquisition and lifetime maintenance, must remain uncertain until specific designs are considered, but we are optimistic in terms of realistic market costs. (MM2)

3. The key issues in the approach to the question of safety are the use of redundancy in vehicle equipment, and the use of a breakdown lane, entry/exit protocol, and handling communication failures. Our study suggests design approaches to deal with these issues. (MM3)

4. Barriers in the I2 scenario would reduce the probability of vehicles and other objects from moving into the AHS lane from the manual lanes. The ability of an automated vehicle to cope with such objects is problematical, making consideration of barrier use part of a realistic malfunction management strategy. (MM4)

5. The check-out process needs to check vehicle components not utilized during the AHS travel. (CO2)

5.3.1.3.2 Safety

One objective of the safety study was to identify AHS safety issues and risks for AHS design consideration. Specific crash types were analyzed to guide future research. Some specific areas of interest were: mixed use of manual and automated vehicles for the I1C1 RSC, safe headway determination, object in the road scenarios, and use of barriers to separate automated from manual travel. This lead to an emphasis being placed on two types of crashes: (1) rear end crashes, (2) barrier related crashes, and (3) object or animal in the road crashes.

Some of our key findings are:

- Crash types similar to those on today’s interstates will probably become the crash types that occur on an AHS under **non-normal operating conditions**. The causal factors will be AHS unique, the number of vehicles involved will probably be greater, and the distribution of crash types will vary from today’s interstate accident picture. The emphasis must be on fail-soft designs that will be geared to the lowest injury-producing crash types. (SI5)

- Data from the Fatal Accident Reporting System (FARS) were used to rank crash types according to risk of a fatal injury. The most common crash types to result in a fatal injury are the single vehicle accidents that are rollovers, barrier related, roadside departures or involve an object or animal in the roadway. Head-on and Sideswipe Opposite Direction are extremely low frequency events on interstates. (SI6)

- Rear-end crashes were analyzed in detail since they are likely to be the most frequently occurring AHS crash type, especially under some very small headway concepts. The primary measure of collision impact severity is ΔV, defined as the change in a vehicle's velocity, taking into account vehicle mass. Occupant injury levels and vehicle damage severity’s were expressed as a function of ΔV. This analysis was performed to estimate "tolerable" ΔVs for collisions on an AHS. Once tolerable ΔVs are obtained, safe headways for travel speeds based on maximum deceleration of a lead vehicle involved in a crash can be calculated. (SI7)

- Vehicle occupants suffered injuries requiring transportation to a medical facility where they were treated and released from crashes in the 6 to 10 mph ΔV range. Injuries requiring hospitalization resulted from crashes in the 11 to 15 mph ΔV range. This not only implies the seriousness of the incident in terms of occupant injury, but also indicates the amount of time necessary to clear the accident scene, and its influence on the perceived safety of the AHS. (SI8)

- Barrier-related crashes represent another potential AHS crash type, particularly for the I2C1 and I2C2 RSCs, where automated lanes and manual lanes may be separated by barriers. CDS data show that left roadside departures account for approximately 78 percent of barrier crashes that occur on roadways with speed limits greater than 50 mph. This finding strongly supports the use of barriers on the AHS since, without a barrier between automated and manual lanes, left roadside departure vehicles from the manual lanes will intrude into the AHS. (SI9)

- The likelihood of a lane-blocking incident on an AHS under normal operating conditions may be viewed as the possibility of a crash with an object or animal in the roadway. Automation is capable of creating a “smart driver” that knows the state of the vehicle, and the limits of the vehicle’s handling capabilities for road and weather conditions, but automation cannot control objects or animals. Therefore, automation must deal with them, particularly on the long stretches of suburban and rural highways where the problem is most significant. (SI10)

- The magnitude of the object in the road problem is not clearly defined. Accident statistics indicate the number of times a vehicle strikes an object or animal in the roadway, not the number of times a driver successfully maneuvers around an obstacle and still maintains control of the vehicle. The cost of preventing these elements from entering the AHS emphasizes the need for detection devices. However, even if it is possible to detect an obstacle that truly needs to be avoided, the longitudinal and lateral control systems must be capable of diverting the stream of vehicles, and they must have the room to maneuver the vehicles safely around the obstacle. (SI3)

- Crashes involving objects or animals represent 5.2 percent of all interstates crashes. Given the 490,336 million vehicle miles of travel on US interstates, this equates to a rate of 0.03 incidents per million vehicle miles traveled. However, this does not account for the situations where the driver encountered an object and successfully avoided the crash. Additional events, under non-normal operating conditions, that may lead to “AHS roadway obstacles” or lane-blocking incidents are: (SI11)

  - Loss of lateral control
  - Offset rear-end crashes
  - Rear-end crashes on low traction surfaces (perhaps due to fluid spills)
  - Lane/change merge crashes
  - Crashes related to driver impairments

5.3.2 Traffic Management Aspects of AHS

Full automation of vehicles operating on an AHS roadway, when viewed collectively, is a form of traffic management. It is a natural extension of the initiatives that are taking place in ITS research and deployments nationwide. These advances in Advanced Traffic Management Systems will be directly applicable to aspects of AHS operation as well be required as a seamless interface to the manual system. Therefore, lessons learned from these initiatives are useful for current and future AHS research.

The RSCs provide a generalized characterization of traffic management capability in terms of the C dimension. The higher C dimension levels facilitate greater traffic flow control. However, the higher C dimensions are more costly. One key finding from the comparable system study involves the desirability of designing for fully centralized control.

- The degree of centralized control and human decision making can slow system response. (CS17)

  The degree of centralized control can slow system response time and reduce the ability to deal with local conditions. This could affect spacing and flow achievable. Highly centralized control approaches can create lags in the control system and make it difficult to deal with local conditions. The requirement for human decision making in the control loop is especially problematic and should be limited to global, non-time-critical-parameters. Finally, the requirement for driver assimilation and interpretation of messages can slow response. Commands sent to the driver should be clear and unambiguous. If a centralized control system is selected for AHS, it must be designed in a way that it does not create serious control lags.

