Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

AHS Safety Issues

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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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NOTICE

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CHAPTER 2: AHS SAFETY ISSUES (TASK N)

1.0 EXECUTIVE SUMMARY FOR AHS SAFETY ISSUES

1.1 INTRODUCTION AND TECHNICAL APPROACH

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

Our technical approach was to focus on specific system features and driver functions associated with the Representative Systems Configurations (RSCs) defined in Volume I, PSA of AHS Overview Report, section 3.0. The six general RSCs, independent of vehicle type, were used. From this perspective, two questions were answered. The first question, "What could go wrong?", was addressed by a Fault Hazard Analysis (FHA) of AHS operations for each general RSC. The second question, "If something does go wrong, what are the consequences?" was answered using statistical accident data bases. The assumptions for this analysis are addressed in section 1.2.

1.2 KEY FINDINGS / CONCLUSIONS FROM SAFETY ANALYSIS

1.2.1 AHS Fault Hazard Analysis (What could go wrong?)

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

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

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

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

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

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

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

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

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

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

1.2.2.1 *Crash Analysis for Design Guidelines*

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

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

Data from the Fatal Accident Reporting System (FARS) were used to rank crash types according to risk of a fatal injury. Table 2-1 lists the individual crash types in order of decreasing likelihood of producing fatal injuries. The most common crash type to result in a fatal injury is the "not a collision with a motor vehicle in transport". The collisions that do not involve another motor vehicle in transport consist of single vehicle accidents that are rollovers, barrier related, roadside departures or involve an object or animal in the roadway. Head-On and Sideswipe Opposite Direction are extremely low frequency events on interstates.

Table 2-1. Ranking by Occurrence of Fatalities on Interstates

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

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

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

Figure 2-1 shows the highest level of medical treatment for striking vehicle occupants as a function of ΔV. Vehicle occupants suffered injuries requiring transportation to a medical facility where they were treated and released from crashes in the 9.7 to 16.1 kph (6 to 10 mph) ΔV range. Injuries requiring hospitalization resulted from crashes in the 17.7 to 24.1 kph (11 to 15 mph) ΔV range. This not only implies the seriousness of the incident in terms of occupant injury, but also indicates the amount of time necessary to clear the accident scene, and its influence on the perceived safety of the AHS.

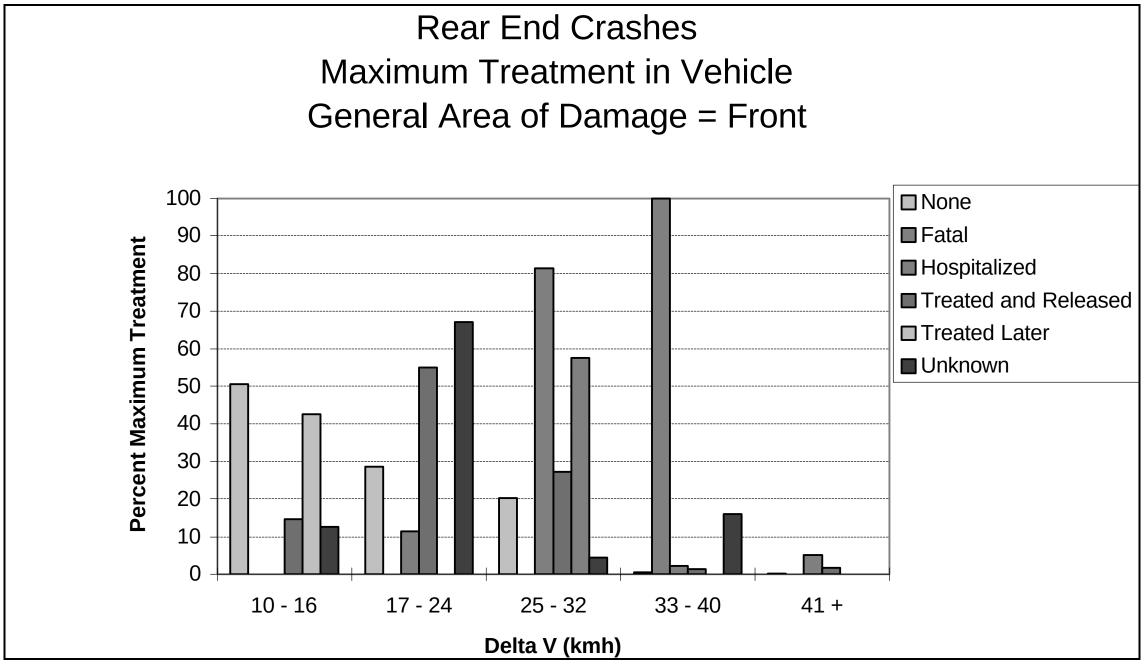


Figure 2-1. Medical Treatment in Vehicle by ΔV

Barrier-related crashes represent another potential AHS crash type, particularly for the I2C1 and I2C2 RSCs, where automated lanes and manual lanes may be separated by barriers. CDS data show that left roadside departures account for approximately 78 percent of barrier crashes that occur on roadways with speed limits greater than 80.5 kph (50 mph). This finding strongly supports the use of barriers on the AHS since, without a barrier between automated and manual lanes, left roadside departure vehicles from the manual lanes will intrude into the AHS.

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

Table 2-2 shows the likelihood of a lane-blocking incident on an AHS under normal operating conditions. Crashes involving objects or animals represent 5.2 percent of all interstates crashes. Given the 490,336 million vehicle miles of travel (VMT) on US interstates, this equates to a rate of 0.03 incidents per million VMT. Additional events, under non-normal operating conditions, that may lead to “AHS roadway obstacles” or lane-blocking incidents are:

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

Table 2-2. Likelihood of Lane-Blocking Incident on an AHS

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

1.2.3 AHS Benefits Analysis

As stated in the section 1.1, the goal of the AHS, under normal operating conditions, is a collision-free driving environment. This assumes full automation and fail-safe malfunction management under any and all circumstances. Based on these assumptions, existing studies on accident causal factor analysis provide a quantification of benefits from an AHS. Estimates of the improved accident picture for an AHS are treated separately for each crash type, where data are available. An assessment of the overall safety benefits derived from an AHS is presented as a range of percent reduction in crash frequencies in table 2-3.

The lower limit is based on General Estimates System (GES) data where a vehicle defect, driver impairment, or inclement weather may have contributed to the crash. Only police-reported information is included in this estimate; there is no assessment of crash cause. This analysis resulted in a 31 percent improvement for all locations combined (table 2-3).

Table 2-3. Percent of Interstate Collisions where Vehicle Defects, Driver Impairment, and Inclement Weather are Involved

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

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

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

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

The data in table 2-4 show the rate of vehicle collisions per million VMT for today’s interstates and estimates of the AHS rate when full automation is assumed. The range of improvement is shown to be 31 to 85 percent. These estimates are based on reductions in collisions; they do not include a factor for increased collision potential due to higher speeds and shorter headways. Collision numbers are from the 1992 General Estimates Systems (GES). They are nationally representative estimates of police-reported interstate accidents by location. Vehicle collision rates are based on VMT on interstates, FARS, 1991.

Table 2-4. AHS Safety Improvements

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

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

1.3 AHS SAFETY RECOMMENDATIONS FOR FUTURE RESEARCH

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

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

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

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

The relationship of ΔV to injury levels and vehicle damage led to the recommendation that ΔVs for rear-end crashes should be limited to 16.1 kph (10 mph). This 16.1 kph (10 mph) limit will minimize the consequences in an unmitigated malfunction scenario. If the system is not able to ensure straight front-to-back rear-end crashes and potential exits for offset rear-end crashes, this recommendation is lowered to ΔVs in the 8 kph (5 mph) range. The lower number is suggested to prevent a vehicle spinning off from a primary crash into a more severe crash type with a barrier or a vehicle in an adjacent lane. The use of anti-lock braking systems will also reduce the likelihood of vehicle rotation under maximum deceleration.

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

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

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

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

2.0 INTRODUCTION

Tremendous improvements have been made in highway safety during the last few decades. Enhancements in vehicle crashworthiness and roadway design are largely responsible for a marked decrease in crash rates and accident severity. Energy absorbing vehicle design, anti-lock brakes, occupant restraint systems, roadside barriers, and new methods of lane delineation are but a few of the outstanding breakthroughs that exemplify these efforts.

The highway system, however, is not only comprised of vehicles and roadway infrastructure, it also includes the human driver. From 1975 to 1986, about 60 percent of fatal crashes were single vehicle crashes and the majority were the result of roadside departures. Driver error, including inattention, fatigue, excessive speed and alcohol/drug impairment, were the primary causes of these crashes.

Automation will replace the human driver with electronics for vehicle control. The challenge for an AHS is to emulate good driving techniques, eliminate driver errors, and eschew introducing causal factors unique to automated control. This sections examines the safety issues and risks associated with meeting this challenge.

3.0 TECHNICAL DISCUSSION

The safety task was addressed in the form of two questions:

- What could go wrong?
- If something does go wrong, what might happen?

The approach for answering these two questions is outlined in Figure 2-2. A Fault Hazard Analysis (FHA) of an AHS was performed to answer the question, “what could go wrong?”. The subsequent analyses were twofold. Malfunction strategies were developed to mitigate the consequences of a fault or hazard (see Chapter 1); and the history of highway operations was reviewed to:

- grow from lessons learned and insights gained through 40 years of experience
- understand the consequences of deviating from a goal of a collision-free driving environment
- quantify benefits derived from AHS operations

To provide a framework for analysis, we defined Representative System Configurations (RSCs) for an AHS. RSCs are generalized design concepts for an AHS. The RSCs range in scope from a mode of mixed manual and automated vehicles sharing the same lanes to dedicated AHS roadways, with various levels of command and control shared between the roadway and the vehicle. The RSC definitions are grouped into six general categories that are independent of vehicle type. The general RSC categories are limited to I1C1, I2C1, I2C2, I3C1, I3C2, and I3C3 to streamline this analysis. A complete description of the RSCs is presented in Volume I, PSA of AHS Overview Report, section 3.0.

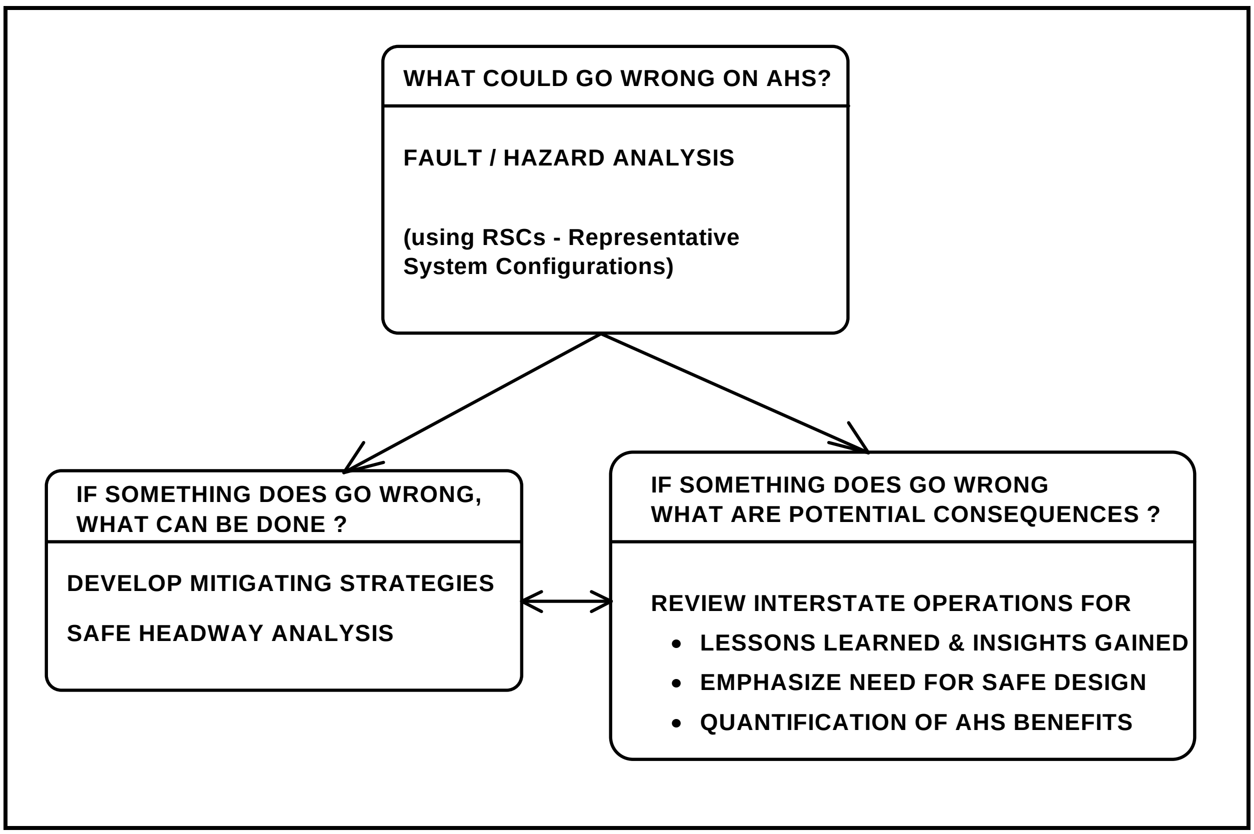


Figure 2-2. Safety Analysis Approach

3.1 AHS FAULT HAZARD ANALYSIS (FHA)

3.1.1 AHS FHA Approach

The fault hazard analysis answered the question "What could go wrong?". A functional decomposition of an automated highway system was performed and is represented in block diagram form in Figure 2-3. The major components of an AHS are:

- Vehicle
- Roadway Infrastructure
- Environment
- Driver
- Payload

The five major components were partitioned into sub-components to determine their potential failure modes. Block diagram representations of the AHS sub-components are presented in Chapter 1 of this volume. This block diagram structure was used to organize the fault hazard analysis tables as a function of the six general RSCs.

The fault hazard analysis tables were constructed by tracking a vehicle as it progresses through a time sequence of events representing the individual phases of AHS operations. These phases are check-in, entry, lateral/longitudinal control, check-out, and exit. The approach addressed potential failures or degradations, their local and system-wide effects on the AHS, and provided an assessment of their criticality prior to any mitigating strategy.

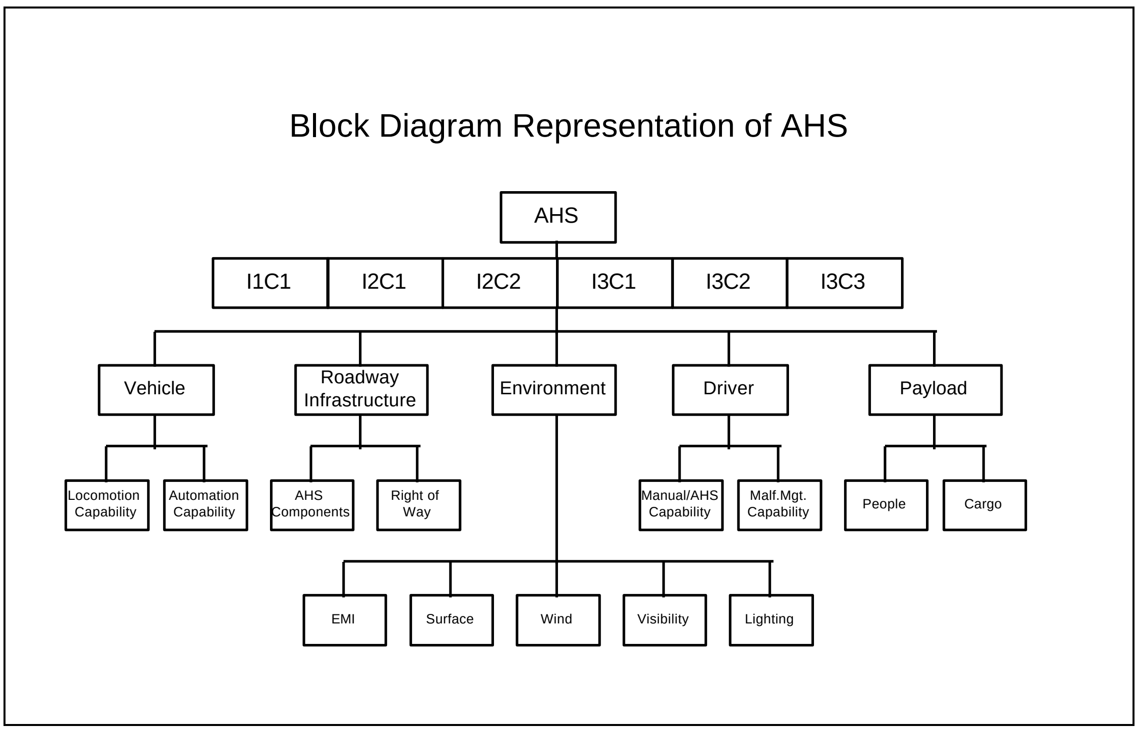


Figure 2-3. Block Diagram Representation of Automated Highway System

Tables 2-5 through 2-8 define the risk assessment codes, used during the fault/hazard analysis, and their acceptability or unacceptability for normal AHS operations. "Acceptable" implies that these issues require no further attention and "Unacceptable" indicates that a control action or mitigating strategy is needed. Acceptable risk codes are 2E to 4E, 3D, 4D, and 4C. All other risk codes are considered unacceptable. A rating for impact on AHS traffic flow is included to add user inconvenience to the risk assessment process.

