Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Executive Summary
Volume One

U.S. Department of Transportation
Federal Highway Administration

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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.

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

NOTICE

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16. Abstract
This document is the draft final report of the Automated Highway System.The activities of Automated Check In,
Check Out,Lateral and Longitudinal Control, Malfunction Management and Analysis, Entry/Exit Implementation, Commercial and Transit AHS Analysis, Vehicle, Operational Analysis, AHS Safety Issues, and Knowledge Based Systems were studied. This document type is resource materials.
This volume is the first in a series. There are nine other volumes in the series.
FHWA-RD-95-XXX Volume 2 Automated Check In
FHWA-RD-95-094 Volume 3 Automated Check Out
FHWA-RD-95-095 Volume 4 Lateral and Longitudinal Control
FHWA-RD-95-096 Volume 5 Malfunction Management and Analysis
FHWA-RD-95-097 Volume 6 Commercial Vehicle and Transit AHS Analysis
FHWA-RD-95-098 Volume 7 Entry/Exit Implementation
FHWA-RD-95-099 Volume 8 Vehicle Operational Analysis
FHWA-RD-95-105 Volume 9 AHS Safety Issues
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiple By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE:	Volumes greater than 1000 L shall be shown in m^3			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(f-32)/9 Or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiple By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
T (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C+32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made comply with Section 4 of ASTM E380.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ABS	anti-lock brake system
AHS	Automated Highway System
AI	Artificial Intelligence
AICC	Autonomous Intelligent Cruise Control
AICC	Adaptive Intelligent Cruise Control
ALK	automatic lane keeping
ANSI	American National Standards Institute
APTS	Advanced Public Transportation System
ASR	anti wheel spin regulation
ASTM	American Society for Testing and Materials
ATIS	Advanced Traveler Information System
ATMS	Advanced Traffic Management System
AVCS	Advanced Vehicle Control Systems
AVI	automated vehicle identification
AVL	automated vehicle location
BAA	Broad Agency Announcement
CICC	cooperative intelligent cruise control
CMAC	Cerbellar Model Articulation Controller
CVO	Commercial Vehicle Operations
CVSA	Commercial Vehicle Safety Alliance
DOT	Department of Transportation
EIA	Electronics Industry Association
EMS	emergency medical services
ERSC	Evolutionary Representative System Configuration
ETC	electronic toll collection
EVM	emergency vehicle management
FARS	Fatal Accident Reporting System
FFBD	functional flow block diagram
FHWA	Federal Highway Administration
FLIR	forward looking infrared radar
FMEA	failure modes and effects analysis
FTA	Federal Transit Administration
GES	General Estimates System
GPS	Global Positioning Satellite navigation system
HAR	Highway Advisory Radio
HAZMAT	hazardous materials
HDS	headway detection system
HOV	high occupancy vehicle
HUD	head-up display
ICAS	intersection collision avoidance system
ICC	intelligent cruise control
ISTEA	Intermodal Surface Transportation Efficiency Act
ITE	Institute of Transportation Engineers
IVHS	Intelligent Vehicle Highway System
KBCon	Knowledge Based Controller
LCM	lane change / merge collisions
LED	light-emitting diode display

LORAN	Land-based Radio Navigation System
MCSAP	Motor Carrier Safety Assistance Program
MOE	measure of effectiveness
NAB	National Association of Broadcasters
NEC	Northeast corridor
NEMA	National Electrical Manufacturer Association
NHTSA	National Highway Traffic Safety Administration
PATH	Program for Advanced Transit and Highways (California)
PCD	personal communication device
PDS	proximity detection system
PPT	personalized public transit
PRT	perception reaction time
PSA	precursor systems analyses
PSAP	public safety answering point
PSS	Public Safety Services
PTS	public travel security
RECA	rear end collision avoidance
RECW	rear end collision warning
RL	reinforcement learning
RSC	representative system configuration
RSPA	Research and Special Programs Administration
RTTASC	real-time traffic-adaptive signal control
SAE	Society of Automotive Engineers
SCP	straight crossing path
SHMS	speed headway maintanence system
SOV	single occupancy vehicle
SRVD	single vehicle roadway departure
TAHSK	Tufts Automated Highway System Kit
TDM	travel demand management
TIA	Telecommunications Industry Association
TMC	traffic management center
TMS	tire monitor system
VMS	variable message sign
VMT	vehicle miles traveled
VRC	vehicle-to-roadside communication

1.0 INTRODUCTION

The Automated Highway System (AHS) challenge, as presented by the Federal Highway Administration (FHWA), is to conduct analyses of today's highways to identify strategies and technologies which will improve the nation's transportation system in terms of effectiveness and level of service. This can be achieved by improvements in safety, efficiency, user comfort, and reduction of environmental impact. The goal of this team's Precursor Systems Analyses (PSA) was to define total system concepts to meet that challenge.

The AHS system shall be collision free in the absence of malfunctions. A malfunction management strategy shall be developed which will minimize the number and severity of accidents should they occur. Increased system efficiency can be achieved by reducing the amount of time to travel a fixed distance by eliminating delays, increasing passenger miles traveled by providing more efficient passenger vehicle fleet operation, improvements to the national economy by decreasing commercial vehicle delays, and improved adverse weather operation. Increased user comfort and service can be achieved by increasing travel time reliability and reducing driver stress. A reduction of environmental impact can be achieved by a decrease in vehicle emissions due to less vehicle idling and more efficient vehicle flow. Land impact can be reduced by increasing system efficiency without the addition of new highway right-of-way. An integration of AHS passenger vehicles with transit and rail operations can increase overall regional transportation efficiency.

1.1 Summary Description of Activity Areas Addressed

This report addresses the nine activity areas of Automated Check In, Automated Check Out, Lateral and Longitudinal Control Analysis, Malfunction Management and Analysis, Commercial Vehicle and Transit AHS Analysis, Entry/Exit Implementation Strategy, Vehicle Operational Analysis, AHS Safety Issues, and Knowledge Based Systems and Learning Methods for AHS.

The Automated Check In and Automated Check Out activity areas address similar issues. There is a duality between the two areas in that check-in is concerned with the fitness of the vehicle to perform automatic control, and check-out is concerned with the readiness of the operator to perform manual control. Both activity areas involve many human factors issues which are similar. These activity areas ensure that the requirements, issues, and risks for safe entry and exit from the AHS are identified.

The Lateral and Longitudinal Control Analysis activity area defined and analyzed the system requirements for lateral and longitudinal maneuverability on the AHS to ensure safe system design and operational efficiency. Technologies, issues, and risks associated with separate lateral and longitudinal control are also addressed.

The Malfunction Management and Analysis activity area identified response options for managing AHS malfunctions. Measures of effectiveness (MOEs) were defined which can then be applied to possible malfunction management strategies to determine the best approach.

The Commercial Vehicle and Transit AHS Analysis activity area provided an analysis of potential scenarios for the integration of AHS into the existing infrastructure by considering the viewpoint in which commercial vehicles are the first carriers of this technology.

The AHS Entry/Exit Implementation activity area identified and addressed various strategies for implementing AHS entry/exit roadway designs. Measures of effectiveness are defined which were then used to evaluate the various configurations.

The Vehicle Operational Analysis activity area addressed the performance and reliability requirements for the AHS vehicle , the feasibility of vehicle retrofit, and the effects of various levels of automation on driver tasks and workload.

The AHS Safety Issues activity analyzed the major technical, design, and implementation issues necessary to provide a collision free driving experience on the AHS.

The Knowledge Based Systems and Learning Methods for AHS examined the extent to which methods and techniques from the area of knowledge based systems and learning methods would be useful as a component of AHS technology.

1.2 Specific Focus of the Contract

The primary focus of this contract was to conduct analysis into the nine activity areas to identify risks and to provide data and insight into pertinent issues effecting AHS. These can then be used to support subsequent phases of the AHS program. The team defined a set of Evolutionary Representative System Configurations (ERSCs), which covered a broad range of vehicle automation and roadway implementation schemes, and which are addressed in section 2.0 of this report. This provided the framework for conducting a unified analysis of the various activity areas.

1.3 Issues Addressed by Activity Area

The various contractor teams participating in the PSA of the AHS are addressing a variety of issues within each activity area. A series of matrixes which list all of the issues addressed by all of the teams are contained in reference one. The lists below contained the issues addressed by this team.

The issues addressed within the Automated Check In activity were:

- Operator interface and human factors.
- Infrastructure requirements.
- Acceptability of the approach.
- Major alternate ways to ensure safe and efficient operation.
- "On the fly" check in.
- Check in scenarios for various entry configurations.

The issues addressed within the Automated Check Out activity were:

- Operator interface and human factors.

- Driver readiness tests.
- Vehicle functions.
- Operator characteristics.
- Infrastructure functions.
- Continuous check.
- Periodic check.
- Instrumentation.
- Check out scenarios for various exit configurations.

The various issues addressed in the Lateral and Longitudinal Control Analysis task were:

- Required vehicle maneuvers
- High level control system requirements.
- Reliability requirements and fail-safe design.
- Driver comfort and acceptance.
- Interactions between manual and automatic control.
- Weather and traffic conditions.
- Maneuver coordination and communications.
- Sensor, actuator and controller accuracy.
- Evolution from today's technology.
- Combined lateral and longitudinal control.

In the Malfunction Management and Analysis activity the issues addressed were:

- Functional analysis to define normal operations.
- Identification and categorization of potential malfunctions.
- Investigation of malfunction detection techniques.
- Definition of MOEs to rate malfunction severity.
- Definition of MOEs to rate malfunctioin responses.
- Development of malfunction management strategies.

Commercial and Transit AHS Analysis addressed the issues of:

- Define design requirements for trucks.
- Define design requirements for buses.
- Note differences in operational characteristics.
- Note differences in AHS strategies.
- Driverless rapid transit or trucking.
- Truck convoying considered.
- Costs/Benefits addressed.

The AHS Entry/Exit Implementation Issues contained:

- Effects of Entry/Exit on Overall Performance of the AHS.
- Relative Viability of Specific Entry/Exit Strategies and Configurations.
- Design Features, Parameters, and Guidelines for Entry/Exit Strategies and Configurations

The issues addressed in the Vehicle Operational Analysis activity were:

- Reliability and fault tolerance.
- Vehicle and driver diagnostics.
- Maintenance.

- Retrofit.
- Evolution of vehicles control.
- Deployment scenarios.

The AHS Safety Issues addressed in this activity were:

- Characteristics of normal operation.
- Characteristics of potential AHS accidents.
- Impact on design issues.
- Impact on implementation issues.

The Knowledge Based Systems and Learning Methods issues addressed were:

- Areas where artificial intelligence (AI) can assist AHS.
- Recommended AI technologies for management of vehicles in traffic.
- Implementation of learning methods in AHS.

1.4 Overall Approach/Methodology Across All Activity Areas

The study commenced with the definition of four Representative System Configurations (RSCs) which were defined during the proposal phase. The RSCs were defined to establish the boundaries of the major design categories of vehicle, roadway, driver, and infrastructure. These four concepts consisted of a vehicle-heavy automation with designated entry and exit concept, infrastructure - heavy automation with designated entry and exit concept, partially automated vehicle on a continuous entry and exit roadway concept, and fully automated vehicle on a continuous entry and exit roadway concept. As the study progressed, it became necessary to more fully define the RSCs to distinguish between a partially automated vehicle and fully automated vehicle. Additionally, the degree of automation could greatly affect the increase in effectiveness of one configuration over another. The resulting five Evolutionary Representative System Configurations (ERSCs) are described in detail in section 2.0.

The approach was to build upon current and planned capability using technology which is available in the near term to define an AHS system to provide the earliest significant performance improvement, to determine how far such a system could go in meeting the growing requirements, and then to identify more advanced technologies as required to meet the tougher challenges downstream.

The various activities followed similar approaches to conducting their analysis. The first step in the methodology was to conduct a literature review and data collection where applicable. This made each group aware of work previously conducted, helped to identify critical topics that were relevant to the activities being studied, and provided a basis for extrapolating the benefits of an AHS from today's roadway system.

Because of the diverse nature of the activity areas studied, each activity also had aspects of the study approach that were unique to the respective activities. A summary of the key elements of the approach specific to each activity area are shown in table 1.

Table 1. Summary Of Activity Area Approaches To The Precursor Systems Analyses

ACTIVITY AREA	APPROACH KEY ELEMENTS
Automated Check-In (and Check-Out	Study diagnostics and instrumentation to minimize driver's responsibility. Ensure driver's ability to regain control (on check-out).
Automated Check-Out	This activity is explained in Automated Check-In.
Lateral and Longitudinal Control Analysis	Establish reliability and fault tolerances from Ford and Daimler-Benz test results and driving simulators. Establish requirements for automatic control, auto/manual transitions, and driver interventio considering driver comfort and acceptance.
Malfunction Management and Analysis	Identify failure components: define an effective malfunction space.
Commercial and Transit AHS Analysis	Evaluate autonomous system against a evolution of roadways for AHS. Provide experimental data.
AHS Entry/Exit	Develop MoEs, qualification, and combination methodology modeling.
Vehicle Operational Analysis	Analyze existing maintenance data; refine diagnostic approach through literature review and new conceptualization; assess retrofitting, failure modes and effect analysis and reliability studies.
AHS Safety Issues	Analyze AHS functions, evaluate safe design requirements, evaluate GES database.
AHS Knowledge Based Systems Analysis	Use decision tree, network, generic and/or Q-learning algorithms based on speed and other performance evaluators.

The use of several face to face coordination meetings early in the study, but after the initial literature and data collection activity, ensured that all team members were using a common baseline of ERSCs. These meetings were also helpful in providing a forum for exchange of ideas among the various team members, for providing the individual activity researchers the perspective of how the other team members viewed the other activities, and the impact of the individual activities and research topics on the other tasks.

As part of the functional analysis process the use of functional flow block diagrams (FFBDs) were used early in the study to define what the various AHS RSC systems must do. The functional analysis process also identifies the operational functions/subfunctions to be performed by the AHS elements (driver, vehicle, roadway). The development of flows of interaction between the functions are accomplished using the FFBDs. This process identified critical functions, determined critical timeline paths for system design, and provided cross inputs between the various activities (i.e., a short check in time conducted on the move reduces requirements for the entry/exit implementation activity).

The final step in the study approach was to synthesize the precursor analyses into an integrated systems approach to the AHS.

1.5 Guiding Assumptions

The deployment of the AHS will evolve over time. Initial market introductions will be based on small, incremental increases in the level of automatic control added onto existing vehicle dynamic systems. The deployment of the AHS will be paced by the general public willingness and ability to purchase the benefits offered. Depending on the level of success achieved by the initial products, this will lead to a more complete implementation of an automated highway system.

The AHS must be accident free in the absence of malfunctions. It must not only be safe, it must appear safe in order to achieve public acceptance.

The AHS must provide clearly visible benefits in order to obtain general public and governmental agency support and willingness to provide the resources to permit complete implementation. The system should provide an improvement in traffic flow, increased reliability over current roadway infrastructure, and provide reliable trip travel times. The minimization or elimination of travel delays and congestion will provide an easily quantifiable benefit that will increase a geographic areas competitiveness in the global marketplace. The AHS should also provide increased user comfort and service while reducing driver stress and thereby contributing to an areas quality of life.

The AHS must have minimal environmental impact. A reduction in environmental impact can be achieved by a decrease in vehicle emissions due to less vehicle idling and more efficient vehicle flow. Land impact can be reduced by increasing system efficiency per acre of land without the addition of new highway right-of-way. An integration of AHS with transit and rail operations can increase overall regional transportation efficiency. The possibility has been raised that increased trip travel time reliability may contribute to increases in urban sprawl.

1.6 Format/Content of the Full Report

This report is organized into ten volumes. The executive summary is contained in Volume 1 which is this volume. The remaining volumes contain an executive summary, an in-depth technical discussion of the work performed, and resulting conclusions for the respective activity area. The remainder of the volumes in the series are organized as follows:

- Volume 2 provides the results of the Automated Check In (Activity Area B).
- Volume 3 provides the results of the Automated Check Out (Activity Area C).
- Volume 4 reports the findings of the Lateral and Longitudinal Control Analysis (Activity Area D).
- Volume 5 presents the findings of the Malfunction Management and Analysis (Activity Area E).
- Volume 6 reports on Commercial Vehicle and Transit AHS Analysis (Activity Area F).
- Volume 7 provides the results of the Entry/Exit Implementation Strategy analysis (Activity Area J).

- Volume 8 presents the Vehicle Operational Analysis (Activity Area L).

- Volume 9 reports the results of the AHS Safety Issues task (Activity Area N).

- Volume 10 provides the findings of the Knowledge Based Systems and Learning Methods for AHS (Other Activity Area).