The evidence for this conclusion comes from study of the air traffic control (ATC) system. The ATC system is highly centralized. The speed, spacing, and flight path of aircraft are determined and controlled from the ground. Human air traffic controllers determine the desired aircraft flight parameters and issue voice commands to pilots, who make appropriate adjustments. This system is slow, cumbersome, and makes the ability to adjust to local conditions (e.g., weather) difficult. It leads to an inefficient use of airspace, because aircraft must be kept widely separated to allow for control system lags.

5.3.2.1 Traffic Management Impacts Related to Exit and Entry

Entry and exit is one of the major components of freeway transportation service. Some might say it is the most important component since it ties directly to origin and destination (OD) pairs, as airline service is tied to city pairs and airport capacity. Entry/exit capacity can dictate a freeway system capacity. As we increase the freeway service lane capacity, demand increase can overload the entry/exits. Local street capacity in the vicinity will, at some point, reach capacity.

However, full automation of vehicles gives a new tool to deal with system overloads. The traffic controller can directly control sector speed and spacing analogous to a space age ramp meter. The relationship between speed and "safe" capacity might contain an optimum, much as manual traffic achieves today, only it is higher and perhaps peaks at a higher speed. The controller can now choose to modify cruise speed, for increased capacity near an entrance region, to provide more space in the lane for a temporary increase in entry flow. Up to the capacity of the entry procedure, the need for queues or entry lane slowdowns can be reduced.

Some of our key findings in this area are:

- Entry/exits are key to AHS practicality since they dictate maximum flows throughout the system, are a big cost driver, and are a primary impact on the community. (EE1)
- The I2 concept (exclusive left lane, shared or exclusive middle lane at access/egress points, manual right lane, unmodified manual entry/exits) allows synchronized access and quasi-synchronized egress. The I2 concept starts to make sense for participation higher than .45 and when flows at or higher than 6000 vph for each direction of a six-lane freeway can be serviced by existing manual entry/exits. (EE19)
- The I3 access/egress process and particularly the cruise speed merge/demerge of large flows would require ATMS supervision and control to prevent system overloads. (EE31)
- AHS exit efficiency will be critical for handling high AHS flow rates. (CS18)

  Bottlenecks can be created at popular exits if the exits cannot handle traffic demand. This could require closing an exit to avoid vehicles from backing-up onto the AHS lane(s). Approaches for mitigating this problem include proactive planning and the use of multiple parallel exits or buffer zones. Proactive planning could include placing, under system control, groups of exits in congested areas (e.g., near an activity center such as a stadium or central business district). Drivers desiring to exit could be assigned an exit by the system in a way that optimizes overall exit efficiency and flow. When there is room, an additional exit lane could be also added.

This conclusion is based on the study of the ATC system and the management of finish chutes at foot races. ATC restricts aircraft take-off permission until landing slots are available. Foot race finishes handle the processing of large numbers of runners at race finishes without backing-up into the race by careful management of parallel finish chutes.

- Certain AHS control strategies call for queuing vehicles at AHS entry points (auxiliary lanes in the I2 configuration and ramps in the I3 configuration). Properly managed AHS traffic maintains queue delays and queue lengths at acceptable values. (RD7)

- Major sources of urban and suburban freeway congestion are incidents (non-recurring), bottlenecks at entry/exit points (recurring), and scheduled maintenance (non-recurring). AHS vehicle instrumentation and Traffic Management (TM) are tools to eliminate congestion, provided poor roadway geometry is corrected. (UR2)

5.3.2.2 Traffic Management Benefits for AHS

Our general findings in the area of AHS traffic management benefits are:

- The attraction of the AHS facility in congestion prone areas results not only from increased capacity, but also, because of the facility’s ability to sustain a constant comfortably high speed of 60 mph at increased volume. (RD8)

- An AHS facility on a congested urban or suburban freeway might tend to reduce the total travel time vehicle-hours in comparison to comparable non-AHS facilities, while satisfying the trip demand. This finding, however, must be tested further using a more precise modeling technique. (RD9)

- AHS traffic controllers, according to derived capacity-versus-speed estimates applicable to automated vehicles, will have the ability to provide a tradeoff between velocity and capacity to accommodate substantial volume variations. (EE6)

- Optimize operational improvements on urban and suburban freeways along with introduction of AHS, as it a part of a Traffic Management (TM) package not a stand alone service. Traffic Management includes; surveillance and control systems, ramp metering, incident management, motorist information systems, HOV facilities, and low-cost geometric improvements. These TM techniques are required to supplement AHS full automation. (UR4)

5.3.2.3 Traffic Management Operations

Current traffic management systems are primarily passive (and at best semi-automatic) and rely on macroscopic state variables such as density and speed to identify congestion and incidents. While traffic flow management requirements of an AHS would vary by RSC, configurations with central control will require a more discrete, microscopic orientation of traffic monitoring and management. The characteristics of traffic flow monitoring and management need to be examined and defined as AHS evolves. (RO1)

Although it is the promise of the AHS to reduce the occurrence of incidents, the impacts of any incident on AHS could be more severe, due to the higher capacities, with regard to traffic operation. Therefore, AHS must improve incident detection and shorten incident response time. The impact of traffic congestion and delay on an AHS lane will be much greater than current impacts to the existing highway system. Therefore, the incident response time must be reduced in order to maintain current highway levels-of-service. (RO2)

5.3.3 Alternate Propulsion Vehicle (APV) Analysis

Environmental issues resulting from current levels of fuel consumption and emissions of spark ignition (SI) vehicles is a risk area for successful AHS implementation. The increased traffic throughput that that the AHS may realize could increase the pollution problems for many areas of the country. Therefore, this study included a technology-based investigation of alternative propulsion systems for use on the AHS. Our key findings are organized by (1) electric vehicles (EVs), and (2) roadway powered electric vehicles (RPEVs).