Table 2-5. Severity Categories for Fault Hazard Analysis

Hazard Severity Categories		
Description	Category	Mishap Definition
Catastrophic	1	Leads to fatal accidents
Critical	2	Leads to accidents causing severe injury and/or significant property damage
Marginal	3	Leads to accidents causing minor injury and/or minor property damage
Negligible	4	Leads to accidents causing less than minor injury, or negligible property damage (e.g., fender bender)

Table 2-6. Probability Categories for Fault Hazard Analysis

Hazard Probability Categories			
Description	Level	Specific Individual Vehicle	Along Specific Stretch of AHS (e.g., between two exits with typical AHS flow Assumptions
Frequent	A	Likely to occur frequently	Continuously experienced
Probable	B	Will occur several times in life of a vehicle	Will occur frequently
Occasional	C	Likely to occur sometime in life of a vehicle	Will occur several times
Remote	D	Unlikely but possible to occur in life of a vehicle	Unlikely but can reasonably be expected to occur
Improbable	E	So unlikely, it can be assumed occurrence may not be experienced	Unlikely to occur, but possible

Table 2-7. System Interference Categories for Fault Hazard Analysis

Hazard System Interference Categories		
Description	Degree	Interference Definition
Critical	I	System stoppage
Major	II	Major traffic slowdown
Minor	III	Traffic slowdown and delay
Negligible	IV	Minor traffic slowdown

Table 2-8. Risk Assessment for Fault Hazard Analysis

Probability	A	B	C	D	E
Severity	**Frequent**	**Probable**	**Occasional**	**Remote**	**Improbable**
1 Catastrophic	1A	1B	1C	1D	1E
2 Critical	2A	2B	2C	2D	2E*
3 Marginal	3A	3B	3C	3D*	3E*
4 Negligible	4A	4B	4C*	4D*	4E*

* implies unacceptable

The assumptions for the fault hazard analysis relative to the six general RSCs are outlined in table 2-9. These assumptions were used to estimate the local and system effects on the AHS for the fault hazard analysis. The general assumptions that apply to all RSCs are:

- AHS engagement is required
- Vehicle check-in is required for AHS engagement
- Automatic lane keeping and longitudinal control are utilized

The six general RSC descriptors assume a driver role of “brain on, hands and feet off”. The I1C1 RSC requires the driver to perform lane change maneuvers, so for this RSC, a “hands on” mode is required periodically. The assumptions for the driver role are:

- Driver plays a vigilant role - Brains on, hands and feet off
- Manual backup mode may be enacted at any time (desirable to decrease speed and increase headway first)
- Driver is an integral but independent part of the AHS - can inform system or reply to requests if necessary
- Driver has a “panic button” in order to resume control (override the AHS) of the vehicle in a life-threatening, emergency situation (i.e. automated control places the vehicle and/or its occupants in danger)
- Driver will gain control of the vehicle immediately after the switch is triggered
- Minimal driver acclimation time to resume control is required since the driver is constantly aware of the environment and vehicle responses.
- The driver will make appropriate decisions and responses after resuming control

An alternative driver role is “brain off, hands and feet off”. This alternative driver role is outlined below, but was not considered for the fault hazard analysis.

Alternate Driver Role:

- Uninvolved driver - Hands and feet off, brain in “background mode”
- Driver plays a minor role in the AHS loop

- Driver is prompted by check-in periodically to determine alertness, awareness, capabilities (check-in intervals may depend on trip duration and environmental and traffic flow conditions)

- Monitor status is reduced so the driver can perform non driving related tasks (e.g., sleep, relax, balance check book, work, etc.)

- Driver has no available manual override switch or back-up mode, system decides when driver will resume control

- System would provide an alarm in case of a failure or upcoming AHS exit and acclimate driver to the situation before manual control is resumed. (Length of time for acclimation might depend on the situation encountered.)

For both driver roles, if it is found that the driver is unable to perform to AHS standards (i.e., driver is incapacitated or impaired, etc.) the system will stop or move the vehicle to the breakdown lane to avoid adverse traffic effects. After the driver's needs are assessed, the system will take the appropriate measures (e.g., emergency medical response, law enforcement, etc.)

3.1.2 AHS FHA Results

The fault hazard analysis tables for the general RSC categories are presented in appendix B. Configurations I2C1 and I3C1 were found to have similar system effects, so only one table was generated for the two RSCs. This was the case for configurations I2C2 and I3C2 also. Risks factors were assigned using engineering judgment to assess the probability of occurrence and the severity of consequences for each fault hazard element. Severity of consequences is expressed in terms of occupant injury, vehicle damage and system throughput. The severity of consequences is expanded in section 2.3.2., where AHS unique accidents are addressed.

The fault hazard tables were constructed using a "bottom-up" approach for each RSC category. Once the failure modes were identified, they were summarized as top level faults or hazards for the AHS sub-components. For example, many mechanical components may lead to a braking system failure, but the net effect is reduced longitudinal control. The system effects for these top level failure modes were categorized by the AHS measures of effectiveness: safety, throughput, driver role and service. The AHS issues, summarized as a matrix of top level failure modes and control level afforded by each general RSC, are presented at the end of this section in table 2-10.

3.1.3 AHS FHA Conclusions

After examining the AHS components with respect to the levels of command and control afforded by the six general RSC categories, the primary conclusions are:

- Automated vehicles must have redundant steering and braking systems. The fault hazard analysis showed that an automated vehicle may need to revert to lower levels of control, and as a last resort, manual control, in the event of a major malfunction. The entire system is dependent on the integrity of the basic vehicle controllers. The consequences of loss of vehicle control, which are detailed in the sections on individual crash types, emphasize the importance of vehicle control at all times, particularly under high speed, short headway conditions.

- The driver role is controversial, particularly as a malfunction management tool. The fault hazard analysis was conducted assuming a driver role of “Brain On, Hands and Feet Off”. An alternative role of “Brain Off, Hands and Feet Off” was identified. Perhaps the issue should not be viewed as black or white. In certain situations, such as a vehicle departing the roadway due to an unmitigated malfunction, time may be available to alert the driver and assume manual control. Manual backup may be totally impractical in managing a malfunction in high speed, short gap distance situations where reaction time is short and speeds are high. Both roles require further research to determine conditions where is it reasonable to hand off control to the driver, or with current technology is it possible to completely remove the driver from the control loop.

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

- The AHS functional decomposition shows the object/animal in the roadway as an external, environmental element. These elements are unpredictable and beyond AHS control. Blocking these elements out of the AHS may be costly and impractical. If these elements are not excluded, then methods must be developed to detect obstacles that should be avoided (i.e., they pose a real threat to a vehicle). Lateral control systems will have to divert vehicles around the obstacle and a path must be available for the diverted vehicles.

Table 2-9. RSC Assumptions for Fault/Hazard Analysis

RSC	AHS Infrastructure	Entry/Exit to Automated Lane	AHS Transition	Highway Role	AHS Lane Change Maneuver	AHS Lane Change Decision	AHS Breakdown Lane	Driver Role
I1C1	Existing Highway	Manual	Left Lane	Advisory	Manual	Driver	Same as existing	Fully Engaged - Alerted upon detection of failure
I2C1	Separated AHS Lane(s)	Automated	Transition Lane	Advisory	Automated	Driver/AHS	Yes	Monitor Role - Alerted upon detection of failure
I2C2	Separated AHS Lane(s)	Automated	Transition Lane	Commands speed and spacing	Automated	Driver/AHS	Yes	Monitor Role - Alerted upon detection of failure
I3C1	Dedicated Highway	Automated	From non-AHS roads through AHS Entry/Exit ramps	Advisory	Automated	Driver/AHS	Yes	Monitor Role - Alerted upon detection of failure
I3C2	Dedicated Highway	Automated	From non-AHS roads through AHS Entry/Exit ramps	Commands speed and spacing	Automated	Driver/AHS	Yes	Monitor Role - Alerted upon detection of failure
I3C3	Dedicated Highway	Automated	From non-AHS roads through AHS Entry/Exit ramps	Commands individual vehicle actions	Automated	Roadway	Yes	Monitor Role - Alerted upon detection of failure

Table 2-10. Fault/Hazards by General RSC Summary Matrix

System Effects							
		RSC Configuration					
Fault Hazard Category	**Issue**	**I1C1**	**I2C1**	**I2C2**	**I3C1**	**I3C2**	**I3C3**
Vehicle							
Braking Failure · Initial braking systems failure detection would prevent AHS engage · Vehicle braking systems would be checked at the biannual AHS inspection · Redundant braking systems employed to avoid systems failure and loss of longitudinal control	**Safety:**	Impaired longitudinal control, possible impact with the leading vehicle	Impaired longitudinal control, possible impact with the leading vehicle	Impaired longitudinal control, possible impact with the leading vehicle	Same As I2C1	Same As I2C2	High system intelligence could minimize effects
	Throughput:	Possible major traffic slowdown and delays	Possible traffic slowdown and delays				A minor problem could allow for continued travel until the next available AHS exit is reached
	Comfort:	Reduced headway	Reduced headway	Reduced headway			
	Driver Role:		It's the driver's decision to leave the AHS	It's the driver's decision to leave the AHS			
	notes:		Severity on AHS lanes may be reduced since braking is not required as often as with Non-AHS travel Surrounding AHS traffic could be notified and may adjust so the vehicle could get to the breakdown lane	Severity on AHS lanes may be reduced since braking is not required as often as with Non-AHS travel Surrounding AHS traffic could be notified and adjust so the system could move the vehicle to the breakdown lane			Severity on AHS lanes may be reduced since braking is not required as often as with Non-AHS travel Roadway could inform and adjust traffic and move the vehicle to the breakdown lane
	Risk:	3E - 2E; III - IV	4E - 3E; III - IV	4E - 3E; III - IV			4E - 3E; III - IV

Table 2-10. (continued) Fault/Hazards by General RSC Summary Matrix

System Effects							
		RSC Configuration					
Fault Hazard Category	**Issue**	**I1C1**	**I2C1**	**I2C2**	**I3C1**	**I3C2**	**I3C3**
Vehicle (cont.)							
Vehicle Slows Down Due to mechanical breakdown/electrical failure · Initial detection might prevent AHS engage · **Risk:** 4A - 3B; IV	**Safety:** **Throughput:** **Comfort:** **notes:**	Possible impact with the trailing vehicle Possible traffic slowdown and delays Reduced headway	Possible impact with the trailing vehicle Possible traffic slowdown and delays Reduced headway VV communication might inform traffic allowing the vehicle to move to the breakdown lane	Possible impact with the trailing vehicle Traffic slowdown and delays are minimized Reduced headway The system can adjust traffic and move the vehicle to breakdown lane or off of the AHS	Same As I2C1	Same As I2C2	Collision potential and traffic slowdowns are greatly reduced compared to other configurations System can adjust traffic and direct the slowed vehicle to the breakdown lane if necessary
Vehicle Suddenly Stops Due to mechanical breakdown/electrical failure · **Service:** Vehicle must be removed quickly to avoid serious traffic delays · **Risk:** 4C - 1D; IV - I	**Safety:** **Throughput:** **Driver Role:** **notes:**	Increased collision potential Major traffic slowdown	Increased collision potential Major traffic slowdown Driver may need to take corrective action Vehicle to vehicle communication might reduce traffic problems	Increased collision potential Traffic slowdown System might adjust traffic around disabled vehicle	Same As I2C1	Same As I2C2	Increased collision potential Traffic slowdown System might adjust traffic around disabled vehicle

Table 2-10. (continued) Fault/Hazards by General RSC Summary Matrix

System Effects							
		RSC Configuration					
Fault Hazard Category	**Issue**	**I1C1**	**I2C1**	**I2C2**	**I3C1**	**I3C2**	**I3C3**
Vehicle (cont.)							
Lateral Control Failure · Initial lateral control systems failure detection would prevent AHS engage · Vehicle steering would be checked at the biannual AHS inspection · Redundant steering systems employed to avoid a lateral control failure · **Safety:** If possible, vehicle would be stopped · **Safety:** Possible collisions with vehicles in adjacent lanes since vehicle lane keeping ability may be lost · **Risk:** 2E - 1E; IV - I	**Safety:** **Throughput:** **Driver Role:** **notes:**	Reduces/ eliminates driver's ability to maneuver laterally and avoid obstacles Possible major traffic slowdown and delays Driver is responsible for corrective action	Reduces/ eliminates ability to maneuver laterally and avoid obstacles Possible major traffic slowdown and delays Vehicle to vehicle communication may notify surrounding AHS traffic Might require barriers between AHS and non-AHS lanes to avoid spill over effects	Possible traffic slowdown and delays AHS could inform and adjust traffic so the vehicle could be stopped or directed out of AHS traffic Might require barriers between AHS and non-AHS lanes to avoid spill over effects	Effects similar to I2C1, however infrastructure is already separated from manual traffic lanes	Effects similar to I2C2, however infrastructure is already separated from manual traffic lanes	Possible minor traffic slowdown AHS could inform and adjust traffic so the vehicle could be stopped or directed out of AHS traffic System response time to a vehicle lateral control failure is critical in avoiding serious impacts
Vehicle Performance Variations · AHS engage is permitted · A concern for I2 RSCs with a transition lane between AHS and manual traffic · **Risk:** 4A - 3A; IV - III	**Safety:** **Throughput:** **notes:**	Increased collision potential Traffic slowdown	Increased collision potential Traffic slowdown System will adjust speed based on the least common denominator	System will adjust speed, spacing and lane changes based on least common denominator	Same As I2C1	Same As I2C2	System will adjust all vehicle actions based on the least common denominator

Table 2-10. (continued) Fault/Hazards by General RSC Summary Matrix

System Effects							
		RSC Configuration					
Fault Hazard Category	**Issue**	**I1C1**	**I2C1**	**I2C2**	**I3C1**	**I3C2**	**I3C3**
Vehicle (cont.)							
AHS Components:							
Actuator Failure 1. AHS Steering 2. AHS Braking 3. AHS Throttle · Initial detection would prevent AHS engage	**Driver Role:**	Driver could resume manual control of the vehicle (response time is critical in avoiding major incidents)	Driver may need to resume manual control and remove the vehicle from AHS traffic (response time is critical in avoiding major incidents)		Same As I2C1	Same As I2C2	Same As I2C2
· Redundant systems would be employed to avoid loss of AHS steering and braking · **Safety:** Loss of vehicle lateral control is the critical issue · **Safety:** Loss of AHS Throttle is the least critical issue · **Safety:** Critical issue if driver response capabilities are insufficient for a given situation (e.g. maintaining gap distance and lane position) · **Risk:** 3E - 1E; IV - I	**notes:**	Impacts depend on the degree of vehicle impairment and the time required to detect failure	Impacts depend on the degree of vehicle impairment and the time required to detect failure Vehicle to vehicle communication could inform surrounding vehicles so the disabled vehicle could exit AHS traffic	System may slow vehicle to a stop or direct it to the breakdown lane System response could reduce adverse system impacts			