2.0 EVOLUTIONARY REPRESENTATIVE SYSTEM CONFIGURATIONS

During the proposal and start-up meetings, the Raytheon team planned to evaluate four Representative System Configurations (RSCs). These four concepts consisted of a vehicle-heavy automation with designated entry and exit concept, infrastructure-heavy automation with designated entry and exit concept, partially automated vehicle on a continuous entry and exit roadway concept, and fully automated vehicle on a continuous entry and exit roadway concept. As the study progressed, it became necessary to more fully define the RSCs to distinguish between a partially automated vehicle and fully automated vehicle. Additionally, the degree of automation could greatly affect the increase in effectiveness of one configuration over another. The Raytheon team concluded that it could best contribute to the AHS effort by focusing its investigation on determining the degree to which an evolutionary approach could meet the challenge by investigating five Evolutionary Representative System Configurations (ERSC). The approach was to build upon current and planned capability using technology which is available in the near term to define an AHS system to provide the earliest significant performance improvement, to determine how far such a system could go in meeting the growing requirements, and then to identify more advanced technologies as required to meet the tougher challenges downstream.

The terms *continuous* versus *designated entry and exit* were confusing since barriers were not discussed. Continuous entry/exit permits the driver to merge into and out of the automated highway system at any point along the road. Designated entry and exit occurs along specific areas of the roadway. These areas can be marked by painting lines in the road. The use of barriers to separate the manual and automated lanes in those areas where entry/exit is not permitted can also be employed. When the designated areas are marked by the use of painted lines, there is nothing to stop the non-compliant driver from entering and exiting wherever they choose. The safety and entry/exit considerations without barriers are similar to continuous entry and exit. Therefore, the decision was made to consider three roadway configurations as designated entry and exit, with and without barriers, and continuous entry and exit.

The work here is based on this aforementioned approach. The five ERSCs, along with the roadway configurations, completely cover the initial four RSCs and in fact provide more depth to the analysis.

The first three ERSCs are envisioned to be single automated lanes, while ERSCs four and five would have multiple automated lanes. Each ERSC was evaluated for the entry/exit conditions of designated entry and exit, with and without barriers, and continuous entry and exit. Figure 1 provides an overview of the key characteristics of each ERSC that will be explained in detail in the following sections.

2.1 Evolutionary Representative System Configuration One (ERSC1)

This configuration is the first step in an evolutionary process from today's highways to a fully automated highway system. The principal components of this configuration are speed headway maintenance system (SHMS), a lateral blind spot warning sensor, and a rear end collision warning system, all of which are located on the vehicle, and a low level of communications between the roadside communications infrastructure and each vehicle. Table 2 provides an overview of the key functions, requirements, and driver/vehicle/roadway tasks for this ERSC.

In ERSC1, the vehicle is equipped with an SHMS that maintains a selected time headway and speed relative to the preceding vehicle by using a computer control system to control the throttle and the brake. The SHMS maintains the selected cruising speed when no vehicle is ahead. It maintains the selected headway during vehicle following. Constant time headway maintains the time between the lead and following vehicle, which results in increased distances between the vehicles as speed increases.

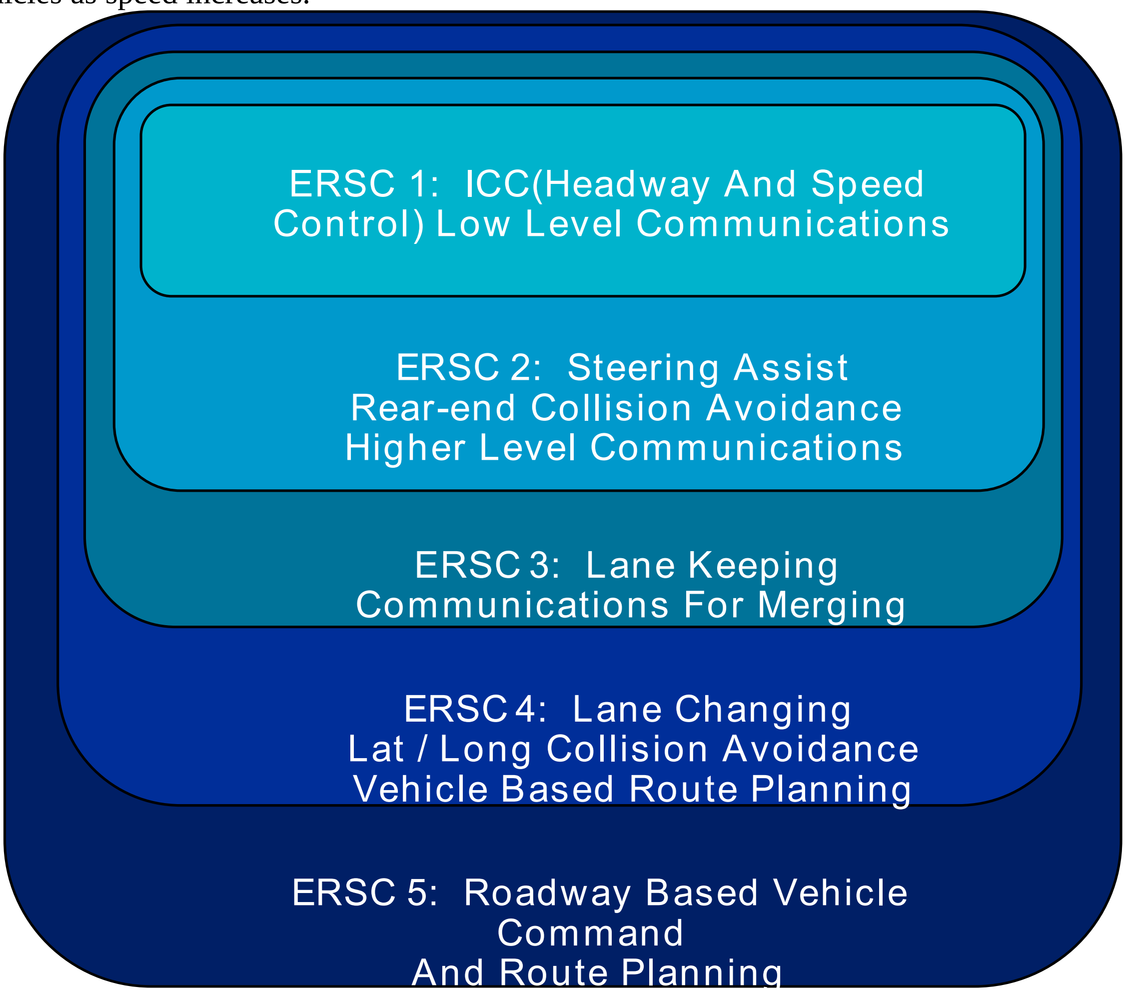

Figure 1. Evolutionary Representative System Configurations

The desired time headway could be input into the SHMS in one of several ways. The first method is for the driver to input the speed and time headway based upon roadway signs which vary depending on traffic density and situation. The driver would have the option of adjusting the time headway setting to a more comfortable distance from the vehicle in front. For example, if the roadway was commanding a two second time headway, but the driver felt more comfortable with a three second time headway, then the driver could make the desired adjustment. The SHMS would not allow the driver to make excessive adjustments to the time headway setting; i.e., a 10 second setting, which would adversely affect system efficiency with no increase in system safety. Another method has the roadside communications infrastructure broadcast time headway and speed settings directly to the SHMS.

Table 2. ERSC1 functions and driver/vehicle/roadway performance requirements

Function/ Section	Requirement	Driver/Vehicle/Roadway Tasks
Speed and Headway Maintenance	- Maintain the selected cruising speed when no vehicle is ahead. - Maintain a selected headway for vehicle following. - Smoothly transition between vehicle following and cruising modes	- Respond to driver commands for setting the cruising speed and minimum headway and maintain that cruising speed and chosen headway in a smooth manner. - Respond to driver commands for enabling and disabling the SHMS safely. - Respond to roadway commands for following target speeds and increasing headway in a smooth manner.
Rear-End Collision Warning	Warn the driver of a potential rear-end collision due to moving or stationary obstacles in the lane on time without false alarms.	- Detect potential rear-end collisions. - Have a high detection rate and a low rate of false or nuisance alarms. - Send driver warnings of rear-end collisions. - Communicate braking data from the preceding vehicle to reduce false alarms.
Blind Spot Warning	Warn the driver of moving or stationary obstacles in the vehicle's blind spot.	- Detect objects in the blind spot on both sides of vehicle. - High detection rate and a low rate of false or nuisance alarms. - Warn driver in time to avoid collision . - Driver enables blind spot warning. - Respond to. driver command to adjust warning thresholds
Driver Interface	- Driver should be able to: • Override the speed and headway maintenance function. • Adjust headway and set cruising speed. • Adjust warning threshold.	- Adjust threshold on warnings. - Enable/Disable automatic functions. - Adjust headway cruising speed. - Interface should be simple to understand and use.
Roadway/ Vehicle Speed and Headway Commands	Senses vehicle average speed and density and environmental conditions then sends commands to smooth traffic flow.	- Roadway measures the average speed and traffic density, and assesses environmental conditions, and calculates vehicle target speeds and minimum safe headways. - Vehicles may display relevant traffic information to driver.
Fall-back Mode to Manual Driving	Driver should be warned of system failures or degradation in time to recover from dangerous situations.	- Sense status of different vehicle control channels. - Safety transfer control to the driver if SHM function fails.

The vehicle maintains knowledge of its own braking capabilities and receive brake data from the forward vehicle. Automatic braking is limited to soft braking that is applied when the engine torque is not sufficient to maintain the selected headway. It does not include hard braking for emergency stops or other situations. The SHMS would notify the driver of the need for emergency braking and begin soft braking, using either brake data sent from the forward vehicle or sensing of the forward vehicle deceleration. Braking data is shared between vehicles for two reasons. The first is to let the following vehicle decide how great a headway to use to ensure safe operation based on the forward vehicle's braking capability. The second is to let the following vehicle know that the lead vehicle is braking and at what level.

A lateral blind spot sensor would warn the driver of vehicles in adjacent lanes to assist the driver during merge procedures during AHS entry and exit. This would most likely be optional equipment, and would not be required for automated lane use at this evolutionary stage.

The vehicle would perform self-diagnostics using built-in tests. These tests could be performed at check-in to the AHS system, through continuous monitoring, or a combination of both. However, all of these tests would be conducted while the vehicle is on the move. The vehicle would inform the roadway of its status as a functioning automated vehicle.

Other vehicle functions, such as propulsion and traction, would be performed in the traditional manner.

The driver maintains control of the vehicle through all phases of the driving operation. The driver is responsible for driving the vehicle into the dedicated lane with the aid of the blind spot warning system. Once in the lane the driver switches the SHMS on and sets the desired headway for vehicle following and desired cruising speed. While the SHMS is engaged, the driver still maintains lateral control (steering) of the vehicle, which consists of lane keeping and lateral collision avoidance. The driver supervises the SHMS and overrides it when hard braking is required for emergency stops or other situations. In the case where headway/speed information is relayed directly to the SHMS from the roadway communications infrastructure the driver would have the option of making adjustments to more comfortable settings, within limits, to these inputs. In case of malfunction of the SHMS or at the end of the trip the driver drives the vehicle out of the automated lane by using the next available exit with the aid of the blind spot warning system. The driver is aided by the rear end collision warning in avoiding rear end collisions. The driver is also responsible for choosing the route of the vehicle and conforming to traffic regulations.

The roadway infrastructure consists of the physical roadway, sensors, traffic management centers, and communication systems.

Only a single dedicated lane of automated traffic is envisioned for ERSC1. This is because the driver is still responsible for maintaining lateral control of the vehicle while traveling in the automated lane. The lane could be isolated and accessed via a dedicated ramp or could be next to a manual lane and accessed at designated points or at any point along the manual/automated lane boundary.

Roadway sensors, either embedded or mounted along the roadside or overhead, would monitor traffic density along roadway sections and demand at entry ramps. These sensors would then send traffic and entry demand information to the traffic management center (TMC) for each roadway section.

The traffic management center synthesizes traffic density and entry demand information with environmental and incident information to arrive at speed and headway settings for the different stretches of roadway. This would provide flow control upstream of an incident or a congested exit, and also ease entry procedures through ramp metering and controlling speed and spacing of vehicles upstream from high demand entry points. Ramp meters provide entry access and flow control under TMC direction.

The TMC transmits speed and headway settings to each roadway section, and provides control of ramp meters. The speed and headway commands for the current section of roadway could be transmitted directly to the SHMS by roadside transmitters, or could be displayed on variable message signs, and the driver would then enter the appropriate inputs to the SHMS.

2.2 Evolutionary Representative System Configuration Two (ERSC2)

In ERSC2, additional capability is added to that established in ERSC1 to ease the burden on the driver. The driver is still responsible for vehicle operation, and the automated roadway still consists of one lane at this stage. Table 3 provides a summary of this ERSC.

In this ERSC the rear-end collision warning system in ERSC1 is upgraded to rear-end collision avoidance. The SHMS and rear end collision avoidance allows the driver complete "feet off" driving in the dedicated automated lane. Full longitudinal collision avoidance capability providing automatic emergency braking using vehicle-to-vehicle communication, and a forward looking sensor allowing braking in response to changes in the forward vehicle speed or in response to obstacle detection, will now be feasible in travel along automated routes.

More sophisticated vehicle-to-vehicle communication is provided to increase the amount of data available to the following vehicle concerning the lead vehicle's braking, velocity, and acceleration profiles and capabilities. These capabilities vary with vehicle weight, speed, tire wear, and brake conditions, etc., from vehicle type to vehicle type and even within vehicles of the same model. Since this capability varies over time, knowledge-based software on board the vehicle might be used to monitor the status of the vehicle's capabilities in these areas. With this knowledge, the following vehicle SHMS could make independent decisions to increase or decrease vehicle headway to improve safety margins or efficiency. In order to more precisely provide a measurement of the vehicle state, additional vehicle sensors would be required such as accelerometers or a more precise speedometer.

The vehicle provides steering assist to smooth the driver's steering by compensating for roadway disturbances, wind gusts, and small driving errors. The vehicle also has lane departure warning to warn the driver of large deviations from the center of the lane.

In ERSC2, the driver is still responsible for steering the vehicle with the steering assist feature helping to avoid unintended lane departure. The driver is also responsible for providing emergency backup for the automated longitudinal collision avoidance feature.

The roadway infrastructure would see the introduction of lane keeping aids if any are required for conducting the steering assist feature. A more sophisticated determination and utilization of traffic information would be conducted by the traffic management center.

Table 3. ERSC2 functions and driver/vehicle/roadway performance requirements

Function/ Section	Requirement	Driver/Vehicle/Roadway Tasks
Speed and Headway Maintenance	- Maintain the selected cruising speed when no vehicle is ahead. - Calculate and maintain a headway for collision-free vehicle following.	- Respond to driver commands for setting the minimum headway and maintain at least that minimum headway - Respond to driver commands for enabling and disabling the SHM function safely - Respond to roadway commands for following target speeds and increasing headway in a smooth manner - Respond to roadway commands for increasing the minimum headway in a smooth manner - Compute a safe minimum headway based on vehicle braking characteristics, and those of the preceding vehicle, and environmental conditions
Rear-End Collision Avoidance	The rear-end collision avoidance function should avoid rear-end collisions due to moving or stationary obstacles in the lane under all road and environmental conditions.	- Detect any obstacle in the lane ahead in time to stop or avoid the obstacle - Actuator response should be fast and free of failures - Low rate of false or nuisance alarms - Deceleration and jerk may reach maximum possible values in emergency stop. - Communicate braking capabilities, declaration, and intentions between vehicles to reduce false alarms and increase safety.
Blind Spot Warning	Warn the driver of potential lane change/merge collision due to moving or stationary obstacles in the vehicle's blind spot	- Same as ERSC 1
Lane Departure Warning	Warn the driver when the vehicle is in danger of leaving the lane.	- Sense the vehicle's position in the lane and estimate its course - Senses roadway preview information - Sends driver cautionary and imminent threat warnings of potential lane departures - Have a high detection rate and a low rate of false alarm
Steering Assist	Works in series with driver to compensate for disturbances due to wind gusts and road surface conditions.	- Roadway measures the average speed and traffic density, and assesses environmental conditions, and calculates vehicle target speeds and minimum safe headways - Vehicles may display relevant traffic information to driver
Driver Interface	- Adjust thresholds on warning - Enable/Disable automatic functions - Adjust headway - Steer vehicle with help from steering assist	- Driver should be able to: • Adjust headway • Adjust warning threshold • Enable/disable automatic functions • Steer vehicle - Interface should be simple to understand and use - No adjustments should be required that take driver's attention away from driving
Roadway/ Vehicle Speed and Headway Commands	Senses vehicle average speed and density and environmental conditions then sends commands directly to vehicle to smooth traffic flow	- Roadway measures the average speed and traffic density, and assesses environmental conditions, and calculates vehicle target speeds and minimum safe headways - Vehicles may display relevant traffic information to driver - Roadway monitors vehicle status at check-in
Fall-back Mode to ERSC 1	Driver should be warned of system failures or degradation in time to recover from dangerous situations	- Sense status of different vehicle control channels - Safety transfer control to the driver if SHM function or rear-end collision avoidance fails

2.3 Evolutionary Representative System Configuration Three (ERSC3)

This is the first ERSC where the driver will begin to enjoy the full AHS driving experience of hands-off and feet-off operation. This ERSC will still consist of only a single automated lane. Table four presents a summary of this ERSC.