5.3.3.1 Electric Vehicles

The current and next generation of alternative propulsion vehicles suffer from decreased performance as compared to the majority of conventional spark ignition vehicles. These deficits encompass all aspects of vehicle performance, from acceleration and braking to vehicle range. These deficiencies, most notably acceleration result from the lack of an adequate energy storage media. Current vehicle designs compromise vehicle performance for range. Therefore, the effectiveness of APVs on an interstate AHS will be severely restricted without a revolution in battery technology. (AP1)

Current and the next generation of APVs may encounter problems on the AHS, depending upon the speed limit of the system. Although many APV designs are capable of speeds in excess of the current national speed limit, these vehicles are electronically limited to speeds in the range of 110 to 130 kmh (68 to 81 mph) to maintain battery charge. The operating speed limit of the AHS will be critical to the ability of the APV to function on the roadway. (AP2)

The acceleration performance of most APV designs are substandard to the majority of the automotive population, but within the range of certain economy class vehicles and light trucks. These values are acceptable for current acceleration and deceleration lane designs as detailed by the American Association of State Highway and Transportation Officials (AASHTO). No modification of design standards would be required to implement the use of APVs, in addition, no roadway modifications would be required of existing roadways. (AP3)

At present, most APVs are conventional SI vehicle that have been converted to APV use. These vehicle conversions result in substantially higher vehicle weights. This factor, along with low rolling resistance tires and a modified weight distribution, may seriously affect the vehicle dynamics in such actions as collision avoidance maneuvers. Without changes to the vehicles braking systems, APV braking performance are significantly longer than the original designs. This could cause problems for AHS platooning and emergency maneuvers. Ground-up electric vehicle designs do not suffer from these braking difficulties. At present, only one vehicle, the General Motors Impact, falls into this category. The limited number of purpose built vehicles illustrates the high cost involved in vehicle development. For the near-term, the APV fleet will consist predominantly of converted SI vehicles, and have a negative effect on performance. (AP4)

Vehicle range is the biggest handicap facing alternative propulsion vehicles. Electric Vehicles (EVs) range is dependent upon the battery storage system utilized. The only certainty of battery technology is that it is uncertain; it is difficult to extrapolate into the future. In the 1960’s, researchers were predicting that electric vehicles would be commonplace in the 1970’s. This prediction was repeated in the seventies. Because current battery technologies do not provide APVs with range and performance comparable to SI vehicles, this prediction has not yet come to fruition. Research is making evolutionary progress in battery technology, but no “revolutionary” breakthroughs are on the horizon. The pace of battery system development will presage the closing of the performance and range gap between APV and SI designs. Because of these trends, battery-powered electric vehicles will not have AHS interstate travel range. (AP5)

As with battery technology, electric vehicle recharging is advancing at a slow pace. Newer, quicker ways of vehicle charging need to be developed for consumer acceptance to rise. Goals for recharging of vehicles need to be in minutes, not hours as is currently the case. Without the installation of special charging equipment, home electric vehicle charging cannot be performed in one to three hours. Older homes may not have the capacity to use this equipment without a complete rewiring. For apartment dwellers, the problem is magnified. The specialized charging equipment will initially require charging stations similar to gas stations to allow quick-charge of these vehicles. These stations may be co-located with gas stations or AHS service areas. (AP6)

If the future holds a breakthrough in batter technology, the interim solution may be hybrid vehicles. These vehicle hold the promise of increased range and reduced emissions. Two variations of hybrid vehicle design exist; series hybrid, and parallel hybrid. Of the two types, series hybrids hold the most promise since they are less complex, produce fewer emissions per distance traveled, and operate as zero emission vehicles (ZEVs) for a greater portion of their driving cycle. With the use of a small on-board SI engine, hybrids have greatly extended range capabilities as compared with EVs, and therefore provide promise as AHS vehicles. (AP7)

Decreased emissions is a major goal of future transportation systems. However, APVs must represent a large portion of the automotive fleet for the benefits to be significant. Regionally, the reduction in emissions depends upon the different types of fuel used (the generation mix) to generate electric power. A vehicle’s emissions may one day be a selling point similar to features such as styling, safety equipment (anti-lock brakes, airbags) and fuel consumption. APVs, especially electric vehicles will have the greatest affect on pollution reduction. The major manufacturer’s disdain for APVs is similar to their general attitude toward small cars, catalytic converters and airbags in earlier years. (AP8)

Vehicle reliability will be equal or greater than conventional SI vehicles, and electric motor reliability may be much greater. Depending on the type of APV, the need for instrumentation monitoring by the driver may decrease because of the less complex overall system. The only specialized training needed is that for AHS operation, which may be identical for all vehicles. Overall, APVs will be easier to use (less complex, no transmission, less maintenance) than comparable SI vehicles. (AP9)

Fleet use could be the first and best use for APVs, Even with the limited range of these vehicle presently, APVs can be used as many types of delivery vehicles. Initially, APVs may be developed for fleet use, independent of the AHS. With further development, they may be suitable for AHS operation. Our findings, on daily miles driven, match other surveys. The majority of fleet vehicles travel less than 70 miles per day. This is within the range of the current generation of APVs. Initially, APVs, EVs in particular will be best suited for inner city travel and not for intra-city or cross country travel. (AP10)

5.3.3.2 Roadway Powered Electric Vehicles

The use of roadway power can be a range extender for electric vehicles. Roadway powered electric vehicles (RPEVs) will initially be used in transit / commercial applications where the vehicle routes are always the same. Initially, RPEV deployment could consist of public transportation operations, such as bus routes and airport shuttles. Roadway power represents a practical solution for eliminating emissions in densely populated areas. RPEVs can play a significant role in transit applications if EV range does not improve. A battery breakthrough could reduce the impact of commuter RPEVs, while transit RPEVs could be modified to battery-electric operation. With batter advancements, RPEV status could change. Transit station recharging could be eliminated if an APV is able to dynamically recharge. RPEVs are still in the experimental stage, but the technology is available, mature, and appropriate for present day systems. RPEVs for transit use are a deployable system. Rubber tired RPEVs would make an excellent replacement for diesel buses, trams, and trolleys. (AP11)