Table 2-10. (continued) Fault/Hazards by General RSC Summary Matrix

System Effects							
		RSC Configuration					
Fault Hazard Category	**Issue**	**I1C1**	**I2C1**	**I2C2**	**I3C1**	**I3C2**	**I3C3**
Vehicle (cont.)							
AHS Components: (cont.)							
Sensor Failure	**Safety:**	Possible collision	Possible collision		Same As I2C1	Same As I2C2	Same As I2C2
· Initial detection would prevent AHS engage	**Throughput:**	Possible major traffic slowdown	Possible traffic slowdown	Possible traffic slowdown if system response is delayed			
· **Safety:** Critical issue if vehicle AHS lane keeping and longitudinal control is lost and driver response is inadequate	**Driver Role:**	Driver could resume manual control of the vehicle	Driver may need to resume manual control and remove the vehicle from AHS traffic	Driver may need to resume manual control and remove the vehicle from AHS traffic			
· **Safety:** Vehicle lane keeping and longitudinal control could be affected · **Risk:** III - II	**notes:**		Vehicle to vehicle communication could inform surrounding traffic so the disabled vehicle could exit AHS traffic	System could inform surrounding traffic so the disabled vehicle could exit AHS traffic			
Communications Failure · Initial detection would prevent AHS engage · VV and /or roadway communications impaired	**Safety:**	Not Applicable	Possible collisions	Vehicle seen as an “Intruder” so the system could inform and adjust traffic to prevent major incidents	Same As I2C1	Same As I2C2	Same As I2C2
· **Safety:** AHS lane keeping and longitudinal control may be impaired	**Throughput:**		Possible traffic slowdown and delays				
· **Safety:** Driver response time is crucial	**Comfort:**		Vehicle speed and spacing affected				
· **Risk:** II - I	**Driver Role:**		Driver may need to resume manual control to remove the vehicle	Driver may need to resume manual control to remove the vehicle			

Table 2-10. (continued) Fault/Hazards by General RSC Summary Matrix

System Effects							
		RSC Configuration					
Fault Hazard Category	**Issue**	**I1C1**	**I2C1**	**I2C2**	**I3C1**	**I3C2**	**I3C3**
Vehicle (cont.)							
AHS Components: (cont.)							
Computer Failure · Initial detection would prevent AHS engage · **Safety:** Critical if vehicle AHS lane keeping control is lost and driver response is delayed · **Driver Role:** Driver response time and performance when resuming manual control is critical for avoiding incidents · **Risk:** II - I	**Safety:** **Throughput:** **Driver Role:** **notes:**	Could result in a collision Possible major traffic slowdown Driver needs to resume manual control of the vehicle	Could result in a collision Possible major traffic slowdown Driver may need to resume manual control and remove the vehicle from AHS traffic VV communication could inform surrounding traffic so disabled vehicle could exit AHS	Traffic slowdown under extreme conditions Driver may need to resume manual control and remove the vehicle from AHS traffic System could inform surrounding traffic so disabled vehicle could exit AHS traffic	Same As I2C1	Same As I2C2	Same As I2C2
Data Link Failure · Initial detection would prevent AHS engage · VV and/or roadway communications could be impaired · **Safety:** Critical if AHS lane keeping and /or longitudinal control are lost and driver response is inadequate · **Safety/Throughput:** Errors in command messages may cause improper vehicle control impacting traffic management · **Risk:** I	**Safety:** **Throughput:** **Driver Role:** **notes:**	Not Applicable	Collisions could occur Possible traffic slowdown Driver may need to resume manual control and remove vehicle from traffic	Driver may need to resume manual control and remove vehicle from AHS For unresponsive vehicles, the “Intruder” response is initiated and traffic adjusted to avoid incidents	Same As I2C1	Same As I2C2	Same As I3C2

Table 2-10. (continued) Fault/Hazards by General RSC Summary Matrix

System Effects							
		RSC Configuration					
Fault Hazard Category	**Issue**	**I1C1**	**I2C1**	**I2C2**	**I3C1**	**I3C2**	**I3C3**
Roadway							
AHS Roadway Components							
Sensor Failure · **Safety:** Possibility of accidents and collision · **Throughput/Service:** A serious failure may require AHS shutdown · **Driver Role:** In a worst case scenario, drivers might need to resume manual control until system returns on line · **Driver Role:** Driver response time is critical in avoiding major incidents · **Risk:** I	**notes:**	Not Applicable	Seriously impacts traffic management since Roadway advisory could be lost Vehicle to vehicle communication might still be available for vehicle based traffic management	Seriously impacts traffic management since lane change maneuvers and vehicle speed and spacing commands could be impaired Vehicle to vehicle communication might still be available for system to revert to C1 control	System is a separated roadway but effects are the same as I2C1	Effects similar to I2C2 Vehicle to vehicle communication might still be available for the system to revert to C1 control	This is the most seriously impacted RSC since all vehicle actions could be affected Vehicle to vehicle communication might still be available for the system to revert to an C2 or C1 control depending on severity
Communications Failure · **Safety:** Possibility of accidents and collision · **Throughput/Service:** A serious failure may require AHS shutdown · **Driver Role:** In a worst case scenario, drivers might need to resume manual control until system returns on line · **Driver Role:** Driver response time is critical in avoiding major incidents · **Risk:** I	**notes:**	Not Applicable	Roadway advisory commands could be affected Vehicle to vehicle communication might still be available for vehicle based traffic management	Serious impacts since vehicle lane changes, speed and spacing commands could be affected Vehicle to vehicle communication might still be available for the system to revert to C1 control	System is a separated roadway but effects are the same as I2C1	Effects similar to I2C2 Vehicle to vehicle communication might still be available for the system to revert to I3C1 control	This is the most seriously impacted RSC since all vehicle actions could be affected Vehicle to vehicle communication might still be available for the system to revert to an C2 or C1 control depending on severity

Table 2-10. (continued) Fault/Hazards by General RSC Summary Matrix

System Effects							
		RSC Configuration					
Fault Hazard Category	**Issue**	**I1C1**	**I2C1**	**I2C2**	**I3C1**	**I3C2**	**I3C3**
Roadway (cont.)							
AHS Roadway Components (cont.)							
Computer Failure · **Safety:** Possibility of accidents and collision · **Throughput/Service:** A serious failure may require AHS shutdown · **Driver Role:** In a worst case scenario, drivers might need to resume manual control until system returns on line · **Driver Role:** Driver response time is critical in avoiding major incidents · **Risk:** I	**notes:**	Not Applicable	Seriously impacts traffic management since system monitoring ability and roadway advisory commands could be lost Vehicle to vehicle communication might still be available for vehicle based traffic management	Seriously impacts traffic management since system monitoring ability, lane change maneuvers and vehicle speed and spacing commands could be impaired Vehicle to vehicle communication might be available for system to revert to C1 control	System is a separated roadway but effects are the same as I2C1	Effects similar to I2C2 Vehicle to vehicle communication might be available for the system to revert to C1 control	This is the most seriously impacted RSC since system monitoring and vehicle actions could be affected Vehicle to vehicle communication might still be available for the system to revert to an C2 or C1 control depending on severity
Data Link Failure · **Safety:** Possibility of accidents and collision · **Throughput/Service:** A serious failure may require AHS shutdown · **Driver Role:** In a worst case scenario, drivers might need to resume manual control until system returns on line · **Driver Role:** Driver response time is critical in avoiding major incidents · **Risk**: I	**notes:**	Not Applicable	Seriously impacts traffic management since roadway advisory commands could be lost Vehicle to vehicle communication might still be available for vehicle based traffic management	Seriously impacts traffic management since lane change maneuvers and vehicle speed and spacing commands could be impaired Vehicle to vehicle communication might be available for system to revert to C1 control	System is a separated roadway but effects are the same as I2C1	Effects similar to I2C2 Vehicle to vehicle communication might still be available for the system to revert to C1 control	This is the most seriously impacted RSC since vehicle actions could be affected Vehicle to vehicle communication might still be available for the system to revert to an C2 or C1 control depending on severity

Table 2-10. (continued) Fault/Hazards by General RSC Summary Matrix

System Effects							
		RSC Configuration					
Fault Hazard Category	**Issue**	**I1C1**	**I2C1**	**I2C2**	**I3C1**	**I3C2**	**I3C3**
Environment							
Roadway Obstacles · Obstacle detection is difficult/impossible to simulate electronically · This is a roadway operations issue · May be more of a factor in rural areas · **Safety:** Vehicle damage or collision could result · **Throughput:** Possible traffic slowdown or stoppage · **Service:** Obstacle must be removed quickly to avoid adverse effects · **Risk:** 3B - 1E; III - I	**Throughput:** **Driver Role:** **notes:**	 Driver may need to direct the vehicle over or around obstacle, response time is critical AHS engage request is at the driver's discretion	AHS transition might be delayed or denied depending on severity Driver may decide whether vehicle can go over object or around it Vehicle to vehicle communication may serve as an early warning system for the system/driver	Possibility of system shutdown under extreme circumstances Driver may decide whether vehicle can go over object or around it Roadway may be able to adjust traffic around obstacle based on driver's decision	Same As I2C1	Same As I2C2	Possibility of system shutdown under extreme circumstances Roadway may adjust traffic around or over obstacle
Incidents · This is a roadway operations issue · **Safety:** Vehicle damage or collision could result · **Throughput:** Possible traffic slowdown or stoppage · **Service:** Incident scene response time is crucial in avoiding possible complications to those involved and serious traffic problems · **Risk:** 3B - 2C; III - I	**notes:**	AHS engage request is at the driver's discretion Driver may need to resume manual control until vehicle is past incident site	AHS engage request is at the driver's discretion System might adjust speed to reduce possibility of further incidents Barriers might prevent spill over effects into manual/automated lanes	Automated control prevents "rubber-necking" reducing the chance that more vehicles could be involved Possibility of system shutdown under extreme circumstances Roadway may be able to direct traffic around incident site Barriers might prevent spill over effects into manual/automated lanes	Same As I2C1	Same As I2C2	Same As I2C2

Table 2-10. (continued) Fault/Hazards by General RSC Summary Matrix

System Effects							
		RSC Configuration					
Fault Hazard Category	**Issue**	**I1C1**	**I2C1**	**I2C2**	**I3C1**	**I3C2**	**I3C3**
Environment (cont.)							
Roadway Sabotage · This is a roadway operations issue · **Safety:** Vehicle damage or collision could result · **Safety:** Increased accident potential · **Risk:** 3D - 1E; III - I	**notes:**	Possible traffic slowdown or stoppage AHS engage request is at the driver's discretion	System shutdown required under severe conditions AHS engage request is at the driver's discretion	System shutdown required under severe conditions	Same As I1C1	Same As I2C2	Same As I2C2
System Traction Degradation · AHS engage permitted unless conditions are extreme · **Safety:** Increased accident potential · **Safety/Throughput:** System may adjust vehicle speeds and maneuvers to suit environmental conditions · **Throughput:** Traffic slowdown · **Risk:** 3A - 3C; IV - I	**notes:**	Driver may experience a reduction in vehicle's lane keeping and longitudinal control abilities	Vehicle may experience a reduction in lane keeping and longitudinal control abilities The roadway control system could advise speed reduction to avoid increased accident potential	Vehicle may experience a reduction in lane keeping and longitudinal control abilities Roadway control could reduce vehicle speeds, adjust spacing and lane change maneuvers to avoid increased accident potential	Same As I2C1	Same As I2C2	Same As I2C2
Reduced Visibility · AHS engage permitted but speed reduction may be required · Degree of impact is depends on the sensors used for vehicle lane keeping and longitudinal control · **Risk:** 3A - 3B; IV - II	**Safety:** **Throughput:** **Driver Role:** **notes:**	Increased collision potential Possible traffic slowdown Impaired visibility may affect driver's lateral maneuvers Situation may have a greater effect on fully manual controlled vehicles	Increased collision potential Possible traffic slowdown Impaired visibility may affect driver's lateral maneuvers VV communications and roadway advisory may adjust to suit conditions	Impaired visibility may affect driver's lateral maneuvers	Same As I1C1	Same As I2C2	Same As I2C2

Table 2-10. (continued) Fault/Hazards by General RSC Summary Matrix

System Effects							
		RSC Configuration					
Fault Hazard Category	**Issue**	**I1C1**	**I2C1**	**I2C2**	**I3C1**	**I3C2**	**I3C3**
Environment (cont.)							
Crosswind · AHS engage permitted unless conditions are extreme · Impacts depend on the sensors used for longitudinal and lane keeping control · Intermittent disturbance to lane keeping control · **Risk:** 3B; IV - I	**Safety:** **Driver Role:** **notes:**	Increased collision potential May affect driver's manual lateral control maneuvers Vehicle systems may be able to adjust to lane keeping disturbance	Increased collision potential VV communications may help traffic adjust to disturbance	Increased collision potential Roadway control will commands to environmental conditions	Same As I1C1	Same As I2C2	Same As I2C2
Driver							
Impairment · AHS engage is not permitted if driver fails initial check-in test · Degree of impairment is a factor	**Safety:** **Throughput:** **Driver Role:** **notes:** **Risk:**	Creation of a minor to major collision potential Possible traffic slowdown or stoppage The driver needs to be fully engaged 3C - 2C; III - I	Increased collision potential Possible traffic slowdown and delays Driver's monitor role and lane change decision impacted Vehicle to vehicle communication may reduce collision potential On-line effects might be minimal 3C - 2C; IV - II	Driver's lane change decisions could be affected Surrounding traffic informed & adjusted to vehicle response Response teams dispatched On-line effects may be reduced 3C - 2C; IV - II	Same As I2C1 except that there would be no spill over effects into manual traffic	Same As I2C2 except that there would be no spill over effects into manual traffic	Under normal conditions only minimal to no adverse effects apply Driver's monitor status might be lost Vehicle could be stopped, moved to the breakdown lane or off of the AHS Response teams dispatched 3C - 2C; IV - II

Table 2-10. (continued) Fault/Hazards by General RSC Summary Matrix

System Effects							
		RSC Configuration					
Fault Hazard Category	**Issue**	**I1C1**	**I2C1**	**I2C2**	**I3C1**	**I3C2**	**I3C3**
Driver (cont.)							
Incapacitation · AHS engage is denied if driver fails the initial check-in test · **Safety/Driver Role:** Might have serious impacts if AHS roadway system fails and the driver needs to resume manual control of the vehicle	**Safety:**	Creation of a major collision potential	Increased collision potential	Possible increased collision potential	Same As I2C1 except that there would be no spill over effects into manual traffic if the situation occurs while the vehicle is on-line	Same As I2C2 except that there would be no spill over effects into manual traffic if the situation occurs while the vehicle is on-line	Under normal operating conditions there would be minimal to no adverse effects
	Throughput:	Possible major traffic slowdown or stoppage	Possible traffic slowdown	Possible minor traffic slowdown			
	Driver Role:	Serious impacts since the driver needs to be fully engaged	Driver monitor role and lane change decision status would be lost	Driver's lane change decisions affected			Driver's monitor status would be lost
	notes:		Vehicle to vehicle communication may reduce collision potential On line effects might be lessened if vehicle could be brought to a stop	Response teams might be dispatched to the vehicle Surrounding traffic informed & adjusted for vehicle response On-line effects might be reduced since most of the vehicle actions are automated			Vehicle can be stopped, moved to the breakdown lane or off of the AHS
	Risk:	3D - 2C; II - I	3D - 2C; IV - II	3D - 2C; IV - II			3D - 2C; IV - II

Table 2-10. (continued) Fault/Hazards by General RSC Summary Matrix

System Effects							
		RSC Configuration					
Fault Hazard Category	**Issue**	**I1C1**	**I2C1**	**I2C2**	**I3C1**	**I3C2**	**I3C3**
Driver (cont.)							
Override of AHS	**Safety:**		May increase accident potential	Increased collision potential	Same As I2C1	Same As I2C2	Same As I2C2
	Throughput:			Possible traffic slowdown			
	notes:	Minimal to no consequences since driver is fully engaged and ready to resume manual control	Surrounding traffic notified and adjusted so the driver could move the vehicle out of AHS traffic if applicable Under normal conditions there would be minimal to no consequences	Under normal AHS operation, the "Intruder" response would be initiated and surrounding traffic adjusted so the driver could move the vehicle out of AHS traffic if applicable			
	Risk:	4D, IV	4D, IV	4D, IV			
Non-AHS Certified · Risk: 3D; III - IV	**Driver Role**:	AHS Engage Denied	AHS Transition Denied	AHS Transition Denied	AHS Access Denied	AHS Access Denied	AHS Access Denied

3.2 AHS POTENTIAL FAULT AND HAZARD CONSEQUENCES

The primary goal of an automated highway system is to provide a collision-free driving environment under normal operating conditions. A secondary goal is to minimize the consequences when operating conditions are not normal, i.e., when something does go wrong. The previous section summarized the potential faults and hazards that may occur on an automated highway. An AHS must be designed such that when single or multiple failures occur that extend beyond the range of the mitigating strategies, the severity of the consequences is minimized. The system must be "fail-soft" to minimize personal injury, vehicle damage, and system down time.

The mitigating strategies prescribed by malfunction management are designed to create a very safe system. However, as a system is being developed, there is always pressure to deviate from a top-level design. Costs need to be trimmed, deadlines need to be shortened, or perhaps the system just runs too slow with all the safety measures implemented. Therefore, it is important to understand the consequences of "cutting corners" so that the ultimate goal of a collision free driving environment is preserved.