Building upon the vehicle capabilities introduced in ERSC1 and 2 automatic lane keeping, to provide hands-off lateral control of the vehicle when operating in the automated lanes, is now introduced. The driver would still have the option of increasing the headway between vehicles by adjusting the SHMS if so desired. The blind spot warning evolves into a lateral collision warning sensor that warns the driver of both the presence and heading of vehicles in adjacent lanes which are potential lateral collisions. This warning will be in time for the driver to respond. It will also be coupled with the steering assist capability to reduce the likelihood of lateral collisions.

A more sophisticated vehicle-to-vehicle communication system would allow out of lane communication with AHS vehicles in adjacent lanes to ease merge procedures and reduce the likelihood of lateral collisions.

The driver is responsible for merging the vehicle into the dedicated lane with the aid of lateral collision warning and maneuver coordination between the vehicles and the roadway. The driver switches the automated mode on and off. Since driving is hands-off and feet-off, the driver has no responsibility during normal vehicle operation in the automated lane apart from deciding the vehicle's route and the end of the trip. The point at which the driver releases manual control could be on a dedicated ramp or in the automated lane depending on the entry configuration. The vehicle uses its on-board diagnostics to notify the driver of the fitness of the vehicle to operate in the automated lane. The vehicle relinquishs control to the driver by alerting the driver when it is time to assume control and transfers control to the driver in a smooth manner that is compatible with the driver's skill and fitness.

It is envisioned that the roadway infrastructure would use the same lane-keeping aids already in place for steering assist. These aids may require more dense spacing on the roadway to provide effective control for lane keeping, especially in turns.

With this ERSC, it may now be possible to begin considering the narrowing of lanes because the precise lateral control is being performed automatically. However, this may not make sense until multiple automatic lanes are available, as in ERSC4; and safety, roadway design, or commercial and transit applications may preclude lane narrowing.

The traffic management center will also continue to evolve and to provide more sophisticated use of traffic information.

Table 4. ERSC3 functions and driver/vehicle/roadway performance requirements

Function/ Section	Requirement	Driver/Vehicle/Roadway Tasks
Automatic Lane Keeping	- Senses the position and course of the vehicle in the lane and generates the appropriate commands for the steering actuator - Keeps vehicle in the center of the lane around curves and on straight-a-way	- Sense position of vehicle in the lane with sufficient accuracy - Sense or receive preview information about roadway geometry - Keep vehicle in the center of the roadway - High reliability required since the driver cannot serve as a back-up in case of failure - Transfer of lane keeping function to driver should be done gradually in a smooth way - Interact with rear-end collision function to avoid spinning or rollover during stopping emergencies around curves
Lateral Collision Warning	Warn the driver of potential lateral collisions due to moving or stationary obstacles around the vehicle	- Detect objects on both sides of vehicle - High detection rate and a low rate of false or nuisance alarms - Warn driver in time to avoid collision - Driver enables warning - Respond to driver command to adjust warning thresholds
Maneuver Coordination	Coordinate lane change/merge maneuvers for entry and exit into the dedicated lane	- Roadway sends commands to increase headway to help vehicles merge into the dedicated lane - Vehicles in dedicated lane respond to headway commands from roadway
Driver Interface	- Adjust thresholds on warnings - Enable/Disable automatic functions - Adjust headway - Show driver what functions are operable at any given time	- Driver should be able to: • Adjust headway • Adjust warning thresholds • Enable/disable automatic functions - Interface should be simple to understand and use - No adjustments should be required that take driver's attention away from driving
Fall-Back Mode to ERSC 2	Driver should be warned of system failures or degradation in time to recover from dangerous situations.	- Sense status of different vehicle control channels - Safety transfer control of steering to the driver if lane keeping fails or degrades
Speed and Headway Maintenance	- Maintain the selected cruising speed when no vehicle is ahead - Calculate and maintain a headway for collision-free vehicle following	Same as in ERSC 2
Rear-End Collision Avoidance	The rear-end collision avoidance function should avoid rear-end collisions due to moving or stationary obstacles in the lane under all road and environmental conditions.	Same as in ERSC 2
Roadway/ Vehicle speed and Headway Commands	Senses vehicle average speed and density and environmental conditions then sends commands directly to vehicle to smooth traffic flow; Performs check-in and vehicle status monitoring.	Same as in ERSC 2

2.4 Evolutionary Representative System Configuration Four (ERSC4)

This concept is the first of the five ERSCs which begins to have the characteristics envisioned in a complete AHS. Multiple automated lanes first appear in this configuration along with the vehicle features described in the three previous ERSCs. Table five provides an overview of the functions and requirements of this ERSC.

The vehicle is now equipped with an automated lane change feature which allows vehicles to move between automated lanes without driver steering. The addition of lateral collision avoidance capability allows vehicles to plan and perform maneuvers to conduct the lane changes. This feature could also allow vehicles to avoid accidents by moving automatically in the lateral direction.

Enhanced vehicle to vehicle communication capability allows coordination with nearby vehicles to conduct coordinated actions such as lane changes, merges, demerges using current vehicle states (velocity, acceleration, jerk, degraded performance) and vehicle requests to change states (change lanes, exit).

Navigation maps within the vehicle will provide autonomous guidance for the vehicle. The vehicle will determine the most optimum route to its destination using current traffic density information being provided by the roadway infrastructure and based on trip parameters that the driver inputs. This feature will allow the vehicle to automatically determine when to initiate lane change requests and to coordinate with nearby vehicles. The autonomous guidance algorithms would migrate through traffic to the left and exit candidates to the right, which should reduce congestion around entry/exit transition areas. Providing information to the vehicle of traffic conditions ahead would result in smoother traffic flow along routes by moving upstream traffic out of lanes which contain stoppages.

The driver is no longer required to perform entry merge and exit demerge if the roadway has dedicated entry/exit ramps. As the vehicle travels down the entry ramp, the vehicle intending to merge would coordinate from the transition ramp with traffic in the travel lanes.

The driver would have the responsibility to enter the trip information into the navigation guidance map.

The roadway infrastructure now consists of multiple automated lanes. This may require additional lateral guidance aids between lanes in roadways and on ramps. An alternative approach is to incorporate algorithms in the vehicle autopilot to conduct lane transition based on *a priori* knowledge of the roadway.

Table 5. ERSC4 functions and driver/vehicle/roadway performance requirements

Function/ Section	Requirement	Driver/Vehicle/Roadway Tasks
Automatic Lane Changing and Keeping	- Smoothly and Safely change lanes - Keeps vehicle in the center of the lane around curves and on straight-aways	- Senses the position and course of the vehicle in the lane and generates the appropriate commands for the steering actuator - Sense or receive preview information about roadway geometry and number of lanes - Keep vehicle in the center of the lane - High reliability required since the driver cannot serve as a back-up in case of failure - Transfer of lane keeping/changing function to driver should be done gradually in a smooth way - Interact with speed and headway maintenance function
Collision Avoidance	Avoid collisions due to moving or stationary obstacles around the vehicle	- Detect objects on both sides of vehicle - High detection rate and a low rate of false or nuisance alarms - Plan evasive actions to avoid collision - Coordinate actions with surrounding vehicles
Navigation/ Route Selection	Select a route to reach the driver's destination	- Receive traffic data from roadway information systems - Dynamically select lanes and route for trip
Maneuver Coordination	Coordinate lane change, merge, speed change and collision avoidance maneuvers in the dedicated lanes	- Roadway sends commands for maneuver protocols - Vehicles send their heading, position, and intention to the vehicles around them - Vehicles send out or respond to emergency signals
Driver Interface	- Show driver route and allow driver to change route destination - Show driver what functions are operable at any given time	- Driver should be able to: • Adjust headway • Adjust warning thresholds • Enable/Disable automatic functions - Interface should be simple to understand and use - No adjustments should be required that take driver's attention away from driving
Fall-Back Mode to ERSC 2	Driver should be warned of system failures or degradation in time to recover from dangerous situations	- Sense status of different vehicle control channels - Safely transfer control of steering to the driver if lane keeping function fails or degrades
Speed and Headway Maintenance	- Maintain the selected cruising speed when no vehicle is ahead - Calculates and maintain a headway for collision-free vehicle following	Same as in ERSC 2. Coordinate with lateral control functions for safe lane changes and collision avoidance
Roadway/ Vehicle Speed and Headway Commands	Senses vehicle average speed and density and environmental conditions then sends commands directly to vehicle to smooth traffic flow; Performs check-in and vehicle status	- Roadway commands different speeds for each dedicated lane

With the addition of the in-vehicle route planning and navigation map guidance feature, the roadway infrastructure will be required to have the communication capacity to broadcast this additional traffic information.

The introduction of multiple automated lanes and the in-vehicle route planning feature will require more sophisticated utilization of traffic information.

2.5 Evolutionary Representative System Configuration Five (ERSC5)

This configuration is the complete AHS system as currently envisioned. There are two concepts for implementing this configuration. The first (5A) is an extension of the previous four configurations in which there was an increase in the vehicle-to-vehicle communications, data exchange, and coordination from ERSC to ERSC. The second concept (5B) relies on the roadway to determine and synchronize the movements of all vehicles.

In the first concept (5A), the roadway infrastructure determines the route (lane and lane changes) for each vehicle. The roadway infrastructure commands vehicles to perform actions (request lane changes, remain in lane, increase headway) and those actions are then coordinated with the nearby vehicles in much the same way as in ERSC4. This requires more detailed knowledge of the traffic density by the roadway infrastructure, but does not require the exact positions of vehicles to be known. This may only require this level of infrastructure control near entry and exit nodes.

In addition to the vehicle following routes determined by the roadway infrastructure, and performing these actions by conducting coordination with nearby vehicles, the vehicle will also transmit vehicle capabilities and destination to the roadway infrastructure. This is necessary since the vehicle characteristics can affect the travel lane chosen by the infrastructure for the vehicle.

New roadway infrastructure responsibilities include receiving transmissions which provide increased amounts of information from vehicles. This data will include destination, current lane, commanded action accomplished, velocity, and headway. The roadway infrastructure has detailed descriptions of current traffic conditions on the roadway including velocities and spacings for each lane, and destinations and rough locations (i.e., distance from next exit or kilometer marker) of individual vehicles.

The roadway infrastructure synthesizes data received from all vehicles and smoothes the flow of traffic by determining vehicle routes using current traffic density information and driver trip parameters, and sending specific commands (change lanes, increase headway) to vehicles. The use of knowledge-based software could allow the roadway infrastructure to predict traffic congestion or bottlenecks before they occur, and manage the traffic flow to prevent their occurrence. For example, the system could predict based on trip origins, current locations, destination, and current vehicle speed that a large number of vehicles are going to simultaneously arrive at the same exit and overwhelm the roadway capacity at this point. The roadway infrastructure would then adjust the commanded speeds of the individual vehicles to optimally time the arrivals at the exit and thereby prevent an overload.

The alternate concept (5B) has the roadway infrastructure performing vehicle coordination. In this concept, the roadway determines and synchronizes the movements of all vehicles. The roadway infrastructure commands vehicles to perform actions (change lanes, accelerate, decelerate, decrease headway) without relying on vehicle-to-vehicle coordination occurring during their execution. This requires the roadway knowing the exact position of all vehicles. The earlier vehicle-to-vehicle coordination could remain as a backup mode in the absence of roadway coordination, and portions of the earlier ERSC's vehicle-to-vehicle coordination could remain during normal operation to verify roadway commands.

In concept 5B, the vehicle follows the commands given to it by the roadway infrastructure. Sensors on the vehicle which are capable of extremely accurate determination of the vehicle's current position as well as other state variables such as velocity, acceleration, and heading are required. This information must be communicated to the roadway infrastructure on a frequent basis. In addition, the vehicle capabilities and destination must be transmitted to the roadway infrastructure so that the roadway can safely command actions.

The roadway infrastructure receives the frequent transmissions from all vehicles on the roadway, synthesizes the frequent data transmissions from each vehicle, and completely coordinates their actions in real time. The roadway infrastructure maintains a complete description of current traffic on the roadway (positions, velocities, accelerations, heading, destinations) and uses this data to determine the optimum traffic management strategy.

3.0 HIGHLIGHTS OF THE TECHNICAL DISCUSSIONS OF EACH ACTIVITY AREA

This section of the report provides a summary of the key findings, conclusions, and recommended further investigations for each activity area.

3.1 Highlights of Automated Check In

The underlying framework in this research is the Evolutionary Representative System Configurations (ERSCs) described above. We have analyzed situations in AHS where transition from manual to automated control takes place. In particular, vehicle fitness testing to ensure safe and smooth automated operation has been emphasized. The check-in procedures presented here and an effective malfunction management system, together with a reliable control system, would ensure a safe, smoothly operating AHS system.

In order to analyze the check-in procedures, we need certain assumptions about the roadway configurations. With the purpose of keeping the treatment general, we introduced three conceptual representative entry configurations: (1)Designated Entry with a Dedicated Entry Ramp; (2)Designated Entry without a Dedicated Entry Ramp; (3)Continuous Entry.
We identified four different categories of check-in tests that could be used to test the fitness of the vehicle to enter an AHS facility:

1. *Initial Testing and Certification:* When the automated function vehicle components are manufactured, these will be tested and certified at the factory. If vehicles are retrofitted with these components, the facility performing the retrofit will be responsible for initial testing and certification.

2. *Periodic Off-site Testing:* In addition to the initial testing, periodic (e.g. once a year) testing will be performed at certain testing facilities to certify the fitness of the vehicle for automated lane driving. The certification may also be coded into the nonvolatile memory of the

microprocessor of the vehicle. All automated components will be tested in the periodic tests. Required driver qualifications, if any, may be certified via periodic driver's license examinations for automated vehicle operators.

3. *On-board Built-in Diagnostic Testing:* On-board diagnostics and self tests performed continuously whenever the vehicle is operating under manual or automated control. These tests start at ignition time, and are performed continuously as long as the vehicle is operating. After the vehicles are admitted into the automated lane, continuous diagnostic checks will be performed to ensure continuous vehicle fitness. Standard fault detection algorithms can be used for On-board Built-in Diagnostic Tests.

4. *On-site Testing at Check-in Point:* Tests performed just before the vehicle joins the automatic lane, possibly while the vehicle is in motion, or at a check-in station.

For each Evolutionary Representative System Configuration (ERSC), alternative scenarios have been developed, and relevant functions to be tested are determined. Each function is then evaluated for its criticality with respect to safety. Criticality and feasibility considerations lead to a subset of functions to be tested for each of the ERSCs. Test procedures for each function in these subsets are also discussed. The main goal is to accomplish all tests while the vehicle is driven under manual control as on-board built-in diagnostic tests. This minimizes the check-in procedures at the check-in site, is transparent to the driver and the traffic flow, and allows smooth transition between manual and automated lane.

Since the driver is ultimately responsible for the overall control of the vehicle at ERSC1 and ERSC2, check-in testing of automated equipment is not essential, and on-board built-in diagnostic testing procedures are required primarily for efficient and reliable operation. The reliability functional requirement imposed on the control system is that, under no circumstances, a single-point failure will cause a catastrophic system failure. Hence, double (or even triple) redundancy is absolutely necessary for a fail-safe design for higher ERSCs (see figure 2). Hence, on-board built-in diagnostic tests are practical for sensor testing since crucial sensor tests can be performed via consistency checks on the redundant paths; on-board built-in tests of control actuators and electronics is also practical, *provided the systems are designed for testability*. This requires certain non-standard design modifications for the brake, throttle, and steering systems that allow on-board built-in diagnostic testing of automatic control electronics and actuators during manual operation. Provided that such testable control system designs are adopted, no on-site tests are expected to be needed. Whenever a malfunction is determined in any redundant path, fall-back procedures to the next lower level of automation not requiring that particular redundancy will have to be initiated.
The operator interface issues may be left to vehicle manufacturers and consumers to resolve within the context of competitive market forces. This process would also involve human factors experiments and experience.

3.1.1 Key Findings

- Since the driver is ultimately responsible for the overall control of the vehicle at lower ERSCs, check-in testing of automated equipment is not essential, and on-board built-in diagnostic testing procedures are required primarily for efficient and reliable operation.

- The operator interface issues may be left to vehicle manufacturers and consumers to resolve within the context of competitive market forces. This process would also involve human factors experiments and experience.
- For higher ERSCs, on-board built-in diagnostic tests are expected to be the predominant type of tests. This is practical for sensor testing, since crucial sensor tests can be performed via consistency checks on the redundant paths; on-board built-in tests of control actuators and electronics is also practical, *provided the systems are designed for testability*. This requires certain non-standard design modifications for the brake, throttle, and steering systems that allow on-board built-in diagnostic testing of automatic control electronics and actuators during manual operation. Provided that such testable control system designs are adopted, no on-site tests are expected to be needed.
- Whenever a malfunction is determined in any redundant path, procedures for fall-back to the next lower level of automation not requiring that particular redundancy will have to be initiated.
- On-board built-in diagnostic testing of the lane keeping sensor can be accomplished in the manual lanes only if portions of the manual lanes are modified to include lane keeping reference aids. This is easily accomplished on the entry ramps and at designated entry points. In continuous entry AHS configurations, the lane keeping aids might be fitted every few miles along portions of manual lanes.
- The gate mechanism is required at ERSC5 to prevent unauthorized vehicles from entering the dedicated lanes. Otherwise, the roadway will have incomplete information about the traffic situation in the dedicated lanes. Because of this, designated entry with a ramp is the only recommended entry configuration for ERSC5.
- Whenever a malfunction occurs at ERSC5, the system falls back to ERSC4, where the vehicle performs many functions performed by the roadway at ERSC5. In ERSC5 operations, these vehicle functions are redundant. In view of the relatively limited efficiency and safety gains expected in going from ERSC4 to ERSC5 this final evolutionary step may not be economically justifiable.

