Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

AHS Safety Issues

U.S. Department of Transportation
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FOREWORD

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

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

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

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

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Director, Office of Safety and Traffic Operations Research and Development

NOTICE

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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
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
CLT	crossing left turn
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	functioal 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
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act
ITE	Institute of Transportation Engineers
IVHS	Intelligent Vehicle Highway System
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
TCS	traction control system
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 EXECUTIVE SUMMARY FOR ACTIVITY AREA

An objective of Automated Highway System (AHS) is a system that will be accident-free in the absence of malfunctions. The requirement that the final AHS concept operate without collisions in the absence of malfunctions ensures that safety will increase compared to today's highways. Since most accidents are due to driver error, the AHS becomes safer with the arrival of each Evolutionary Representative System Configuration (ERSC) as driver responsibilities are transferred to more reliable automated systems.

Roadway travel has become increasingly safe with traffic related fatalities in 1992 the lowest in 30 years. The interstate highway system accounted for approximately 290,000 accidents in 1992. The system had the lowest fatal accident rate of all highway classes in 1991 according to the Fatal Accident Reporting System (FARS). However, this still constituted 11 percent of all fatal crashes, or approximately 4000 fatal crashes on the interstate system. Other controlled access highways, such as freeways and expressways, accounted for an additional 1600 fatal accidents.

Most of the reduction in highway fatalities have been due to improvments in and introduction of increased technology such as seat belts and shoulder restraints, air bags, and improved vehicle crashworthiness.[(1)] Still accident prevention is currently the only way to prevent 50 percent of all traffic fatalities.[(2)] These are the types of accidents to be mitigated by an Automated Highway System.

The approach used in the study was to proceed in a series of steps. The first step was empirical and was used to identify the top level functions that would take place in an AHS. These functions were entry into the AHS, travel on the AHS, and exit from the AHS.

The next step was heuristic, studying the General Estimates System (GES) data to learn what kinds of accidents occur most frequently on today's interstate. The majority of accidents on the interstate system involving more than one vehicle are comprised of rear end collisions. Driver workload associated with entry/exit maneuvers and high volume/capacity ratios on mainline sections of the interstate system in urban areas are the primary causes.

The third step was analytical and assessed the impacts on the system design depending upon the implementation approach. Within the framework of the ERSCs, system design requirements must be evaluated with safety in mind. It was concluded that continuous entry/exit implementation poses the most severe safety implications for the AHS. Safe following distances must account for differences in braking capability and speed between vehicles. Parametric tradeoffs of key system interrelationships, such as between the forward looking sensors field of view and radius of curvature of entrance ramps, are presented.

The final step showed how a deductive approach could be used as a method to quantify safety benefits achievable by the AHS. With each ERSC come added features that potentially increase the safety of the system. A method is shown how this benefit can be quantified by analyzing accident data and determining what types of accidents will be mitigated by the introduction of new technologies. From this analysis, the type and number of accidents reduced can be determined for each ERSC and a qualitative and quantitative measure of overall system safety can be made.

It was concluded that large safety benefits will not be achieved until full implementation and market penetration of AHS technology. Early primary benefits come from intervehicle equipment versus expensive infrastructure modifications. Longitudinal control technology (collision warning/avoidance) provides the largest initial payoff. New safety issues particular to AHS are identified. For example, will a driver who has become accustomed to traveling on the AHS with shorter time headways maintain this behavior when they are off the system under manual control?

2.0 INTRODUCTION FOR ACTIVITY AREA

This section of the report provides a description of the activity, the purpose of this effort, a listing of the issues addressed, an overview of the overall approach, and a summary of the guiding assumptions.

2.1 Description Of Activity Area

The AHS Safety Issues activity was to use relevant results from existing and ongoing Federal Highway Administration (FHWA) and National Highway Traffic Safety Administration (NHTSA) studies and other sources to identify, consolidate, and discuss the AHS safety issues to be resolved, and risks to be addressed to provide AHS users with a collision-free driving environment under normal operating conditions including entry to and exit from the system.

2.2 Purpose Of This Effort-Specific Focus

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.

2.3 Issues Addressed

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.

2.4 Overall Approach For This Activity Area

Safety is the foremost consideration in the design of an AHS. While developing the system configurations, it was necessary to analyze how safety would influence various aspects of the design requirements. Figure 1 illustrates the safety analysis methodology which was applied.

The first step (Block A of figure 1) is to conduct a functional decomposition of the AHS. This activity identifies essential functions the system must perform to handle each vehicle, and shows their logical sequences and time relationships. At the top level (appropriate at this stage of concept development), system operation may be decomposed into three functions: 1) Entry Onto AHS, 2) Travel on AHS, and 3) Exit From AHS. As a result of this process characteristics of normal operation are identified.

Step B identifies hazardous situations which may arise within each system function, and attempts to trace them to their underlying causes. Step G, an analysis of the General Estimates System (GES) databases, is conducted in support of (B) to determine historically the frequency of accidents in given situations. Section 4.1 provides a fuller description of the GES database analysis. This process addresses the issue of characteristics of potential AHS accidents.

Step C attempts to eliminate or reduce the potential for hazardous situations through the system design. Design standards such as those from American Association of State Highway and Transportation Officials (AASHTO) and Institute of Transportation Engineers (ITE) are used as guidance. Step C is intended to influence the direction of ongoing subsystem studies (Block H), to determine whether the safety issues can be technically and cost effectively resolved within the design. The results of this step provide requirements on safe system design.

All safety issues addressed are communicated with the Malfunction Management Strategy assessment task (Block F). The philosophy is that for every hazardous situation which the system is designed to alleviate, there must be a malfunction management strategy in case the system fails to perform. For example, if speed and headway maintenance is designed into the system, a malfunction management strategy must be developed in the event that it fails. To safely implement the AHS in some situations it may be necessary to incorporate redundancy into the system design for safety critical items instead of relying on the driver to implement malfunction strategies. This process addresses the impact on implementation issues.

Step D identifies any remaining system hazards unresolved by the system design. These are hazards which will be addressed by the later ERSCs.

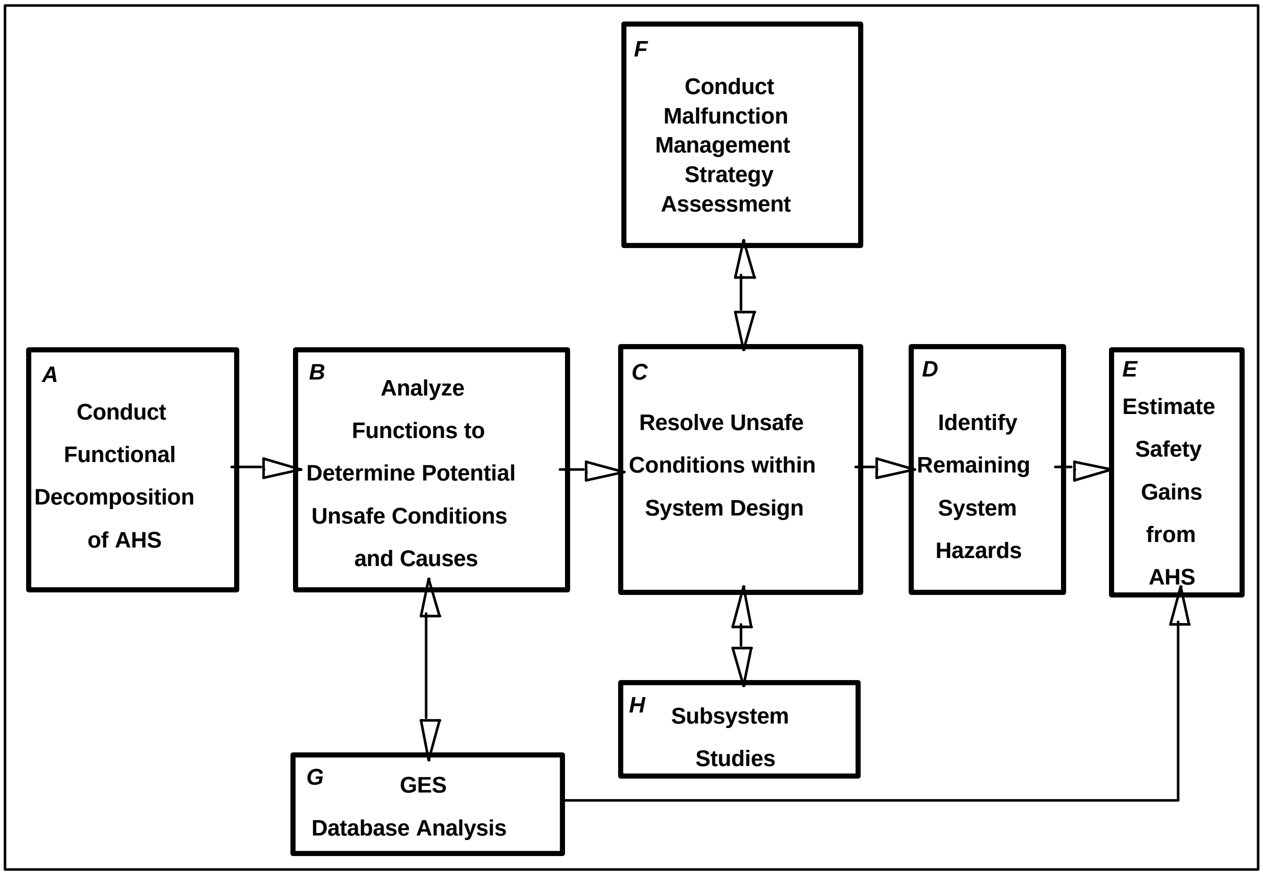

Figure 1. Safety issue study methodology

Finally, Step E estimates safety gains provided by the ERSC under consideration. Estimates are made by considering the types of technologies introduced in each ERSC, the types of accidents these technologies are anticipated to prevent, and the damage and injury associated with these accidents. From these an attempt is made to project similar accident types into the hypothetical environments associated with the ERSCs.

This review was of collision characteristics associated with vehicle operations in the early 1990's and that as past enhancements in vehicle technologies have led to accident reductions then future enhancements to vehicles without AHS could also be expected to improve conditions, especially Adaptive Cruise Control and lane keeping functions. With the implementation of Intelligent Transportation Systems (ITS) other than AHS to the roadway system, some reduction in accident experience could be realized through a reduction in vehicle delay and congestion levels. This infrastructure improvement may be short-lived however, as traffic growth increases, capacity gains associated with ITS may begin to disappear.

2.5 Guiding Assumptions - Origins and Rationale

The key guiding assumption was that the AHS is to be collision free in the absence of malfunctions as specified by the Broad Agency Announcement (BAA) for the Precursor Systems Analyses (PSA) of AHS.[3] Additionally, for users of the system to be at ease, the system must not only **be** safe, it must **appear** safe. Conversely, the appearance of safety must always mean that, intrinsically, the system actually is safe.

Other assumptions were:

- Operation in a freeway type of roadway was assumed.
- The AHS will operate in a wide range of weather conditions.
- Only instrumented vehicles will be allowed to operate on instrumented roadways
- Initial deployment emphasis is expected to be on automobiles and commercial vehicles with vehicle dynamics and operating characteristics similar as those found on vehicles today. Pallets of vehicles or vehicles powered by electric rail were not considered.

3.0 EVOLUTIONARY REPRESENTATIVE SYSTEMS CONFIGURATIONS (ERSC)

Initial analysis concluded that the PSA could best contribute to the AHS effort by focusing its investigation on determining the degree to which an evolutionary approach could best meet the AHS 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, 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 first three ERSCs are envisioned to be single automated lanes, while ERSCs four and five would have multiple lanes. Figure 2 provides an overview of the key characteristics of each ERSC. This approach is explained in detail in Volume One of this report.

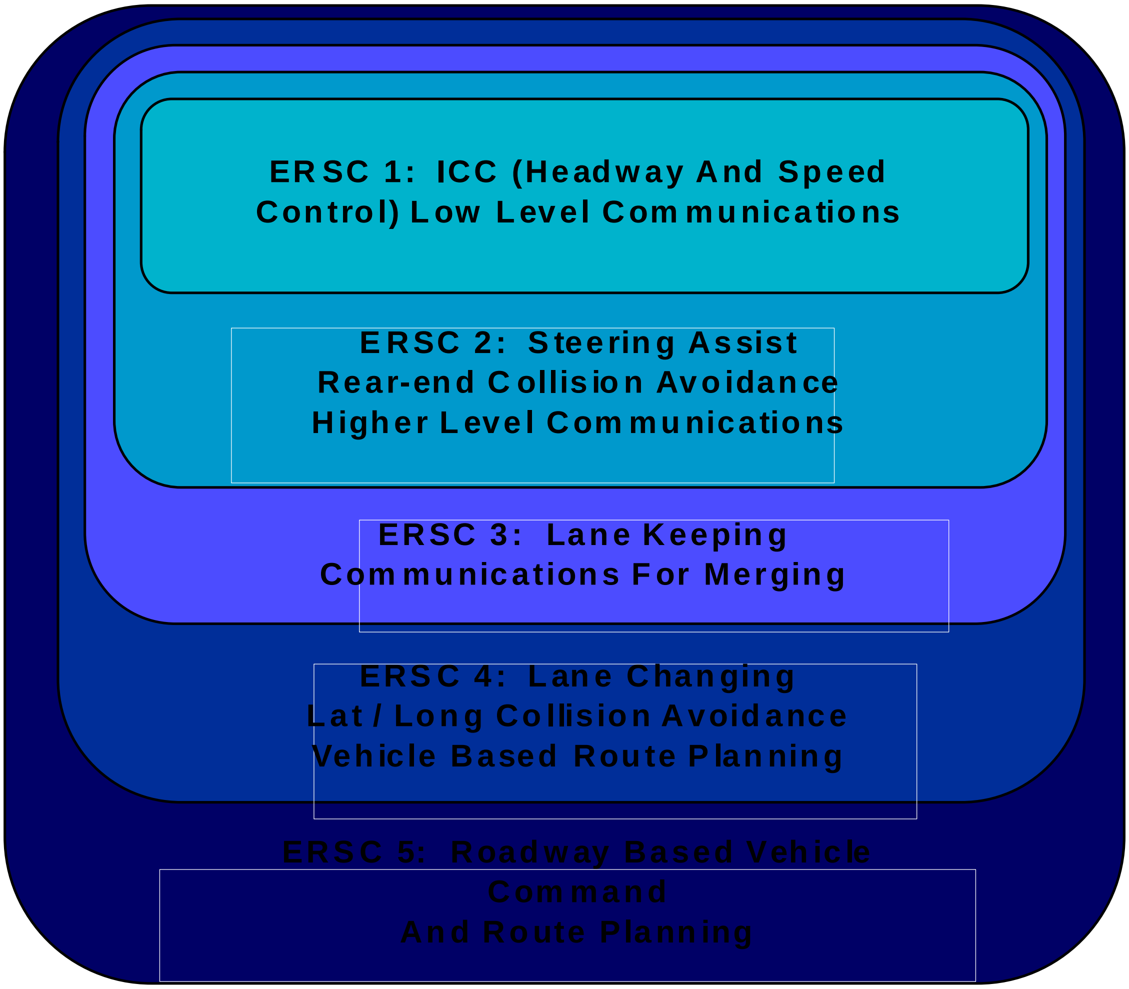

Figure 2. Evolutionary Representative System Configurations

4.0 TECHNICAL DISCUSSIONS OF EACH STEP

The safety issues associated with the top level functions of Entry onto the AHS (Section 4.1), Traveling on the AHS (Section 4.2), and Exit from the AHS (Section 4.3) will be addressed. The safety analysis for each of these functions is conducted using two complementary approaches. The first approach is heuristic, studying the GES data to learn what kinds of accidents occur most frequently in today's roadway situations. The second approach is more analytical, working out the physics of accidents both in these situations and in AHS scenarios. The goal of this two-pronged approach is to uncover critical safety issues which influence AHS design.