Examining the history of interstate operations also allows for estimation of the improvements an AHS can make. Previous studies have reviewed the circumstances surrounding accidents and made assessments regarding the causal factors contributing the to crash. Removal of these causal factors are a function of the command and control capabilities of the individual RSCs, the percent participation of automated vehicles, and the degree to which the automation technology and/or vehicle inspections can eliminate existing causal factors.

Factors that may add to the accident picture are the reliability of new electronic components, and increased likelihood of multiple vehicle crashes due to the tight spacing configurations. Constants in the accident picture are environmental hazards such as obstacle/animal in the roadway and sabotage.

The goal of this section is to envision the tradeoffs between controllers: the human driver and automated technology. It deals with the question, if something does go wrong, what will happen. What type of crashes will occur on an automated highway system and under what conditions? Technology may be able to eliminate or drastically reduce human error, but can it emulate good driving skills without creating new errors of its own. Interstate operations are reviewed to:

- show the consequences of unmitigated malfunctions in terms of occupant
- injury and vehicle damage severity
- provide design guidelines for an AHS
- quantify benefits of an AHS.

3.2.1 AHS Crash Analysis

3. 2. 1.1 Crash Analysis Databases

An automated highway is an extension of and a major enhancement to the existing roadway system. The representative system configurations (RSCs) defined in section 3.0 of the Overview Report describe infrastructures very similar to our present day interstate highways. Therefore, the analysis of conventional highway accidents is restricted to interstate crashes only. This data provides the basis for quantifying the design risks and the AHS benefits. Where crashes other than those occurring on interstates are examined, the exception is noted.

Three accident data bases are available to describe the accident picture on interstates in terms of the frequency of accident types and their accident characteristics. The data files are:

- General Estimates System (GES)
- Crashworthiness Data System (CDS)
- Fatal Accident Reporting System (FARS)

The GES data file is a nationally representative probability sample of police reported crashes that occur annually in the United States. GES cases are sampled from police reported crashes that result in a fatality, injury or major property damage. GES data are restricted to information provided on the police report. The police reports are reviewed by a data coder and translated into GES variable codes. The GES sample size is moderate, therefore reliability is greatest for high-frequency crash types and least for low-frequency crash types.

The CDS data file represents a probability sample of police reported accidents in the United States. These accidents are characterized by a harmful event such as property damage or personal injury and must involve passenger cars, light trucks, or vans which were towed from the scene due to damage. CDS data is obtained from a review by accident researchers of police reports, crash investigations and interviews of all persons involved in the crash. CDS accident cases are a subset of the GES accident cases.

FARS is a census of data on all fatal crashes in the US. FARS contains descriptions of each fatal crash using variables characterizing the accident, vehicle and people involved. The Police Accident Report is the primary source of information on each fatal crash, although supplementary information is also used, such as coroner's reports on blood alcohol content.

GES data is used to describe the general characteristics of an accident, i.e. manner of collision, weather, road surface condition, and location. Since CDS data is derived from several sources and is reviewed by accident researchers, CDS data is used for specific 'accident details such as occupant injury severity, vehicle damage and where applicable, the change in velocity (AV) of a vehicle involved in a collision. Based on their sampling criteria, both CDS and GES represent accidents that are more severe than the general accident population of police-reported and non-police-reported accidents. FARS data is used to identify the most serious accidents on interstates. Fatalities on interstates are under-represented in GES since they are low-frequency events (0.06 percent of all police reported accidents).

The numbers reported in table 2-11, and throughout this report, are weighted estimates for GES data and actual police reported numbers for FARS data. For accident related variables (i.e., number of accidents, # vehicles involved) the numbers reflect one entry per accident. For vehicle/driver related variables (i.e., accident type) or accident variables crossed with vehicle variables, the numbers represent one entry per vehicle. Therefore the term "accident" or "crash" is used to discuss general information common to all vehicles involved in a mishap and the term "collision" is associated with each individual vehicle, since one vehicle may experience different crash characteristics than another vehicle involved in the same accident.

3. 2. 1.2 Scope and Severity of Interstate Crash Problem

The magnitude of the interstate collision problem and its significance with respect to the overall number of accidents in the United States is shown in table 2-11. The total number of police reported accidents in the U.S. is estimated by the 1992 GES data file to be 5,992,937 accidents. Interstate collisions represent 4.8 percent of the total accident picture; 1.3 percent of the interstate accidents result in a fatality.

Table 2-11 Scope of Interstate Crash Problem

Data file	Category	#Accidents	# Vehicles
GES	All Crashes	5,992,937	10,265,147
	Interstate Crashes	287,453	502,123
FARS	All Fatal crashes	34,928	58,605
	Fatal Interstate Crashes	3,788	6,420

Figure 2-4 shows the manner of collision, i.e. the orientation of the vehicles in a collision, for all accidents on interstates and fatal accidents on interstates. Collisions that do not involve another motor vehicle in transport (rollovers, roadway departures) are the most common manner of collision on interstate highways - they represent 42 percent of all interstate accidents and 69.4 percent of all fatal interstate accidents. Rear-end collisions rank second (36 percent of interstate accidents, but only 12 percent of fatal accidents) and angle/sideswipes rank third.

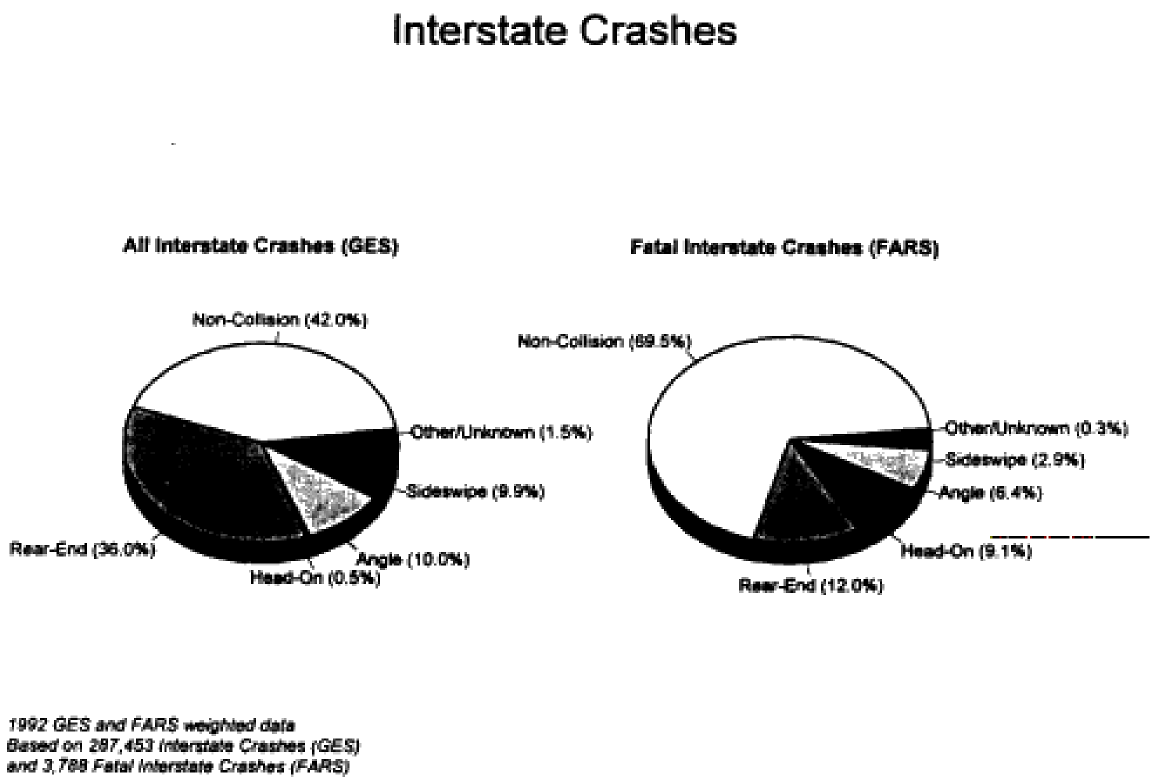


Figure 24. All Interstate Crashes and Fatal Interstate Crashes

Table 2-12. GES and FARS "Non-Collision" Crashes

Crash Type	GES	FARS
Rollover	11,806 (9.8%)	736 (28.0%)
Collision with Traffic Barrier or Bridge Structure	42,330 (35.1%)	644 (24.5%)
Collision with Non-Fixed Object	20,973 (17.4%)	672 (25.5%)
Collision with Fixed Object	30,261 (25.1%)	533 (20.3%)
Other Non-Collision	14,672 (12.2%)	47 (1.8%)
Total	120,746 (100.0%)	2,632 (100.0%)

Table 2-12 breaks out "non-collision" category from figure 2-4. Collisions that do not involve another motor vehicle in transport consist of single vehicle accidents that are barrier related, roadside departures (rollovers), or involve an objed or animal in the roadway. These accident types are treated individually in this analysis. For GES data the most common "non-fixed object in the roadway" is an animal and for FARS data it is a pedestrian.

Table 2-13 ranks the individual crash types by frequency of occurrence of fatal injuries. The most common crash type to result in a fatal injury is the "not a collision with a motor vehicle in transport".

Table 2-13. Ranking by Occurrence of Fatalities on Interstates

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

3. 2. 1.3 Crash Analysis Approach

Our approach was to review the existing knowledge of highway and vehicle safety to provide design guidelines for an AHS. In this light, the team examined "relevant" conventional highway crash types that are most likely to occur in future AHS scenarios if design standards are compromised. These scenarios were envisioned within the context of the six general RSCs. The analysis deals with crash types that may occur where single or multiple fault/hazards occur or where there are manually ddven vehicles mixed with automated vehicles.

The major interstate crash types are:

· Rear-End
· Barrier-Related
· Run-Off-Road
Object/Animal in Roadway
Lane Change/Merge
· Driver Impairments
Mixed Vehicle Type

The analysis results depict the accident types in terms of the severity of consequences. The likelihood of occurrence is presented for conventional highways with an estimate of causal factors that may be eliminated through automation. Measures of effectiveness for AHS performance are vehicle occupant injury level and vehicle damage severity. For each crash type, an attempt is made to envision the improvements made possible by an AHS and the potential for unique causal factors that may lead to each crash type. The intent of this effort is to raise AHS design considerations, estimate potential AHS benefits, and provide support information for tradeoff issues such as safety vs. cost and practicality for barriers, breakdown lanes, safety gaps, bVs, etc.

3.2.2 Rear-End Crash Analysis

The rear-end crash is the second most common crash type on today's interstates. Interstate rear-end crashes represent 36 percent of interstate accidents, and 12 percent of fatal accidents. Vehicles on an AHS will be traveling at high speeds with close headways. The demand for increased throughput will drive speeds and headways to their limits. Under normal operations, with sound safety practices, this will be a collision free environment. However, in an unmitigated failure mode where vehicles are tightly packed, the rear-end crash will probably be the most frequent AHS crash type. Rear-end crashes are examined to:

- understand the causes and circumstances of rear-end crashes to aid designers in avoiding the occurrence of this crash type

- envision unique causal factors that may lead to rear-end crashes on an AHS

- estimate benefits of an AHS in terms of eliminating causes of rear-end crashes

- establish relationship of/~V (change in vehicle velocity) to injury severity and vehicle damage for striking and struck vehicles

The applicablitiy of the CDS's algorithms to calculate ,~V for the vehicles involved in rear-end crashes makes this crash type particularly important to study. CDS data files provide/~V estimates for stdking and struck vehicles involved in rear-end crashes, along with occupant injury and vehicle damage information. These variables provide a means to represent injury levels and damage severity as a function of AV. This information can be used to establish guidelines for "tolerable" AVS for AHS accidents which can then be used to determine safe gap distances between vehicles traveling at high speeds with short headways.

The GES and CDS data filters used to characterize rear-end crashes are described in appendix C.

3.2.2. 1 Rear-End Crashes Resulting from AHS Unique Situations

An automated highway environment has tremendous potential for eliminating rear-end crashes due to driver error, vehicle defects, and environmental conditions. However, the technology required to remove existing causes of accidents has the potential to fail and cause accidents in its own right. Table 2-14 depicts AHS unique situations that may lead to rear-end crashes.

All of the representative system configurations (RSCs) have situations that may lead to rear-end collisions. Unmitigated single or multiple fault/hazards that affect longitudinal control can easily lead to rear-end collisions when vehicles are traveling at high speeds with short headways. Obstacles or animals in the roadway are a threat not easily controlled. A sudden stop by the lead vehicle can create a situation where it is difficult for the trailing vehicle to avoid a rear-end crash, and most alternatives are less attractive. Crashes or Sabotage that damage communication equipment may compound the problem. The "brick wall" theory may actually be realized by unprotected barrier end treatments or bridge abutments.

In addition to the fault/hazard elements that may lead to rear-end collisions, mixing of manual and automated vehicles may pose a unique causal factor for rear-end crashes. Manual vehicles have a much greater reaction time than automated vehicles. Clinical studies have been conducted to obtain estimates for vehicles that were operated manually and automatically. The tests showed the reaction time for an automated vehicle is approximately 0.3 seconds; this number may be lowered as sensor and technology improvements are made. Reaction time for a manually operated vehicle is approximately 1.75 seconds, although this is highly dependent on the individual driver. Any situation on an automated highway that involves an automated vehicle leading a manual vehicle has potential for the automated vehicle to brake suddenly and the manual vehicle being unable to react in time and consequently impact the rear end of the automated vehicle. Table 2-14 summarizes scenarios that may lead to read-end type collisions and the RSCs where these situations may occur.

Table 2-14. AHS Scenarios with Rear-End Collision Potential

Situation -> Rear-End Collision	Applicable RSC's
manual vehicle trailing an automated vehicle that suddenly brakes or stops Reaction time for automated vehicle: -0.3 sec. Reaction time for manual vehicle: ~1.7 sec. (*)	I1C1 12C1 & 12C2 Transition lanes
improper lane change by manual or automated vehicle	IIC1
improper merge into transition lane	12C1 & t2C2
reduced visibility conditions	IIC1, 12C1 & 12C2 Transition lanes Sensor dependent for remaining RSCs
system traction degraded due to surface or weather conditions	I1C1 12C1 & 12C2 Transition lanes
lead vehicle deceleration rate :, trailing vehicle's maximum deceleration capabilities due to differences in vehicle braking characteristics or insufficient reaction time of trailing vehicle	12C1, 12C2 13C1, 13C2, 13C3
vehicle sensor, computer, communication or data link failures	12C1, 12C2 13C1, 13C2, 13C3
roadway sensor, computer, communication or data link failures	12C1, 12C2 13C1, 13C2, 13C3
multiple malfunctions occurring simultaneously	12C1, 12C2 13C1, 13C2, 13C3
manual backup mode is in effect (particularly if ddver is impaired or incapacitated)	12C1, 12C2 13C1, 13C2, 13C3
roadway obstacle present or incident occurs	All RSCs
vehicle longitudinal control and/or actuator failures	All RSCs
sabotage	All RSCs

*(Transportation Research Circular 419, 1994)

3. 2. 2. 2 Characteristics of Interstate Rear-End Crashes

Rear-end collisions aro the second most common accident type on interstate highways, yet they tend to be a low injury producing event. Rear-end crashes represent 36 percent of all interstate accidents, but only 12 percent of all fatal interstate accidents. An overview of interstate roar-end crash characteristics is presented in this section. Support data aro provided graphically in Appendix C.

Figure 2-5 presents the environmental characteristics for roar-end crashes on interstates. An overview of the general roar-end crash picture shows that most roar-end crashes occur in urban and suburban areas on dry roadways, with natural or artificial lighting and no adverse weather conditions. These characteristics suggest that the more congested areas aro scenes for roar-end crashes and that the roadway and environmental components of the system aro not major contributors.