RPEVs can be operated on the AHS with minimal effect. The electromagnetic field (EMF) emitted by RPEVs is equivalent to household appliance or less. This is acceptable at the present known EMF safety standards. No interference should occur with non-RPEV vehicles operating on or near a RPEV or RPEV roadway. As stated previously, current designs for RPEVs are within the known safety standard for EMF. However, this area needs to explored further due to the potentially serious consequences of EMF in general. The RPEV induction system is a viable candidate for EV charging. This system can eliminate plugs and cables and is passive in use. If the use of APVs started in New York State in 1994, and increased substantially each year, it will tax power resources in New York in the year 2011. This assumes no new generating capacity is acquired in that time frame. (AP12)

The inductive coupling required in the RPEV/AHS lane can act as a lateral guidance system available to all vehicles. Many EV designs are already incorporating “drive-by-wire” steering to reduce vehicle weight. Inductive lateral guidance has been tested and have proven effective. (AP13)

Emissions reductions achieved using an RPEV-based AHS would be much larger than those of a non-RPEV AHS. This is an attractive alternative which promotes compliance with the 1990 Clean Air Act. (AP14)

The top design issues jointly affecting APVs and AHS are:

> Range/ Charging - If current battery and charging technology are not improved by the time of AHS implementation, APVs will experience reduced AHS capabilities. Limited vehicle range can impair AHS interstate travel.
>
> Top Speed - Future APV designs must be capable of matching AHS design speeds. Limited top speed can negatively impact AHS throughput and increase travel time.
>
> Fleet / Transit Use - To meet CARB mandated sales goals, manufacturers have focused on APVs for fleet use. This feature will facilitate AHS equipment implementation.
>
> RPEV Lane Design - If RPEVs are used on the AHS, overall lane design must be standardized and power, billing, and EMF issues resolved. RPEV lanes can provide lateral guidance to all vehicles using the RPEV / AHS road.

The major limitation of these vehicles is range. The use of hybrid vehicles, which can extend the range of APVs transitions the use of all the different types of APVs on the AHS. The differences in performance characteristics (acceleration, braking, dynamics) between APVs and SI vehicles is decreasing and may be eliminated by the time AHS is implemented. (AP17)

5.4 BENEFITS AND COSTS

The economic goals (potential benefits) and potential costs of an AHS system program are many. To roadway operators, who are concerned with operational parameters, AHS should increase vehicular throughput and operational efficiency, particularly in inclement conditions such as adverse weather. To society as a whole, an AHS corridor should reduce trip times, improve trip and schedule reliability, improve safety, and enhance personal mobility. An AHS system should accomplish these and other goals while reducing vehicle operating costs, reducing societal insurance costs, and perhaps reducing the cost of making an individual trip by automobile. Achieving these very broad goals through implementation of such an advanced technological system is an extremely challenging task.

The cost benefits task, conducted within this study, was only able to begin to determine economic feasibility for a system at this stage of development. This task was not designed as a final say in whether to proceed with any particular AHS program. Rather it only sheds light on methods to properly evaluate and appraise an AHS.

Our specific charge was to develop a conceptual framework for analyzing costs and benefits; determine cost and benefit measures; list and rank by importance of impact such measures; examine how such measures are affected by the evolutionary deployment of AHS systems; and, finally, examine the critical threshold points of incremental costs and benefits across various system configurations. Also, we were to examine four specific roadway deployment scenarios and report on benefit and cost measures to support the more generalized analysis.

5.4.1 Framework

Formulating the expected costs and benefits of an automated highway system requires the use of a conceptual framework for determining types of costs and benefits, measures of cost and benefits, and understanding the uncertainty of estimates derived as a result of the framework. We have developed an analytical matrix that accomplishes this task. We have also evaluated the major factors affecting the incremental costs of an AHS system, from initial research, to early deployment, through ongoing operations.

We have identified the most important benefit measures as travel time savings, from the point of view of AHS road users themselves; accident avoidance and congestion avoidance benefits, from the societal point of view; and traffic throughput from the road operator's point of view. In addition, there are significant construction and ongoing operations and maintenance benefits to be gained as a result of secondary or "multiplier" effects of spending resources in deploying such systems regionally, or even nationally. Other benefits, such as productivity improvements at the workplace, were left as an area for further research.

On the cost side, AHS roadways will incur substantial infrastructure construction, operating and maintenance costs. In addition, there are the costs of on-board electronics, as well as the added costs of the electronics system infrastructure. A proper evaluation of AHS systems will thus have to consider these cost components.

We then defined the economic rationale behind cost-benefit analysis. The strongest principle of a sound investment in a project is its internal rate of return, which is the discounted present value of its projected income stream net of its initial investment and all other costs to be incurred during its projected lifetime. A project with a projected rate of return that is both large and positive is indeed a project that should be undertaken. Alternatively, we reviewed the net present value appraisal method. A project should be undertaken if its net present value, or its net discounted stream of future income minus costs, is positive. For example, we found that travel time savings will accrue to some roadway users after implementing an AHS system. These savings, expressed in dollars, constitute one component of the annual stream of expected benefits. On the other hand, annual periodic payments need to be made for the upkeep of the roadway, to take another example. These payments are counted in the future stream of costs. (CB1)

For this detailed analysis, we judged travel time savings, accident cost savings, and the secondary economic effects of ongoing operations and maintenance activities on societal output and employment to be the most important and most easily quantifiable categories of economic benefits. On the cost side, we found that the major component of system costs is the actual construction cost of the AHS roadway. Other important costs include system infrastructure costs, vehicle electronic costs, and the costs of ongoing operations and maintenance. (CB3)

5.4.2 Scenario Results

To apply our general principles, we then considered four candidate real roadways where deploying some form of AHS would be possible and even desirable. We looked at New York's Long Island Expressway and the New York State Thruway, Baltimore's section of Interstate 495 and Boston's Interstate 93. Our analysis of these roadways suggested that, at least conceptually, AHS deployment would pass a numerical cost-benefit test on only one roadway scenario, New York's Long Island Expressway, a particularly congested roadway with parked peak hours of congestion, and a roadway with significant commercial vehicle access as well as transit (bus) use. However, that is not to suggest that AHS as currently configured does not make economic sense anywhere else.