It should be noted that this review was of collision characteristics associated with vehicle operations in the early 1990's and that as past enhancements in vehicle technologies have led to accident reductions then future enhancements to vehicles without AHS should also be expected to improve conditions, especially Intelligent Cruise Control (ICC) and lane keeping functions.

Also, with implementation of Intelligent Transportation System (ITS) elements other than AHS to the roadway system, some reduction in accident experience could be realized through a reduction in vehicle delay and congestion levels. This infrastructure improvement may be short-lived however as traffic growth increases the capacity gains associated with ITS may begin to disappate.

4.0.1 General Estimates System (GES) Database Analysis

The General Estimates System (GES), administered by NHTSA, collects accident data from a nationally representative probability sample selected from all police-reported crashes. By restricting attention to police-reported crashes on traffic ways resulting in property damage, injury, or death, the GES concentrates on those crashes of greatest concern to the highway safety community and the general public.

The system has created a data file for each year since it began operation in 1988, consisting of approximately 90 data elements categorizing accident conditions and results.[4] Each file contains data on a sample size of about 45,000 accidents which occurred in that year. From these samples, statistics can be extracted which are indicative of overall trends on crash causes and their severity.

Analysis of the GES data provided a means for quantifying the level of safety of each ERSC. The data was examined using R:BASE, a PC based database manager loaded with data files from 1992. Proper interpretation of the data required an understanding of the definitions of the data elements; important definitions have been provided throughout the discussion. Furthermore, the analysis required careful selection of only that data applicable within the context of the AHS environment. Misuse of the data can lead to erroneous conclusions.

Since AHS implementation is envisioned for highways (as the name suggests), accident data on "Interstate Only" is more directly applicable than that for "All Roadways". A comparison of the distribution of first harmful event for accidents on all roadways against accidents on interstates only reveals some interesting differences, as shown in figure 3.

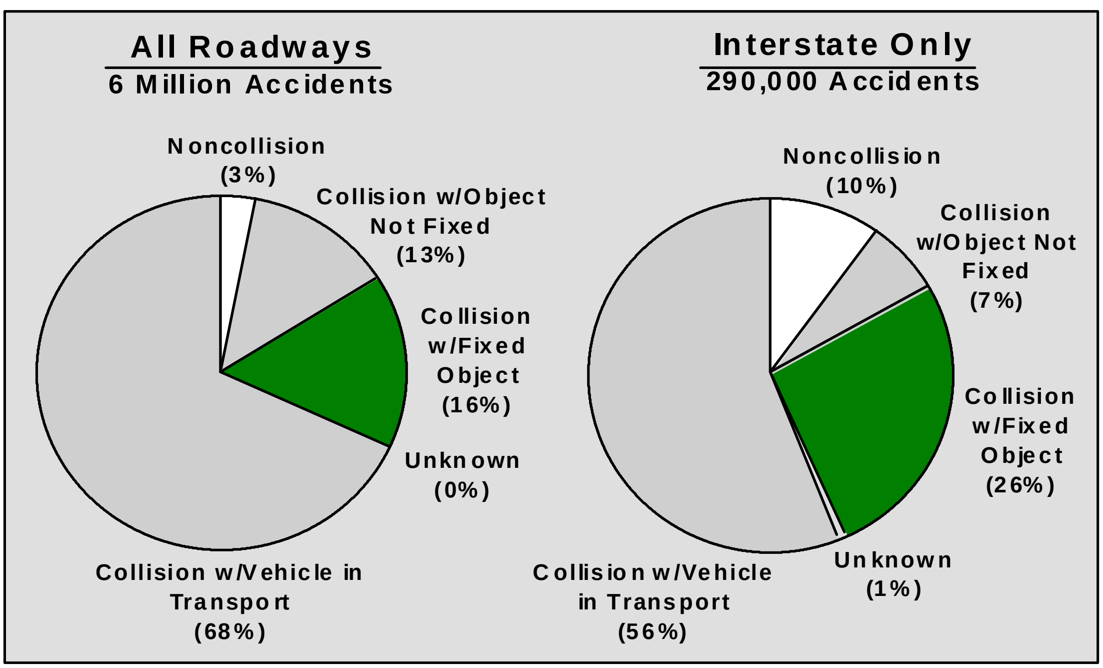

Figure 3. First harmful event, on interstates vs all roadways

The first harmful event is defined as the "first" property damage or injury-producing event that can be determined to have happened in the accident. The data shown for 1992 indicates that Interstates have a higher frequency of collisions with fixed objects (such as structures, poles, barriers, trees) and non-collision accidents (including rollovers, fire/explosion, falls from a vehicle, and injuries in a vehicle) than on all roadways. When attempting to quantify numbers of accidents reduced by AHS technologies, only interstate travel will be considered. This may be considered conservative, since technology in AHS vehicles (e.g., warning sensors) will remedy some of the accidents on all roadways . Calculations will use as a baseline figure 290,000 total accidents on interstates in 1992. The percentages shown for interstates (derived from the GES sample size) will be applied.

4.0.2 Safety Analysis of Top Level Functions

Figure 4 shows the breakdown of accident occurrence location for interstate crashes, based on 1992 GES data. The majority of accidents (81 percent) occurred along stretches of highway, where a vehicle spends most of its travel time. In the relatively uncontrolled environment of today's highways, this is not surprising.

In contrast, once a vehicle safely enters AHS control, it should experience relatively few hazards during travel (in the absence of malfunctions). Section 4.2 examines crash causes on "non-junction, non-interchange", and analyzes the requirements on AHS components designed to mitigate these causes with each ERSC. First, however, the function of Entry onto AHS will be analyzed.

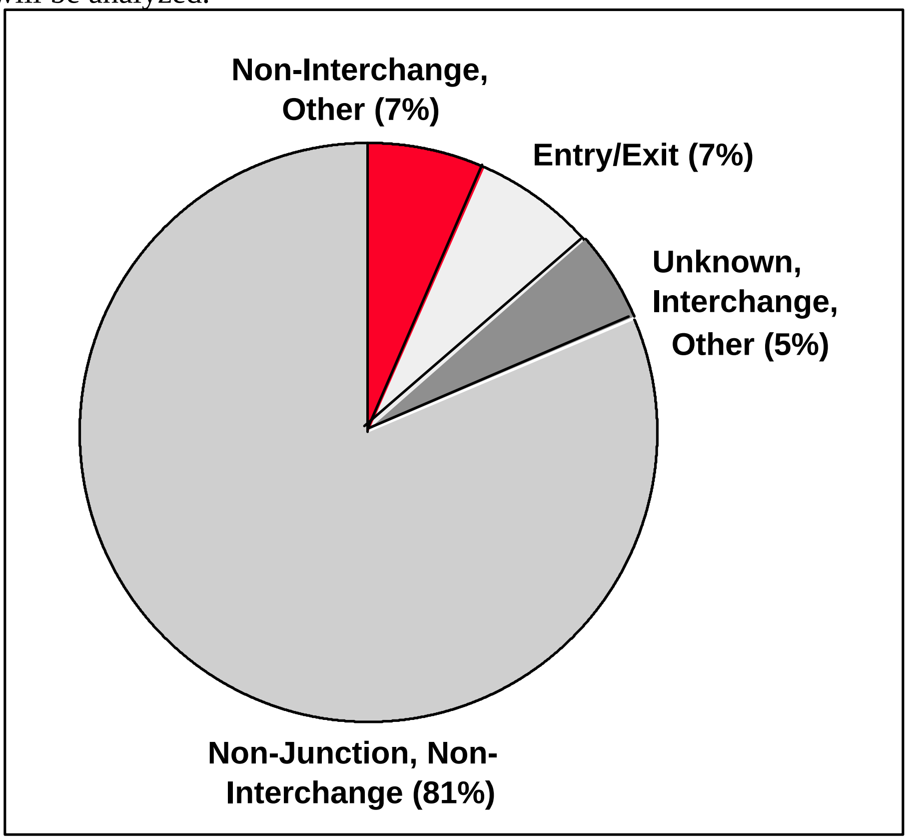

Figure 4. Accident occurrence location for interstate crashes

4.1 Entry Onto AHS

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 within each lane, the time required to conduct the actions, and the driver involvement in the early ERSCs.

4.1.1 GES Accident Data Analysis - Entry

The 1992 GES data in figure 4 showed that 7 percent of interstate accidents occurred on entry/exits. This is a relatively small percentage primarily because vehicles spend only a small fraction of their trip time entering or exiting, however, all of the complex actions that a vehicle will encounter on the AHS occur within these regions. Many challenging safety issues present themselves during this function. Indeed, entering the traffic stream is the first hazardous situation the AHS equipped vehicle faces.

Figure 5 shows the distribution of First Harmful Event for interstate entry/exit accidents, based on 1992 GES data. Note that the GES database does not distinguish between entry and exit road sections. The data indicates that about two-thirds of entry/exit accidents are collisions with vehicles in transport. Another 22 percent are collisions with fixed objects (generally guardrails, barriers). Further investigation of these accidents tells more about how they might be prevented with AHS.

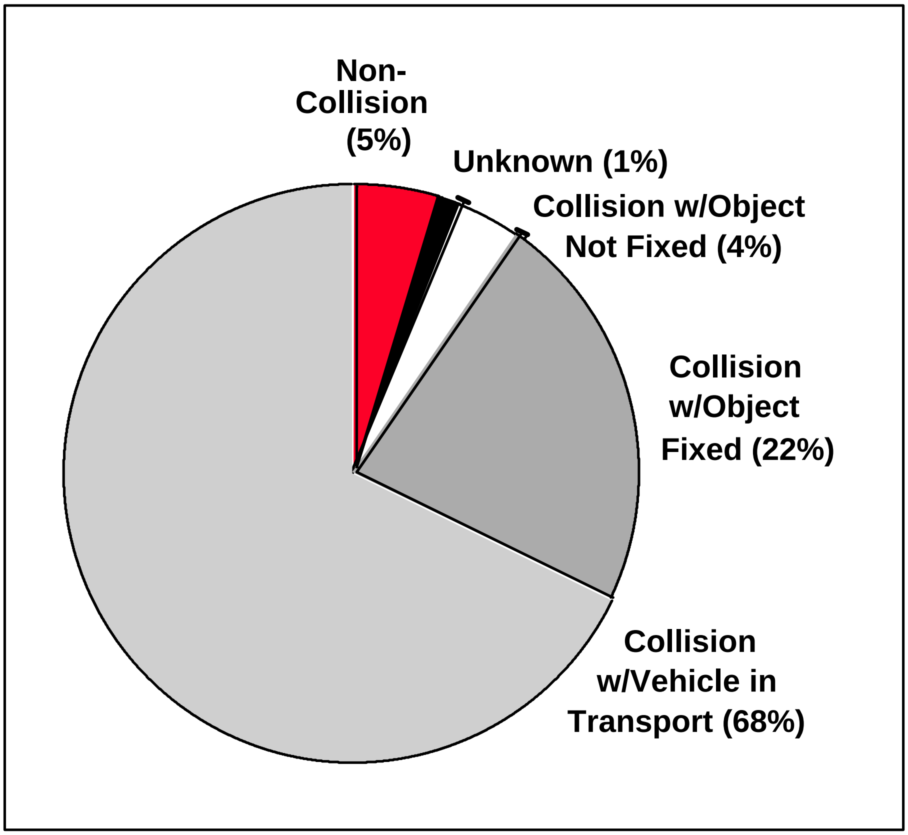

Figure 5. First harmful event, interstate, entry/exit crashes

Figure 6 gives the breakdown of the Manner of Collision for two-vehicle collisions. The vast majority (73 percent) are rear-end collisions, the remaining collisions are mostly categorized as either angle(11 percent) or sideswipe (15 percent).

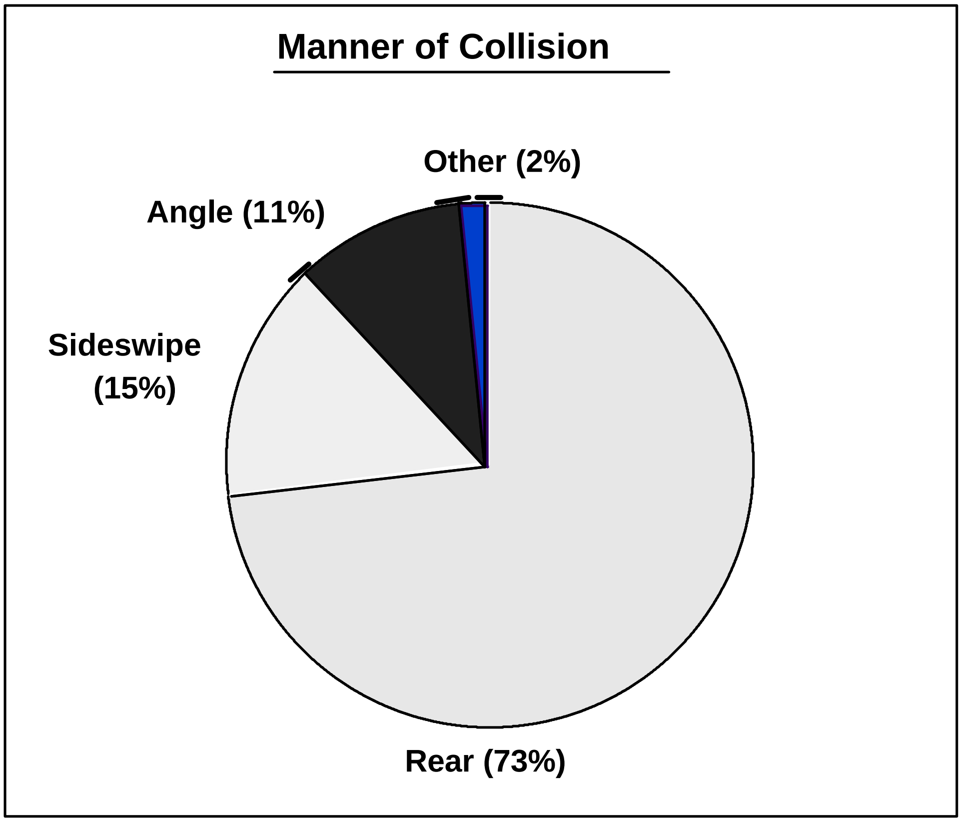

Figure 6. Manner of collision, interstate, entry/exit, collision with vehicle in transport

Causes for each of these types of vehicle-to-vehicle collisions may be postulated as shown in Table 1.