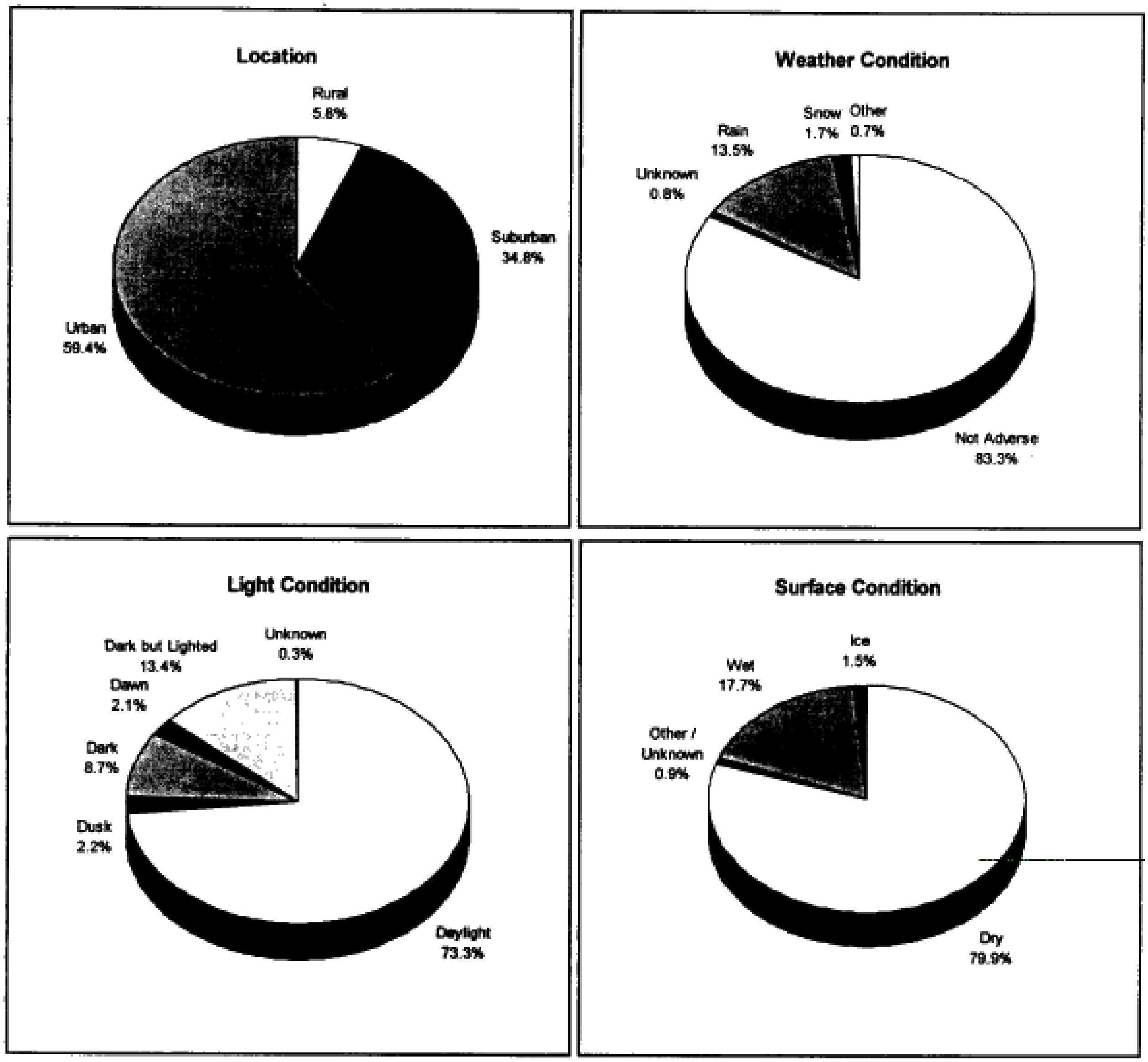


Figure 2-5. Environmental Characteristics for Interstate Rear-End Crashes

Figures 2-6 and 2-7 show the severity consequences for interstate rear-end crashes. Approximately 91.0 percent of rear-end crashes result in no injury or a possible injury as the most severe injury level reported for any occupant in the vehicle. The data indicate fatal injuries occurring at urban crash sites, but not at suburban or rural locations for the 1992 sampling period. However, information is limited to police reported data, so injuries treated later may be omitted. CDS data provide a better picture of injury levels associated with a crash. An additional concern with rear-end crashes is the potential for a struck vehicle to rotate into another lane which can lead to a crash type with more severe consequences.

Interstate rear-end crashes generally result in minor to moderate vehicle damage. Approximately 42 percent involve moderate to severe property damage.

Rural locations have a higher frequency of crashes with severe (disabling) vehicle damage, although almost half have minor damage. Very few rear-end crashes result in no vehicle damage.

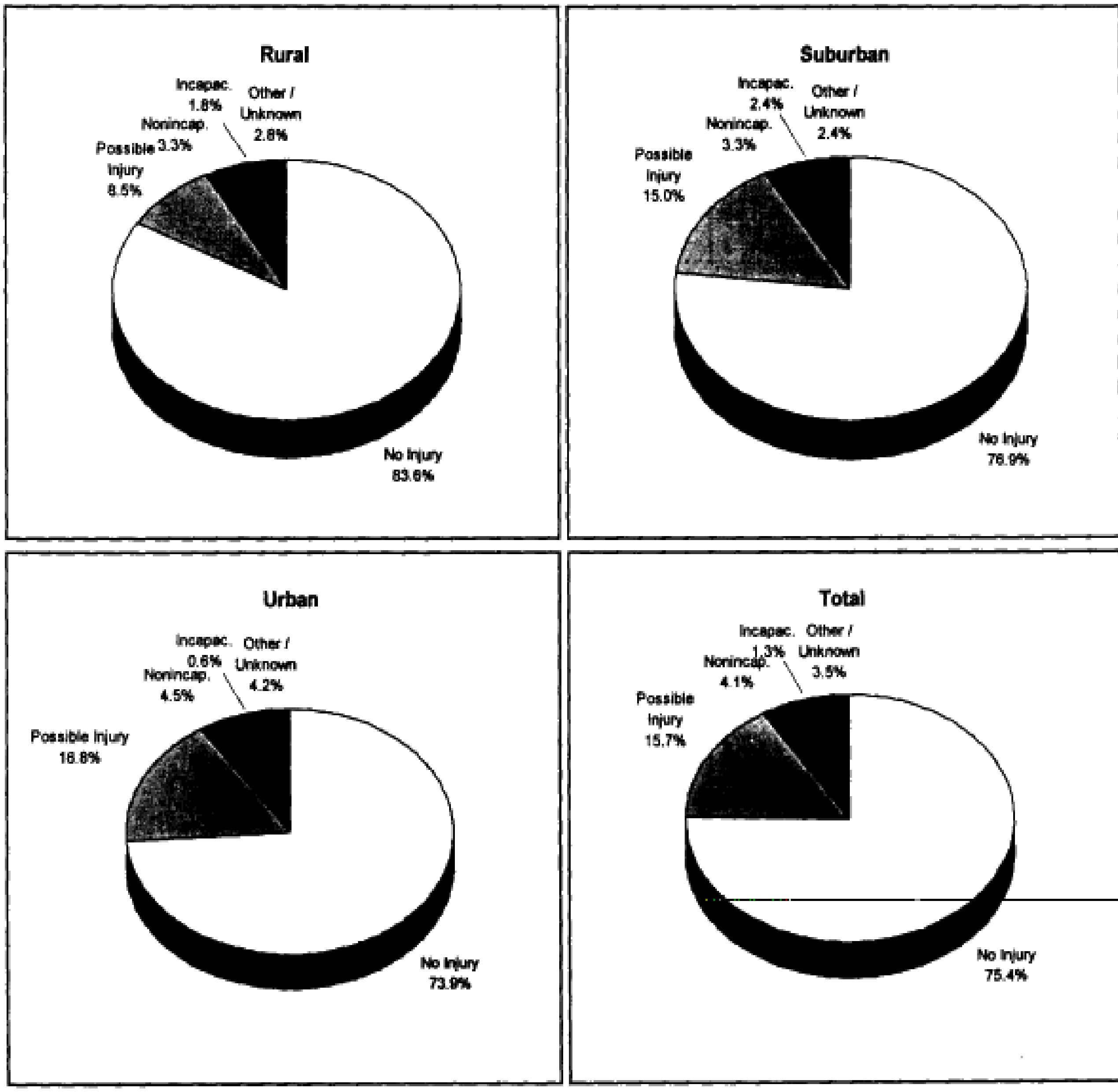


Figure 2-6. Occupant Injury Severity by Location for Interstate Rear-End Crashes

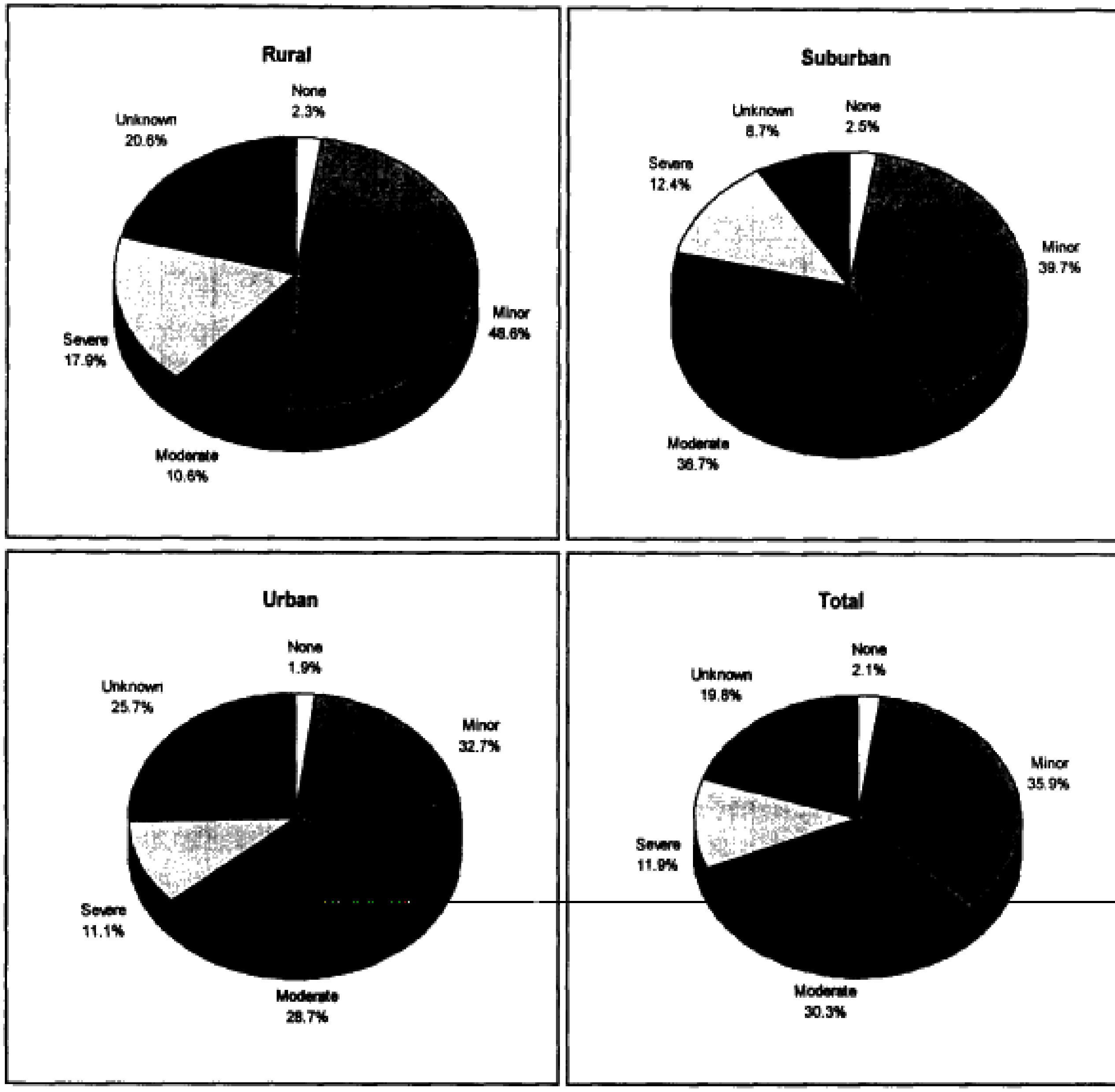


Figure 2-7. Vehicle Damage Severity by Location for Interstate Rear-End Crashes

Data highlights from tables presented in appendix C are summarized below:

1. Injury Severity by Road Surface Condition: Rear-end crashes on snow or slush have the highest frequency of no injury. Rear-end crashes on ice are more apt to have more "possible" to "incapacitating" injuries. Dry road conditions have the highest occurrence of fatals.

2. Vehicle Damage by Road Surface Condition: Minor vehicle damage is most common for rear-end crashes on snow or slush covered roads. Moderate to severe vehicle damage is more common on dry or wet roads.

3. Number of Vehicles Involved by Location: Urban interstate locations are more likely to have multiple rear-end crashes - one third involve 3 or more vehicles. Approximately 80 percent of rural and suburban interstate rear-end crashes involve 2 vehicles.

4. Time of Day by Location: Peak driving hours are a common time for interstate rear-end crashes - the highest frequency occur during the 3-6 pm time slot.

5. Vehicle Defects by Vehicle Role: The majority of vehicles (93.6 percent) involved in interstate rear-end collisions are reported as free of defects that may have contributed to the cause of the crash. For those vehicles with defects, the most commonly failed component for striking vehicles are brakes and for struck vehicles are tires.

6. Violations Charges by Vehicle Role: Approximately 34 percent of the drivers of striking vehicles are charged with a violation, as opposed to 5 percent of the drivers of struck vehicles. Drugs are the most common offense charged to striking vehicle drivers.

3.2.2.3 Review of Causal Factors for Rear-End Crashes

A clinical analysis of 74 rear-end crashes on all roadways was conducted by Calspan for a collision avoidance program completed under contract to NHTSA. The report (Knipling, 1993) shows that the primary causal factor for rear-end crashes is inattention to the driving task for the driver of the striking vehicle. The term "driver inattention" in this study broadly applies to situations where a conscious, unimpaired driver does not properly perceive, comprehend, and/or react to a crash threat. Driver inattention includes preoccupation, distraction (inside or outside the vehicle) and improper lookout.

A second major causal factor for rear-end crashes is "following too closely", which in many cases may be combined with "driver inattention". The combined causal factors of driver attention and following too closely account for 82 percent of the rear-end crashes. The remaining causal factors, which account for 7.2 percent of the cases, are:

- alcohol involvement
- poor judgment
- encroachment of other vehicle
- vehicle failure (brake loss)
- driver's vision obscured
- icy road (vehicle unable to stop)

Clearly, an automated system that can remove driver error from the driving task would be highly successful in reducing the frequency of occurrence of rear-end crashes, assuming that the automation system does not replace the driver error causal factors with its own set of unique AHS causal factors.

3.2.2.4 Injury Severity and Vehicle Damage as a Function of Δ V

Rear-end crashes are the most common type of vehicle-to-vehicle accident on interstates and due to close vehicle spacing will probably be the dominant crash type on an AHS. The primary measure of collision impact severity for rear-end crashes is quantifiable in terms of the change in velocity (Δ V) for the vehicles involved in rear-end crashes and is available in the CDS data files. The Δ V information can be related to occupant injury and vehicle damage severity, to estimate "tolerable"ΔV levels for collisions on an AHS. Once "tolerable"Δ Vs are obtained, "safe" headways for travel speeds and maximum deceleration of a lead vehicle can be calculated.

Two primary measures of effectiveness for an AHS are occupant injury and vehicle damage severity. In the CDS data file, injury severity is described by the Abbreviated Injury Scale (AIS), and the metric of vehicle damage chosen for this analysis is the extent of vehicle crush.

The Abbreviated Injury Scale is a short-hand way of objectively describing the nature and severity of injuries sustained in traffic accidents. AIS classifies injuries by their threat to life; it is not a rating of associated pain or recovery time. Very few injuries are rated on the AIS scale as "maximum" or "untreatable". However, it is possible for a victim to die as a result of serious, severe or critical injuries. The AIS codes, their description and examples of injuries in each class are presented at the end of this section in table 2-15.

Vehicle damage is described in terms of extent zones. Extent zones provide a generalized description of vehicle residual deformation, that is, they represent the segment of the vehicle into which the crush damage protrudes. The extent zones for a passenger vehicle are briefly described here, for a detailed discussion the reader is referred to the Collision Deformation Classification Training Manual (Hendricks, 1981).

Front extent zones 1-5 are five equal zones obtained by dividing the longitudinal distance from the front most point of the vehicle to the centerline of the base of the windshield. Zone 6 represents the longitudinal width (depth) of the windshield. Zones 7 and 8 are two equal zones that divide the distance between the windshield top molding and the B-pillar, i.e., the front door latch pillar. Zone 9 is everything rearward of the B-pillar. For rear extent zones, the process is reversed. Zones 1-5 are five equal zones dividing the distance from the rear most point to the base of the rear window; zone 6 is the depth of the rear window; zones 7 and 8 equally divided the rear window top and the B-pillar; zone 9 is everything forward of the B-pillar.