There are several reasons for this. One, our current evaluation methods are relatively crude, and cannot capture the major societal effects of general improvements in living standards or in workplace productivity as a result of reducing the stress, fatigue and accidents involved with major commuting patterns. Two, our analysis is preliminary and is entirely limited by the many assumptions used in our traffic analysis, cost estimates, and roadway deployment scenarios. It is entirely possible that as we refine our work in these and other areas, we will derive performance gains that are much more substantive. Three, there are too many uncertainties with regards to the possible makeup of future AHS systems that concluding at this stage that AHS has only limited economic applicability would be too premature. Clearly, AHS displays a considerable amount of promise with regards to potential economic gain, and this needs to be carefully developed further. Particularly since AHS will undoubtedly involve a significant commitment of public resources, its justification will hinge on the ability to develop and achieve such gains. (CB4)

5.5 INSTITUTIONAL AND SOCIETAL SYSTEM IMPACTS

All of the preceding analysis hinges, to a very large degree, on the view of AHS by transportation related institutions and society as a whole. The importance of the institutional and societal aspects of AHS design, development and deployment can not be understated. AHS deployment is not just a technical installation exercise to provide a service. **Impacts on land use planning, air/noise pollution and public/political acceptance are probably more important than solving mechanical, electronic, and concrete problems**. If the development of the system is to be market driven, it must earn support from the myriad of associated transportation institutions. Since transportation is so pervasive in our society, these institutions are numerous. The support must also be enduring and that is why it is characterized as “earned” support. It will take work to earn the required support and the work must begin now.

During this study we documented the panoply of institutional and societal issues and risks that confront the effort to deploy Automated Highway Systems. The methodology involved a multi-stage process of reviewing all available literature regarding the subject of automated vehicles and highways and of Intelligent Transportation Systems (ITS). The initial research lead to a categorization of AHS-specific issues and risks that was later modified to conform with commonly accepted categories being used by the ITS community.

Perhaps, the most important finding of this task is that there are **likely to be no insurmountable institutional and societal barriers — show stoppers — to the evolutionary deployment of AHS.** This does not mean that surmounting some barriers will be easy. There is much to do before AHS deployments, beyond initial test sites, are feasible. This finding itself rests on two of the earliest conclusions of this research effort:: (1) Institutional and societal issues and risks vary enormously depending on the RSC to be deployed; mainly due to the very broad nature of the RSCs studied, and (2) based on an analysis of the introduction and acceptance of comparable, earlier technologies; the likely availability of funding, and the need to resolve some institutional and societal barriers incrementally as part of the ITS technologies deployment process, even before AHS; AHS must develop evolutionary from less infrastructure and outside-the-driver command and control technologies to more infrastructure dependent and greater outside-the-driver command and control technologies. (IS1, IS2, IS3)

Other key findings in the areas of air quality, land use, ITS versus AHS issues, social equity, transportation planning and liability:

- Beyond confirming early (pre-PSA) predictions that AHS would be expected to provide air quality benefits — based on the assumption that carbon monoxide would be reduced simply because vehicles would move more consistently at higher speeds — it is likely that AHS will provide air quality benefits not only by reducing CO emissions, but also by reducing <u>both</u> the hydrocarbons and nitrogen oxides that create the more serious air quality problem of ground-level ozone. (IS4)

- Many institutional/societal issues that arise in connection with AHS are not unique to AHS, but rather, related to any plans to build roads today or in the future. The AHS effort cannot be expected to address, let alone resolve, all of these larger societal and historical issues. On the other hand, these issues can become barriers to the deployment of AHS. And to the extent that AHS may accentuate the effects of how some of these issues are perceived, for example, urban sprawl, the AHS effort must be aware of its place in this larger context of institutional and societal issues and be prepared to address such issues in its deployments. (IS5)

- The awareness that AHS is likely to evolve evolutionary from ITS technologies and that the ITS effort is addressing many of the same institutional and societal issues does not mean that all of these issues will be resolved through the ITS deployment process prior to the time when it is technologically feasible to deploy AHS. Nor can the AHS effort expect that even those institutional and societal issues that are "resolved" in the process of deploying ITS will necessarily simply "go away" for AHS. Moreover, there are institutional and societal issues that are likely to arise specifically with AHS, as opposed to ITS, technologies. (IS6)

- If the AHS technology is not generally available at modest cost, there are important equity issues involved in reserving or constructing a lane for the use of relatively wealthy private vehicle owners. (IS7)

- The AHS effort must play "catch-up" with the long-term state and regional transportation planning already well underway in response to previous state and federal mandates and the more recent 1990 amendments to the Clean Air Act and 1991 Inter-modal Surface Transportation Efficiency Act (ISTEA). Transportation plans for the next 20 years in congested areas in many cases are looking to rail projects to address many of the same transportation issues that an AHS might conceivably address. (IS8)

- Application of the technology to a mode of transportation that serves moderate-income commuters in an existing, heavily used corridor under the institutional jurisdiction of relatively few actors provides the kind of setting that could allow an early AHS success. AHS proponents must focus on both short-term and long-term opportunities by being aware that it is the institutional and societal milieu that determines if, when and where new technologies such as AHS will be deployed and being prepared to:

  Maximize the use or imminent improvement of existing facilities to demonstrate the benefits of AHS, even, or perhaps particularly, when the technology is used exclusively for non-personal vehicles, and that <u>such an early win opportunity may be represented by the desirability of automating the existing Lincoln Tunnel exclusive bus lane in New Jersey</u>, and support the development of non-AHS facilities where there may be a good opportunity for later conversion to automation. (IS9)

- AHS will face liability issues. These should be anticipated and plans made to avoid or overcome legal challenges. We live in a litigious society. It seems clear that AHS implementations will face legal challenges (like all other systems). These can stem from manufacture errors, defective design, failure to warn, and/or product/service misrepresentation. AHS development should be managed in a way that minimizes legal vulnerability. Safety analyses will be required to support design decisions. It will be important to educate drivers about AHS capabilities, limitations, and safety procedures. Plans for updating