Table 1. Postulated causes Of entry/exit collisions

Rear End	*On Entry:* Vehicle in front stops or slows because of lack of opening and following vehicle collides with lead vehicle. *On Exit:* Queue forms on exit ramp which backs traffic up the ramp and exiting vehicles cannot stop in time and collide.
Angle	*On Entry:* Merging vehicle misjudges ability to merge into travel lane. *On Exit:* Exiting vehicle tries to exit from far lane and strikes vehicle in lane close to exit .
Sideswipe	*On Entry and Exit:* Multiple lanes merging on entrance or exit ramp result in collision.

Geometric and/or other physical conditions may also have a causal effect increasing the chance of driver error. These could include limited acceleration lanes, close interchange spacing, and multiple and rapid decision points required of motorists. These geometric conditions are numerous in urban areas where construction of the facilities was completed through the late 1960's.

Details of the GES database generally support the intuition behind the postulated causes in table 1. For example, the Critical Event which made Rear-End Crashes Imminent was, as expected, most often listed as "in another vehicle's lane traveling in the same direction at a higher speed" (81 percent). For Angle and Sideswipe collisions, it was usually " encroaching" (89 percent and 94 percent, respectively). It can also be noted that in almost all of these entry/exit crashes, the driver was not reported to be distracted and driver vision was not obstructed.

This part of the analysis considers which AHS features will mitigate which types of accidents during entry. The three major types of vehicle-to-vehicle collisions indicated by the GES data, (rear-end, angle, and sideswipe), as well as collisions with fixed objects will now be addressed.

Rear-end collisions on entrance ramps, if caused in the manner postulated above, could be alleviated through better driver awareness. The driver's ability to keep an eye on the vehicle just ahead is complicated by having to monitor traffic in the adjacent lane in order to find a sufficient gap in which to merge. The problem is basically not being able to look in two places at once. Sample results from NHTSA's driver workload assessment show that on average a driver looking in the left mirror to detect an object has their eyes off the road an average time of 1.85 seconds.[(1)] If the driver is glancing in the left mirror to discriminate objects then the average time off the road increases to 2.79 seconds. A vehicle traveling at 72 km/h (45 mi/h) on the entry ramp preparing to merge would travel 46 m (150 ft) in 2.79 seconds.

Theoretically, additional sensors should increase driver awareness to prevent rear-end accidents on entrance ramps. The speed and headway maintenance system (SHMS) and rear-end collision warning (RECW), both introduced in ERSC1, are based on forward looking sensors and low level communication (braking information) with the vehicle ahead. If these systems are designed to function on entrance ramps, they will be able to warn the driver looking over his shoulder to slow down for slower or stopped vehicles ahead.

In ERSC2, the rear end collision avoidance (RECA) feature would automatically stop the vehicle to prevent a rear end collision. Assuming this feature is engaged on an entrance ramp, it should eliminate rear end collision during entry altogether (in the absence of malfunctions). Issues associated with the functionality of these features will be discussed in section 4.2.2.

Angle and Sideswipe collisions, as they occur while merging on entry, are not directly addressed until ERSC3. ERSC1 and ERSC2 include an optional blind spot sensor, but it would not be designed to look for fast-approaching vehicles from behind in adjacent lanes. The blind spot sensor would probably result in only a minor accident reduction during entry; preventing some sideswipes at the last moment before merging, when the entering vehicle has achieved approximately the same speed as unseen car in the adjacent lane. ERSC3 introduces a lateral collision warning sensor designed to sense these fast approaching vehicles, in conjunction with communication for merging. These features of ERSC3 help the driver mitigate these types of collisions during entry.

Collisions with fixed objects, which the data shows are generally guardrails and barriers, could only be partially mitigated on entrance ramps until ERSC4. Speed maintenance, beginning in ERSC1, could be engaged on portions of some ramps; however, as long as the driver is responsible for merging, his speed and lateral control are potentials for error.

ERSC4 brings lateral collision avoidance, and automatic lane changing and merging. By ERSC4 the driver is out of the loop; the entrance function is fully automated In ERSC5, the roadway can even smooth the merge operation by controlling traffic flow upstream to create gaps for entering merging vehicles.

4.1.2 Safety Issue Influences on System Design - Entry

For the manual operator to safely change lanes from the manual lane of a highway to an automated lane, knowledge of the traffic on the automated lane must be known for a certain distance in front and behind. Additionally awareness of the vehicles in front in the manual lane must be maintained. These distances depend primarily on the difference in traveling speeds of the two lanes. The driver must be able to sense the traffic, either through vehicle or roadway sensors, communication, or vision.

The parametric tradeoffs which are conducted in this section and in section 4.2.2 make the simplifying assumptions of constant acceleration rates for vehicles. The intent of this report was not to conduct the detailed design of the AHS but to identify the interrelationships between the key parameters of the system components and to provide a top level assessment of those concepts which may be credible and those which have pitfalls. In-depth modeling and detailed design tradeoffs must be conducted before any AHS is implemented.

Figure 7 illustrates the situation created in the enter AHS function in the continuous entry and exit without a transition lane. The manual lane has a speed limit of 22 m/s (50 mi/h) and the automated lane has a commanded speed of 31 m/s (70 mi/h) in the situation shown.

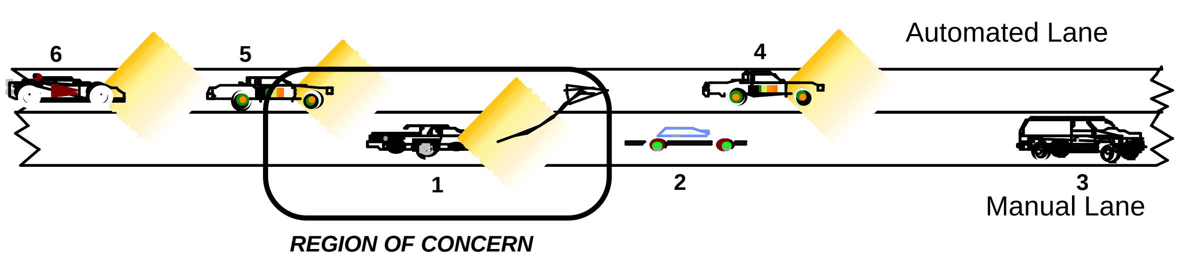

Figure 7. Continuous entry onto AHS situation

In figure 7, vehicle 1 is an AHS-capable vehicle which is traveling in the manual lane and desires to enter the automated lane. The first concern of vehicle 1 is to maintain awareness of the vehicles in front of it in order to avoid longitudinal collisions. If vehicle 3 is 3 km in front of vehicle 1 and both vehicles are traveling at the same speed, then vehicle 1 certainly does not need to maintain awareness (track) on vehicle 3. However, a closer vehicle, as in the case of vehicle 2, may require constant track. Several factors determine a vehicle's forward region of concern.

If the velocity of vehicle 2 is greater than the maximum velocity that vehicle 1 attains while conducting the merge into the automated lane and this remains true throughout the merge procedure, then vehicle 1 does not need to be concerned with vehicle 2 since the distance between vehicles is increasing.

If the speed of the vehicles in the manual lane is the same as the speed of the vehicles in the AHS lane, then vehicle 1 just needs to find an opening in the automated lane and merge in.

The primary factor for determining whether a vehicle is in the forward region of concern is the minimum safe distance based on braking capability. This is a function of reaction times, differences in braking capability between the two vehicles, and time headway and is addressed in section 4.2.2.

If the speed of the automated lane is greater than the speed of the manual lane, then the merging vehicle (vehicle 1 in figure 7) must accelerate to the AHS speed either before or after conducting the maneuver into the AHS or utilizing a combination of each.

The case where vehicle 1 accelerates to the automated lane commanded speed while still in the manual lane and then conducts the maneuver into the automated lane would reduce transients imposed on the automated lane and their associated safety impacts. However, there are several factors which affect the safe operation of the manual lane. These factors are the distance between the vehicle desiring to merge (vehicle 1) and the vehicles in front of it (vehicle 2), the acceleration rate of vehicle 1, difference in vehicle speeds, downstream travel conditions affecting the operation of vehicle 2, and the time for vehicle 1 to conduct the merge.

Figure 8 presents how these factors interact. The abscissa shows differences in vehicle velocity when the lead vehicle (2) is slower than the merging vehicle (1) at the time when vehicle 1 starts to accelerate. In cases where both vehicles are traveling at the same speed, the difference is of course zero. The ordinate shows the required distance between vehicles as a function of constant acceleration rates of 1 m/s^2 (0.1 g) and 2.5 m/s^2 (0.25 g) and acceleration periods of 1 and 10 seconds. The minimum acceleration rate of 1 m/s^2 is attainable by vehicles today, and the acceleration rate of 2.5 m/s^2 is the upper limit of acceleration for passenger comfort. One second was selected as a minimum acceleration period and time in which to move out of the manual lane and 10 seconds as the maximum.

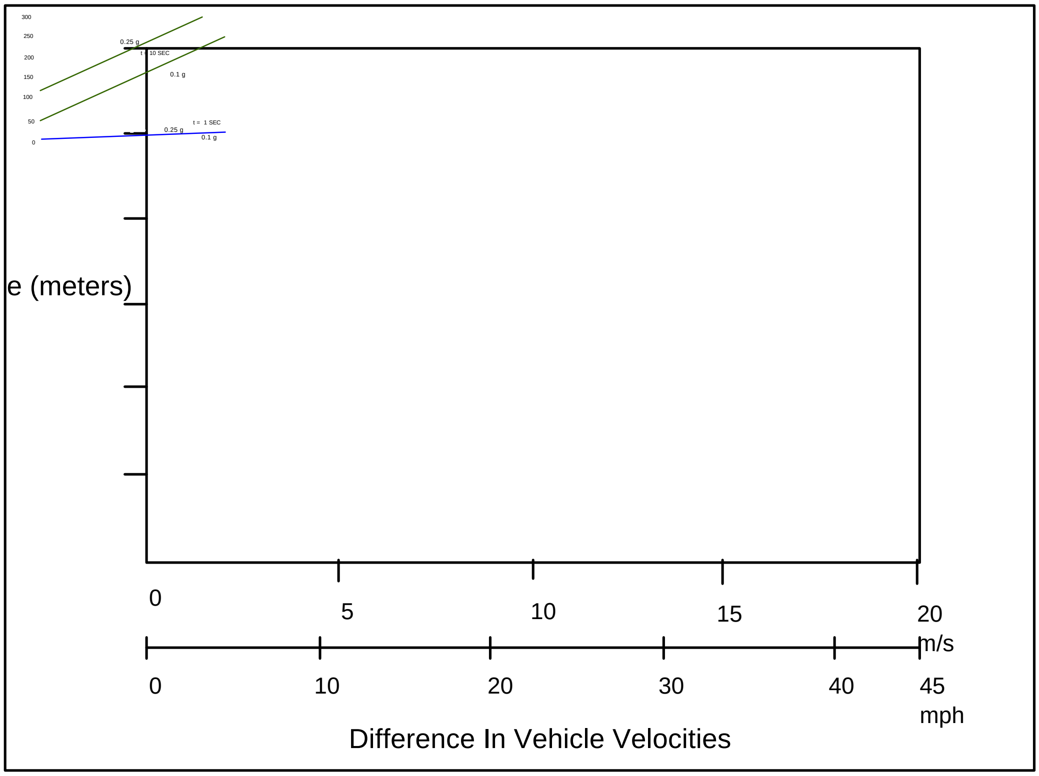

Figure 8. Distances required between vehicles

Studies have shown that drivers operate vehicles over a wide range of speeds when conditions permit. Figure 9 gives the distribution of representative passenger car speeds on rural interstate highways.[(5)] In the 1987 study, under normal driving conditions, 10 percent of vehicles adopted speeds under 80 km/h (50 mi/h), while another 10 percent adopted speeds over 113 km/h (70 mi/h). Roughly 5 percent went under 72 km/h (45 mi/h), while another 5 percent went over 121 km/h (75 mi/h). These examples illustrate that large differences in velocity regularly occur, and the AHS design must account for them.

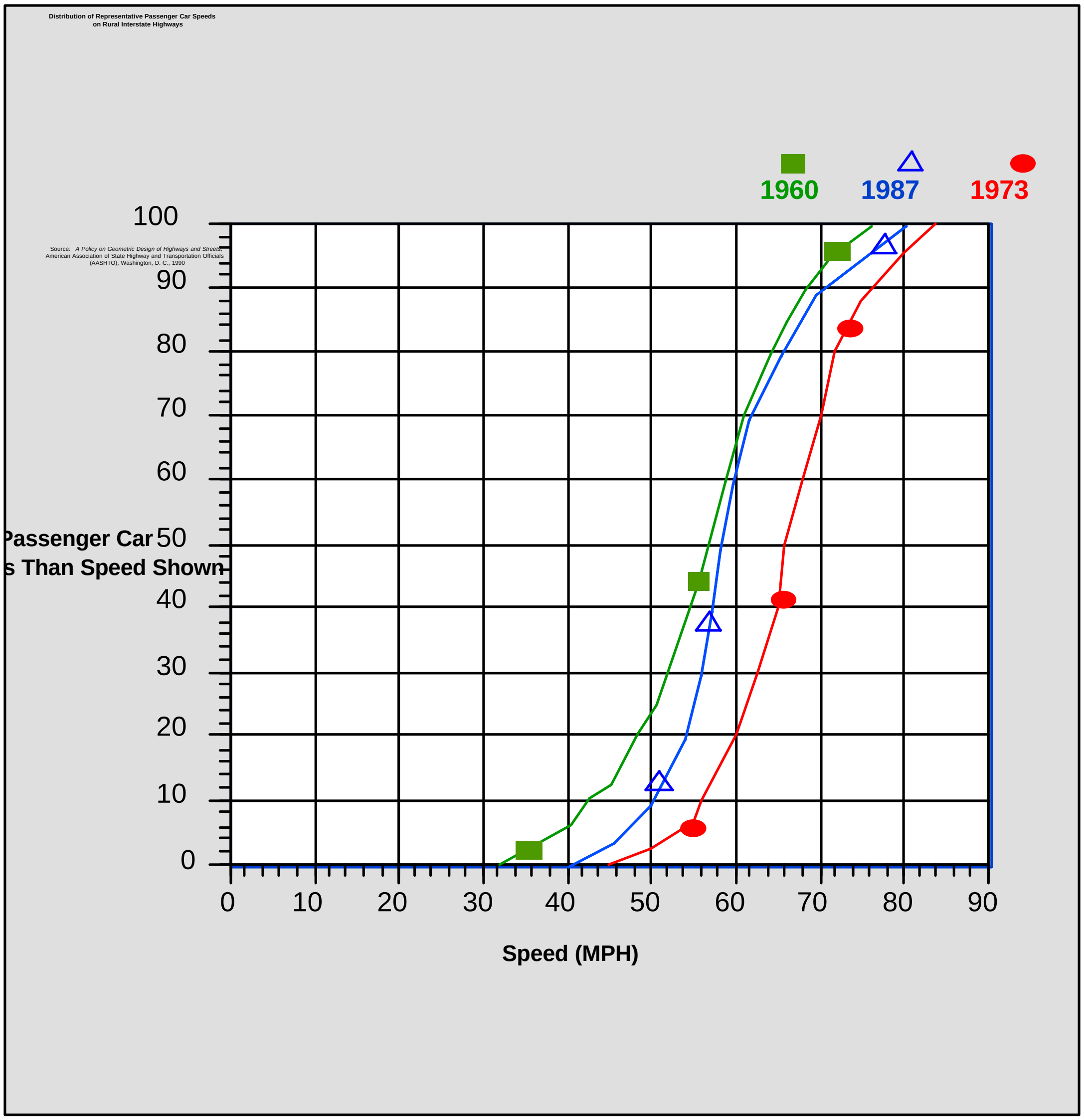

Figure 9. Distribution of vehicle speeds

Figure 10 shows the time it takes for a vehicle to accelerate from an initial velocity, shown along the abscissa, to a final velocity of either 25 m/s (55 mi/h) or 31 m/s (70 mi/h) at a constant acceleration of 1 m/s^2 (0.1 g) or 2.5 m/s^2 (0.25 g). For example, a vehicle traveling at 22 m/s (50 mi/h) at a constant acceleration of 1 m/s^2 (0.1 g) would reach 32 m/s (70 mi/h) in 10 seconds.