3.1.2 Conclusions by Issues Addressed

The conclusions addressing the issues specified in section 1.3 are covered in the key findings in the preceding section.

3.1.3 Recommended Further Investigations

- In order to deal with operator interface issues, extensive human factors experiments and experience will be needed.
- The design modifications required for the brake, throttle, and steering systems that allow on-board built-in diagnostic testing of automatic control electronics and actuators during manual operation needs to be developed.

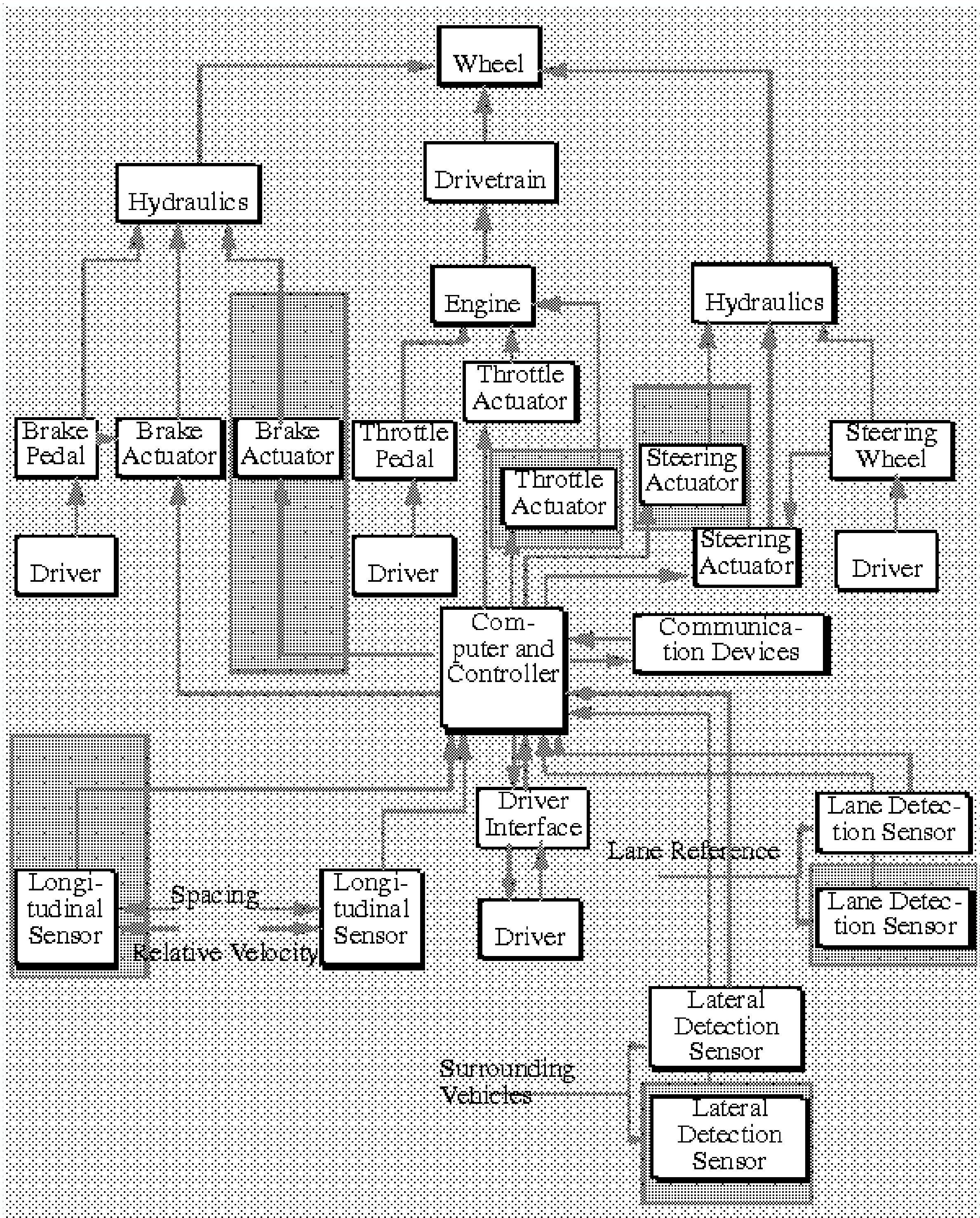

Figure 2. Conceptual Diagram of the AHS Vehicle (hatched rectangles indicate redundant components, the computer has built-in redundancy)

3.2 Highlights of Automated Check Out

The underlying framework in this research is the Evolutionary Representative System Configurations (ERSCs) described above. We have analyzed situations in AHS where transition from automated to manual control takes place. In particular, driver readiness testing to ensure safe and smooth transition from automated to manual control has been emphasized.

In order to analyze the check-out procedures, we need certain assumptions about the roadway configurations. With the purpose of keeping the treatment general, we introduced three conceptual representative entry/exit configurations: (1) Designated Entry/Exit with a Dedicated Entry/Exit Ramp; (2) Designated Entry/Exit without a Dedicated Entry/Exit Ramp; (3) Continuous Entry/Exit.
For each Evolutionary Representative System Configuration (ERSC), alternative scenarios describing the sequence of events in nominal operations are described. This clarifies the role of the driver, vehicle, and roadway in check-out operations and enables us to perform a functional analysis by constructing functional flow block diagrams, and performing a task analysis for critical functions of the driver. This task analysis will focus on key issues and risks related to check-out, rather than trying to be exhaustive and detail oriented.

There are four general functions involved in a check-out operation:

1. The system alerts the driver that exit operations should be initiated.

2. The system puts the vehicle in an operational region that is within the capabilities of the human driver. This will typically involve increasing the headway and reducing the speed.

3. The system performs a driver readiness test to assess readiness of the driver to resume control.

4. The control of the vehicle is transferred to the human driver.

Note that not all four functions will be present for every ERSC. In particular, the driver readiness tests are not expected to be introduced until ERSC3 where hands off/feet off operation starts. We show that, by appropriate design considerations, driver readiness testing procedures can be created such that they measure driving performance directly, while they appear natural and reasonable to the driver. We present a novel testing procedure which also ensures a safe, effective, and smooth transition from automated to manual driving mode. In this procedure, the authority of the automatic controller is gradually decreased, while the manual control authority is gradually increased (see figure 3). This gradual transfer of control continues as long as the driver is capable of performing the manual control part of this hybrid, automatic/manual controller. The system monitors the driver's progress, and accelerates or slows down the transfer of control from automatic to manual. The system will not sacrifice safety at any point; hence, whenever the driver's performance is determined to be unsatisfactory, the automatic control authority may be increased to adequately control the vehicle. This could be achieved by letting the automatic controller provide an admissible envelope of trajectories for manual control. The speed of this procedure can also be adjusted as a function of the driver's performance, so that a skillful, alert, and fast responding driver could resume control within a few seconds.

The operator interface issues may be left to vehicle manufacturers and consumers to resolve within the context of competitive market forces. This process would also involve human factors experiments and experience.

3.2.1 Key Findings

Many functions at lower ERSCs are identical or very similar to the manual driving situation. In particular, no specific driver readiness test should be necessary at these levels.

The operator interface issues may be left to vehicle manufacturers and consumers to resolve within the context of competitive market forces. This process would also involve human factors experiments and experience.

The vehicle should create a large enough gap before transferring the control of the vehicle, so that the driver resumes control in a driving situation that is compatible with the relative slowness and imprecision of human response.

By appropriate design considerations, driver readiness testing procedures can be created such that they measure driving performance directly, while they appear natural and reasonable to the driver. We presented a novel testing procedure which also ensures a safe, effective, and smooth transition from automated to manual driving mode.

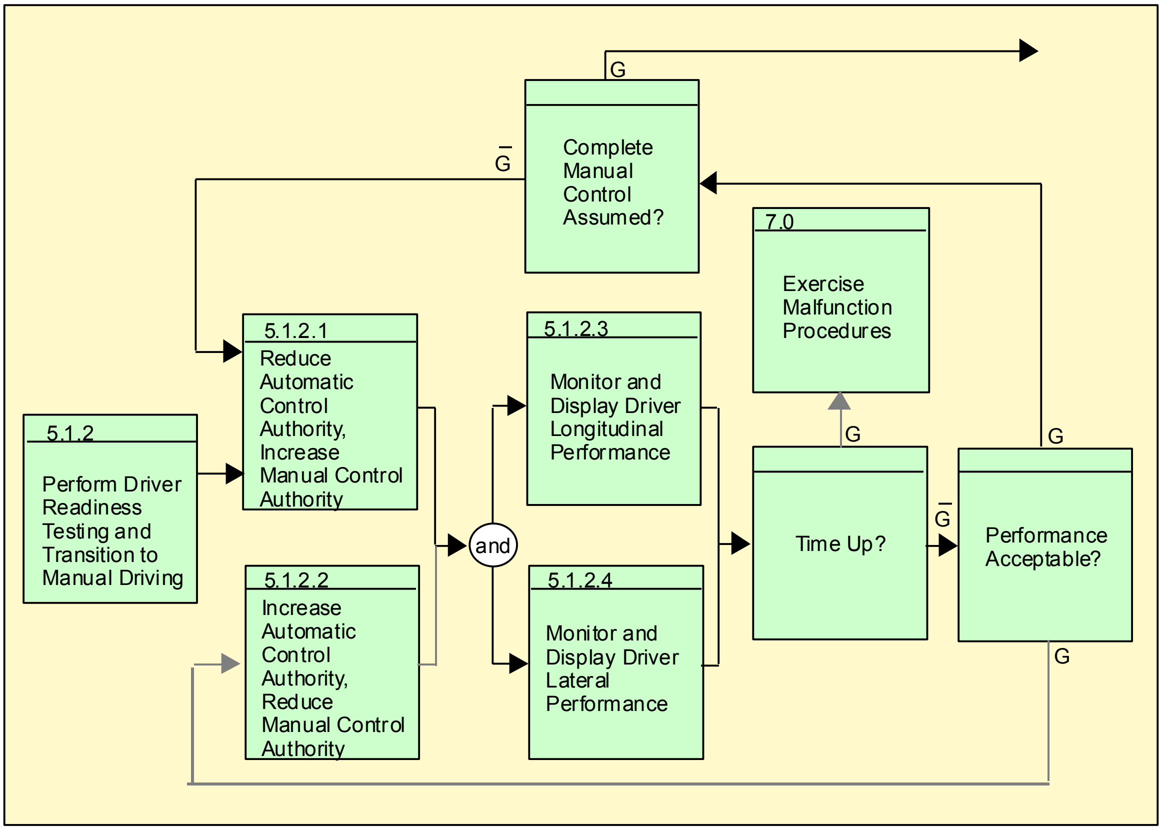

Figure 3. Detailed flow block diagram of driver readiness testing

At ERSC4 and ERSC5, the exit ramp or portions of the manual lane need to be modified to allow lane keeping operations, since the transition from automated to manual control takes place on the ramp or in the manual lanes.

The vehicles whose drivers fail the driver readiness test will be brought to a stop. A designated area for this purpose is desirable.

3.2.2 Conclusions by Issues Addressed

The conclusions addressing the issues specified in section 1.3 are covered in the key findings in the preceding section.

3.2.3 Recommended Further Investigations

In order to deal with operator interface issues, extensive human factors experiments and experience will be needed.

The driver readiness testing concept introduced here needs to be developed further, and subjected to extensive human factors experiments.

3.3 Highlights of Lateral and Longitudinal Control Analysis

The analysis presents requirements, issues, and risks associated with lateral and longitudinal control of vehicles operating on the AHS. The analysis is conducted by following a possible evolutionary path for the automation of lateral and longitudinal control. This evolutionary path is described by five evolutionary representative system configuration (ERSCs). The ERSCs are characterized by various levels of automatic longitudinal and lateral control functions. The analysis has focused on the performance and reliability requirements of lateral and longitudinal control functions. The performance requirement analysis covers driver comfort and acceptance issues during automatic control and transitions between automatic and manual control in addition to investigating the sensor, actuator and controller requirements for the control systems. The reliability requirements analysis uses NHTSA's accident rates data to quantify the reliability requirements in various levels of vehicle automation. This report derives the reliability functional requirements for the automatic systems used in lateral and longitudinal control. The reliability functional requirements allow us to assess the required redundancy and structural complexity in implementing these automatic systems. This information can be used to estimate the cost and difficulty to build the automated highway systems.

3.3.1 Key Findings

Vehicle-to-vehicle communication can reduce the number of false alarms in rear-end collision warning systems without reducing the detection rates. Each vehicle sends its braking data to the vehicle behind it. These communications can serve as a sort of electronic brake light for the vehicle behind. This lets the following vehicle anticipate the braking of the vehicle ahead. This warning can decrease the number of false alarms in the rear-end collision warning system.

Traffic flow can be improved for low levels of automation by applying a roadway controller. This controller eases roadway congestion by regulating vehicle speed along sections of the roadway. This can smooth the traffic flow and decrease backups due to incidents on the roadway. Studies at USC show smoother traffic flow and less back-up on roadways that use this type of controller.

Our original evolutionary design split the development of full lateral control into two parts. The first part was automated lane keeping, the second part lane changing and lateral collision avoidance. These control modes should not be separated since the driver becomes a passenger once the vehicle takes over lane keeping. Human factors studies show that humans do not perform monitoring tasks well.

At each stage of the AHS evolution, drivers are required to have basic understanding about the system operation so that drivers can interface with the AHS safely and efficiently. The drivers will need to be trained to handle the tasks and workload.

Vehicles require a distance and closing rate sensor for speed and headway maintenance or intelligent cruise control. This system can also warn the driver of potential rear-end collisions. The rear-end collision warning system computes the Time-to-Collision and warns the driver of a potential collision in time to avoid the collision (about 1.5 sec before the collision). The sensors for this type of system only need to be accurate to within 3-5 km/hr.

As the AHS evolves to higher ERSCs, the driver's functions are gradually replaced by the automatic control systems of vehicle and roadway. These systems needs to be more reliable than human drivers so that the AHS can be accepted by the public. They also need to be fail-safe to guarantee the safety of drivers. The reliability requirements may substantially increase the component redundancy and design complexity.

The reliability requirements for automatic systems in each ERSC can be used to assess the required component redundancy and design complexity. This gives us a way to estimate the gaps between ERSCs in terms of technical difficulties, cost and risks.

Safety and efficiency benefits in higher ERSCs can only be realized by heavily instrumented vehicles, roadway lane reference aids and the roadway navigation system. It will take joint efforts of the public, the automobile manufacturers and the government to settle the potential legal and liability incurred from the AHS operation.

3.3.2 Conclusions by Issues Addressed

Communication systems and sensors such as radar will be used on vehicles in all stages of AHS deployment. When multiple radar operate in a small area at similar frequencies, the radar on different vehicles may interface with one another. This interference could lead to shorter sensor ranges and poor performance. Such interference is a safety issue since the sensors or communications systems may not work as expected. This issue may also effect how the highways are built and what separation is required between lanes.

Communication is crucial in improving the performance of vehicle lateral and longitudinal control. The government will need to set communication frequencies and protocols so that a common communication system can be used on all highways.

Multiple types of driver warnings for lateral/longitudinal collisions will be installed on the vehicle in the early stages of the AHS deployment. Some examples are rear-end collision warnings and lateral collision warnings. The driver may experience warning overload and warning confusion problems while interfacing with other vehicle and roadway functions.

Collision avoidance systems use braking and steering to avoid crashing into other vehicles or stationary obstacles in the lane. The vehicle may be liable for collisions caused by its failures. This may have impact on the automobile manufacturer's willingness to produce automated vehicles. It may also affect the design and operation of the automated systems. The legal system may need to limit manufacturer's liability.

Collision avoidance requires combined lateral and longitudinal control. Our work proposes an evolutionary system for the development of AHS. In one partial automation scenario the driver can override the automatic lane keeping system but not the longitudinal control for the throttle. The driver may not be able to perform lateral collision avoidance maneuvers using steering control only.

A roadway controller that sends speed commands to vehicles can smooth vehicle speeds and improve traffic flow when incidents occur. The vehicle's can respond to the roadway controller commands automatically as in done in the Prometheus project or the driver can change the vehicle's cruising speed. If the vehicle automatically responds to the speed commands from the roadway, the driver's reliability in detecting rear-end collision danger may be degraded. The driver may be put into a situation that he/she can not handle and may blame the roadway for any rear-end collision. The roadway may be liable for accident caused by incorrect speed commands. However, if the vehicle does not respond directly to roadway speed commands, the effectiveness of the roadway traffic flow control will be affected since the driver may not follow the roadway commands.

As the AHS evolves to higher ERSCs, the vehicle and roadway take away more lateral and longitudinal control functions from the driver. The reliability and fail safe design requirements impose considerably more redundancy and structure complexity on the automatic systems. The cost and technical difficulties of deploying these systems increase rapidly.