AHS to avoid antiquated technology will need to be made, and AHS must be based on capable technology. Government standards and design redundancy can help reduce liability for private industry. Since legal foundations are built on precedents, legal issues left unaddressed will be decided in court. (CS14)

Additional findings in the area of AHS funding and AHS sponsorship follow:

- Long-term and continuous financial support for AHS deployment must be secured. For the long-term success of AHS, it is important to ensure that funding for the project is sufficient and guaranteed. If the funding is not sufficient, it may be difficult to raise funds at a later date. If the funds are not guaranteed, they may be cut at any time, and battles for project financing will be ongoing. Further, funding needs to be specific to the goals of AHS, and pay-as-you-go financing is preferable to borrowing. (CS3)

- Support from influential persons in Government and industry is important for large programs. The success of many large-scale projects has been facilitated through the commitment of high ranking officials from Government or industry who were willing to work hard to ensure the success of the projects. AHS will benefit from such an individual (or group) to help secure the necessary financing and support, and to help maintain enthusiasm for the project during all stages of design and implementation. (CS4)

- Cost and time estimates for developing AHS must be carefully and accurately determined. Budget overruns and schedule slippage can lead to negative publicity, poor public acceptance, and reduced political support for the system. System design, testing, and implementation must remain within budgetary guidelines and time constraints for the project to ensure continued support. Cost and schedule "bad news" can reduce public acceptance of AHS, even when the shortfalls are due to estimation errors, rather than the more serious system problems. Also, it is important to plan for schedule and cost contingencies. AHS developers must carefully make realistic estimates concerning the amount of time the system will take to implement, and the amount of money it will cost to complete. Overly optimistic budget and schedule estimates look good at planning time but lead to almost certain failure, at least as measured against budget and schedule. (CS7)

- The successful development of AHS requires that all stakeholders, both public and private, have a significant role in AHS development. A consortium approach to AHS development is needed to ensure that the AHS system is successfully implemented. It will allow the project to benefit from a wide range of expertise and perspectives, and to share the costs involved with implementation. Even more importantly, cooperation among the various industries and organizations interested in AHS will facilitate efficient and effective designs that can be supported by products and services developed independently, yet which must operate within a common infrastructure. The motivation for investment, participation in the consortium, and diligence in the task comes from the increased market share potential that results from design participation. Winners and losers are sorted out in the market place. (CS8)

5.6 FUTURE WORK

The task area results only scratch the surface of AHS design trade-offs. Additional research recommendations to provide more design details are presented below. These recommendations are organized into the four main topic areas that were used above for the presentation of results.

5.6.1 AHS Configurations and Deployment

5.6.1.1 Roadway Configuration

Three different design alternatives within the RSC I2 configuration need to be studied in depth. They are:

1. Continuous transition lane and continuous entry/exit versus entry/exit at discrete locations.

2. Provision and configuration of an AHS breakdown lane or shoulder.

3. Physical barriers versus striping.

These alternatives have an important influence on the AHS physical design and right-of-way requirements. The selection of the alternatives is, however, largely dependent on safety issues, longitudinal control issues, and entry/exit issues. Although these issues are discussed under the separate tasks, their resolution is key to roadway design.

5.6.1.2 Modeling and Simulation

Existing models enable studies to be carried out at the following levels:

- Area Wide Level

- AHS Network Design Level

- Microscopic Level

This task only utilized models at the first two levels. Recommendations about model enhancement in these two levels follows.

Area Wide Level

This level is useful for establishing the “catchment area” for AHS and the effect on non-AHS roadways. The TRANPLAN model was used in the study. These models are generally based on the use of trip generation and trip assignment on a daily average (or other average) basis. The model is generally developed on an area wide basis. The model does not provide for discrete placement of traffic controls; thus, it is most useful to establish general trip patterns; not to study detailed implementations. Limitations which were encountered included the following:

- It is not feasible to convert the daily model to a peak hour model. This strongly limits the ability of the model to generate trip demand and trip tables for the

AHS Network Design which can be used during peak periods and various other periods.

- TRANPLAN has no current capability to model different AHS MP at different locations or at different distances from the AHS. The modeling effort for this study assumed a constant level of MP for the entire area.

- TRANPLAN has no capability to model trip based AHS user costs (tolls).

It is recommended that the investigation of a model which corrects these deficiencies be considered.

AHS Network Design Level

Case studies were conducted at this level by using the INTEGRATION model. This level is intended to model the AHS network (AHS roadways and non-AHS roadways which are significantly affected by AHS traffic). The intent is not to model on a microscopic basis but rather to establish the network traffic flows, identify flow problems, and obtain the performance characteristics for different design alternatives. INTEGRATION was designed for modeling highways. AHS lanes, ramps, and traffic flows were modeled by adapting the freeway and ramp flow characteristics to the approximate characteristics of the AHS, but this could only be accomplished imperfectly. AHS flow characteristics which could be adapted to the specific design are preferred.

Development of a Methodology to Determine AHS Entry and Exit Locations. The development of entry and exit locations for the three urban scenarios was performed by considering entry and exit volumes together with OD characteristics. With the possibility of using either RSC I2 or I3 access configurations, a large number of designs are possible. Several design combinations were heuristically developed for each case study, and the preferred approach was selected.

It is recommended that research be considered to develop a more structured methodology. Such a methodology might use a combination of data based and rule based techniques.

5.6.1.3 Evolution versus Revolution

Considerable effort should be given to a practical evolution plan. How will the various IVHS equipment such as intelligent cruise control evolve into AHS? A road map is needed to determine how AHS can evolve and be implemented considering market penetration and minimal impact on existing traffic flow.

5.6.2 Technical Aspects

5.6.2.1 Automation Capability

5.6.2.1.1 Control

Control of the steering, throttle, and brakes is, of course, the heart of an automatic highway system. We have concluded that several areas need immediate study. These areas are discussed below.