CDS data for a set of straight front-to-back rear-end collisions with little or no offset are selected to examine a typical AHS type of accident and to assess injury levels and vehicle damage at varying AV levels. The selected cases are represented by:

- crashes involving two passenger cars where no other objects are contacted. Situations where the vehicle is involved in a rear-end collision and subsequently strikes a barrier or some other vehicle that may cause the occupants to suffer greater injury, not due to the rear-end collision, are eliminated.

- No tellover or fire codes - eliminates crashes where occupant injuries and/or vehicle damage may be greater due to some other non-collision event.

- Accident type is "Same Trafficway, Same Direction" where the struck vehicle is either stopped, moving at a slower speed or decelerating or experiencing contrel/traction loss or maneuvering to avoid a collision with a vehicle, object or animal.

- General Area of damage is "front" or "back" to eliminate angular collisions that may develop large lateral velocities.

- Total damage distribution is a "wide" to eliminate crashes where there is a narrow impact area or a sideswipe - this greatly affects the deformation extent zone data. If the striking vehicle contacts the side/rear of the struck vehicle and rides up the side of the struck vehicle then the extent zone is large but is not representative of major vehicle damage.

The maximum occupant injury in each vehicle relative to the ΔV experienced by each vehicle is presented in figures 2-8 through 2-11 for both the striking and struck vehicles. Occupant injury is expressed in terms of AIS in figures 2-8 and 2-9 and required treatment in figures 2-10 and 2-11. As shown in the GES data, rear-end crashes tend to be a low injury producing event and the occupants of the striking vehicle are more prene to injury than the occupants of the struck vehicle.

Figure 2-8 shows that for the striking vehicle, as ΔV increases, the frequency of "not injured" decreases and the frequency of minor and moderate injuries increases. Also for striking vehicles, moderate injudes begin to appear in the 9.7 to 16.1 kph (6 to 10 mph) ΔV range. Injuries resulting from crashes with greater than 32.2 kph (20 mph) AV have a wide range of severity distribution. For struck vehicles (figure 2-9), the trends are not as clear, but serious injuries begin to appear in the 17.7 to 24.1 kph (11 to 15 mph) ΔV range.

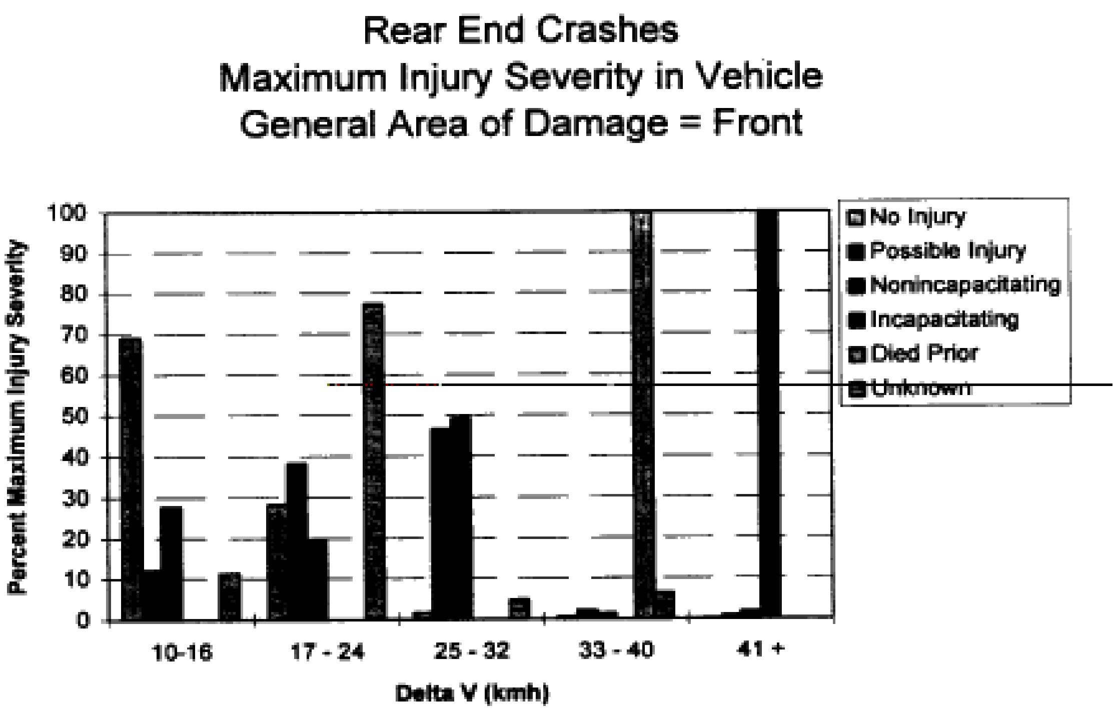


Figure 2-8. Injury Severity by AV for Striking Vehicles in Rear-End Crashes

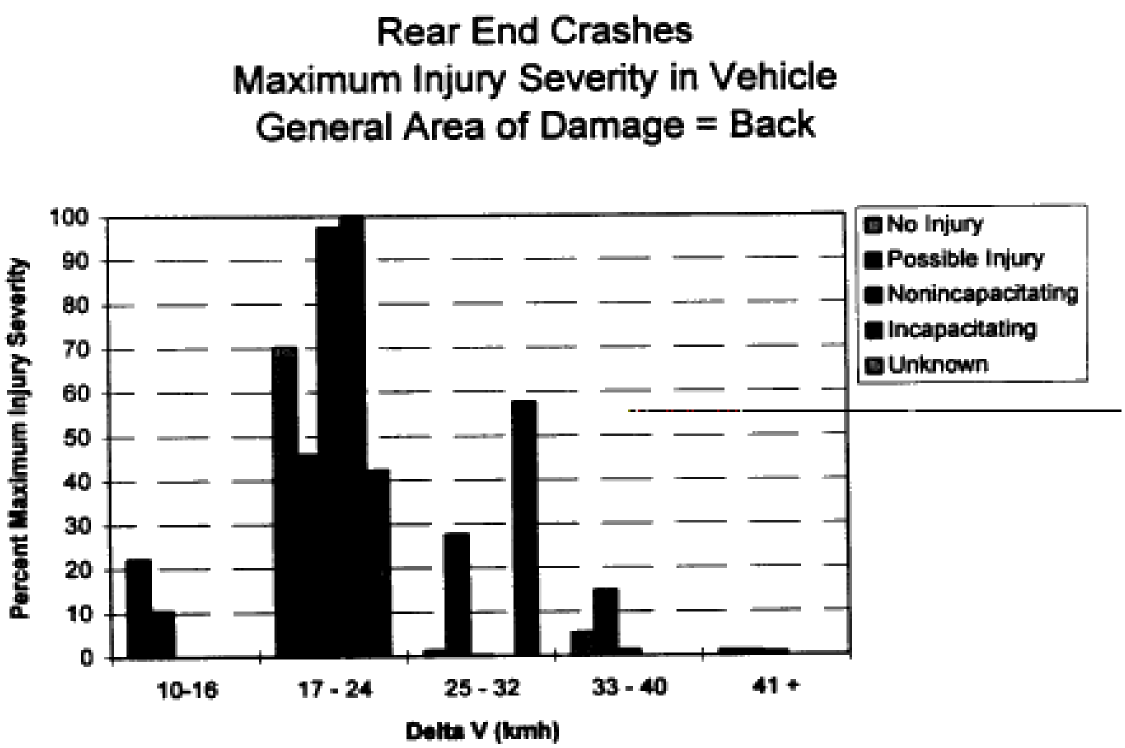


Figure 2-9. Injury Severity by AV for Struck Vehicles in Rear-End Crashes

In terms of medical treatment, figures 2-10 and 2-11, vehicle occupants are being transported to a hospital, treated and released as a result of crashes in the 9.7 to 16.1 kph (6 to10 mph) AV range. Vehicle occupants are being hospitalized for injuries resulting from crashes starting in the 17.7 to 24.1 kph (11 to 15 mph) ,ΔV range. This not only implies the seriousness of the incident in terms of occupant injury, but also the amount of time necessary to clear the accident scene, and the perceived safety of the automated highway system.

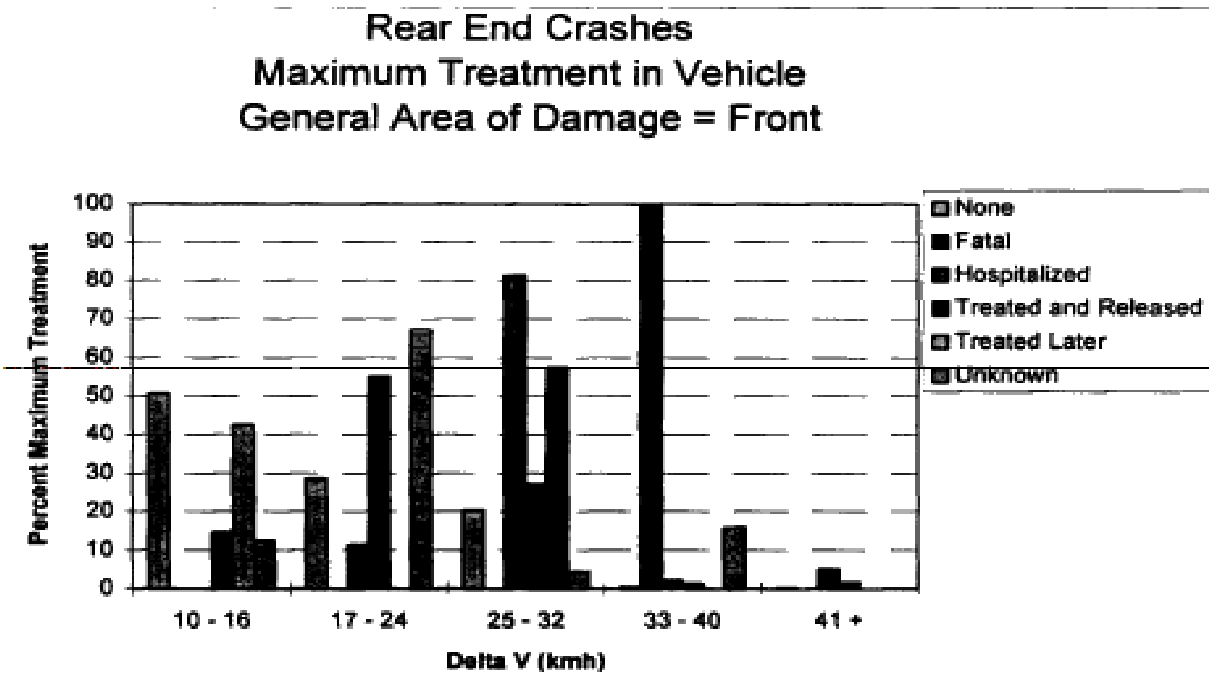


Figure 2-10. Medical Treatment by AV for Striking Vehicles in Rear-End Crashes

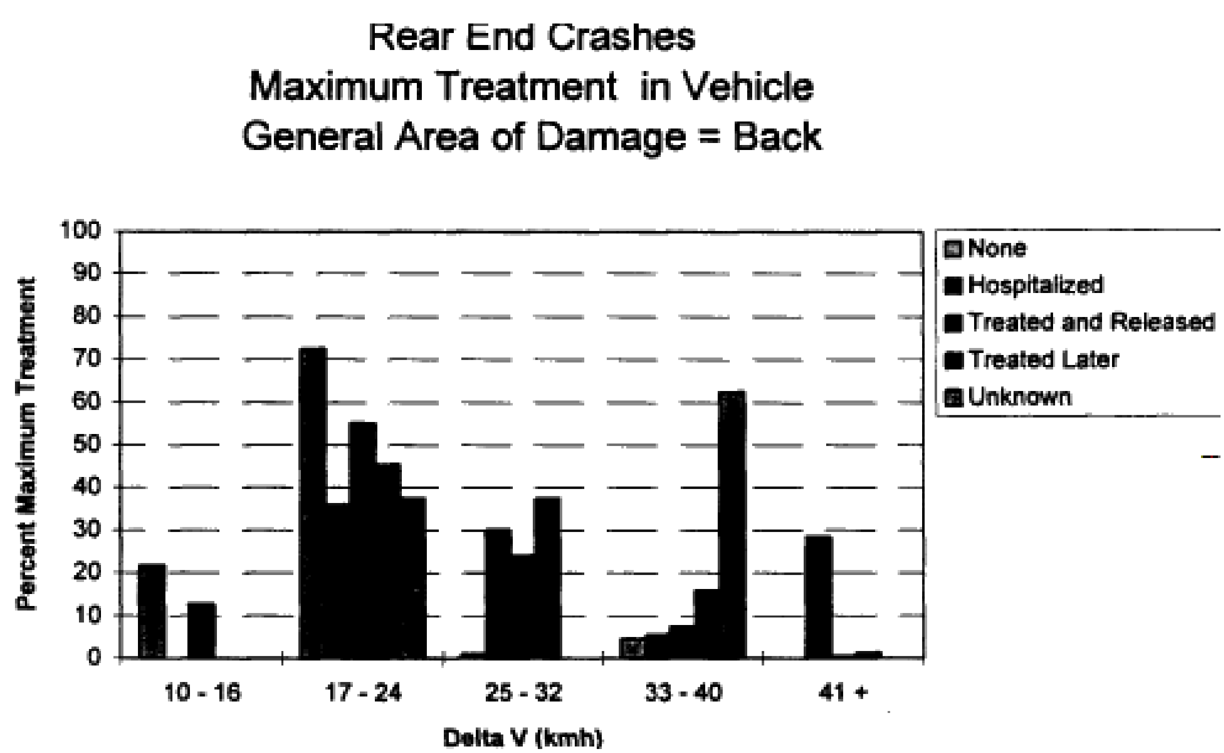


Figure 2-11. Medical Treatment by AV for Struck Vehicles in Rear-End Crashes

Fatal injuries appear for occupants of striking vehicles in the 33.8 to 40.2 kph (21 to 25 mph) ΔV range. The highest injury level for occupants of struck vehicles is "serious" - which occurs in the 17.7 to 24.1 kph (11 to 15 mph) ΔV range. The maximum injury for each vehicle occupant as a function of ΔV iS shown in figures 2-12 and 2-13 for restrained and unrestrained occupants. The highest injury level for restrained occupants is "moderate", only unrestrained occupants are reported as having serious or fatal injuries. A restrained occupant is defined as someone that is using a passive or active belt system or is protected by a deployed airbag.