Typical situations can be constructed using figures 8, 9, and 10 to show the spacing required for safe merging. For example, if both vehicles 1 and 2 were traveling at speeds of 22 m/s (50 mi/h), then the difference in vehicle velocities is zero. If vehicle 1 accelerates at a constant rate of 1 m/s^2 (0.1 g) for 10 seconds from 22 m/s (50 mi/h), then the resulting speed is 32 m/s (70 mi/h), as previously explained. The resulting required distance of 49 meters between vehicles 1 and 2 is determined by reading up the ordinate of figure 8. If vehicle 2 was closer than this distance, then vehicle 1 would collide with vehicle 2 before reaching 32 m/s (70 mi/h).

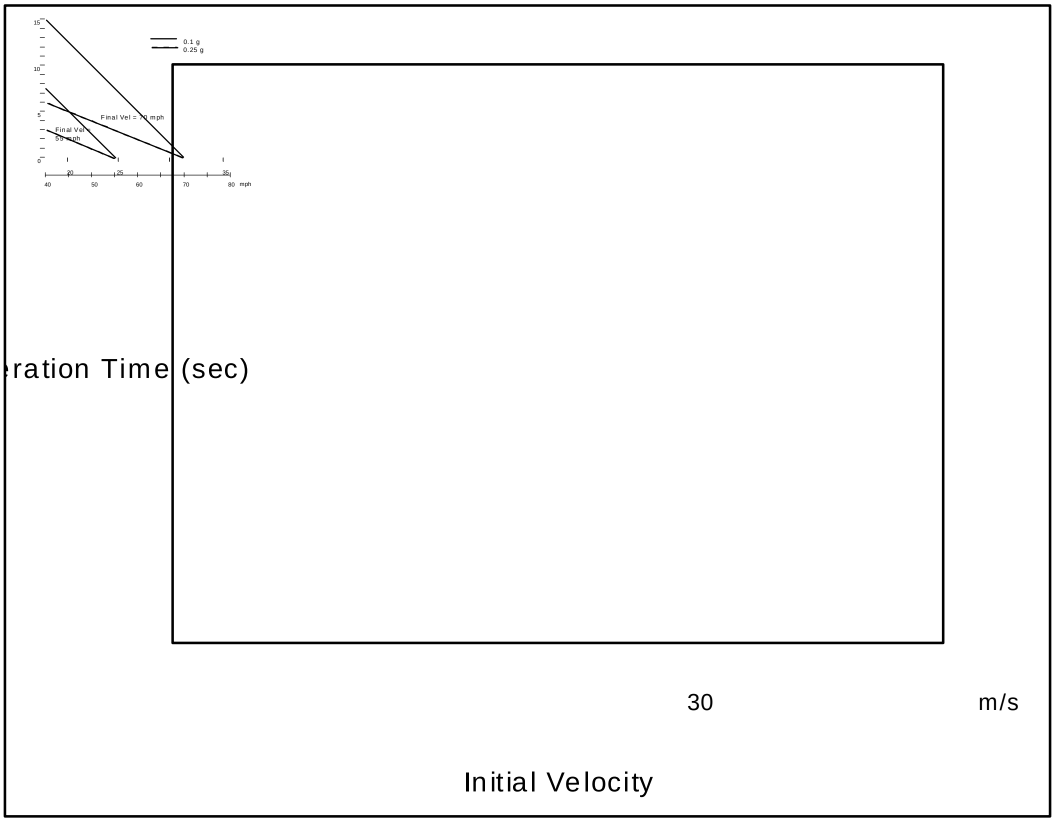

Figure 10. Acceleration time required

In manual lanes, there is a good possibility that manual only equipped vehicles could be going slower than vehicle 1 or the speed limit. This could be especially true in those situations in which the automated lane is adjacent to two lane single direction facilities which could be typical of rural areas. In these cases a full mix of vehicles (cars and trucks) in all manual lanes is permitted. Trucks in the left lane attempting to pass another truck on an upgrade may be going much slower than the speed limit. For example, in figure 7 vehicle 2 could be traveling at 15.6 m/s (35 mi/h) instead of at 22 m/s (50 mi/h). If vehicle 1 was coming up on vehicle 2, and vehicle 1 was traveling at 22 m/s (50 mi/h), then the difference in vehicle velocities is 6.4 m/s (15 mi/h). If vehicle 1 increased its speed up to 31 m/s (70 mi/h) in order to merge into the AHS, then according to figure 8 there would have to be 116 meters between vehicles 1 and 2 for 1 m/s^2 (0.1 g) accelerations and 190 meters for 2.5 m/s^2 (0.25 g) accelerations. These distances require that no other vehicle come between vehicles 1 and 2 during the acceleration period; otherwise vehicle 1 cannot reach the required velocity. If vehicle 1 came closer to vehicle 2 than the minimum distance, then vehicle 1 would need to decelerate to a speed of less than vehicle 2; in this case less than 15.6 m/s (35 mi/h) in order to increase the distance between itself and vehicle 2. In heavy traffic situations it is unlikely (based on personal observation) that distances as great as 150 meters will remain open with vehicles under manual control maneuvering through such traffic.

The other option is for vehicle 1 to merge into the AHS lane and then accelerate to the commanded velocity. In this instance, vehicle 1 must now be concerned with the vehicles which are behind it in the automated lane. These would be vehicles 5 and 6 in figure 7. In light density traffic situations, this may be acceptable. If vehicle 6 is 4 km behind vehicle 1, then intuitively vehicle 1 does not need to be concerned about vehicle 6. In heavier traffic situations, several concerns arise. First, vehicle 1 must find an opening in the traffic which is large enough to merge into. In high traffic density or platoon situations, this could create a queuing problem with a long service time. In the early ERSCs, the driver is still in the loop and driver impatience could create unsafe situations. In latter ERSCs, the system must be capable of conducting check-in on the move and then taking control of the vehicle directly from the manual lane and then accelerating it. However, in latter ERSCs the roadway infrastructure could command vehicle openings. This would have to be accomplished by slowing vehicle speeds in the AHS lane in order to create the openings. This could result in a transient in the automated lane, creating safety issues and reducing optimum AHS efficiency if not properly conducted.

If we assume that the vehicles traveling on the AHS should not have to slow down to allow another vehicle to merge, then the merging vehicle must know that no oncoming vehicles are within a certain distance. This distance will depend on the speed at which the vehicles on the AHS are traveling, and on the current speed and acceleration capability of the merging vehicle. The distance at which vehicle positions must be known will influence system design requirements such as ramp curvature and size, merging lane distance, sensor requirements, etc.

Figure 11 presents the results of the analysis to determine the required separation between merging and rear approaching vehicles as a function of the difference in their velocities. The shaded area is the region between an assumed minimum acceleration rate of 1 m/s^2 (0.1g), which is attainable by vehicles today, and an assumed acceleration rate of 2.5 m/s^2 (0.25g), which is the upper limit of comfort in vehicles. If vehicle 1 is going 31 m/s (70 mi/h) when it merges into automated lane shown in figure 7, and if vehicle 5 is going the commanded speed of 31 m/s (70 mi/h), the theoretically minimum separation between the vehicles is required. However, to ensure safe operation, this distance should be increased to the normal platoon spacing or the minimum safe distance for this speed.

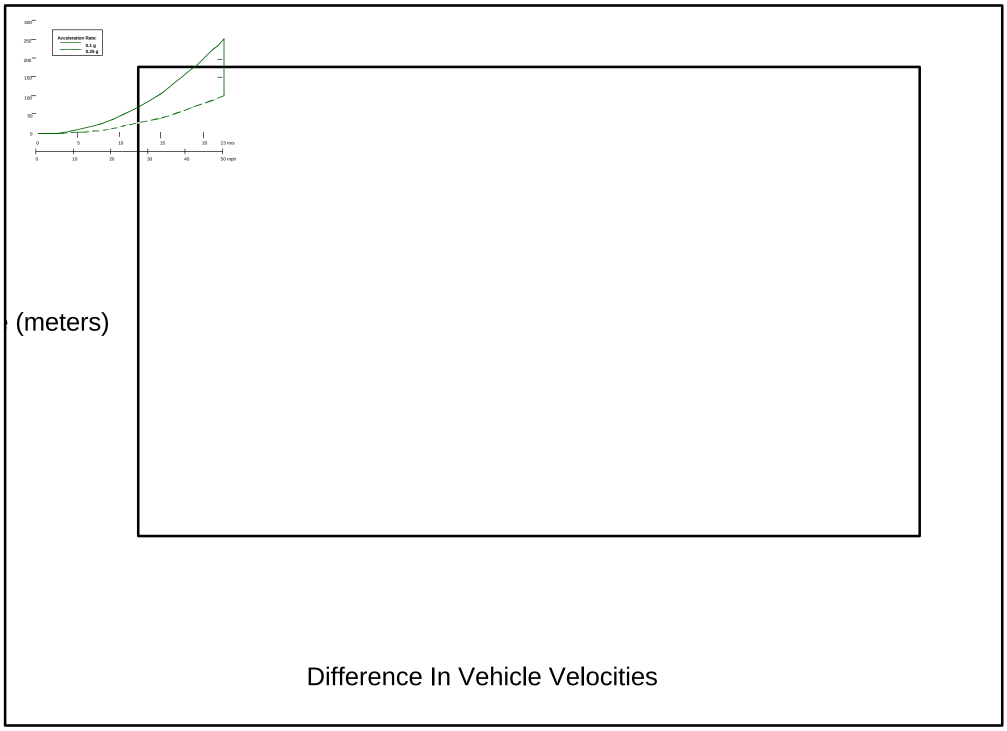

Figure 11. Distance required between merging and rear approaching vehicle

If vehicle 1 is traveling at 22 m/s (50 mi/h) when it merges and vehicle 5 is traveling at 31 m/s (70 mi/h), then the 9 m/s (20 mi/h) difference in vehicle velocities requires a separation of 41 meters for 1 m/s^2 (0.1 g) constant acceleration, or 16 meters for 2.5 m/s^2 (0.25 g) constant acceleration by vehicle 1. If vehicle 5 was closer than these distances for the given conditions, then a collision between the vehicles would occur before vehicle 1 reached 31 m/s (70 mi/h) unless vehicle 5 decelerates.

The discussion up to this point on entering the AHS dealt with only continuous entry and exit. The introduction of a transition lane or designated entry without barriers, as shown in figure 12, could help to alleviate many of the safety situations just discussed.

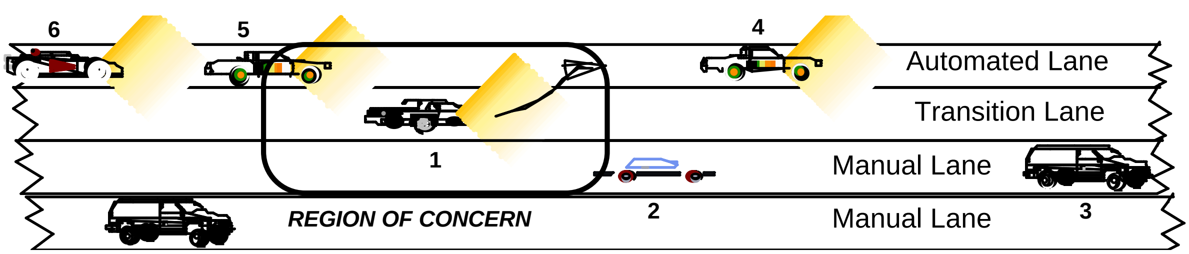

Figure 12. Entry onto AHS with transition

Since only AHS capable vehicles are allowed in the transition lane, then the difficulties encountered in the continuous entry and exit configuration with vehicles ahead of the merging vehicles traveling at a speed less than the AHS lane commanded speed should be alleviated.

This will help to reduce the merging vehicle's region of concern and reduce the requirements imposed on system components. Traffic densities in the transition lane should not be as large as in either the manual or AHS lanes since only merging traffic, not through traffic, would be permitted However, this could introduce safety problems with the associated weaves being simultaneously conducted by vehicles entering and exiting the AHS. The proper placement of the transition zones, with possibly some dedicated to entry and some to exit, or the use of dedicated ramps, should alleviate congestion at nodes.

The use of dedicated entry and exit ramps introduces another concern for system design considering that most ramps are curved (this would also be true for continuous entry and exit on curves). In this situation the sensor field of view must be large enough to detect forward vehicles which are on the ramp in time to allow the rear vehicle time to slow down or stop if necessary. The required forward viewing distance is a function of the difference in velocities between the two vehicles and the following vehicles braking capability. The ability to sense this far, assuming the sensor has the range capability is a function of the sensor field of view and the ramp curvature. Figure 13 shows how the same sensor field of view can cover a further distance down the ramp with a larger radius of ramp curvature.