- The longitudinal simulation effort, performed within this study, should be continued and expanded to include lateral control. Studies should be made with multiple vehicles in a car-follower mode to develop tradeoff data between sensor accuracy, performance, and ride comfort so that preliminary specifications can be developed for sensors and to evaluate various concepts for lane change, merge and demerge maneuvers.

- Promising sensor techniques for lateral position measurements and headway measurement should be developed and tested. Prototypes should be built and tested. In particular, the magnetic markers or nails developed on PATH program should be further developed and refined. The advantages of all weather, low cost, and high reliability make it a forerunner technique that should receive serious consideration.

- A detailed study, including simulations, should be made of the potential mutual interference problem of headway radars or lidars. These studies should consider the expected density of radars one would experience on a multiple lane, high density AHS roadway. Can the mutual interference be managed?

- Communication system concepts need to be defined and studied. These systems should consider the vehicle-to-vehicle and vehicle-to-roadway needs for lateral and longitudinal control, including lane-changing merge and demerge for an autonomous vehicle system, as well as for general information flow.

- Tests should be conducted with an instrumented vehicle to collect data on maneuver parameters such as longitudinal accelerations. The relationship between lateral and longitudinal accelerations and ride comfort need to be developed. Tests should be made with a closed-loop longitudinal control system. Noise-like errors should be introduced to cause various levels of vehicle accelerations that would be used to develop a relationship between accelerations and ride comfort.

- Tests should be conducted with a vehicle-mounted differential GPS system that employs carrier phase tracking and pseudolites to evaluate the potential for using GPS combined with stored map data to provide lateral and longitudinal control. These tests should be conducted in urban areas and in tunnels.

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

- The minimum space into which an automated vehicle can be safely maneuvered should be defined on the basis of realistic control capabilities and reasonable wind gusts, roadbed unevenness and other disturbances.

5.6.2.1.2 Driver Role

Based on our knowledge of what issues must be addressed during the check-out process, we can make the following recommendations for future work.

- Additional study on the ability of a driver to retake manual control of his/her vehicle at high speeds and close headways is warranted.

- We recommend an experimental approach to the determination of the passing criteria for the check-out process. Individual variability, as well as the level of participation in the eventual AHS design, must both be taken into account.

- We stress the importance of designing the check-out process based on human factors considerations (e.g., information processing, vigilance, and interaction with automation), and in cooperation with other AHS design tasks (e.g., entry/exit, malfunction management, and lateral/longitudinal control).

5.6.2.1.3 Reliability, Malfunction Management, and Safety

Malfunction Management

- Preliminary subsystem design studies should be performed and integrated into an overall system design containing life cycle cost/reliability tradeoffs.

- Redundant subsystems should be considered to obtain reliability goals with the following design questions addressed.

  - Use of dissimilar technologies as part of the redundancy
  - Failure detection availability
  - Failure identification technique
  - Transition without dynamic disturbance
  - Common mode failures

- The driver role in malfunction management should be studied in simulations and field tests.

- A target basic vehicle locomotion MTBF should be established by standards organizations and vehicle manufacturers.

- Further study is needed to resolve the issues of

  - a continuous breakdown lane
  - malfunctions during access and egress functions
  - management of communication failures

- Realistic affordable methods for managing the problem posed by an object in the lane must be developed. This study should consider the role of barriers in the AHS designs placing an automated lane contiguous to those used by manual traffic.

- A related study should address the legal implications of enforcing traffic laws addressing obstruction of AHS traffic. Such violators should be easily detectable and therefore easy to fine or at least bring to trial. The delay caused in the AHS lane is, in worst case, equivalent to stopping three or more lanes of today's congested manual traffic. There appears to be no method short of a physical gate or severe legal consequence to prevent intended or negligent obstruction.

Vehicle Operations

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

Check-in

- Studies should continue to address how various monitoring instrumentation could be implemented for functions not currently monitored on vehicles, such as coolant and transmission fluid levels.

- A study should be conducted of the various actuator technologies that could be employed to provide steering control and brake operation. Both of these areas are safety-critical (particularly the steering), and will most likely require redundant components to provide the required extremely low probability of failure. This study should address reliability, cost, and ease of implementation.

- A system architecture study of the vehicle equipment monitoring system should be performed. Issues such as how the various sensors are monitored, built-in-test commanded and performed, and dynamic test executed need to be addressed. Outputs of this study would include a plan for how all the vehicle health monitoring, malfunction detection, and management would be integrated.

- Future studies and analysis of check-in should be combined with the malfunction management efforts into a single area. Check-in testing is a subsection of the larger area of malfunction detection and management.

Safety

Major concerns that require future research are listed below.

- The two driver roles of "brain on, hands and feet on" and "brain off, hands and feet off" identified during the fault hazard analysis must be investigated, although perhaps not as a black and white issue. In situations, such as a malfunctioning vehicle departing the roadway, time may be available to alert the driver and assume manual control. In situations where reaction time is short and speeds are high, manual backup may be totally impractical. An evaluation of the limits of driver capabilities will be required to resolve this issue.

- The object/animal in the roadway is a thorn in the side of the AHS. The tradeoffs in cost and practicality of excluding these elements from the AHS environment versus detection and avoidance need to be addressed.

- The levels of maintenance and inspection will be regulated to be high for AHS-equipped vehicles. Vehicle system monitoring will increase awareness of needed repairs. Public willingness must be evaluated to determine where the attraction of an automated system falls off as a function of the demands placed on automated vehicle owners.

- The relationship of ΔV to injury levels and vehicle damage led to the recommendation that ΔVs for rear-end crashes should be limited to 10 mph. This 10 mph limit will minimize the consequences in an unmitigated malfunction scenario. If the system is not able to ensure straight front-to-back rear-end crashes and potential exits for offset rear-end crashes, this recommendation is lowered to ΔVs in the 5 mph range. The lower number is suggested to prevent a vehicle spinning off from a primary crash into a more severe crash type with a barrier or a vehicle in an adjacent lane. The use of anti-lock braking systems will also reduce the likelihood of vehicle rotation under maximum deceleration.