3.3.3 Recommended Further Investigations

There are significant human factors issues for warnings and the driver interface that must be researched for even low levels of automation. More research needs to be done on the interaction and prioritization of these warnings for the driver.

More human factors studies need to be done on how effectively a driver can do in lateral collision avoidance using only manual steering control.

First the designers need to decide when the warning system should be turned on: always on, only when turn signal on, or turned on when steering column shows lane change. The warning thresholds for emergencies and driver awareness must also be set. The system must avoid nuisance alarms, yet detect vehicles accurately. The types of alarms and warning must also be researched. The emergency alarm needs to be directional to get fast driver response. ERSC 1 introduces multiple types of driver warnings for blind spot and rear-end collision avoidance. Research needs to be done on the interaction and prioritization of these warnings for the human driver.

Communication plays an important role in the lateral/longitudinal control automation. Research needs to be done on communication protocol design and frequency band acquisition.

As the vehicle assumes more of the driver tasks, the driver may pay less attention to the other vehicles or the highway. This increases driver reaction time to emergencies requiring lateral collision avoidance. The type of feedback that the driver needs from the system needs to be studied.

The sensors for collision avoidance must recognize hazardous situations quickly and accurately. More research needs to be done to reduce the number of false alarms and improve the detection performance of these systems.

The fully automated vehicles perform maneuver coordination to further reduce accident rates and improve traffic flow rates. This will require complicated vehicle-to-vehicle communication and maneuver protocols. Maneuver protocols to insure safe and efficient maneuver coordination have to be studied.

If a dedicated lane has a lane reference aid failure in some roadway sections, the AHS may have to prohibit vehicles from entering those sections. This will reduce the highway flow rate and cause traffic control problems. Further research is required to design reliable and robust lane reference aids.

The reliability and fail-safe design requirements impose considerable cost and technical difficulties in deploying the AHS. More research in sensor and actuator technologies, controller design, and AHS operational strategies is needed to alleviate these difficulties.

3.4 Highlights of Malfunction Management and Analysis

The goal of any malfunction management strategy is to prevent malfunctions from occurring and when they do occur to mitigate their effects. The purpose of this effort is to define a methodology for identifying potential malfunctions and then identify measures of effectiveness (MOEs) which can be used in evaluating and selecting the optimum response. The first step in this process is to develop a through understanding of the system's normal operations. This can be accomplished by using a systems engineering based functional analysis approach. This approach allocates a set of operational functions which define normal operations to physical elements in the system design. In a system as complex as the AHS, it is anticipated that a wide range of operating conditions will define the system boundaries. Two approaches used to conduct malfunction identification are to consider a loss in functionality of an operational requirement and to consider a component failure within a particular system element. Once malfunctions have been identified, two key attributes to consider are their likelihood of occurrence and their severity of impact on normal operations. Finally, it is advantageous to assemble multiple response options to a particular malfunction. Each of these responses to a particular malfunction could have a different implementation time for restoring normal system operation or other performance measures such as user cost, system cost, likelihood of successful implementation, severity of impact on safety, system efficiency, and user comfort. Situational factors about the system operation at the time of malfunction must often be considered when selecting the most appropriate malfunction response.

3.4.1 Key Findings

A complete set of malfunction management strategies will balance the desire to have the system perform without failing with the need to respond to failure when it inevitably occurs, within the constraints imposed by safety, system efficiency, user comfort, and cost.

A complete evaluation of malfunction management options includes cost/benefit tradeoffs between the preventative reduction in the probability of malfunction occurence and the responsive reduction in the severity of the malfunction given its occurrence.

The time criticality and potential severity of certain malfunctions preclude dependence on system responses once the malfunction occurs. In these instances the malfunction management strategy must rely on built in redundancies either in the vehicle or roadway infrastructure.

Reliance on the driver (perceptions, capabilities, predictability, and accountability) for malfunction prevention, detection, diagnosis, and execution of management tasks is a risk/challenge.

Certain malfunctions do not lend themselves to a straight forward methodological breakdown. The complexity of the AHS assures that malfunction management will be a continuously evolving process.

The transient effects of a particular management response may outweigh the benefits gained by its implementation.

3.4.2 Conclusions by Issues Addressed

The systems engineering approach of functional analysis provides a complete framework around which to define the normal operations of an AHS.

The best method for identifying a malfunction is for the identification process to occur as close to the source as possible. This is beneficial in that it increases the probability of detection and diagnosis while reducing the time from when the event occurs to when it is detected.

Based on their criticality and reliability, functions need not have the same frequency for detecting failures (polling). Continuous monitoring can be accomplished through the use of built in test (BIT). Diagnostic tests can be programmed into the system to occur at appropriate or opportune times such as engine start up. Regularl inspections of subsystems can also be scheduled. Additionally, observations of operational deviations can be indicative of malfunctions that were not directly detected by diagnostic means. For instance, a vehicle's malfunctioning speed controller could be observed by the driver, another vehicle, or even the roadway.

The appropriate MOEs to evaluate the merit of individual managing strategies are safety, efficiency of the system, user comfort, and cost. Safety should include a reduction in the likelihood of an accident and a reduction in the severity of an accident (personal injury and property damage). The system efficiency must include the reduction in the likelihood of disruption to the system and a reduction in the effects on the system given a disruption. User comfort rates the desirability of the service provided from the perpective of a typical potential system user. Cost includes the additional cost required to implement the strategy considering both vehicle and infrastructure. This last factor could impact other areas such as market penetration. Other secondary MOEs exist, but many are less quantifiable and result from improvements concerning the primary MOEs (i.e., improved system efficiency also results in improved air quality and user desirability). Further, caution must be exercised when developing the MOEs that sight of the key parameters effecting the system is not lost and that so many MOEs are involved that decision making becomes cumbersome.

The final step is the development of strategies to mitigate malfunctions. Situational factors must be considered in order to select the most appropriate malfunction management response. Certain malfunctions may have several feasible response options. No single malfunction management response to a particular malfunction may be the most appropriate under all conditions.

Situational factors such as the local roadway configuration, incident response vehicle availability, traffic and weather conditions, driver capability, etc., may weigh more heavily into a more optimal, adaptive response selection decision process. Therefore, appropriate information about these factors must be made available at the point where the decision is made.

In addition to considering the situation in which the malfunction occurs, the transient effects of a particular management response may outweigh the benefits to be gained by its implementation.

	Transient Effects				Result of Response			
Malfunction V1 ~ failed optical guidance system	Safe - ty	Sys. Eff.	User Com	Likeli -hood	Safe - ty	Sys. Eff.	User Com	Cost
Malfunction Management Strategies								
Ø ~ No action	B	A	B	C	E	C	C	A
1 ~ Stop vehicle & tow	B	E	E	C	A	A	E	B
2 ~ Redundant component	B	A	B	B	A	A	A	C
3 ~ Manual steering (ERSC1)	D	C	D	C	B	C	D	A
4 ~ Exit automated lane	C	B	B	C	A	A	E	A
5 ~ Automated reduced speed	A	C	C	A	B	E	E	A
6 ~								

	A	B	C	D	E
Severity or Cost:	Slight	Moderate	Major	Severe	Critical
Likelihood:	Very rare	Improbable	Remote	Occassional	Probable

Figure 4. Potential Malfunction Responses for Lateral Guidance Control Malfunction V1 in ERSC3

Figure 4 illustrates such a situation and highlights the relative effectiveness of several potential response options to a lateral guidance control malfunction in the partially automated ERSC3. A more detailed description of this process is given in Volume 5. In this case, the postulated malfunction addressed is to the optical guidance system in the vehicle which tracks lane reference markers and is responsible for lane keeping in this ERSC. Lane keeping is a time critical function: a complete loss in its functionality results in a highly unacceptable state due to safety concerns. For this reason, redundancy is built into the design. It is assumed that the other postulated lane keeping system (vehicle tracking magnetic nails imbedded in road surface) is fully functional at the time of the optical system failure.

As seen in figure 4, if no response is taken (~ no action) in the presence of an optical lane tracking system malfunction, the system could otherwise operate quite benignly with the magnetic tracking system. However, the system is unacceptably dependent on a single lane keeping system, and there would be serious safety concerns if the vehicle's magnetic nail tracking system failed or if the nail markers were somehow obstructed from the tracking system.

The first response option depicted (1 - stop vehicle and tow) prevents the malfunction from causing a safety concern and eventually removes the problem from the system. The response result restores normal operations to the system at the expense of inconveniencing the malfunctioning vehicle's passengers (travel plans not satisfied) and the minor system cost of dispatching a tow truck to the scene. While the response result may be an acceptable option, the transient effects of this response in a heavy traffic environment may be intolerable. ERSC3 is depicted as a single lane configuration. A vehicle stopped in the lane for any significant time would critically impact system efficiency and the user comfort of many. Such a disturbance to the system could introduce safety concerns unrelated to the original malfunction.

Another response option (3 - manual steering (like falling back to ERSC1)) has severe safety concerns in the transient response of implementing the strategy. The end result of this response is a single vehicle performing manual lane keeping in a system otherwise occupied by vehicles under automated lane keeping control. This requires the driver to perform a function that he or she had not planned on, but still allows them to realize their travel needs. Sufficient safety should be gained with an altered speed and headway policy for this vehicle, but this could adversely impact system performance if the current ERSC3 travel conditions allowed for fast travel at high traffic densities. The transient effects of this response are a concern because the driver may not be immediately fit to respond to the system request to resume manual control. This issue and the uncertainty of driver compliance rates this a severe user comfort concern. Also, safety is a severe concern here. Under normal check-out operations, transition to manual control happens at planned times and locations known to the system and driver. In this case, the notice could be rather sudden, and after transition the vehicle stays in the lane.

3.4.3 Recommended Further Investigations

A goal of the AHS is accident free operation in the absence of malfunctions. However, the best method for managing malfunctions is to take action to prevent their occurrence. Technology being developed today for road networks deals primarily with incident management. A goal of malfunction management is to mitigate these incidents prior to their occurrence by identifying warning signals and taking preemptive action. This is an advance over the technology being deployed today. Additional studies should be conducted to determine potential technologies for creating this advancement. Some of these potential technologies are in the areas of expert systems and stochastic processes.

3.5 Highlights of Commercial Vehicle and Transit AHS Analysis

In contrast to most automobiles, commercial vehicles are bought and operated to earn profit. Desirability and feasibility of an AHS for commercial and transit vehicles depends on the willingness of the commercial truck operators to pay for AHS investments. The final AHS concepts as well as the steps to get there have to be designed with this in mind.

3.5.1 Key Findings

<u>Introduction Strategies for Commercial AHS</u>

Databases containing German freight distribution have been extensively analyzed to assess the potential for combining trucks in convoys. A significant percentage of traffic is generated from carriers sending more than one truck between the same cities within a short period of time.

These all are prime candidates for AHS introduction. Combinable volumes are greater for typical re-shipment places like port-cities.

Several factors influence the feasibility of bundling. The technology to realize the bundling need only be standardized within one carrier but would certainly be less expensive if used between potentially competing companies.

Sufficient travel distance between origins and destinations and available similar travel plans for two or more trucks are necessary. Additional manpower at the destination site can reduce the benefit, especially for longer truck convoys.

Simulation of mixed AHS and non-AHS Traffic

Extensive studies have been conducted simulating mixed traffic between truck platoons and manually driven passenger cars. Depending on the truck to car ratio and the length of convoys, significant increase in throughput and/or decrease in travel time has been found.

Communication and Control Concepts for Commercial AHS

Truck Platoons with sophisticated control and communication structures have been realized in simulation. Two-vehicle platoons have been studied in live testing.

Under normal driving conditions, longitudinal and lateral control can be independently designed. However in emergency situations , like sharp braking in a curve, lateral and longitudinal movements are coupled and must be regarded together.

Lateral control can be realized with known approaches and linear models. Good control quality can be achieved with a variety of controllers.

Longitudinal control however deals with strong nonlinearities in the drive train and with large variations of the parameters. Specific difficulties with respect to longitudinal control of trucks as opposed to passenger cars have been identified. These are caused by drive train design, mass of the vehicle, engine power and braking capabilities. Most of these difficulties have been overcome. The longitudinal control of one vehicle following a leading truck with a headway of 10m has been demonstrated. This headway is precisely maintained even if the leading truck does braking and acceleration maneuvers. However, extremely heavy braking of the leading vehicle consumes about 3.5 m of this distance.

A 2.45 GHz link between the convoy vehicles has been proven to be a safe economical communication means.

A standard video camera has been used successfully as a sensor for both following standard road markings as well as for precise distance measurements to the preceding vehicle (maximum distance error at 10m about +/- 1 cm).

Lateral vehicle guidance along pavement markings using these video sensors has successfully been adapted to heavy trucks. A test truck is able to drive at a speed up to 90 km/h with a lateral deviation of less than 10 cm.

Analysis of an existing transit AHS system

O-Bahn is a transportation system consisting of busses that can be steered by the driver and but also guided like trams. A bus is driven manually in suburbs and will enter a special roadway in the city center changing to an automatic guided mode. Thus the width of a special bus lane or tunnel is kept to a minimum. The report describes the components of the system and the operational data and experiences with the system and also the acceptance of the system by customers and practical experience in every day operation.

3.5.2 Conclusions by Issues Addressed

Commercial vehicles already operate in platoons. Up to three unmanned trailers are towed by a tractor for long-distance freight transport. Costly transfer of the cargo to distribution trucks for final delivery is normally necessary. A logical AHS-like concept would be to equip the trailers with their own drive train and to couple them electronically to the leading vehicle thereby forming truck convoys.

In order to provide maximum use of truck convoys from the beginning, the system should be usable on any highway without extra infrastructure and the driver remains as a backup and supervisor.

Initially, two vehicles can be electronically coupled (bundled). The leading vehicle will be steered by the driver, followed by the second, unmanned vehicle. Personnel costs for long-distance driving will be reduced. The two vehicle system can be extended to allow additional vehicles to be coupled together. As soon as the number of convoy able vehicles reaches a certain percentage of the trucking fleet, special AHS-lanes will be assigned to them or built for them around congested regions. Operators of equipped cargo vehicles will get an extra benefit due to more predictable travel times.

Combining trucks in convoys frees up space for passenger cars so that even from automating truck traffic, automobiles will have substantial benefits on manual lanes.

Stable longitudinal control of a truck platoon driving with very short distances between trucks will be one of the most challenging problems for commercial AHS. The long lag-time in the drive train due to diesel engines, the relatively small engine power per mass and the large variation of possible loads represent a special challenge for the control of trucks as opposed to passenger cars.

Experience with previously developed laterally guided systems show that reliable operation can be achieved.

3.5.3 Recommended Further Investigations

Data on freight movements are highly competition sensitive and difficult to obtain. Therefore available German data were used. The developed methodology should be applied to U.S. freight data.

Lane change and following behavior on U.S. freeways is significantly different from driving on German two-lane freeways. The developed simulation model for studying the effect of truck convoying in mixed traffic should be modified accordingly.

Longitudinal control of trucks is much less developed than their lateral control. Further research is needed to control the drive train and the braking properties of trucks. Different brake systems simultaneously in use in today's commercial vehicles, such as engine brakes, retarders, and pneumatic brakes and the additional degree of freedom of articulated trucks need special attention.

3.6 Highlights of Entry/Exit Implementation Strategy

This section presents these findings, conclusions and recommendations from the AHS Entry/Exit Implementation Strategy analysis, organized around the three major issues addressed, which were identified in paragraph 1.3.

3.6.1 Key Findings

The conclusions and recommendations that are presented in later subsections can be generalized as the following key findings:

- The AHS cannot be developed in a single massive project - there are too many independent funding decision makers (vehicle owners and road system owners/operators), a large majority of those cost/benefit based decisions would have to be supportive and timely. *The AHS will be developed in incremental and evolutionary steps as the user market will support with their spending decisions.*

- Efficient operation of the entire AHS system will be gained or lost at the entries and exits. Entries are the only points at which demand related congestion can be controlled. A single blocked or congested exit can bring the entire upstream system to a halt. Lane changing and merging at the entries and exits are the most complex and dangerous routine activities that will occur on the AHS; therefore, most accidents and efficiency problems will occur there. *The AHS must be managed as a system, especially the entries and exits, to achieve the desired levels of efficiency and throughput.*

- Any of the possible entry/exit strategies and configurations will work under light traffic flow conditions. *Only the most well conceived and carefully managed entry/exit strategies and configurations will allow the AHS to function efficiently at the highest desired traffic flows.*

3.6.2 Conclusions by Issues Addressed

Effects of Entry/Exit on Overall Performance of the AHS. The first major conclusion here is that *the AHS and its entries and exits must be designed and managed as a system* if the AHS is to operate efficiently at traffic flow rates higher than is possible on current freeways.

It is assumed that, to the degree possible, the AHS sections and each entry/exit will be initially developed and upgraded periodically to accommodate the existing level of demand. Since additional capacity comes in discrete increments, demand is likely to be frequently out of balance with AHS capacity. (The upgrades are likely to be made by converting manual lanes to AHS.) Therefore, it is necessary that access to the AHS be managed to prevent congestion caused by over demand.