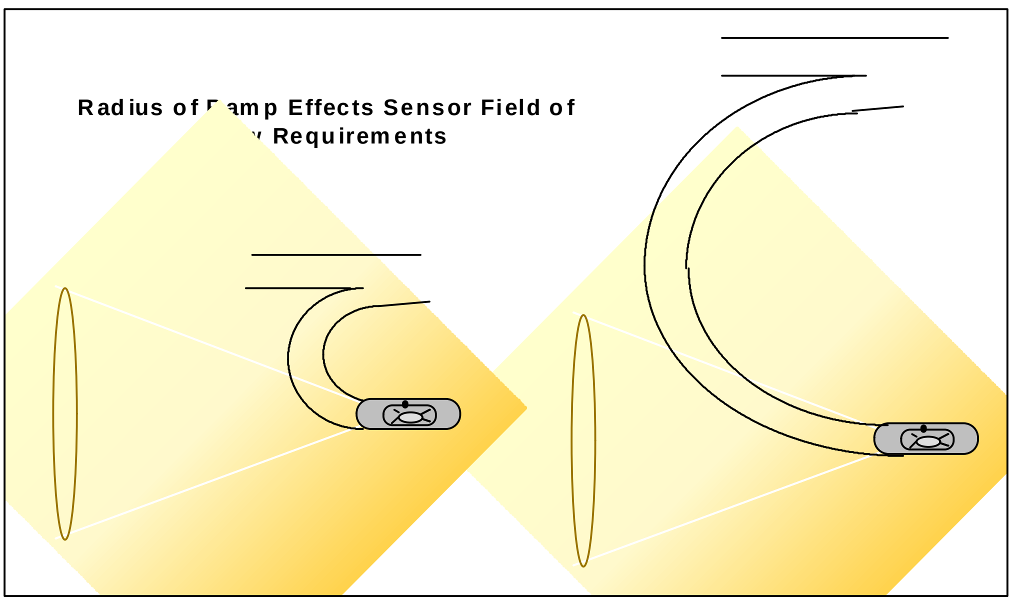

Figure 13. Radius of ramp curvature effects sensor field of view requirements

4.1.3 New Safety Issues Introduced by AHS - Entry

The majority of current interstate entry/exit accidents have been shown to be rear end collision between two vehicles. It has also been postulated that the driver, while looking in the mirror to find a place to merge , loses track of the vehicle in front. It is very probable that the introduction of a SHMS would play a large role in reducing these type of accidents. In order for this to occur, the sensor must be operational prior to the location where these accidents typically occur on the ramp. However, the transition from manual to automatic or to turning on the SHMS cannot be so complicated as to further distract the driver from watching the road ahead. The driver workload assessment study conducted by NHTSA shows that on average it requires a driver 11.31 glances with an average duration of 1.33 seconds to manually tune a car radio resulting in an average time of eyes off the road of 15.1 seconds.(1)

The introduction of a SHMS shows the promise of reducing rear end collisions. With the reduction of this type of collision, angle and sideswipe collisions will then comprise a larger percentage of entry/exit accidents. This does not mean that the total number of these types of collisions will increase.

High vehicle density of some AHS concepts (5000 vehicles per lane per hour) complicates entry. Finding safe gaps in which to merge becomes more difficult without help from the roadway in creating such gaps through flow control before the entrance.

4.2 Travel on the AHS

This section discusses safety issues associated with travel on non-junction, non-interchange sections of the AHS. While the GES data of figure 4 showed that this is where the majority of accidents occur on today's highways, for the AHS system - in the absence of malfunctions - this part of the trip should be relatively uneventful. All of the functions which occur during this segment of the journey (speed/headway maintenance, lane changing) are functions which will have already been solved for entry. As the system concept evolves from ERSC to ERSC, the technologies introduced are expected to bring about safety improvements where they are needed the most. Examination of the GES accident database again provides insight into the causes of accidents today.

4.2.1 GES Accident Data Analysis - Travel

Details taken from the GES data show in figure 14 the breakdown of first harmful event for interstate non-junction, non-interchange crashes.

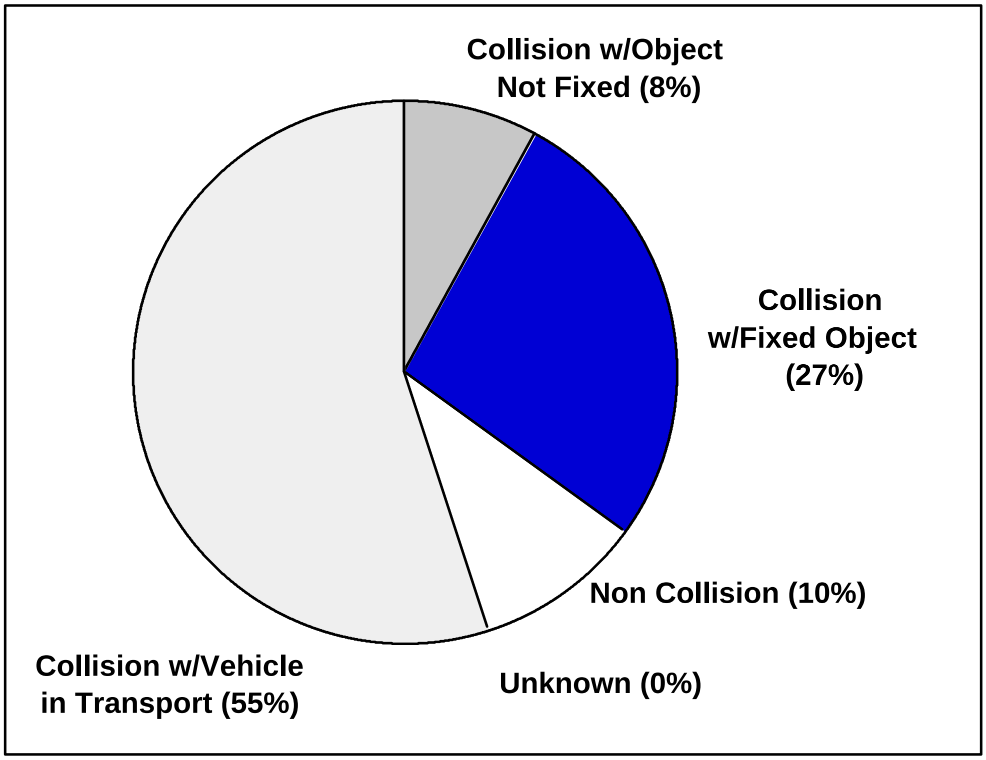

Figure 14. First harmful event for interstate non-junction, non-interchange crashes

The data shows that most (55 percent) accidents which occur while traveling on the interstate are collisions with vehicles in transport with collisions with a fixed object (27 percent) the second most frequent. Non-collisions, which primarily consist of rollovers, jackknifes, and fires, account for 10 percent.

The remaining 8 percent were collisions with "objects not fixed" (ignoring the "unknowns", which make up less than 1 percent). More than half of these were collisions with animals in the roadway. Determining how hard the requirement to handle unpredictable events such as these should be is a difficult safety issue.

Returning to collisions with a vehicle in transport, a closer examination of the *manner* of collision reveals that 63 percent were rear-end collisions as shown in figure 15.

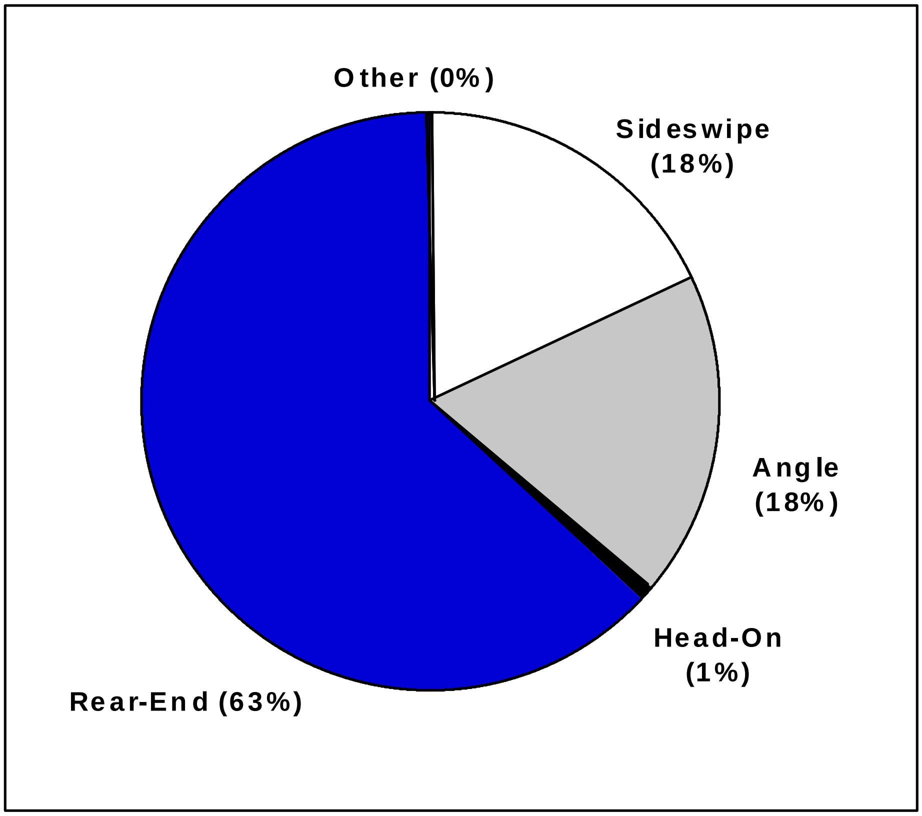

Figure 15. Manner of collision, two-vehicle crashes on interstate, non-junction, non-interchange

Details in the database can check our intuition into what causes each type of accident, to ensure that AHS design properly addresses these causes. Figure 16 shows a breakdown of "critical event initiated by this vehicle which made the crash imminent" for Rear-End Collisions on Interstate, Non-Junction, Non Interchanges.

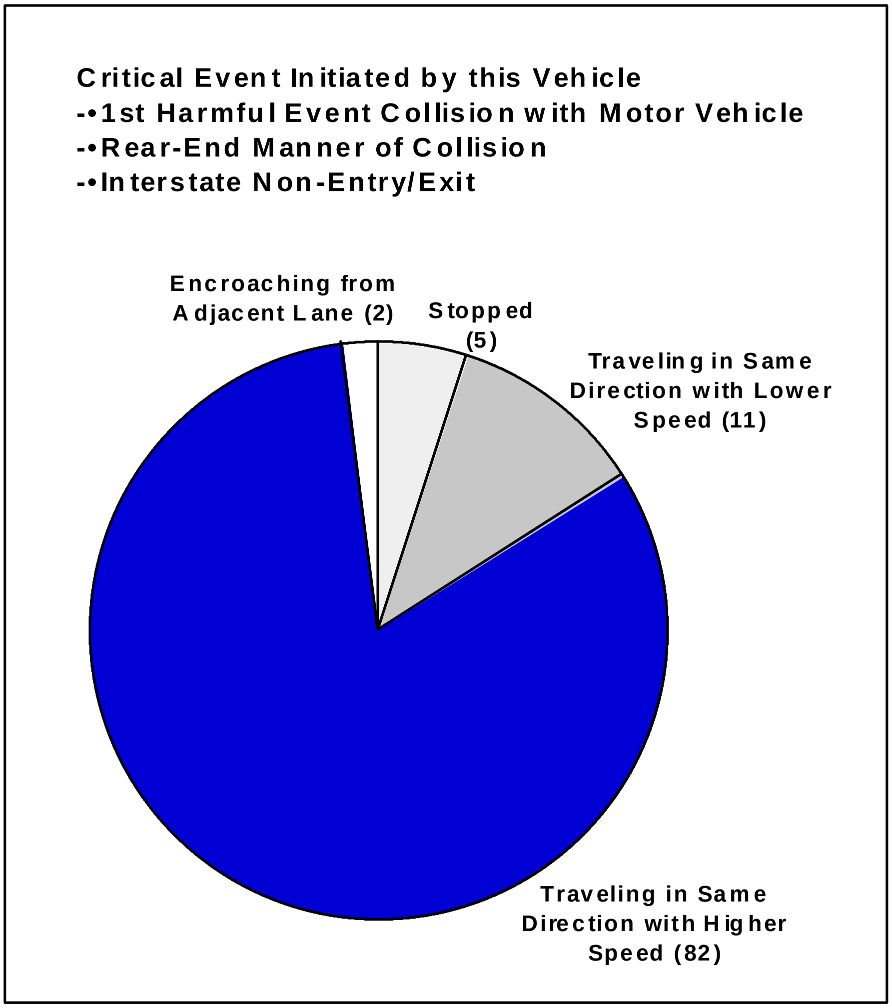

Figure 16. Critical event initiated by this vehicle which made crash imminent, rear-end collisions on interstate, non-junction, non-interchange

The data confirms the obvious: the vast majority of rear end collisions were blamed on a vehicle traveling in the same direction with higher speed. The "movement prior" to this critical event was found to mostly be "traveling straight".

Various studies have shown that driver's may not apply their brakes when the brake light of the vehicle in front comes on because they may have been inattentive, gathering other information before making a decision to apply brakes, slow to realize what the vehicles ahead were doing, or simply misjudged the risk of the lead vehicle's deceleration.[6,7]

The speed and headway maintenance system (SHMS) and rear end collision warning (RECW) introduced in ERSC1 should result in a significant decrease in rear end collisions. The rear end collision avoidance (RECA) feature in ERSC2 would eliminate rear end collisions during travel in the absence of malfunctions. Design considerations (e.g. what the minimum headway should be) for these systems are discussed in section 4.2.2.

Figure 17 shows the "critical event initiated by this vehicle which made the crash imminent" for angle collisions on interstate, non-junction, non-interchanges.

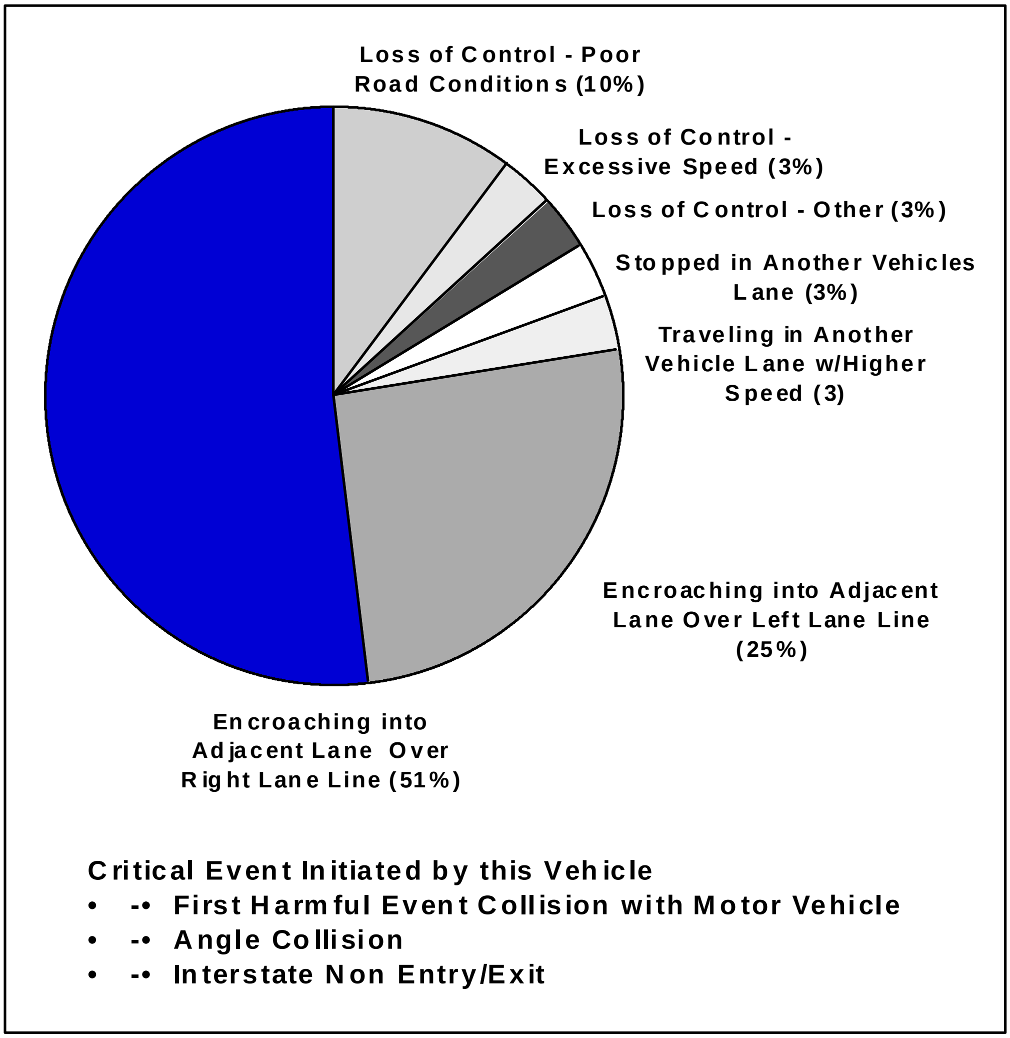

Figure 17. Critical event initiated by this vehicle which made crash imminent, angle collisions on interstate, non-junction, non-interchange

The data indicates that most (51 percent) of angle collisions are initiated by a vehicle encroaching into another lane. A similar breakdown (not shown) points to the same cause for sideswipe collisions (85 percent). This is not surprising. Figure 18 gives the distribution of "movement prior" to encroachment (on interstate, non-junction, non-interchange; two-vehicle collisions).