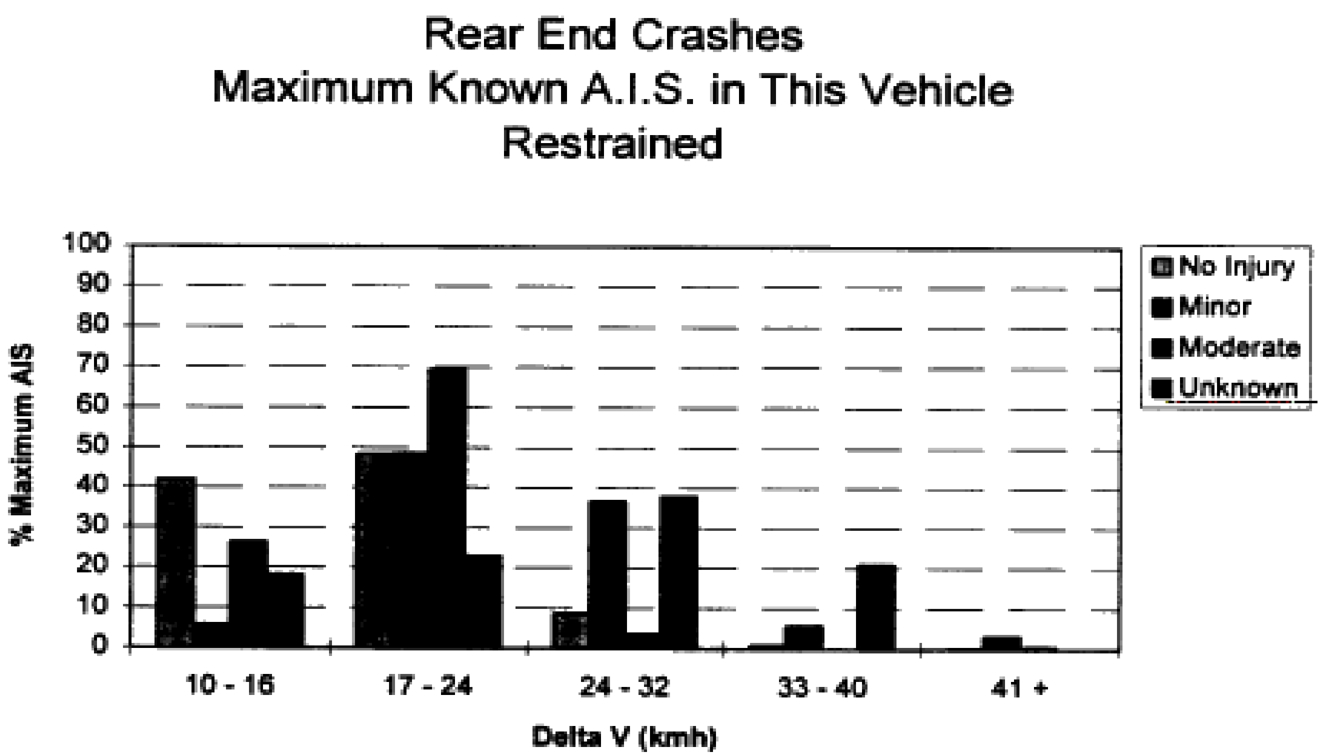


Figure 2-12. Injury Severity by AV for Restrained Occupants of Vehicles in Rear-End Crashes

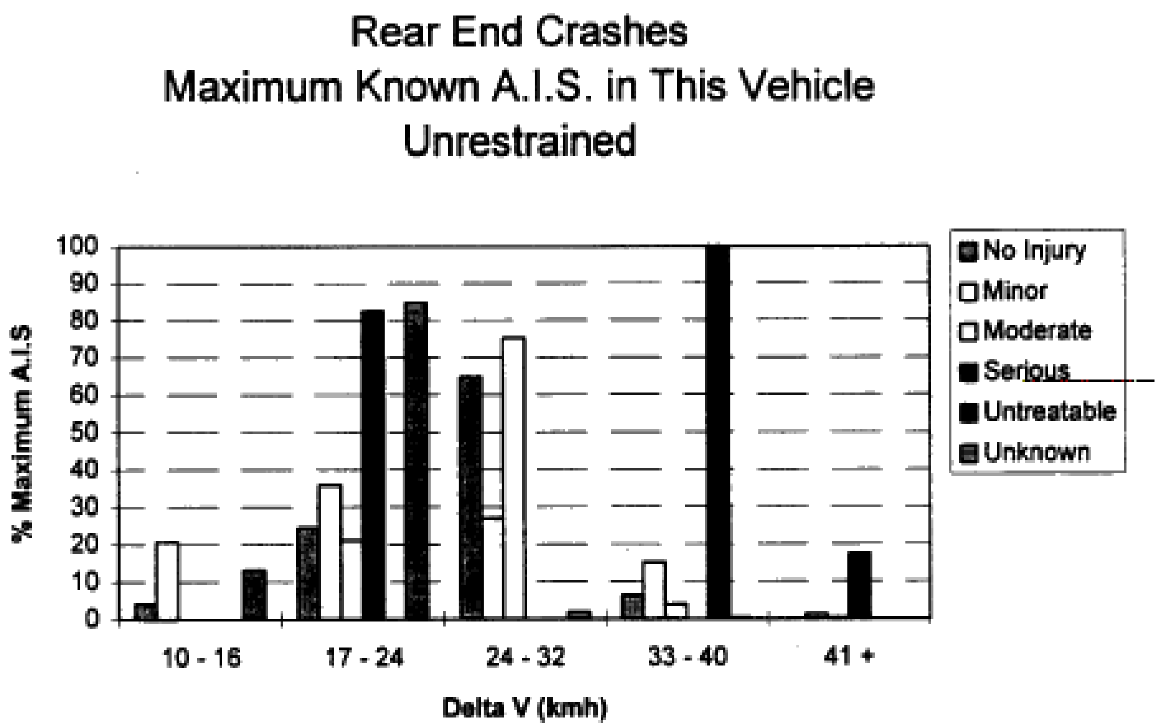


Figure 2-13. Injury Severity by ΔV for Unrestrained Occupants of Vehicles in Rear-End Crashes

The extent of vehicle damage as a function of/~V is shown in figures 2-14 and 2-15. Vehicle damage exhibits a more obvious relationship with ΔV than occupant injury - probably due to vehicle occupants having a wide range of existing health conditions and age factors which affect their ability to withstand an impact. For striking vehicles, damage into higher extent zones progresses somewhat linearly with increasing ΔV. Crush into extent zone 3 is the highest degree of damage recorded for striking vehicles and residual damage into extent zone 3 begins in the 17.7 to 24.1 kph (11-15 mph)ΔV range. Struck vehicles exhibit higher extent zone damage than striking vehicles. This is probably an artifact of the definition of extent zones, since vehicle rear overhangs tend to be much shorter than vehicle front overhangs.

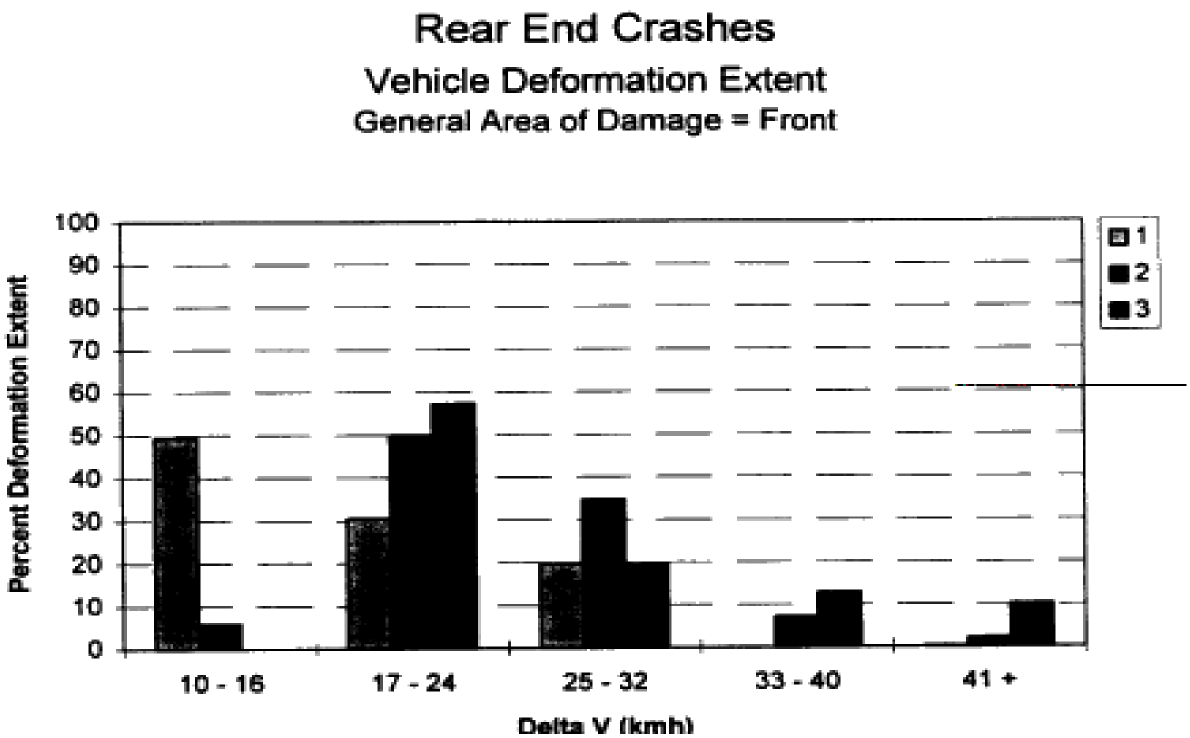


Figure 2-14. Deformation Extent by ΔV for Striking Vehicles in Rear-End Crashes

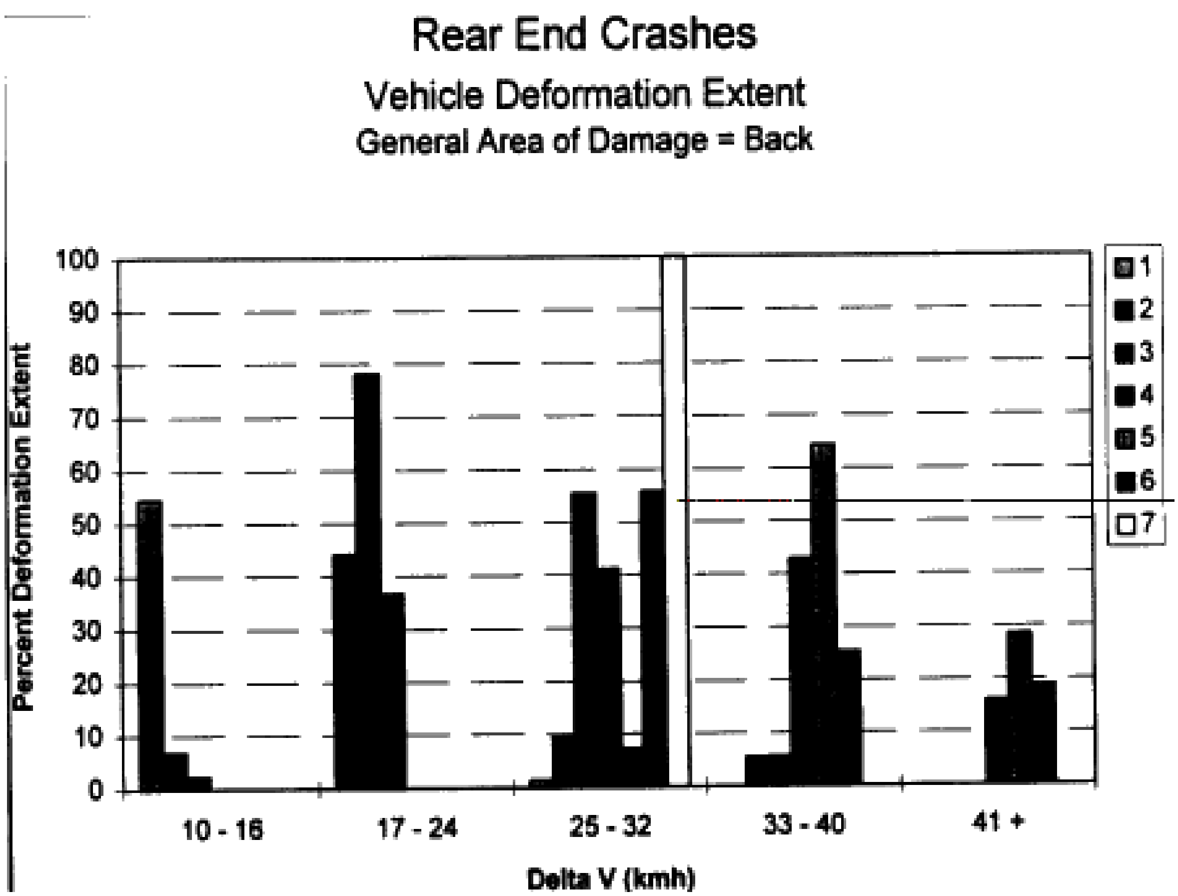


Figure 2-15. Deformation Extent by ΔV for Struck Vehicles in Rear-End Crashes

Table 2-15. Injury Examples for Abbreviated Injury Scale (AIS}

AIS Code	Injury Examples
1 Minor	Whiplash Minor skin abrasions, contusions and lacerations Rib fracture (1 rib) Iris, retina lacerations Nose fracture (closed) Teeth dislocation or loosening or fracture Joint sprains, contusions
2 Moderate	Cerebral concussion Internal organ contusion, minor laceration Rib fracture (2-3 ribs) Joint dislocation or laceration into joint Major facial laceration (>10 cm long and into subcutaneous tissue) Minor laceration of carotid artery, jugular vein
3 Serious	Amputation at any point of upper extremity except finger Amputation below knee, entire foot Massive destruction of bone or muscles/nervous system/vascular system Major facial laceration with blood loss > 20% by volume Minor laceration of pulmonary artery or vein
4 Severe	Lower extremity amputation above knee Major arterial injury such as rupture, complete transection, segmental loss, or complete circumferential involvement, blood loss > 20% by volume Major laceration of pulmonary artery or vein Severe heart contusion (hematoma)
5 Critical	Coronary artery laceration Brain stem contusion, infarction, injury involving hemorrhage Unconsciousness > 24 hours or with neurological deficit
6 Maximum (untreatable)	Multiple heart lacerations Brain stem laceration, crush, penetrating injury, decapitation Crush of substantial portions of the chest cavity including internal organs

3.2.2.5 AHS Implications and Conclusions from Rear-End Crash Analysis

- Rear-end crashes are a frequently occurring, but low injury producing, event and have a high probability of becoming an AHS accident type.
- Impact severity quantified in terms of AV and related to occupant injury and vehicle damage provides a basis for determining safe gap distances.
- Restraint systems are effective in reducing injury levels in rear-end crashes.

- Data from the causal factor analysis of rear-end collisions indicates that 82 percent of rear-end crashes are due to driver inattention and following too closely.

- The combination of automated control and vehicle system monitoring/inspection has the potential to remove 80 to 90 percent of the causal factors cited for rear end crashes such as driver error and vehicle defects.

- Likely causal factors for AHS rear-end crashes indicate the importance of the mitigating strategies prescribed in malfunction management and the value of implementing a reliable system versus a tradeoff in quality for cost or throughput quotas.

3.2.2.6 Recommendations from Rear-End Crashes Analysis

- The relationship of ΔV with occupant injury and vehicle damage for a typical AHS crash type (straight front-to-back rear end collisions) supports a recommendation that AHS collisions should have ΔVs no greater than 16.1 kph (10 mph). However, the potential for a lateral offset rear-end collision that induces rotation for the struck vehicle which may then be subject to a more severe crash type lowers this recommendation to ΔVS in the 8 kph (5 mph) range.

- All occupants of an automated vehicle should be restrained.

- Consider adding AHS relevant variable information to CDS data collection effort.

- CDS data set should be expanded to included general descriptive information, or perhaps have a key to link the cases back to their original GES case number to obtain this information.

- Algorithms should be developed to estimate ΔVs for multiple rear-end collisions and accident types other than rear-end collisions.

- Update and enhance CDS User's Guide.

3.2.3 Barrier Crash Analysis

The use of traffic barriers to separate automated and manually controlled vehicles is examined in this section. A primary argument supporting the use of barriers is to prevent the intrusion of vehicles between automated and manual lanes in the event of an accident. The presence of a barrier, however, creates a safety hazard, as a struck barrier may cause the driver to lose control of the vehicle, particularly when traveling at high speeds. To evaluate the effect of traffic barriers on AHS safety requires both knowledge of the traffic barrier problem that exists on today's highways and AHS design requirements.

Traffic barrier crashes typically involve a single vehicle departing the roadway and striking a barrier. Barrier collisions consist of three general categories: low angle impacts, large angle impacts, and rollovers. A low-angle impact occurs when a vehicle deviates from the lane of travel and contacts the barrier. The barrier deflects the vehicle in the direction of the traffic flow. Minimal injury or damage usually result from this type of collision. Barrier sideswipes (a type of low angle impact) are most likely under-represented in accident data files as the resulting injury and damage severity is minor and consequently not police reported. A large angle collision can occur when a vehicle crosses lanes and steers into the barrier in a head-on direction, or when a vehicle drives head-on into a barrier terminal. Personal injury and property damage can be severe, particularly at high speeds. Severity of barrier terminal crashes can be reduced through the use of barrier end treatments, such as crash cushions and break-away posts. Rollovers may also result in severe injury and damage. Contact with different types of roadside barriers (e.g., a guardrail vs. a lane divider) can result in distinctively different types of rollovers (see appendix D).

The section begins with a discussion of barrier crashes that may result from AHS unique situations. The safety benefits derived from longitudinal barrier use on an AHS am reviewed, as well as barrier characteristics and impact performance relative to AHS applications. A description of the barrier systems, including guardrails or roadside barriers, median barriers and end treatments is provided in appendix D. Concluding the section is an analysis of barrier crashes on current day highways using various accident databases. The extent of the barrier crash problem (i.e., likelihood of occurrence), barrier crash characteristics, vehicle behavior and associated injury severity and vehicle damage are examined and implications for an AHS are considered.

A study of traffic barrier crashes is required to:

- envision unique AHS causal factors that may lead to traffic barrier crashes on an AHS
- assess barrier characteristics and impact performance relative to AHS applications
- understand the causal and situational factors of today's interstate traffic barrier crashes to assist designers in developing an infrastructure which avoids or reduces the occurrence and severity of this crash type
- estimate the benefits of an AHS in terms of eliminating causes of traffic barrier crashes
- address the trade-off issues associated with barriers on the 12C1 and 12C2 RSCs, given the frequency of this crash type on present day interstates

3.2.3. 1 Barrier Crashes Resulting from AHS Unique Situations

AHS technology has the potential to eliminate many of the factors that lead to traffic barrier crashes. Causal factors that may be reduced include driver misperception, driver judgment error, vehicle defects and adverse environmental conditions. The same AHS technology intended to enhance highway safety is also susceptible to system failures/malfunctions that could create new types of causal factors for traffic barrier crashes. Table 2-17 provides an overview of AHS scenarios and associate RSCs that could lead to traffic barrier crashes.