Some of the design and operational management *requirements* for the AHS must be:

- The volume of vehicles entering at each entry must be controlled to prevent more vehicles from entering than can be accommodated given the capacity of the downstream section.
- The volume of vehicles entering at each entry must be controlled to reserve sufficient capacity for downstream entrances to receive equitable service.
- The volume of vehicles exiting at each exit must be controlled to prevent back-up onto the AHS lane(s). This may require rejection routing of vehicles at upstream entrances that are bound for the congested exits.

A second major conclusion relevant to the effects of entry/exit on the overall AHS is that *management of merging activities at entries and exits is necessary* if the AHS is to operate efficiently at traffic flow rates higher than is possible on current freeways. This requirement applies particularly to merging when entering the AHS traffic stream, but will also be necessary when exiting onto freeway lanes during heavy traffic flow.

To achieve efficient merging of traffic streams at the AHS entries, it will be necessary to design into the entry/exit pair:

- An ability to detect and evaluate the sizes of available gaps in the established traffic stream of the target lane, and
- An ability to coordinate the entering vehicle's release, acceleration and path (in later configurations) to safely intercept a known, preserved or created gap, and merge into it.

Relative Viability of Specific Entry/Exit Strategies and Configurations. The first major conclusion as to the viability of the various entry/exit strategies/configurations analyzed is that all are likely to be present somewhere in a nationally deployed AHS.

Overall conclusions concerning the entry/exit strategies/configurations are that:

- The most effective and safest of the entry/exit configurations are the surface street-to-AHS and the freeway-to-AHS dedicated separate entry/exit with simultaneous ramps (see Figure 5). These are the entry/exit strategies/configurations that are most amenable to positive control of entry/exit, management and coordination of merging, and that have the exit positioned just prior to the entry on *both* the AHS and manual lanes. These are moderately expensive strategies/configurations, and are most appropriate in urban environments where the AHS traffic flows will be the heaviest. ***These are the recommended AHS entry/exit configurations.***

- The least effective strategies/configurations have AHS entry from and exit to contiguous manual freeway lanes, either on a continuous basis or only in designated zones. The entering and exiting vehicles cannot stop or slow significantly, their access between manual and AHS lanes cannot be effectively controlled, and their merging cannot be effectively managed or coordinated. *These entry/exit strategies/configurations are the least expensive and have the highest potential for safety problems.* However, at light-to-moderate traffic flows on the AHS and similarly light-to-moderate entry/exit volumes, these configurations may be adequate. These are the traffic conditions that may exist in rural and semi-rural areas that are not on major intercity or cross-country routes. These are the locations where the more expensive, effective and safe entry/exits may not be affordable.

- Moderately effective entry/exit strategies/configurations are those that provide a transition lane between the freeway manual lanes and the AHS lane(s), either continuous or in designated entry/exit zones. *If the transition lane is continuous, this is the most expensive configuration.* If the transition lanes are limited to designated entry/exit zones, they are in an inexpensive enhancement to the contiguous lane entry/exit configurations. These configurations are significantly safer than the contiguous lane entry/exit configurations.

  Entering and exiting vehicles may be allowed to continue in motion while manually searching for a merging gap in the target lane, or their speed and position may be controlled to coordinate with the arrival of a suitable merging gap. The former case places the configuration closer to the capabilities of the contiguous lanes, and the latter case allows and almost requires the transition lane to be configured as a designated separate entry/exit which is closer in capability to the best configurations.

- *Barriers between the manual freeway and AHS lanes are a recommended safety feature in all entry/exit configurations where possible.* They have a negative effect on access and have little impact on effectiveness. The safety threat addressed by the barriers is strictly that of the manually controlled or out-of-control vehicle in the AHS lane(s), which is a real and legitimate hazard. Barriers do not, however, address the more significant safety hazard associated with conflicts while legitimately merging into the AHS or manual lanes.

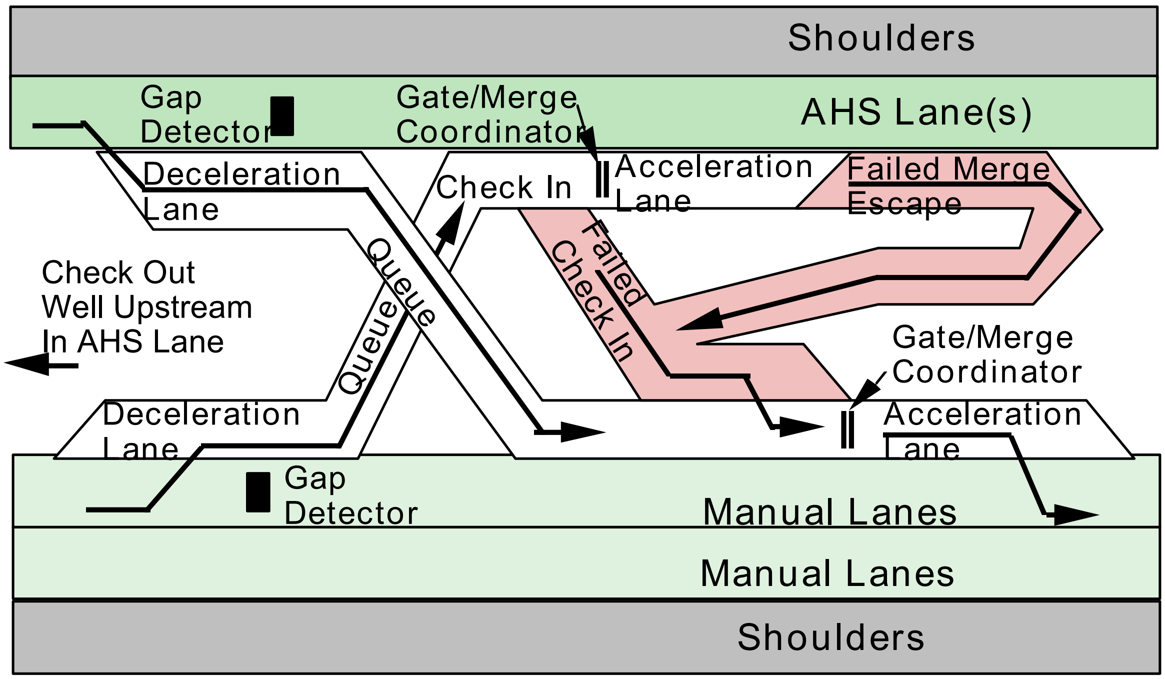

Figure 5. Recommended AHS Entry/Exit Configuration

A conclusion with regard to the specific entry/exit strategies/configurations is that *the design and operation of the AHS entries and exits external to the AHS itself will have a strong influence on the effective operation of the AHS itself.* For the two most important categories of entry/exit strategies/configurations:

- The freeway-to-AHS entry/exit strategies/configurations cannot escape from their dependence on the freeway. If the freeway is heavily congested and performing poorly as a result, the AHS will also perform poorly.

- The surface street-to-AHS entry/exit strategies/configurations cannot escape their dependence on the surface streets. If the surface streets feeding the AHS entry or fed by the AHS exit are heavily congested, or the AHS entries and/or exits are poorly designed with inadequate capacity, the AHS will perform poorly.

Design Features, Parameters and Guidelines for Entry/Exit Strategies and Configurations. These conclusions are based on the assumption that the AHS will be tightly managed to allow only the traffic flows and entry/exit volumes that the AHS sections, entries and exits were designed to accommodate. The most important of the design conclusions are:

- For the recommended entry/exit configurations, a deceleration lane contiguous to the manual and AHS traffic lanes just prior to their exit points, and an acceleration lane contiguous to the manual and AHS traffic lanes just prior to their entry points are strongly recommended.

- For the recommended entry/exit configurations, the entry/exit ramps and transition lanes (when merges are managed and coordinated) will only need to accommodate the queues that result from the probabilistic variations in the balance between entry/exit demand and queue service rates (availability of suitable merging gaps). Since the queuing analysis was not accomplished in this effort, the design equations for this queue length were not derived.

3.6.3 Recommended Further Investigations

There are several outstanding needs associated with AHS entry/exit. Further research is recommended in each of the following areas:

- System level models that would allow investigation of the AHS system-wide management recommendations made herein do not exist. Such a tool would be invaluable in designing, developing and testing the principles and algorithms necessary to implement AHS system-wide management.

- Mathematical models of the interacting traffic steams at the AHS entry/exits in the ERSCs are incomplete and those used in the entry/exit analysis are not well justified. Once the AHS prototype system configuration (one or a set) is accepted for development, accurate mathematical descriptions of the traffic streams involved would be very beneficial for direct use in design and for implementing the AHS system-level simulation model recommended above.

- Design principles, guidelines, and equations for the specific structures, capabilities and features for the AHS entry/exit configurations are incomplete. These cannot be completed until the mathematical descriptions of the interacting traffic steams are completed. These design tools are needed to design, simulate, and develop prototype entry/exit configurations.

3.7 Highlights of Vehicle Operational Analysis

The vehicle operational analysis deals with the study and analysis of the operational issues and risks associated with the development, operation, and deployment of vehicles for the chosen five evolutionary representative system configurations (ERSCs). The study includes issues related to reliability, maintainability, vehicle and driver diagnostics, retrofit to vehicles that were produced before the vehicles for each ERSC developed and discussion of possible deployment scenarios for AHS.

Our overall approach is based on the concept of evolution of vehicle control that is captured by the proposed ERSCs. We study each ERSC separately. We first specify the vehicle functions and interface with driver and roadway and present the functional and reliable requirements that need to be met. We perform a system level failure modes and effects analyses (FMEA) whose result is a list of potential failure modes, their potential causes and effects and a list of design requirements and recommendations. The severity and occurrence ratings of the failure modes are presented and used to classify the criticality of the various vehicle functions. The design requirements and recommendations include the need for redundancies, diagnostics, changes in the system design, the feasibility of retrofit, etc. The results of the FMEA form the core of our analyses and allow us to study the increase in complexity and number of issues and risks associated with vehicle operation as we move from one ERSC to the next one.

Our guiding assumptions in the FMEA and in our analyses in general, are the past history and current trends in vehicle control and automation and the current sensor, actuator technology. These assumptions led us to the concept of evolution of vehicle control that is reflected in the proposed ERSCs. The proposed ERSCs allow us to deal with each automated vehicle function separately without being overwhelmed with the complexity of a fully automated vehicle. Furthermore, one can also view the proposed ERSCs as degraded modes of operation of a fully automated vehicle roadway system. Such degraded modes of operation could be unavoidable because no system could work with optimum performance all the time and under all environmental and roadway conditions. For each ERSC we assume that each vehicle is treated as autonomous with respect to safety. In other words the vehicle does not rely on the roadway or other vehicles to guarantee its safety but rather it uses its on board sensors and intelligence to protect itself from colliding with other vehicles or obstacles. The vehicle functions for each ERSC are designed to provide collision free vehicle following and operation under normal operating conditions. Since no low delta velocity collisions are allowed, the organization of vehicles in platoons of specified size and with very short headway's is considered to be unnecessary and has not been studied.

3.7.1 Key Findings

The reliability requirements for the vehicle functions increase considerably as we go from ERSC1 to ERSC 5. Figure 6 gives an indication of the number of potential failure modes with the highest severity rating generated by the FMEA for each ERSC. The biggest jump occurs when we go from ERSC1 to ERSC2. In ERSC1 the driver is a back-up for the speed and headway maintenance function which is the main automated vehicle function in ERSC1. The driver is responsible for collision avoidance and steering. As a result the number of potential vehicle failure modes with high severity is fairly small. By moving to ERSC2 where we introduce a full authority longitudinal controller that calculates on line the vehicle headway a considerable larger number of high severity failure modes is possible. Table 6 gives a list of all the basic vehicle functions and subsystems that need redundancies in order to meet the required reliability levels and reduce the severity of the potential failure modes. The number of redundancies increases considerably as we automate additional driving functions by going from ERSC 1 to a higher one.

Every vehicle function that affects the motion of the vehicle and/or has an impact on safety has to be designed so that it never puts the driver in a situation he/she cannot handle. Such situations were identified in ERSC2 and ERSC3 and modification of the vehicle and roadway functions were proposed to eliminate them.

Redundancies alone will not achieve the high level of reliability that is essential for AHS. Appropriate diagnostics and control logic are essential in switching from a faulty redundant path to a healthy one without degrading performance and safety.

A vehicle shall not be considered fit to operate on AHS if any one of the redundant paths is faulty. As a result all redundant paths shall have diagnostics that monitor their functionality. The monitoring is possible if all redundant paths are activated during vehicle operation.

The vehicle functions shall be designed so that during normal operation and transitions the driver is never put in a situation he/she cannot handle. For this reason, the driver shall not have the capability of overriding automated driving functions such as the full authority longitudinal controller, the lane keeping and lateral controller. The driver, however, shall be able to request a transition to manual control. The system shall respond to this request if conditions are safe by following a check-out procedure during which the vehicle adjusts its speed and headway to comfortable for human driving levels and the driver takes over control gradually provided he/she is fit to operate the vehicle.

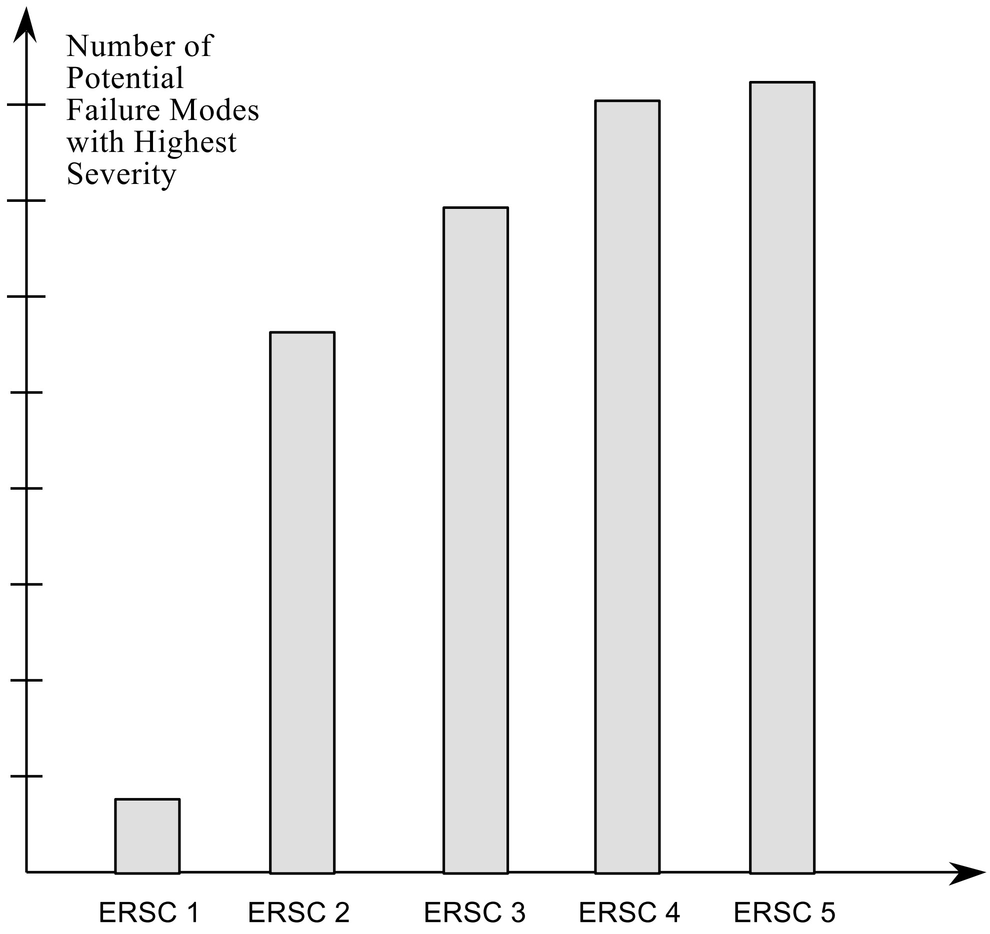

Figure 6. The number of potential failure modes with the highest severity rating generated by the FMEA

Our analysis indicates that all automated vehicle functions have to be protected from failures by using redundancies and on board diagnostics. Vehicles will not rely on the roadway to check their functionality and reliability. The redundancies and on board diagnostics will allow the monitoring of the vehicle components and subsystems even during manual driving. As a result no time consuming and elaborate on site check-in tests may be required. The driver may be notified before even reaching AHS whether his/her vehicle is fit to operate on AHS.

Table 6. Required Redundancies

Vehicle functions and/or subsystem	ERSC 1	ERSC 2	ERSC 3	ERSC 4	ERSC 5
Longitudinal measurements (speed, range, relative speed)	X	XX	XX	XX	XX
Controller Electronics and Software	X	XX	XX	XX	XX
Disability of Automated Functions	X	X	X	X	X
Calculation of Headway		XX	XX	XX	XX
Vehicle to Vehicle Communication		X	X	XX	XX
Brake Subsystem		X	X	XX	XX
Roadway Lane Reference Aids		X	XX	XX	XX
Lateral Position Sensor		X	XX	XX	XX
Steering Subsystem			XX	XX	XX
Lateral Measurements for Lane Changing			X	XX	XX
Throttle Subsystems				X	X
Vehicle to Roadway Communicatio					X

The evolution of vehicle functions from ERSC1 to ERSC5 does not imply that vehicles built for a lower ERSC can be upgraded to be used for a higher ERSC. The design and reliability requirements may differ from one ERSC to another. As a result each ERSC calls for new designs, vehicle functions, subsystems, and components.