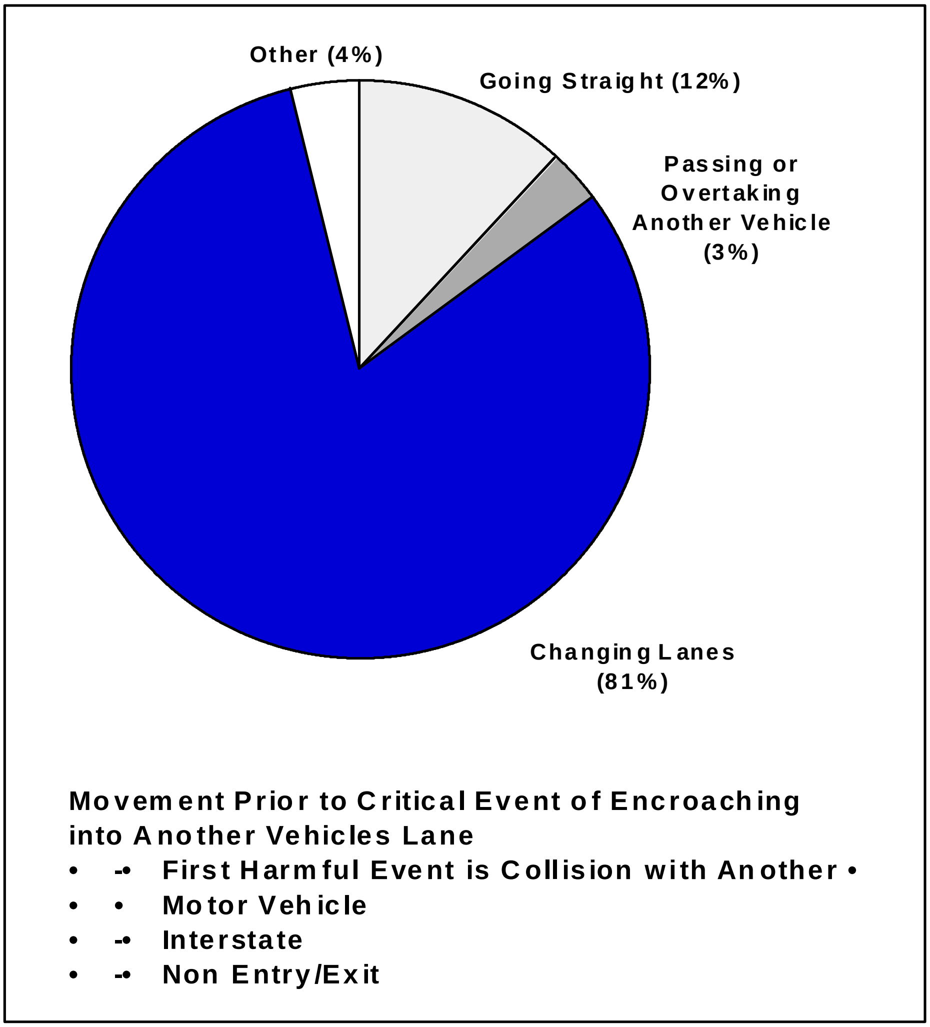

Figure 18. Movement prior to critical event of encroaching into another vehicles lane

Figure 18 indicates that encroachment leading to angle or sideswipe collisions usually occurs when a vehicle changes lanes. According to the data, encroaching results much less often from drivers going straight who simply wander out of the lane.

The GES analysis provides insight into which AHS features will reduce the most accidents during travel. Clearly, the SHMS, RECW, and RECA features should mitigate the most prevalent type of accident, rear-end collisions. Introducing these safety enhancing features to vehicles early on in AHS development should translate into immediate safety gains which will help win public support for AHS. The influence of safety issues on the design of these particular systems during travel is discussed in section 4.2.2.

With respect to angle and sideswipe accidents, the data suggests that they are mostly related to lane changing. Since multiple AHS lanes will not be introduced until ERSC4, travel in earlier ERSCs does not involve lane changing. Thus, the possibility for angle and sideswipe vehicle to vehicle collisions during travel does not even exist in ERSCs 1, 2, or 3. (This should give driver's more peace of mind as they gradually relinquish control of the vehicle through the evolutionary approach.) However, blind spot and lateral collision warnings, if operated by equipped vehicles on non-AHS roads, could certainly reduce angle and sideswipe accidents during lane changing operations there.

In ERSC4, automatic lane changing will eliminate most vehicle-to-vehicle angle and sideswipe accidents. Automatic lane keeping will counter the problem of the occasionally distracted or inattentive driver who veers out of lane.

In ERSC5, the possibility of hazardous situations during travel should be even further reduced as roadway route planning tends to minimize the number of lane changes during a trip.

4.2.2 Safety Issue Influences on System Design - Travel on AHS

As discussed, the SHMS will be relied upon to eliminate the most prevalent type of accident, rear-end collisions, beginning with ERSC1. As stated in section 2.5, the key guiding assumption used in this study is that the AHS must be collision free in the absence of malfunctions. The system must not only **be** safe, it must **appear** safe. The analysis shown is to ensure that collisions between vehicles do not occur.

If a condition occurs, however, it may be possible to achieve minimal damage and injuries with low delta velocity collisions which could occur with closely following vehicles. In this instance low delta velocity collisions are defined to occur between two vehicles both of which are moving. It is our initial conclusion, based on casual discussions with others, that users would not feel that such a system was safe.

Further study is required to quantify the safety of small spacing between vehicles. One such area requiring study is what happens when these low delta velocity collisions occur in turns or under other conditions when the velocity vectors of all the vehicles involved are not oriented in the same direction. This may not be the case in a situation where a vehicle has struck a deer, suffered a catastrophic blowout, or where the collision occurs in a curve. One such example is the spectacular low delta velocity collisions which occur on occasion at the Indy 500.

Another major point of our analysis is that differences in vehicle capabilities, particularly braking, must be acknowledged and accounted for in the system design. Capabilities must be monitored over time, and factored in when determining safe following distance and speed in dynamically occurring situations. The use of knowledge based computer systems may have a high payoff potential in this area. Sensor and communications packages must be adequately designed to provide the driver or vehicle with timely information.

The distance between vehicles must be great enough to significantly reduce the likelihood of a collision. The minimum safe following distance is a function of the following:

- The time it takes for the following vehicle to recognize that the lead vehicle is braking and therefore apply its own brakes (sensor, communication).
- The deceleration rate of the lead vehicle during that time.

- The difference in the vehicle velocities.

- The difference in the vehicle braking capabilities (deceleration).

For example the worst case, and the one that requires the greatest spacing, occurs when the lead vehicle brakes suddenly at its maximum braking capability and the following vehicle cannot decelerate as quickly (due to greater weight, braking system, tires, etc.) and is accelerating. In this situation, the minimum safe distance is determined using the formula:

$$\text{minimum safe distance} = v1^2/2*a1 - v2^2/2*a2 - 0.5 * (a1)*(\text{reaction time})^2 \quad (1)$$

Where **v1** is the lead vehicle velocity
a1 is the lead vehicle deceleration rate
v2 is the following vehicle velocity
a2 is the following vehicle deceleration rate
reaction time is the time from the application of the lead vehicle's brakes and the application of the following vehicle's brakes.

Of course, this is the theoretical minimum distance assuming a typical reaction time and knowledge of the vehicle velocities and braking profiles. If the vehicle velocity and brake data are not known, then the distance will have to be determined using the worst case values for the unknown data. There should also be an additional distance added on to the theoretical minimum to account for external influences (i.e., wet pavement)

Figure 19 shows the minimum safe following distance as a function of the reaction time. The minimum safe distance is going to be different depending on the relative speed and braking capability of the lead vehicle and following vehicle. The worst case, which requires the largest separation, is when the following vehicle is going faster than the lead vehicle and has poorer braking capabilities. Such a situation could occur when a vehicle is attempting to join with a platoon ahead of it. For example, assume vehicle one in figure 19 is the last car in a platoon. Vehicle 2 is attempting to join up with the platoon. Vehicle one is traveling at 121 km/h (75 mi/h) with a deceleration capability of 8 m/s^2 (the top curve in the figure). Assume vehicle two is going 8 km/h (5 mi/h) faster or 129 km/h (80 mi/h) in order to catch up to the platoon. Vehicle 2, since it is larger and its brakes are more worn than vehicle 1, has a deceleration capability of 7 m/s^2 which is a little slower than vehicle 1. If all of the vehicles are equipped with a communication system that receive broadcast messages from the lead vehicle, so that all vehicles begin breaking at the same time, then for purposes of this analysis the reaction time is zero. Since the reaction time is zero the minimum safe distance for the situation just described is 21 m. As long as vehicle 2 is 21 or more meters away from vehicle 1 then it could stop safely in this situation. If vehicle 2 reduces its speed to the same as vehicle 1, or 121 km/h (75 mi/h), then it can close to within 10 m as shown by the third curve from the top. Sensitivity to reaction time can be evaluated by reading out the abscissa. This figure also shows that many factors must be considered when safely closing gaps between vehicles.

Even the situation where both vehicles are traveling at the same speed and have a difference in deceleration of 1 m/s^2 (only 0.1 g which is not an unreasonable distribution) much larger distances between vehicles are required than proposed in some cases of vehicle platooning.

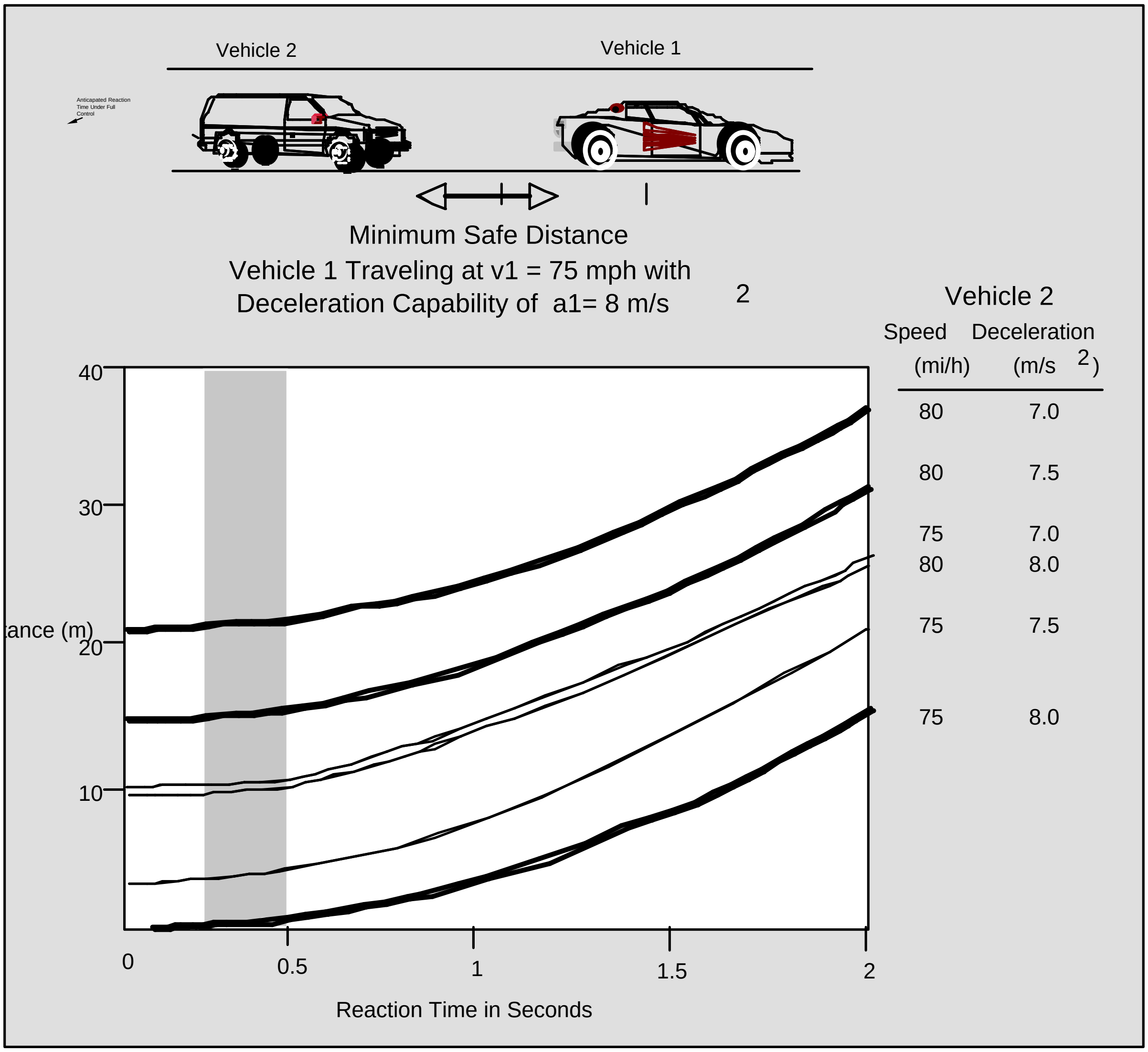

Figure 19. Minimum following distance

The braking deceleration's shown are examples which would be characteristic of hard braking in an emergency. Since the goal of AHS is to have safe and efficient operation in the absence of malfunctions our initial impression is that occasions for braking in the AHS system would want to be minimized in order to prevent transients (slinky effect) from being imposed, therefore, the majority of occasions in which braking does occur is when a malfunction has occurred (flat tire, broken tire rod) and hard braking is required.