- Review of current barrier design standards is warranted in light of AHS applications. The AHS operating environment may have vehicles traveling at speeds greater than those considered for present-day barriers. Also, in the event of a malfunction, multiple collisions are more likely to result than on today's highways. The role of barriers may increase on an AHS, and the new requirements must be identified and incorporated into practice.

- Many crash types related to driver impairments, in particular drowsy drivers, will be eliminated by an AHS. However, crashes involving intoxicated drivers is not one of them. Intoxicated drivers are not permitted on the AHS, and if they are already on, getting them off is a problem. An AHS is meant to create a collision free driving environment. This is an AHS safety issue that requires further consideration.

- Causal factor analysis specific to interstate highway crash types should be conducted to focus design strategies and quantification of benefits. Also, algorithms to estimated ΔVs for multiple rear-end collisions and other crash types should be developed.

- The results of this study are based on general RSC concepts. A distinct possibility is that the automated highway will take form through an evolutionary process starting at the low end of the infrastructure/command and control implementations and gradually develop into a separate infrastructure with full roadway and vehicle control. Urban configurations may be quite different from rural configurations. The range of configurations that are selected for implementation will have specific safety implications that will require detailed analyses of the selected scenarios.

- The relationship of collision velocity to injury severity at speeds less than 10 fps should be more fully defined for AHS-equipped vehicles as part of the lane capacity definition for access design.

- Safety policy should be examined to define what would be acceptable to AHS designers, to users and to insurance companies. The role of a barrier between an automated lane and the manual lanes sharing the same roadbed in the I2 concept would be part of the mishap scenario definition as part of this policy.

The presence of a barrier in the I2 concept allows access/egress only in specific places.

5.6.2.2 Traffic Management Aspects of AHS

Recommendations (EE)

1. The relationship between AHS entry/exit and ATMS should be tested in appropriate traffic models.

2. Realistic applications that minimize expensive infrastructure modifications (I1 and I2) should be given high priority in further development. Requiring an I3 early development has less appeal since it sets up high political and social hurdles.

3. The minimum space into which an automated vehicle can be safely maneuvered should be defined on the basis of realistic control capabilities and reasonable wind gusts, roadbed unevenness and other disturbances.

4. Access/egress operations and procedures should be tested, first through modeling and simulation but then on the test track to obtain reliable data.

5. The I1 concept is forecast to relieve a congested freeway with low participation. This prediction should be studied through simulation and then operationally tested.

6. The AHS/ATMS interface for access/egress regions and for entry/exits should be studied. The AHS potential benefit to ATMS on a regional basis using realistic conditions at these locations needs to be modeled as part of this study.

5.6.2.3 Alternative Propulsion Vehicle (APV) Analysis

Further research is recommended in the following APV areas:

- Advancing battery technology is the most pressing problem affecting alternative propulsion vehicles and their use on the AHS.

- Quick (less than ten minutes), safe recharging must be developed simultaneously along with advancements in battery technology.

- APV safety research and testing is lacking; this issue needs further investigation before AHS implementation.

- Further study is needed on long range (20 to 50 years) electric power requirements of electric vehicles and RPEVs, and the projected generating capacity, generation mix, and emissions at that time.

- Hybrid vehicles, especially series hybrids, as extended range APVs, may bridge the gap between internal combustion and electric vehicle performance. Hybrid vehicles may resolve APVs AHS performance limitations.

- Roadway powered electric vehicles (RPEVs) are the least researched APV technology. RPEVs may provide EVs with the range and performance capabilities necessary for AHS.

- The effects of weather (snow, ice) on powered roadways and the AHS are unknown. Safety impacts must be assessed.

- Lateral and longitudinal guidance of RPEVs on the powered roadway/AHS. RPEV lanes can provide measures of vehicle lateral control.

- Alternative energy storage systems (mechanical batteries, ultracapacitors, fuel cells) may overcome current-generation APV range and performance limitations. These systems could provide APVs with adequate AHS performance.

- Any adverse electro magnetic field (EMF) effects of RPEVs on humans and AHS/equipment need to be addressed.

- APV research is advancing rapidly; further study of both domestic and foreign APV advancements is needed. With technological advancements, the APV performance limitations discussed may be remedied.

5.6.3 Cost and Benefits

The most critical path for future research on the costs and benefit factors in evaluating proposed AHS systems is to investigate, develop and refine work on its performance gains as well as its incremental cost components. The state of the art in traffic engineering needs to be brought to bear on systems that have yet to see operational testing. Much needs to be accomplished in the area of on-board system configurations to enable some form of costing analysis to be done with greater precision than is currently achievable. Much more detailed research needs to be accomplished on the safety improvements promised by AHS. Stakeholders in the systems community need to be better integrated in systems definition to enable more accurate market definition, as well as to achieve a better sense of the ultimate consumer cost parameters. This is perhaps the most fertile area for future research, since cost-benefit analysis of tomorrow's AHS roadways depends crucially on the quality of the inputs from work on roadway deployment and operations, safety analysis, roadway configurations and systems infrastructure, and so on.

5.6.4 Institutional and Societal System Impacts

Recommendations for further research during the next phase of the AHS effort are summarized below:

- Tort and product liability — further research into the most viable of the several potential approaches for addressing this issue.

- The extent to which AHS will induce demand for additional trips and for trips by low-occupancy vehicles that might otherwise be made by public transportation, and the extent to which AHS will encourage trips of greater distance — increased VMT — to take advantage of time savings.

- Further research into how the issues of public acceptance and education might guide how any initial test deployments are structured, how their expectations are defined, and how their results are interpreted and disseminated.

- The amount of revenue that might be raised with each type of funding source for AHS, the reliability and cyclical variability of revenues from each, and the political/institutional implications of each.

- Additional research into those potential applications of AHS technology that would be of particular interest to previously-identified potential stakeholder groups, and particular research into how AHS might be used to improve local control of traffic and improve community livability.