3.7.2 Conclusions by Issues Addressed

Reliability

- The vehicle reliability requirements increase considerably as the level of vehicle automation increases from one ERSC to the next. In order to meet these requirements a considerable number of redundancies and diagnostics need to be introduced that will make the vehicle highly complex.

- A number of technical issues need to be resolved before deploying a full authority longitudinal controller, an automated lane keeping controller, or a full authority lateral controller.

- Despite the availability of various sensors for intelligent cruise control the sensor technology is still not mature to meet the functional and reliability requirements involved in the implementation of a full authority "feet off" longitudinal control.

- Using *today's affordable* sensor technology, it will be difficult to keep the vehicle in the center of the lane under *all* highway speeds, environmental and traffic conditions, and roadway configurations.

- Automated lane changing is one of the most difficult functions due to the tremendous sensor requirements involved. The sensors have to cover a wide field of view, process information fast and distinguish between threatening and non threatening situations. Emulating the human driver's senses in this case is a challenging technical problem that needs to be resolved. Vehicle to vehicle communications may be necessary in addition to all other sensor requirements in order to resolve the problem at least theoretically. The use of a large bandwidth communication system may be necessary in order to meet all the reliability requirements.

- Collision avoidance is another important function that involves serious issues and risks. In ERSC 4, 5 where vehicles change lanes automatically calculating the time to collision and distinguish between threatening and non threatening vehicles or obstacles is a difficult task. In such an environment any vehicle in the vicinity could be classified as threatening. The use of vehicle to vehicle communications may help alleviate some of the problems but it is not clear how all the reliability requirements will be met.

- Every vehicle and roadway function that affects the motion of the vehicle and/or has an impact on safety has to be designed so that it never puts the driver in a situation he/she cannot handle.

- The vehicle shall be considered unfit to operate on AHS if any one of its redundant vehicle functions or components is faulty.

Vehicle Diagnostics

- Every vehicle function that affects the motion of the vehicle has to be protected with redundancies and on board diagnostics. As a result elaborate and time consuming on site check-in tests at the entrance to AHS may not be necessary.

- Our analysis calls for a significant number of built-in tests and on-board diagnostics to monitor the functionality and health of all automated functions and of the components that affect them as well as the health and their redundant paths. Every vehicle function that affects the motion and safety of the vehicle has to be protected from failures by using redundancies and extensive diagnostics. On-board diagnostics can be used to detect failures or malfunctions fast and help to isolate them as early as possible.

- The availability of relatively low cost electronics and computers make the use of extensive diagnostics possible and desirable. The current trend in today's vehicle designs is the use of extensive diagnostics for components such as electronic fuel injection, electronic engine management, anti-lock brakes etc. This trend is expected to continue and be amplified in the development of vehicle for ERSC 1 to 5.

Driver Diagnostics

- It is unlikely that drivers would accept any diagnostic methods that require the mounting of sensors or devices on their body.

- A feasible method for assessing the fitness of the driver to perform certain driving functions during and after transition from automatic to manual mode is to have the driver perform the actual driving function in a low authority control fashion and under the supervision of the automated system.

Maintenance

- Current vehicle electronics are designed to be free of maintenance for most of the life of the vehicle e.g. 10 years or 150,000 miles. This trend is expected to continue with vehicles for AHS where the number of electronic components will be considerably higher.

Retrofitting

- The retrofit to vehicles that were produced before the vehicles for an ERSC were developed even though technically feasible is going to be expensive. It is unlikely that it will be desirable to users and automobile manufacturers.

- The evolution of vehicle functions from ERSC 1 to ERSC 5 does not imply that vehicles built for a lower ERSC can be upgraded to be used for a higher ERSC. The design and reliability requirements differ from one ERSC to another considerably. As a result each ERSC calls for new designs, vehicle functions, subsystems, and components.

Deployment Scenarios

- All the ERSCs call for an integration of the vehicle automated functions with the roadway functions in order to improve traffic flow efficiency. For such an integration to be possible, government and automobile manufacturers need to work together .

- Due to the technical issues involved in the development and deployment of fully automated vehicles, vehicle control will follow an evolutionary path. The vehicle for ERSC 1 is a natural evolution of the current vehicles and could be used in a first deployment stage of AHS. For such a deployment to be possible, government and automobile manufacturers will need to work closely with the in order to establish standards and resolve potential liability issues.

- ERSC 2 and 3 pose several design deficiencies from the point of view of reliability and need to be modified in order to become possible candidate for deployment.

- The deployment of ERSC 4 and 5 does not seem to be feasible in the near future due to the tremendous reliability requirements, the lack of mature and affordable sensor technology and the lack of clear understanding of the issues involved without the deployment of simpler AHS architecture. Even if the cost is not an issue, the deployment of ERSC 4 or 5 from the technical point of view is a very challenging problem.

3.7.3 Recommended Further Investigations

- Due to the complexity of issues involved in the development of automated vehicles and intelligent highways, the notion of evolution makes a lot of sense. Evolution, however, will require short and long term planning. Further research is required in order to understand the dynamics and market forces behind evolution of vehicle control and roadway intelligence that will lead to a first stage deployment of AHS.

- The choice of a safe headway to be used for vehicle following so that no rear-end collisions take place when the preceding vehicle brakes during emergencies depends on a lot of factors including the braking capabilities of the vehicles involved, sensor/actuator characteristics, the friction coefficient between tires and the road, the speed of the vehicles etc. The reliable on line measurement of these factors is an issue that needs to be resolved.

- The selection of the headway by the vehicle in ERSC2 to ERSC5 raises several liability issues that need to be resolved. It is assumed that the vehicle selects the headway by taking into account all relevant factors obtained through on line measurements and from vehicle to vehicle communication. A conservative choice may lead to a large headway that will affect capacity and efficiency whereas a short headway will have a negative impact on safety. If the goal of AHS is to increase capacity, the selection of the headway should not be left to the driver due to the randomness in human choices and the possibility of having considerably larger than necessary headway's.

- The use of warnings in ERSC1 to 3 together with automated driving functions raises several important human factors issues that need to be studied. For example when and how to give warnings; especially those warnings associated with lane departure and lane changing. How do warning affect the driving tasks of the driver and his/her interface with the automated functions? If two or more warnings are activated at the same time, would the driver experience confusion or panic?

- The role of the driver during fall-back modes poses several human factors issues that need to be addressed. The fall-back from ERSC 5 to ERSC 4 doesn't pose any problem to safety. The fall-back from ERSC 4 to ERSC 3 or lower requires the driver to assume the responsibility of certain driving tasks. Whether the driver can understand the different modes of operation and be able to switch from one mode to another and perform his/her duties are human factors issues that need to be studied. These studies may conclude that the only possible modes that the driver can understand and adjust fast is the manual one and one of the ERSCs used. This will imply that a malfunction in the automatic lane changing function of a vehicle in ERSC 4 say will require the vehicle to return to manual mode and the driver to drive the vehicle to the exit by going through automated lanes. Such an approach will raise several human factors and safety issues that need to be addressed.

- The roadway based navigation of vehicle in ERSC 5 requires the acquisition and processing of a tremendous amount of data. It is unlikely that the computing requirements can be met with today's computer technology especially if the computations are performed by a central computer. Furthermore, the optimization of a dynamic system such as traffic flow on the vehicle level could be an intractable theoretical problem. More research is required in order to study the feasibility of optimizing traffic flow characteristics by controlling the motion of individual vehicles.

3.8 Highlights of AHS Safety Issues

Although perfect safety has always been, and will continue to be, a primary goal of transportation technology, the fact is that no transportation system has yet achieved it. The AHS will certainly lead us closer to that goal, but, to do so, accidents and their causes must be understood and analyzed with scientific rigor. The purpose of this effort is to identify and discuss the major technical, design, and implementation issues and risks of providing AHS operators with a collision-free driving environment under normal operating conditions including entry to and exit from the system.

3.8.1 Key Findings

The full safety benefits will not be achieved until the full implementation and market penetration of AHS technology is achieved. The AHS should not be described as providing significant safety benefits, although it may provide significance benefits in congestion and pollution reduction and increased user comfort, until the system has matured. However, the interstate highway system today accounts for only 5 percent of the total accidents, and 10 percent of fatal accidents, which occur in the United States. Even with complete elimination of accidents on the interstate system, a worthy goal, many accidents will still remain. While AHS technology (i.e., SHMS) should provide a benefit on non-AHS roads, this benefit needs to be studied.

The largest percentage of accidents on the interstate system are rear-end collisions. Longitudinal control technology (SHMS) promise the biggest benefit in reducing these types of accidents and should be the leading candidate of initial AHS technology introduction.

Driver reaction time in complex situations are slow. The driver probably cannot be depended upon, especially in the latter ERSCs with hands-off, feet-off, operation, to serve as emergency backup.

The location on the AHS entry where transition from manual driving to automatic occurs can have a large impact on safe operation. The majority of accidents which occur on entry/exit situations are rear-end collisions in which the driver's view is not obstructed. A possible explanation is that the driver's workload is heavy in this situation. The driver is looking for a place to merge into the traffic stream, is adjusting vehicle speed to move into the slot, and must also maintain awareness of the vehicle in front. Studies have shown that a driver tuning a radio can result in an average time of eyes off the road of 15 seconds. The transition process must either not increase the driver's workload or must occur in a region of the entry way so as to not impact safe operation.

The GES database includes data for both entry and exit in the same variable. It is recommended that the database be changed to include separate variables for entrance and exit ramps. Additionally, information to determine where on the ramp accidents occurred (first third, second third) would be helpful in determining where transition should occur.

Safe following distances between vehicles must account for differences in vehicle capabilities such as braking. In addition, the forward viewing distance of the lead vehicle and reaction time can effect vehicle spacing. It is unlikely that users would find low delta velocity collisions acceptable.

The vehicles forward looking field of view must be matched to the roadway radius of curvature that it will encounter.

Entry/exit areas are a critical area for system design. These areas provide the critical interface into and out of the vehicle stream. In this area all of the functions which the AHS must be capable of performing occur. Transition from manual to automated control, merge and diverge, sensing of surrounding vehicles, and lane changing must occur.

Continuous entry/exit poses severe safety concerns and can drive system design requirements. Additionally, since barriers are not possible in this configuration, it is not possible to keep the errant, manual only vehicle driver out of the automated lanes.

3.8.2 Conclusions By Issues Addressed

The characteristics of normal operation were determined by first using the process of functional flow block diagrams. The most critical area for safe normal operation of the AHS is in the areas of entry and exit. During these top level functions all of the functions which must occur during normal operation must take place. The safety issue involved with entry is to allow the merging vehicle to enter the lane without causing an accident. When a vehicle merges onto an automated lane, either from a dedicated entry way, from a transition lane, or directly from a manual lane, several functions must take place once the vehicle has passed the check-in procedures. The vehicle or driver must remain aware of any vehicles which are forward of it, it must sense the vehicles which are in the adjacent lane in which it wishes to merge, there must be a space in the adjacent lane which can accommodate the merging vehicle, and the vehicle must adjust its velocity to permit safe maneuvers into this space. All of these actions are affected by the relative velocities between vehicles, the level of traffic density, the time required to conduct the actions, and the driver involvement in the early ERSCs. Once the vehicle is on the system the other function which must take place (lane keeping, speed headway maintenance, etc.) have already been exercised during the entry function.

The characteristics of potential AHS accidents were determined in a heuristic manner by analyzing the GES data to learn what kinds of accidents occur most frequently on today's interstate situations. The second approach was to understand the physics of accidents in both these situations. Rear end collisions comprise the largest percentage of accident types on today's interstate system. A method for determining the benefits to be achieved by the introduction of AHS technology was developed. Figure 7 presents how the results of this methodology can be presented to assist decision makers in making AHS deployment decisions. This figure is more for illustrative purposes only since it is based on very top level analysis without the benefit of any detailed computer simulations. A recommendation is that further work be conducted in this area.

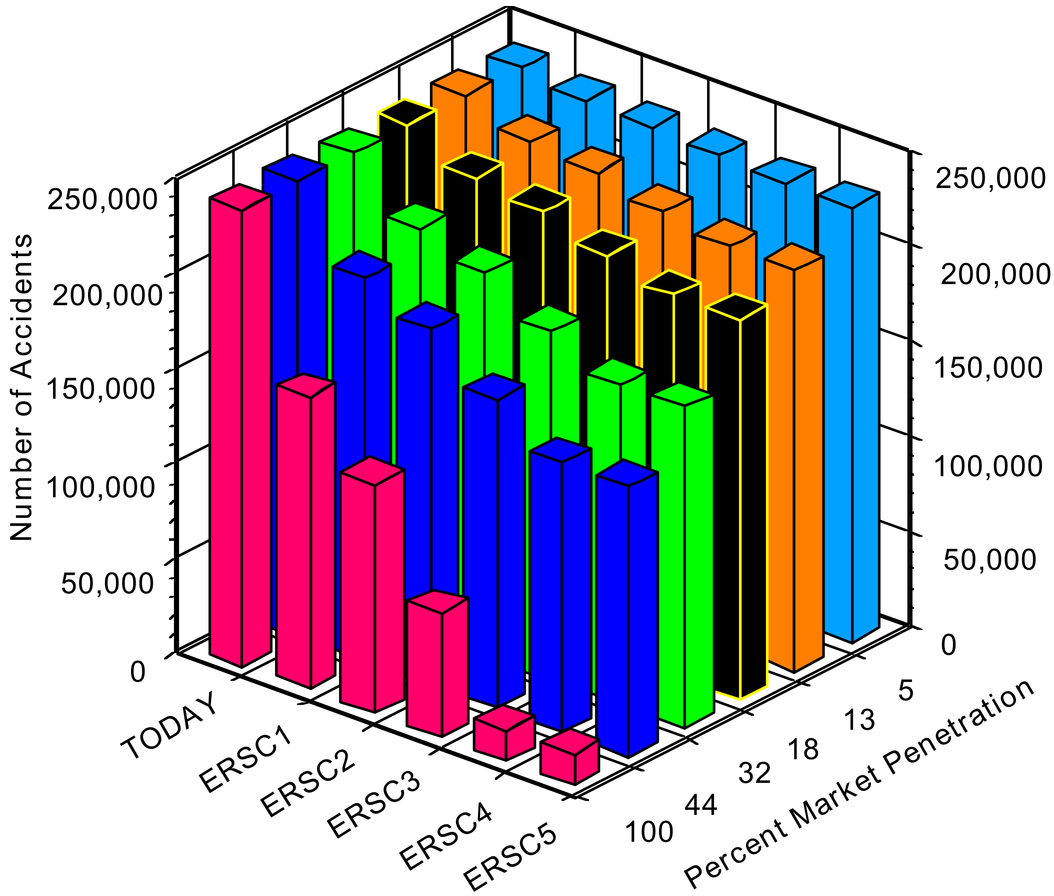

Figure 7. Postulated safety benefits of AHS technology on the interstate system,non-junction, non-intersection

As shown in figure 7 the trends show that the full safety benefits will not be achieved until the full implementation and market penetration of AHS technology is achieved.

The impact on design issues is that the system must not only be safe, it must appear safe. It is very unlikely that users would find low delta velocity collisions to be acceptable. Safe following distances between vehicles must account for differences in vehicle capabilities such as breaking. In addition, the forward viewing distance of the lead vehicle and the reaction time can effect vehicle spacing. The largest driver on vehicle sensor design requirements is posed during entry/exit situations when differences in vehicle speeds could be great. These differences can be exasperated by the continuous entry/exit implementation. Key interrelationships between design variables were also discussed.

The impact on implementation issues is that continuous entry/exit implementation poses serious safety issues. Transition between driving modes could increase the driver's workload during critical periods of the entry/exit process. The length of time of this transition and the associated driver actions could influence where in the entry/ exit process transition must occur thereby impacting the civil engineering of these structures.

3.8.3 Recommended Further Investigations

The largest area of uncertainty is in the area of human factors and how the driver will react to transition from manual driving to automatic and back. The amount of time to accomplish these activities, the impact on the driver workload, and the speeds at which they can take place will impact many areas of system design such as entry/exit construction and vehicle sensor requirements. Studies should also be conducted to determine the possibility of off-system accident incident potential in corridors near the system as drivers exit the system. Will those AHS drivers maintain headway habits off the system with non-AHS vehicles in the traffic stream?

The lack of computer simulations of AHS technology, traffic command and control algorithms, and AHS configurations prevent in-depth tradeoffs from being conducted.

The safety benefits that AHS technology will provide off the AHS on non-AHS roads should be analyzed.

3.9 Highlights of Knowledge Based Systems And Learning Methods to Help AHS

The following sections address the key findings and conclusions of the uses of knowledge based systems and learning methods in the AHS.

3.9.1 Key Findings

The key findings of this activity area are:

- We should incorporate the management of malfunctions, both onboard and in other vehicles into *normal* operations as much as possible.