In the fully automated system, reaction time should be closer to zero. However, in configurations where the driver is involved (earlier ERSCs), it is extremely important to consider an appropriate range of reaction times.

Several sources referenced in the Traffic Engineering Handbook suggest that appropriate values for driver reaction time, often referred to as Perception Reaction Time (PRT), may be even higher than the AASHTO design standard of 2.5 seconds. The AASHTO standard allocates 1.5 seconds for perception and decision and 1.0 second for response.(5) Others suggest from 3.2 to 3.5 seconds.(8)

Figure 20 shows reaction time to expected and unexpected information as an increasing function of information content.(9) The message is that reaction time increases with decision complexity. More recent studies have suggested that the element of surprise increases PRT by about one-third to one-half.(10)

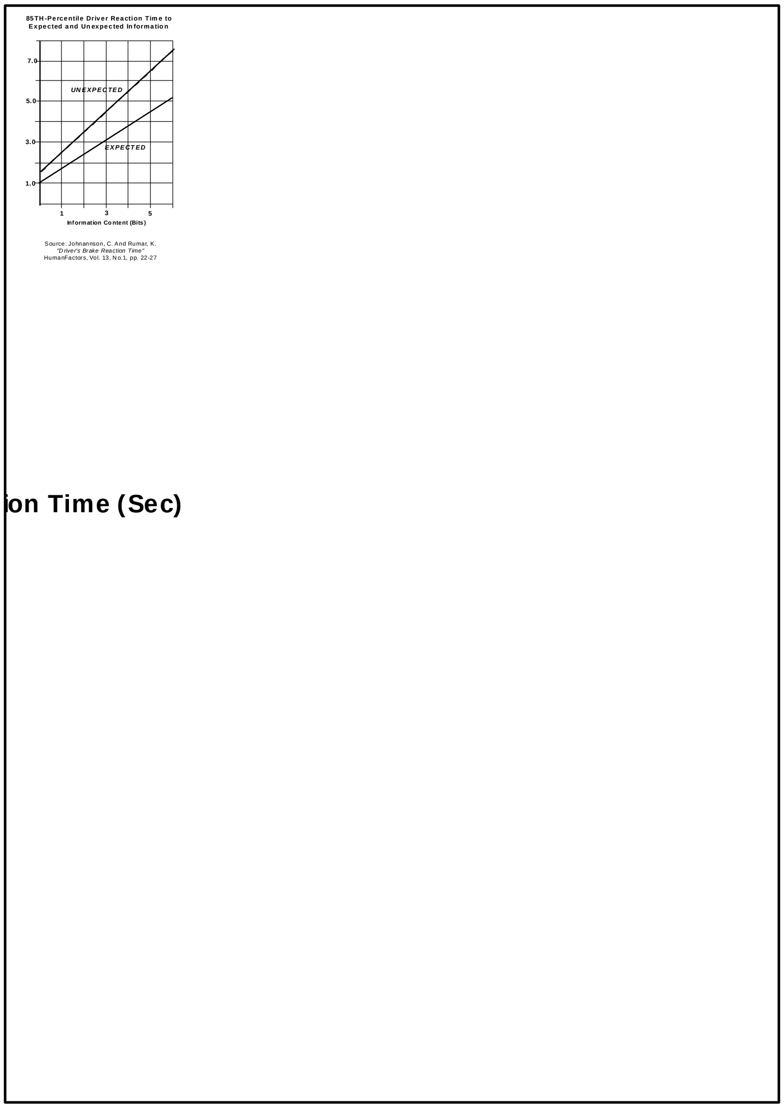

Figure 20. Reaction time as a function of decision complexity

To ensure safety, the AHS design process will need to properly account for reaction time (by the driver or the system, depending on the ERSC) in determining headway and sensor range requirements.

The maximum speed at which vehicles can travel is limited so that system safety can be maintained. Maximum speed has to be limited depending on road and weather conditions, vehicle performance, and the performance of vehicle and roadway sensors depending on the amount of control assumed by the vehicle. An important factor to be considered is how far objects can be detected in front of the vehicle.

A vehicle equipped with intelligent cruise control that is not following another vehicle requires a forward looking sensor capable of detecting stationary/slower moving vehicles and objects in the roadway ahead. The minimum range at which a detection must be made in order to stop the vehicle short of a collision with the object or slower moving vehicle is determined from the following:

- Processing time after detection to decide whether braking is necessary
  - system software

- Time delay from braking decision to application of brakes
  - physical system

- Maximum time required to go from present speed to either a complete stop, or to slow down enough such that a collision is avoided
  - vehicle velocity
  - vehicle weight
  - braking system
  - tire condition
  - weather conditions (coefficient of friction between road and tire)
  - road curvature, super elevation and grade.

Assuming the worst case, that of an object or vehicle that is completely stopped:

$$\text{Detection Range Required} = (\text{Delay Time})*(\text{Vehicle Vel}) + (\text{Vehicle Vel})^2 / (2*\text{Deceleration}) \quad (2)$$

Where deceleration is the rate at which the vehicle can decelerate taking into account the factors listed above.

Figure 21 shows the sensor range required as a function of the vehicle velocity. The top curve represents the sensor range required assuming a driver reaction time of 2.1 sec. The curves under this one show the sensor range required for shorter delay times of 1.5 sec and 0.5 sec. As expected, as the delay time is reduced, the distance at which an object is detected is reduced.

Example: Vehicle Traveling at 33.5 m/s (75 mi/h)
1 sec processing time for braking decision
0.5 sec time delay from braking decision to start of braking process
8 m/s^2 deceleration rate

$$\begin{aligned}\text{Detection Range Required} &= (1.5\ \text{sec})*(33.5\ \text{m/s}) + (33.5\ \text{m/s})^2 / (2*8\ \text{m/s}^2)\\ &= 50.29 + 70.25\ \text{meters}\\ &= 120.5\ \text{meters}\end{aligned}$$

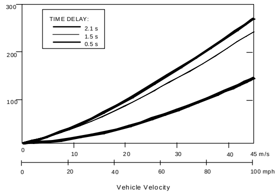

Figure 21. Forward sensor range required

The detection range required will influence the type of forward looking sensor to be used on the vehicle in the early ERSCs and will influence the level of vehicle detection required of the infrastructure in advanced ERSCs.

4.2.3 New Safety Issues Introduced by AHS - Travel

One situation in which a lane change could have a catastrophic impact on the system is the situation in the continuous entry and exit (no barrier) in which a manual driver conducts an unauthorized entry onto the AHS. In all likelihood, a driver that would conduct such an action is not in possession of all their faculties. This situation could be alleviated with designated entry with barriers and appropriate check in procedures.

In the early ERSCs when the system is equipped with only one lane this could create problems on upgrades if trucks and buses are allowed into the system. Such vehicles would need to be equipped with the power trains to allow these vehicles to maintain the speed of the AHS. On downgrades these vehicles would need to have the appropriate breaking capability to maintain AHS safe operation.

4.3 Exit From AHS

When a vehicle exits the AHS, the issues of lane changing and merging again must be considered. The transition from automatic to manual driving is only a slight change for the driver in the early ERSCs (longitudinal control only) but is a drastic change in the later

ERSCs. The safety issue that must be addressed when exiting AHS is one of making the driver aware that they are now responsible for control of the vehicle.

4.3.1 GES Accident Data Analysis - Exit

Since the GES database has a single category for entry/exit accident location, details specific to exits cannot be extracted. Combined Entry/Exit accident data was analyzed in section 4.1.1.

4.3.2 Safety Issue Influences on System Design - Exit

The actions which must occur to safely exit the AHS (maintain speed/headway, sense forward, rear, and adjacent vehicles, change lanes) are all actions which have occurred either during entry or during the journey. No new requirements on system components have been identified.

The major design issue effecting safe operation is the configuration of the exit. This should be viewed from the perspective of a fast vehicle merging into a slower lane. Continuous entry and exit would require the vehicle to either slow down in the AHS lane, thereby disrupting traffic flow, and then merging into the manual lane, or find a gap in the manual lane large enough to permit safe deceleration in that lane. This assumes that the traffic density of the manual lane will be low enough to permit such a maneuver to occur.

The use of a transition lane may provide a viable alternative under some conditions. However, if the manual lanes become backed up with traffic then it is possible, depending on the transition lane length, that the transition lane could become congested resulting in slow downs on the AHS. Also, general mainline conditions dictate how far in advance vehicles must exit AHS lanes.

4.3.3 New Safety Issues Introduced by AHS - Exit

The most important issue to be concerned with exit from the AHS is the transition from automatic control of the vehicle back to the driver. In section 4.1.3 it was discussed that a driver workload such as tuning a radio can result in an average time of eyes off the road of 15.1 seconds. The length of time required for the driver to resume control and the speed at which the vehicle is traveling during this process will impact the safe exit design. Contingencies must be made to handle situations in which the driver cannot assume control. For example, drivers who enter the AHS while under the influence of alcohol or other drugs may not be capable of passing the check out procedures.

Studies should 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? One other area is driver action off of the AHS given controlled roadway, low headway operation versus general manual driving procedures. Will the AHS driver continue earlier behavior?

4.4 Identification Of Remaining Safety Issues and Hazards

The overall number of remaining safety issues decreases as the AHS evolves. One would not expect to see the full safety benefit of an AHS until ERSC5. In the early ERSCs, the driver retains much of the responsibility for control of the vehicle and therefore driver error can still create many hazardous situations. While the AHS is supposed to be an accident free system (fully equipped vehicles in large numbers in multiple long-length systems) the ERSC steps to full AHS could develop a different accident pattern in fatal, serious, or property damage only incidents until the fully secured system is in place. In fact, the possibility exists that more accidents of a particular type will arise as a result of partial automation. For example, the introduction of the ICC in ERSC1, without the introduction of steering assist or lane keeping, could possibly result in an increase in drowsiness resulting in drifting out of the lane or running off the road. The NHTSA statistics for 1992 indicate that there are approximately 50,000 police-reported crashes (on all roads) in which driver drowsiness/fatigue was cited as a potential contributing factor. This may account for as many as 4 percent of all fatalities.[(1)] While overall safety will improve with each ERSC, the distribution of accident causes may change with each step.

Table 2 summarizes the AHS potential safety benefits derived from technology introduction. The key technologies introduced with each ERSC are listed on the left; the accident types they are expected to reduce are indicated by shaded boxes to the right.

Table 2. AHS potential safety benefits derived from technology introduction

ERSC Technology		Accident Types Reduced			
		Collision with Motor Vehicle	*Collision with Fixed Objects*	*Collision with Non-Fixed Objects*	*Non-Collision*
1	SHM (Speed & Headway Maintenance)	rear-end			
1	Low Level Commo	rear-end			
2	Steering Assist		barrier, guardrail, post, crash cushion, ditch		rollover
2	Rear End Collision Warning	rear-end		parked cars, animal	
3	Lane Keeping		barrier, guardrail post, crash cushion, ditch		rollover
3	Commo for Merging/ Rear End Collsion Avoidance	angle, sideswipe, rear-end			
4	Lane Changing	angle, sideswipe			
4	Lat/Long Collision Avoidance			animal	
4	Vehicle Based Route				
5	Roadway Based Vehicle Command and Route Planning				

ERSC1:
Improvements: SHMS and low level communication between vehicles (braking level, RECW) mitigate rear-end vehicle-to-vehicle collisions somewhat.

Remaining Hazards: Some angle and sideswipe collisions will still occur since driver is responsible for merging into and out of the single automated lane during entry and exit. Collisions with fixed and non-fixed objects (guard rails, barriers, animals, etc.) and non-collisions (rollovers) are still a hazard since the driver is responsible for lateral control.

During travel, angle and sideswipe collisions are not applicable since there is only a single travel lane.

ERSC2:
Improvements: Steering assist reduces collisions with fixed objects outside the lane somewhat, as well as rollovers. Rear end collision avoidance (RECA) further mitigates rear-end collisions and collisions with parked cars and animals ahead in the roadway.

Remaining Hazards: Collisions with fixed objects and rollovers are not eliminated altogether, since the driver retains control of steering. Animals entering the roadway from the side still present a hazard. Angle and sideswipe collisions during entry and exit remain a hazard, since the driver is still responsible. Neither are applicable during travel, since there is still only a single automated lane.

ERSC3:
Improvements: Automated lane keeping (ALK) further mitigates collisions with fixed objects out of lane, as well as rollover type non-collisions. Communication for merging reduces angle, sideswipe, and rear-end collisions during entry, but not altogether, since the driver is still responsible. Angle and sideswipe collisions during travel do not apply since there is still only a single automated lane.

ERSC4:
Improvements: Automated lane changing virtually eliminates angle and sideswipe collisions during entry. These type of collisions now apply during travel since multiple lanes are allowed; however, automated lane changing is designed to prevent them. Complete lateral and longitudinal collision avoidance should further reduce collisions with fixed objects, and with animals entering the roadway.

Remaining Hazards: Residual hazards such as animals entering the roadway which cannot be avoided.

ERSC5:
Improvements: Improvements are primarily in efficiency, not safety. However, roadway based vehicle command and route planning allow for better regulation of traffic to reduce hazards and malfunctions.

Remaining Hazards: Residual.

Certain categories of accidents, such as non-fixed objects in the road, can never be totally eliminated. For cases such as these, malfunction management strategies will be studied which will contribute to a safe system design and hopefully prevent an increase in accident causes due to the introduction of technologies.

4.5 Quantification Of Level Of Safety For Each ERSC

This section presents a method for attempting to quantify safety benefits that may be achieved with the introduction of various AHS technologies. During the course of the National AHS Consortium it may become necessary to make decisions concerning either the order or the benefit of introducing different technology. For example, while this study has introduced five ERSCs, further study may show that there is not a large enough increase in benefits to go from one step to another. It may make sense to skip one or more of the ERSCs. It may also be beneficial to analyze various segments of the AHS system (entry/exit as compared to the entire AHS roadway) to help develop information as to which segments could best benefit and possibly to help identify potential problem areas.

The quantification of AHS safety benefits starts with the analysis of the GES historical traffic accident data to determine the distribution of causes. This distribution is applied to recent interstate accident figures to form a baseline. The benefits prescribed to each technology introduced in the ERSCs are then used to conduct the assessment of potential accident reduction. It has already been shown in this report that rear end collisions composed the largest percentage of multiple vehicle accidents on the interstate system and that driver inattention is a large contributing factor. One could therefore deduce that the introduction of a SHMS could provide a major contribution to the reduction of these kinds of collisions for the reasons explained in prior sections.

Table 3 presents the breakdown by accident type on the interstate system for entry/exit and non-junction, non-interchange situations. This data is based on 1992 GES data. The numbers were arrived at by taking the percentages of accident type occurrence by location determined by database analysis and multiplying by the total number of accidents on the interstate.