- We should design each AHS vehicle to have effective predetermined responses to a large number of traffic situations, but

- We should also design each AHS vehicle to be able to respond effectively to new situations.

The last finding places a significant burden on AHS. The traditional engineering approach has the human engineer performing all of the analysis and design work. The result is a machine or piece of software that meets the original requirements but which does not include explicitly any of the knowledge that went into the design. In other words, the product typically cannot modify itself to handle situations unforeseen by the engineer. But this is precisely what we are recommending. We should give to each vehicle that capability to *design* a response to a new situation as well as to *execute* that response. For this type of capability, we must turn to AI technologies.

We note that our effort has focused primarily on the latter phases of AHS. In the context of our group's ERSCs, we have focused on ERSCs 4 and 5, where there is full automation of vehicles. There is a role for AI technologies earlier in the evolutionary process. However, given that this task had limited resources, we focused on these larger issues. Furthermore, of the four areas that we have identified where AI can be helpful, we have focused on the first and second. Namely, we have examined how to control an individual AHS vehicle at a high level in a variety of traffic situations, with a particular emphasis on situations where there are malfunctions either onboard the vehicle or in nearby vehicles.

One might ask: Why is controlling the high level actions of a vehicle so complicated?

- It is an expert behavior, as exemplified by the fact that there is wide variability in the way that people drive, and that there are recognized expert drivers.

- The available data about the environment is inaccurate and incomplete. For example, if the car to your left is beginning to swerve into your lane, you cannot tell if it is due to wind, due to a momentary lapse by the driver, or due to an intentional lane change (albeit a dangerous one). Thus your interpretation of a given situation relies upon predictions of the behaviors of others. Sometimes these are merely educated guesses because there are not only the laws of physics at play here, but the intentions of the other "driver," be they human or machine.

- We must handle our own malfunctions. Should we immediately stop, move to a breakdown lane, or "limp home"? Which is safe? Which is most effective for the overall traffic flow?

- We must respond to malfunctions in nearby vehicles. The car to our left is swerving towards us. What should we do?

- Many different situations may arise and many combinations of situations may arise.

We are thus left with the question: How can a system respond effectively to a large number of situations? One way is with a structure similar to a decision tree. The tree is designed by engineers off-line and the vehicle uses the tree to determine responses on-line. But is this possible? Is the space of situations small enough or regular enough so that complete coverage can be gotten? We think not. Also, will the decision tree work if the vehicle's information is incomplete? Will it get "stuck" in the tree, or might it be unable to disambiguate among possibilities?

The AI technologies that attend to this type of situation are expert systems, knowledge based planning, and learning methods. The latter two enable the system to respond to new situations. Planning methods handle these situations on-line. Learning methods typically discover these new situations and the best responses off-line using a simulated environment.

3.9.2 Conclusions by Issues Addressed

Our primary conclusions are that AI technologies, particularly knowledge based systems and learning methods, can make strong contributions to AHS, especially in the following four areas:

- *Management of malfunctions onboard the vehicle:* While onboard malfunction detection is probably left to more conventional technologies, determining the best response to malfunctions may need the power and flexibility that AI technologies can bring to bear.

- *Management of each automated vehicle in traffic* (i.e., controlling its high level movements such as stay in lane, change lanes, exit, speedup, etc.): In order to deal with the inherent complexity of AHS, a powerful and flexible high level control system is needed. AI technologies can help meet this need.

- *Overall traffic management:* For efficient and effective use of automated highways, AI scheduling and planning methods can be extremely beneficial.

- *Sensor interpretation and fusion:* In particular, there is vast potential for machine vision to collect valuable data about the environment. Moreover, the problem of fusing data from several sources into a coherent picture of the environment may be helped by AI technologies.

In any eventual AHS, there will be widely varying capabilities among the possibly millions of AHS vehicles because there will be a mixture of new and old models, plus there will be widely varying levels of maintenance. Also, with that many vehicles, there will be numerous malfunctions. Hopefully, these will mostly be minor, but some will be major. Moreover, the world is complex and unexpected things can happen, such as a moose entering the highway, or a refrigerator falling off a truck.

The conclusion that we draw from the above intuitive argument is that, even with full automation, the AHS environment will not be highly structured. By that, we mean that it will not be easily predicted nor subject to analysis. Moreover, if we allow for AHS environments that allow mixed populations of "drivers" -- i.e., mixing human drivers with automated vehicles -- then the structure of AHS and the predictability of any given situation drops enormously. As a result, in order to manage an automated vehicle in an AHS, the vehicle must be able to deal effectively with an enormous number of possible traffic situations. The number of situations is enormous because we include situations involving minor and major malfunctions, plus unexpected events (e.g., moose on the highway).

3.9.3 Recommended Further Investigations

The following is recommended:

- Each AHS vehicle have the capability to plan its own maneuvers and execute them.

- Further investigate the following areas, particularly with regard to AHS applications: KB planning (to handle new situations), learning methods (to handle new situations and to improve responses to already known situations), and expert systems (for overall high level control).

By incorporating the ability to plan new maneuvers, we gain new flexibility but we do not lose the ability to use preprogrammed responses to certain known situations. The vehicle should be designed so that if the current situation is familiar and the vehicle knows how to respond, then it should perform the preprogrammed response. However, if a new situation is encountered, or if the vehicle determines that the preprogrammed response is unsafe, then the vehicle should plan its own response if there is time. If there is not enough time, it should perform a backup emergency maneuver.

In our investigation of Knowledge Based Controller (KBCon), the prototype KB high level controller we developed, we found that on-line planning was not as time consuming as we feared because the search space was deliberately kept small. However, we worked with a small prototype. With full planning capability, it is not clear whether or not a real time response is possible. Also, the current research in planning is not up to the challenge presented by AHS. In KBCon, we took many shortcuts in the planner. Considerably more research in planning for AHS-like environments, both basic and applied, is needed. For the other parts of KBCon, such as the classification methods used to predict the motion of nearby vehicles, we found that a simple knowledge representation scheme plus a rule based system was adequate for the task. By scaling up to realistic AHS size, we not do expect to encounter fundamental problems, except those of validation and verification, which are difficult to attain in any AI system. Also, while we cannot be certain given our limited study, it is likely that this portion of the system can be made to respond in real time.

We recommend that reinforcement learning (RL), in conjunction with an AHS simulator, be used as a tool to help design controllers. We do not recommend that an RL module be a component in an actual AHS system. Since an AHS system will be operating at velocities and time intervals unfamiliar to human drivers, we should not rely solely on human experience when designing an AHS vehicle controller. We believe RL can be used to help design controllers, or to improve existing controllers by adjusting parameters such as headway. As part of our study, we implemented an RL module and ran it in the simulated Tufts Automated Highway System Kit (TAHSK) environment. Our RL module uses a three-layer feedforward artificial neural network to evaluate traffic situations. This network operates quickly enough to be useful for this research; however, we recommend exploring the possibility of replacing it with a Cerbellar Model Articulation Controller (CMAC) network, which may exhibit better generalization abilities in this domain.

4.0 OVERALL CROSS-CUTTING CONCLUSIONS/OBSERVATIONS

The deployment of the AHS is likely to take place in stages following an evolutionary path. Each stage of the deployment should provide an obvious benefits to the users. These benefits could be in the areas of increased safety, reduced congestion, increased travel time reliability, increased user comfort, and reduced environmental impact.

Each area will not achieve the same incremental benefit with the introduction of the various ERSCs. For example, the largest increase in safety benefits is not achieved until ERSC4, with hands-off, feet-off operation and automated lane changing, reaches full market penetration and AHS deployment along the entire interstate system. However, large benefits in reduced congestion and environmental impact may be possible with the introduction of low level partial automation in ERSCs 1 to 3. Reduce land impact may not be achieved until the introduction of automated lane keeping in ERSC 3 which could possibly permit the narrowing of lanes.

Figure 7 presents a method of portraying possible safety benefits with the introduction of various levels of technology and market penetration. This figure represents preliminary results and is explained in detail in Volume 9. This method could also be used for quantifying the other benefits (congestion, travel time, environmental impact) and for conducting comparisons. The lack of an appropriate computer model of the potential AHS configurations prevents this from being accomplished. It is strongly recommended that development of such a model be an early high priority of the National AHS Consortium.

The evolutionary approach raises questions concerning the best method for achieving deployment of the required technologies. Retrofitting of vehicles is an expensive proposition and is unlikely to be accepted by the users. Automotive manufactures would have to consider retrofit in the design of the vehicles. A complete redesign of basic vehicle functions may be necessary going from one ERSC to a higher one. The required level of reliability of the automated vehicle functions call for considerable number of redundancies and on board diagnostics. This number increases considerably with the level of automation as discussed in Volume 8.

Dependent on implementation schedule and roadway infrastructure (not sensors or AHS related needs, just available roadway capacity) the loss of a lane on most facilities will have a dramatic impact on the speed profiles in the adjacent non-AHS lanes, especially during peak periods of operation. During ERSC 1 and possibly the early phases of ERSC 2, this is expected to be apparent when the number of vehicles eligible to enter the AHS lanes is minimal compared to the number of vehicles in the general traffic stream.

The functions of entry and exit create the most stressing requirements on the AHS and have the most cross-cutting impact on the most activity areas. This is because the entry/exit is the critical interface into and out of the vehicle stream .While the safety analysis of General Estimates System (GES) accident data shows that entry/exit accidents account for only seven percent of the accidents which occur on the interstate system, and one could therefore reasonably conclude that most of the effort of AHS should be devoted to solving the problems along the rest of the roadway, if the design issues of entry and exit can be solved most of the rest of the AHS design will be answered. This is because check in/out, transition from manual to automatic and back, maintenance of time headway while vehicles are accelerating/decelerating, lane change, and all of the other functions of the AHS occur within the check in/out regions.

The check in process can have a major impact on entry design if not properly conducted. The approach which shows the most promise is to make use of on-board diagnostic and knowledge based systems to conduct continuous monitoring of the vehicle even when the vehicle is operating in manual mode. This is practical for sensor testing, since crucial sensor tests can be performed via consistency checks on the redundant paths and on-board tests of control actuators and electronics is also practical provided the systems are designed for testability. This requires certain non-standard design modifications for the brake, throttle, and steering systems that allow on-board, built-in diagnostic testing of automatic control electronics and actuators during manual operation. Provided that such testable control system designs are adopted, no on-site test are expected to be needed. On-board built-in diagnostic testing of the lane keeping sensor can be accomplished in the manual lanes only if portions of the manual lanes are modified to include lane keeping reference aids. This is easily accomplished on the entry ramps and at designated entry points. In continuous entry AHS configurations, the lane keeping aids might be fitted every few miles along portions of the manual lanes.

The major benefit to be achieved by conducting check in on the move is the elimination of the need for queues for vehicles waiting to conduct the check in process and the associated expense of providing storage space and time delay to the driver.

During the check in process, the transition from manual to automated longitudinal and lateral control (in the latter ERSCs) of the vehicle occurs. As shown in Volume 9 the majority of entry/exit collisions are rear end while the driver's vision is not obstructed and the driver is not distracted. It is postulated that the major cause of these accidents is due to the lead vehicle stopping or slowing down due to a lack of opening in the vehicle stream, while the following vehicle, whose driver is looking over their shoulder or in the rear/side view mirror to find their own opening, does not notice the lead vehicle decelerating and a collision results. It is therefore important that the transition from manual to automatic occur prior to where these type accidents occur.

An important parameter for ensuring that the transition from manual to automatic can occur is that the lead vehicles on the ramp are within the field of view of the following vehicle's longitudinal sensor in order to permit detection in enough time to prevent collisions. This is dependent on the variables of sensor field of view, entry ramp radius of curvature, the relative speeds between the lead and following vehicles, and the braking capabilities of the two vehicles. A larger sensor field of view permits a smaller ramp radius of curvature while a narrower field of view requires a larger ramp radius of curvature. This could impact entry implementation of the AHS and whether entry ramps must be rebuilt thereby incurring additional expense and time for AHS deployment.

Another factor which effects entry into the AHS, especially in the later ERSCs, is the capability of the lateral collision avoidance sensor to detect approaching vehicles in the adjacent lane into which the entering vehicle desires to merge. The entrance ramp must be designed to allow the lateral sensor line of sight upstream of the adjacent travel lane to permit detection of vehicles in the travel lane approaching the ramp/lane merge. The distance that the sensor must be able to see upstream of the merge area is dependent upon the relative speeds of the merging vehicle on the ramp and the vehicles in the travel lane. Large differences in relative speed require longer detection ranges. These large differences in speed are more likely to occur in continuous entry situations and less likely with dedicated ramps. For example, non AHS vehicles slowing due to grades may not permit an AHS-bound vehicle to accelerate to gain access. This is discussed in detail in Volume 9.

Once the vehicle has entered the vehicle stream the functions which occur during travel (lane change, speed headway maintenance) are the same as the actions for entering.

When the vehicle arrives at its destination the vehicle must exit the travel lanes, transition to manual control, and check out of the system. The vehicle should create a large enough gap before transferring control of the vehicle so that the driver resumes control in a driving situation that is compatible with the relative slowness and imprecision of human response. The requirement to create this gap and for the associated slowdowns to leave the AHS lane in the continuous entry/exit configuration may cause a ripple effect in the in the automated lane and it's impacts would be further magnified with vehicles desiring to enter the AHS lane. In addition the impact of road grade is an issue.

The most appropriate diagnostics to be used for driver readiness testing during transition are those that directly monitor and assess driver's performance while they appear natural and reasonable to the driver. It is possible to design a system that allows a limited driving authority while under the supervision of automated functions. This authority gradually increases to a full one provided the driver's performance is acceptable thereby creating a safe, effective, and smooth transition. This area requires much more in-depth human factors study especially to determine the length of time for the transition to safely occur. This length of time will effect exit ramp design considerations.

Malfunction management strategies will vary with the degree of automation provided in the various ERSCs. The first three ERSCs are partially automated systems where the driver is still required to perform some functions during normal operation. Designing and selecting the best malfunction management strategies for these ERSCs require evaluating the driver' ability to detect and respond to malfunctions. Relying on the driver to sense a malfunction or to evaluate a situation and determine the best management response leaves the system vulnerable to human error. It seems, however, that the system can be responsible for the primary detection of malfunctions for any new automated features (longitudinal and lateral control) and many of the traditional features not currently monitored. This can be accomplished using built-in diagnostics and knowledge based systems. Almost every new component being developed is being designed to monitor its own functionality and report any deviations. This technology is providing cost effective and reliable means of detecting component failure which can be applied to the equipment in both the vehicle and the roadway. This reduces the driver's responsibility of detecting malfunctions to more of a secondary, backup role.

Selecting the best response, given a malfunction and successfully executing that response, presents more of a challenge in a partially automated system. The most obvious difficulty lies in the fact that the capabilities of driver's vary greatly. This must be considered when weighing alternate responses to a malfunction. Another potentially more unpredictable variable in determining the correct response is the different perceptions of a situation which might arise in different individuals. The correct malfunction management response for a malfunction is situationally dependent and therefore requires a determination of the external environment after the malfunction has occurred. Even if the driver's capabilities are roughly the same, and they therefore see the same external environment, one may perceive the environment to be safe enough for a particular response and the other may not. A person may therefore avoid choosing this response even if the situation dictated its choice. If the response is to leave the automated lane, then the vehicle may remain in the lane for a longer period than it should and adversely affect system efficiency and safety. If the driver perceives the environment safe enough to exit, and it is not, then an even more dangerous situation arises. When educating the driver to choose the correct response, given this sort of a situation, these factors must be considered. The system designer has to determine if the transient effects of having drivers attempt a particular response after a malfunction outweigh the benefits to the system given the response's successful implementation.

The narrowing of lanes from 3.6 m (12 ft) to 2.4 m (8 ft) provides an attractive solution to reducing environmental impact in terms of land usage. This is because three 2.4 m (8 ft) lanes can be placed in the same space as two 3.6 m (12 ft) lanes. Today's commercial intermodal transportation system relies heavily on standard size shipping containers for the movement of goods between ships, rail, and trucks. These containers are either bulk cargo containers, which are placed on flat bed semi-trailers at the appropriate trans-shipment location, or cargo van semi-trailers which are towed by tractor-trucks. All of these containers are approximately 2.4m (8 ft) wide and bulge laterally when fully loaded. Either the width of these containers would have to be reduced, thereby having a major impact on the entire shipping industry, or the AHS lane width requirements would have to be larger than 2.4 m (8 ft), thereby negating the original intent. Finally, lateral vehicle guidance must provide for some deviation along the vehicle path. Tests have been successfully conducted using a standard video camera as a sensor for both following standard road markings as well as for precise distance measurements to the preceding vehicle. The lateral vehicle guidance along pavement markings using these video cameras has successful been adapted to heavy trucks with a lateral deviation of less than 100 mm (4 in) at a maximum speed of 90 km/h (48.5 mi/h) as reported in Volume 6. Accounting for lateral deviations on either side of the center line (assuming the 100 mm (4 in) is the 3 sigma value) and allowing for 100 mm (4 in) for container bulge a lane would have to be at least 2.75 m (9 ft) wide.