Table 3. Breakdown of collisions on interstates

	Entry/Exit Situation		Non Junction Non Interchange	
Collision with Vehicle in Transport	13,979		131,030	
- Rear End		10,223		82,644
- Head On		0		758
- Angle		1,477		23,764
- Sideswipe		2,070		23,395
- Other		209		469
Collision with Fixed Object	4,610		63,828	
Collision with Object Not Fixed	723		19,863	
Non Collision	986		24,423	
Unknown	292		734	
	20,590		239,877	

Table 4 presents estimates for potential accident reductions in the entry/exit area by type for each ERSC. This table assumes all interstates and vehicles were AHS equipped. Accident reduction percentages were subjectively assumed to determine first order trends. The percentage reductions are relative to the overall baseline and not between ERSCs. A brief rationale for each estimate is provided in table 4 with more detailed explanations having appeared throughout this report. Further indepth analysis in this area should be conducted using computer simulations.

Table 4. Rationale for projected crash reductions for interstate, entry/exit situation

Crash type	**ERSC1** *ICC (Headway & Speed Control) Low Level Communications*	**ERSC2** *Steering Assist Rear-End Collision Avoidance Higher Level Communications*	**ERSC3** *Lane Keeping Communications for Merging*	**ERSC4** *Lane Changing Lat/Long Collision Avoidance Vehicle Based Route Planning*	**ERSC5** *Roadway Based Vehicle Command & Route Planning*
Collision with vehicle in transport Rear-End	Reduced 20% due to SHMS and forward looking radar	Reduced 75% due to rear end collision warning	Reduced 75% due to rear end collision avoidance	Eliminated due to merge coordination	Eliminated due to merge coordination
Head On					
Angle	Not Reduced	Reduced 20% due to low level communications	Reduced 80% due to communications for merging	Eliminated due to merge coordination	Eliminated due to merge coordination
Sideswipe	Not Reduced	Reduced 20% due to low level communications	Reduced 80% due to communication s for merging	Eliminated due to merge coordination	Eliminated due to merge coordination
Collision with Fixed Object	Not Reduced	Not reduced since steering assist not envisioned to be operating on entry/exit	Not reduced since lane keeping not used on entry/exit and steering assist	Eliminated due to lateral collision avoidance	Eliminated due to lateral collision avoidance
Collision with Object Not Fixed	Reduced 25% due to forward looking radar	Reduced 50% due to rear end collision avoidance	Reduced 65% due to rear end collision avoidance	Reduced 70% due to addition of lateral collision avoidance	Reduced 70% due to addition of lateral collision avoidance
Non Collision	Not Reduced	Not reduced since steering assist not envisioned to be operating on entry/exit	Not reduced since lane keeping not envisioned to be operating on entry/exit	Reduced 70% due to addition of lateral collision avoidance	Reduced 70% due to addition of lateral collision avoidance

Figure 22 projects crash reductions for interstate entry/exit situation for the different ERSCs based on the accident data contained in table 3 and the postulated crash reductions in table 4. The figure assumes that all interstates are 100 percent AHS capable. This certainly is not going to happen all at once. However, it can give an indication of the final AHS potential. A parameter that is varied and shown is market penetration. The market penetration variables shown are based on trends for the entire automotive industry, are indicative of penetration for anti-lock brakes and passenger vehicle airbags and correspond to the first five years of each components introduction. Market penetration of 100 percent is shown for comparison purpose. As can be seen in the figure, significant safety benefits are not achieved until more advanced levels of technology and large scale deployment is achieved. This is not to say that significant benefits would not be seen earlier in the areas of increased efficiency and reduced environmental impact for example. The benefit of this type of analysis is that these types of comparisons can be made to help guide towards the best deployment path.

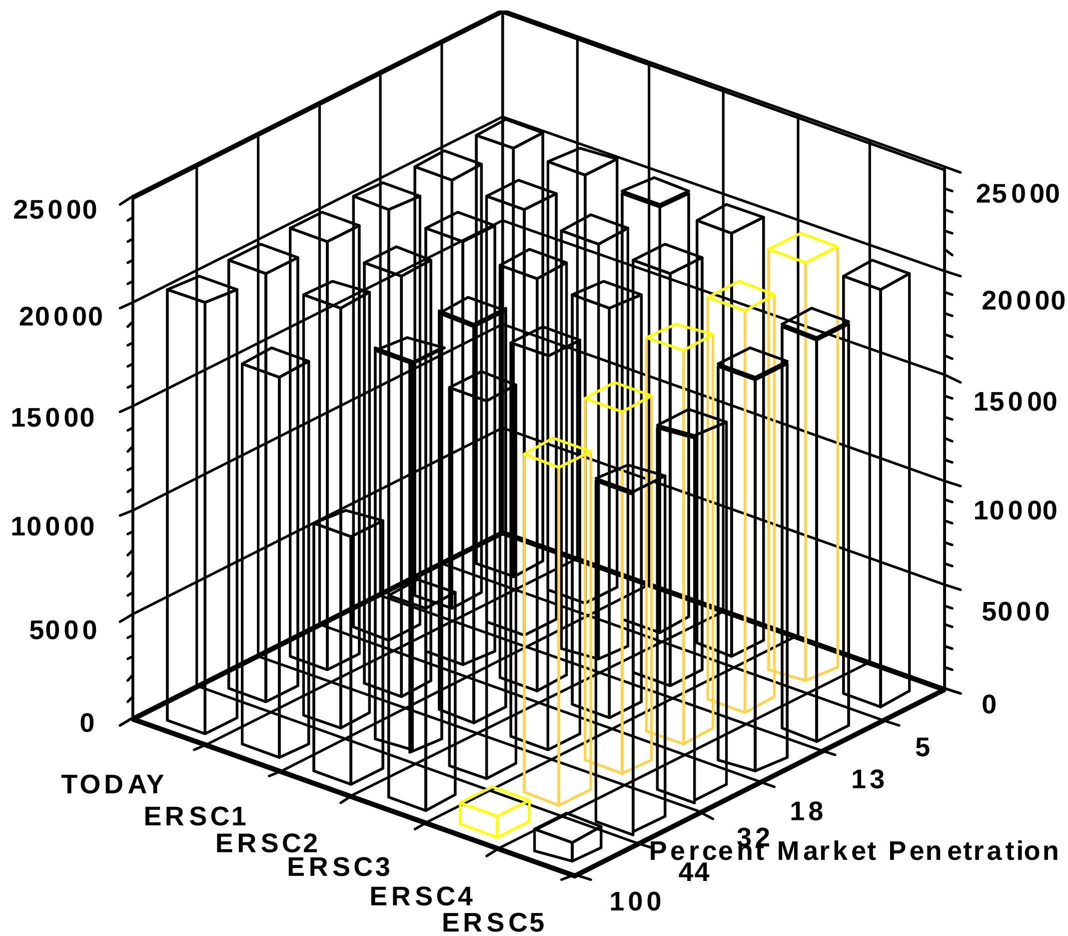

Figure 22. Projected crash reduction for interstate, entry/exit situation

Table 5 is similar to table 4 in that it postulates potential accident reductions for parts of the interstate besides entry/exits. Differences in the accident reduction potential are due to the way the various technologies are assumed to be employed along different segments of the roadway. For example, lane keeping may not be employed early enough in entry/exit situations to provide a large reduction in collision with a fixed object. A factor that will impact this is where the transition from manual driving to automatic driving occurs relative to the location on the entrance/exit where the majority of these kinds of accidents occur. One would expect to see a significant reduction in collision with a fixed object accidents for vehicles traveling in the AHS lane once lane keeping is employed.

Table 5. Rationale for projected crash reductions for interstate, non-junction, non-interchange

Crash type	**ERSC1** *ICC (Headway & Speed Control) Low Level Communications*	**ERSC2** *Steering Assist Rear-End Collision Avoidance Higher Level Communications*	**ERSC3** *Lane Keeping Communications for Merging*	**ERSC4** *Lane Changing Lat/Long Collision Avoidance Vehicle Based Route Planning*	**ERSC5** *Roadway Based Vehicle Command & Route Planning*
Collision with vehicle in transport					
Rear-End	Reduced 45% due to SHMS and forward looking radar	Reduced 75% due to rear end collision warning	Reduced 75% due to rear end collision avoidance	Eliminated due to merge coordination	Eliminated due to merge coordination
Head On	Reduced 100% with check in	Reduced 100% with check in	Reduced 100% with check in	Reduced 100% with check in	Reduced 100% with check in
Angle	Reduced 80% due to low level communications	Reduced 80% due to low level communications	Reduced 80% due to communications for merging	Eliminated due to merge coordination	Eliminated due to merge coordination
Sideswipe	Reduced 80% due to low level communications	Reduced 80% due to low level communications	Reduced 80% due to communications for merging	Eliminated due to merge coordination	Eliminated due to merge coordination
Collision with Fixed Object	Not Reduced	Not Reduced	Reduced 75% due to lane keeping and steering assist	Eliminated due to lateral collision avoidance	Eliminated due to lateral collision avoidance
Collision with Object Not Fixed	Reduced 55% due to forward looking radar	Reduced 65% additional reduction due to steering assist	Reduced 70% due to lane keeping	Reduced 80% due to addition of lateral collision avoidance	Reduced 80% due to addition of lateral collision avoidance
Non Collision	Not Reduced	Reduced 30% due to steering assist in entry/exit	Reduced 50% due to lane keeping	Reduced 50% due to addition of lateral collision avoidance	Reduced 50% due to addition of lateral collision avoidance

Figure 23 projects crash reductions for travel along the AHS based on the data contained in table 3 and the postulated crash reductions in table 5. This figure is included to show that the distribution of safety benefits may differ along different segments of the AHS.

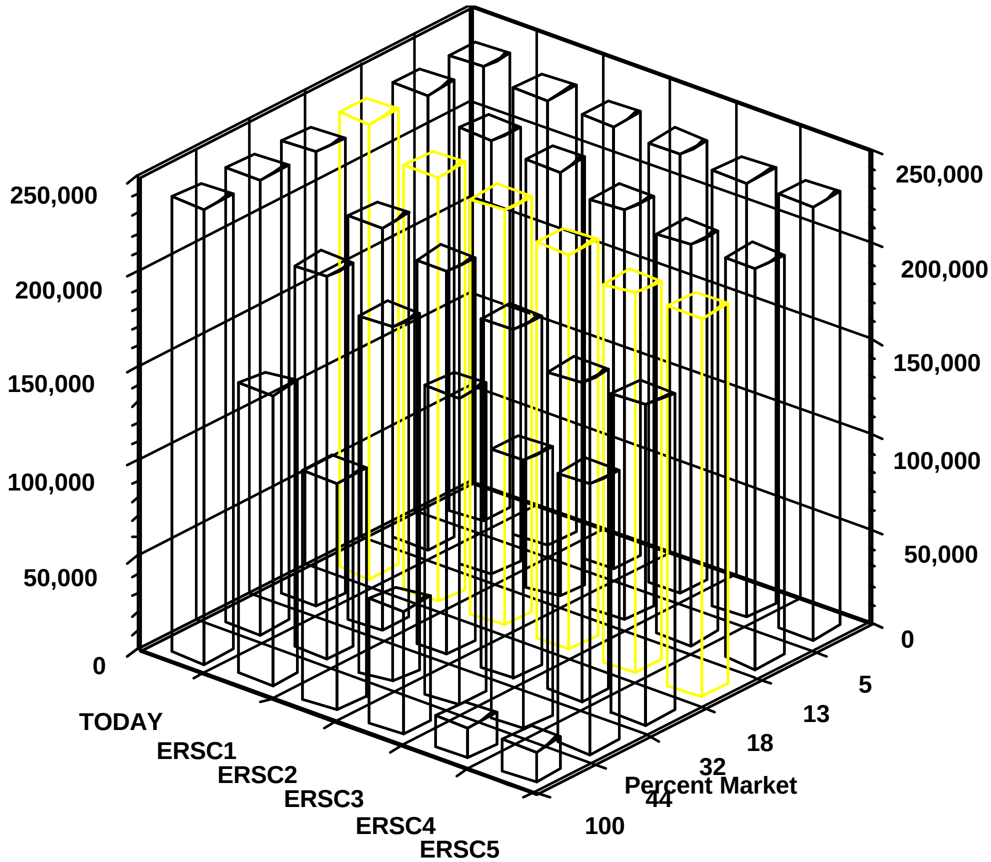

Figure 23. Projected crash reduction for interstate, non-junction, non-intersection

Table 6 provides data concerning the economic cost of crashes/injuries.[11]

Table 6. Economic cost of crashes/injuries

Injury Severity	1993 Dollars				1992 Dollars			
	Human Capital		Comprehensive		Human Capital		Comprehensive	
	Per Injury	Per Crash	Per Injury	Per Crash	Per Injury	Per Crash	Per Injury	Per Crash
No injury (O,0)	1,612	4,174	1,912	4,948	1,570	4,065	1,862	4,819
Possible (C,1)	8,661	13,978	20,629	30,263	8,435	13,614	20,091	29,474
Non-Incapacitating (B,2)	12,967	20,472	40,524	58,582	12,629	19,938	39,468	57,153
Incapacitating (A,3)	45,331	64,229	206,792	278,614	44,150	62,555	201,402	271,352
Fatality	847,859	958,989	2,890,136	3,289,531	825,761	933,995	2,814,810	3,203,796

Additional analysis could be conducted using the data contained in table 6 to determine the cost benefits achieved by reducing accident and injury. This can be accomplished by factoring the human capital costs into the number of accidents by severity which occur. This method accounts for the direct and indirect cost to individuals and society due to decreases in health due to motor vehicle crashes. This process measures the reduction in production and consumption to society due to these injuries. In addition, the resources consumed in response to , and those directly attributable to, the accident such as travel delay and property damage, are considered.

5.0 CONCLUSIONS

The following conclusions and recommendations have been reached concerning AHS safety issues:

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

- Early primary benefits are to come from intervehicle equipment and not from infrastructure and is more cost effective than thatrequired for future infrastructure design.

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

- Driver reaction times 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. 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 change 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. AHS entry/exit from manual and/or transition lanes will also require multiple "entrances/exits" and therefore increase movements to/from the left lanes. This presents additional conflicts and opportunties for accidents.

- The minimum number of total lanes required for any adjacent automated/manual highway is three. This configuration permits one AHS lane and two manual lanes. Less than two lanes in the manual lanes does not allow faster traffic to pass slower traffic, does not account for the slow down of truck traffic on upgrades, and complicates entry/exit into the manual lanes from surface streets.

- The roadway system must recognize speeds and decisions required of the driver.

- Two types of systems must be considered for safe AHS design. One type is long haul traffic over many miles of travel where handoff to the driver is an issue due to driver alertness. The other is a short commute, typical of a drive to work. In this instance handoff to the driver is probably not as big an issue. However, aggressiveness and the display of on-system driving (short headway, faster speed) carried to off- system may be more significant.

- A computer simulation of AHS technology is required in order to ensure safe system design.

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