The infrastructure for the I1 category allows a mix of manual and automated vehicles to travel in the same lane on an existing freeway. Barrier use in this case would be the same as existing highway barriers. No division between automated and manual lanes is required.

The 12 infrastructure has dedicated AHS lanes as part of an existing manual freeway. Barriers in 12 would contain automated vehicles in the event of a lateral control system failure and prevent spill-over between automated and manual lanes during an accident. Spill-over would still be possible in the transition lanes, however. Research on barrier end treatment will be required to determine how to avoid making the barrier end a safety hazard for vehicles traveling in the transition lane.

The 13 infrastructure has dedicated and self-contained AHS lanes. Barriers in this system would function similarly to those on existing highways. Barrier end collision is not an issue in 13 since no transition lanes are required. Table 2-16 provides a description of the AHS infrastructure and their barrier requirements.

Table 2-16. Barrier Use Considering AHS Infrastructure

Type	Description	AHS Considerations
I1C1	No physical diversion between automated and normal lanes. Automated and manual vehicles travel in same lane on existing highway	• No median barrier required between automated/manual lanes • Potential selection/upgrading of roadside barriers and end treatments required for high AV and MVE impacts
12C1 12C2	Dedicated AHS lanes part of existing highway. Barriers separate manual and automated lanes except at transition lane locations.	• Selection/upgrading of median barriers and end treatments located between manual and automated lanes required for high AV and MVE impacts • Selection/upgrading of roadside barriers and end treatments required for high AV and MVE impacts • Selection/upgrading of median end treatments for angled impacts on both sides and for head-on impacts
13C1 13C2 13C3	AHS lanes are dedicated and self-contained. Barriers separate manual and automated lanes.	• Selection/upgrading of median barriers required for high AV and MVE impacts • Selection/upgrading of roadside barriers and end treatments required for high AV and MVE impacts

Table 2-17. Scenarios with Traffic Barrier Crash Potential

Situation --> Barrier Crash	Applicable RSCs
Result of attempted corrective actions by a manual vehicle trailing an automated vehicle that suddenly brakes	I1C1
Result of offset rear-end crash due to: manual vehicle trailing an automated vehicle that suddenly brakes or stops	I1C1
Result of side impact due to manual vehicle intruding into automated lane	12C1, 12C2
Result of malfunction during transition lane maneuvers	12C1, 12C2
Result of offset rear-end crash due to: lead vehicle deceleration rate > trailing vehicle's maximum deceleration capabilities due to differences in vehicle braking characteristics or insufficient reaction time of trailing vehicle	IIC1,12C1, 12C2 13C1, 13C2, 13C3
reduced visibility conditions	IIC1 Sensor dependent for remaining RSCs
system traction degraded due to surface or weather conditions	I1C1 Sensor dependent for remaining RSCs
vehicle sensor, computer, communication or data link failures	IIC1,12C1, 12C2 13C1, 13C2. 13C3
roadway sensor, computer, communication or data link failures	12C1.12C2 13C1, 13C2, 13C3
multiple malfunctions occurring simultaneously	12C1, 12C2 13C1, 13C2, 13C3
manual backup mode is in effect (particularly if driver is impaired or incapacitated)	12C1, 12C2 13C1, 13C2, 13C3
roadway obstacle present or incident occurs	All RSCs
vehicle lateral control and/or actuator failures	All RSCs
sabotage	All RSCs

The likelihood of AHS traffic barrier collisions increases with the occurrence of system failures/malfunctions affecting lat/long vehicle control. A quick recovery would be necessary to avoid striking a barrier system. In the event of a lateral impact of a manual or transitioning vehicle striking an automated vehicle, a fast response by the lat/long control system would be required to prevent the automated (struck) vehicle from impacting the barrier. Offset rear-end crashes also present a scenario in which an automated vehicle could be propelled into a barrier unless avoided through a tightly controlled and highly damped lat/long system response. This type of crash introduces a large error term into the lateral control system that must be corrected !nstantaneously without large overshoots that may reedirect the vehicle into another vehicle's path.

The safety benefits derived from longitudinal barrier use in AHS are as follows:

· Prevent accident spill-over between manual and AHS lanes

· Restrain AHS vehicle movement in the event of a lateral control system failure

· Prevent unauthorized/inadvertent entry into AHS lanes

· Provide fixed wall reference for vehicle lateral control system

· Provide noise barrier in urban/suburban areas

· Provide an approach consistent with current highway design and maintenance procedures

3.2.3.2 Barrier Characteristics and Impact Performance Relative to AHS Applications

Longitudinal barriers are positioned parallel to the direction of vehicle travel. They serve to protect vehicles from potential roadside hazards and safely redirect errant vehicles in the direction of the traffic flow. Longitudinal barriers are typically classified according to their deflective qualities:

1) Flexible systems - allow considerable deflection during a crash. The impact forces on the vehicle are less than those imposed by other types of barrier systems. The system is designed to contain the vehicle as opposed to redirect it. Comprised of posts connected by cable or beams, the system is designed to break away from the posts in the impact area. However, the posts outside the impact area serve to contain the vehicle. More lateral clearance is required from other objects because of the relatively large amount of barrier deflection that occurs during a crash. The use of a flexible barrier system in an AHS may not be feasible or desirable since a lateral clearance in excess of 1.5 m (5 ft) is required to accommodate dynamic deflection of the barrier. Large angle impact collisions on the AHS are not anticipated, based on narrow AHS lane widths, and this may permit the use of a more rigid barrier system with a smaller lateral clearance requirement.

2) Semi-rigid systems - are designed to provide resistance through the flexure and tensile strength of the rail. Posts near the area of impact are designed to break away and distribute the impact force to the surrounding posts. Posts outside the impact area serve to limit the amount of deflection the longitudinal structure undergoes and redirect the vehicle in the direction of the traffic flow. Lateral deflection of the semi-rigid barrier system is 0.6 to 1.5 m (2 to 5 ft) which would increase the lane width requirement in an AHS.

3) Rigid systems - are designed not to deflect during a crash. They are typically. used on medians or shoulders where shallow impact angles are anticipated to occur. At greater angles of impact, the barrier deceleration forces increase which results in increased vehicle deformation. Rigid barrier systems suffer little damage during an impact and, therefore, require minimal maintenance. A rigid barrier requires no additional space for lateral deflection and therefore is the most efficient barrier system regarding land use in an AHS. However, in the event of a large angle impact, greater personal injury and vehicle deformation typically occur with the rigid barrier than with flexible or semi-rigid barriers.

An assessment of barrier performance is summarized in table 2-18.

Table 2-18. Barrier Assessment Performance

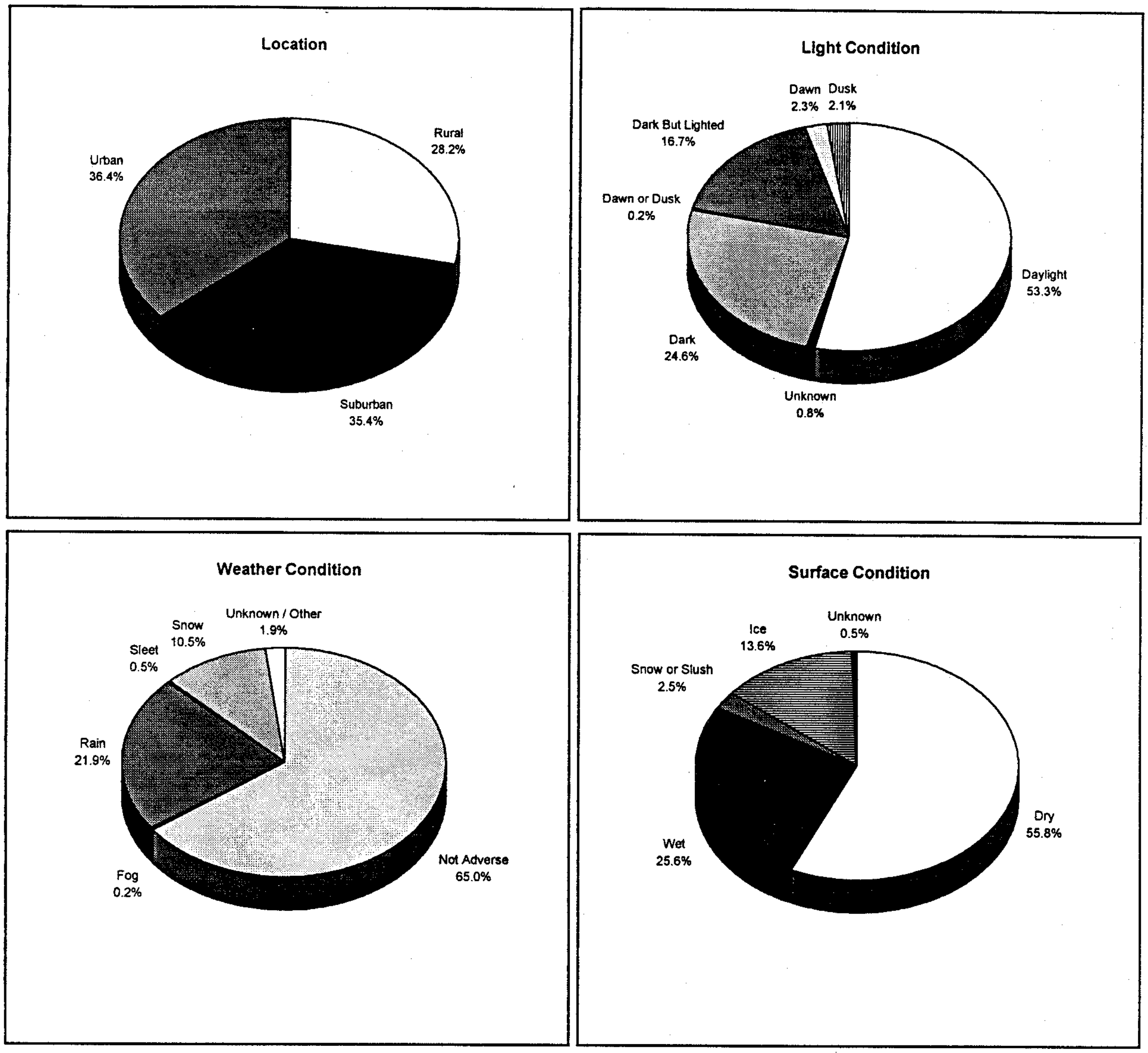
BARRIER TYPES	PERFORMANCE
Flexible Systems	- Low injury potential - Low vehicle damage potential - Large deflection - 3.4 m (11 ft) or less - Redirection limited to 2041 kg (4,500 Ib) vehicles or less - Vaulting/underdde - High post-impact maintenance - Low initial cost
Semi-rigid Systems	- Higher injury potential - Higher vehicle damage potential - Less deflection - 1.5 m (5 ft) or less - Redirection of 18,144 kg (40.000 Ib) vehicles or less (i.e., high performance systems) - Less vaulting/underride - Limited post-impact maintenance - High performance systems greater initial cost
Rigid Systems	- High injury potential - High damage potential - Minimal deflection - Some vaulting of high CG vehicles - Minimal post-impact maintenance - Low initial cost

3.2. 3.3 Characterfstics of Interstate Traffic Barrfer Crashes (GES)

According to the 1992 GES data file, there were 45,611 interstate traffic barrier crashes. This represents 9.1 percent of total interstate crashes (see table 2-11). A summary of interstate barrier crash characteristics is presented in this subsection. Support graphics for the data can be found in appendix D.

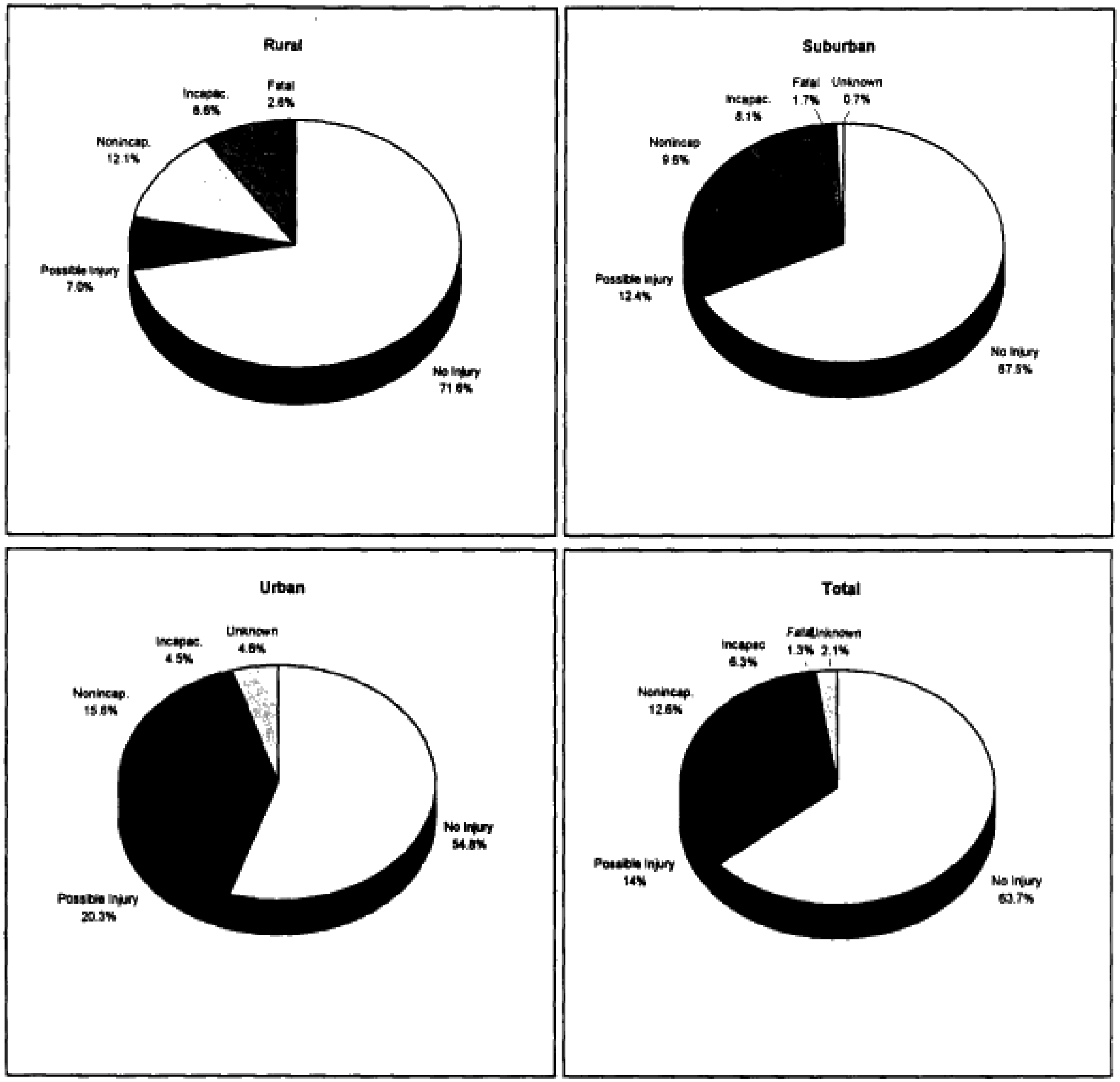
The analysis is limited to crashes occurring on an interstate where the first harmful event is a collision with an impact attenuator/crash cushion, bridge structure (bridge pier/abutment/parapet end/rail), concrete barrier or other longitudinal barrier type.

The environmental characteristics for interstate barrier crashes is presented in figure 2-16. As it can be seen, barrier related crashes are somewhat evenly distributed across urban, suburban and rural locations, with the majority occurring in urban locations (36.4 percent). The greatest number of barrier related crashes occur under daylight conditions (53.3 percent) and they occur twice as frequently as dark condition crashes (24.6 percent). Lighting a dark area appears to decrease the number of barrier related crashes by approximately 8.0 percent, compared to dark conditions. More than half of barrier related crashes occur on dry pavement (56.8 percent) and far more barrier related crashes occur when no adverse weather conditions exist (64.9 percent). It appears that adverse roadway surface or weather conditions do not significantly increase the likelihood of a vehicle striking a barrier.



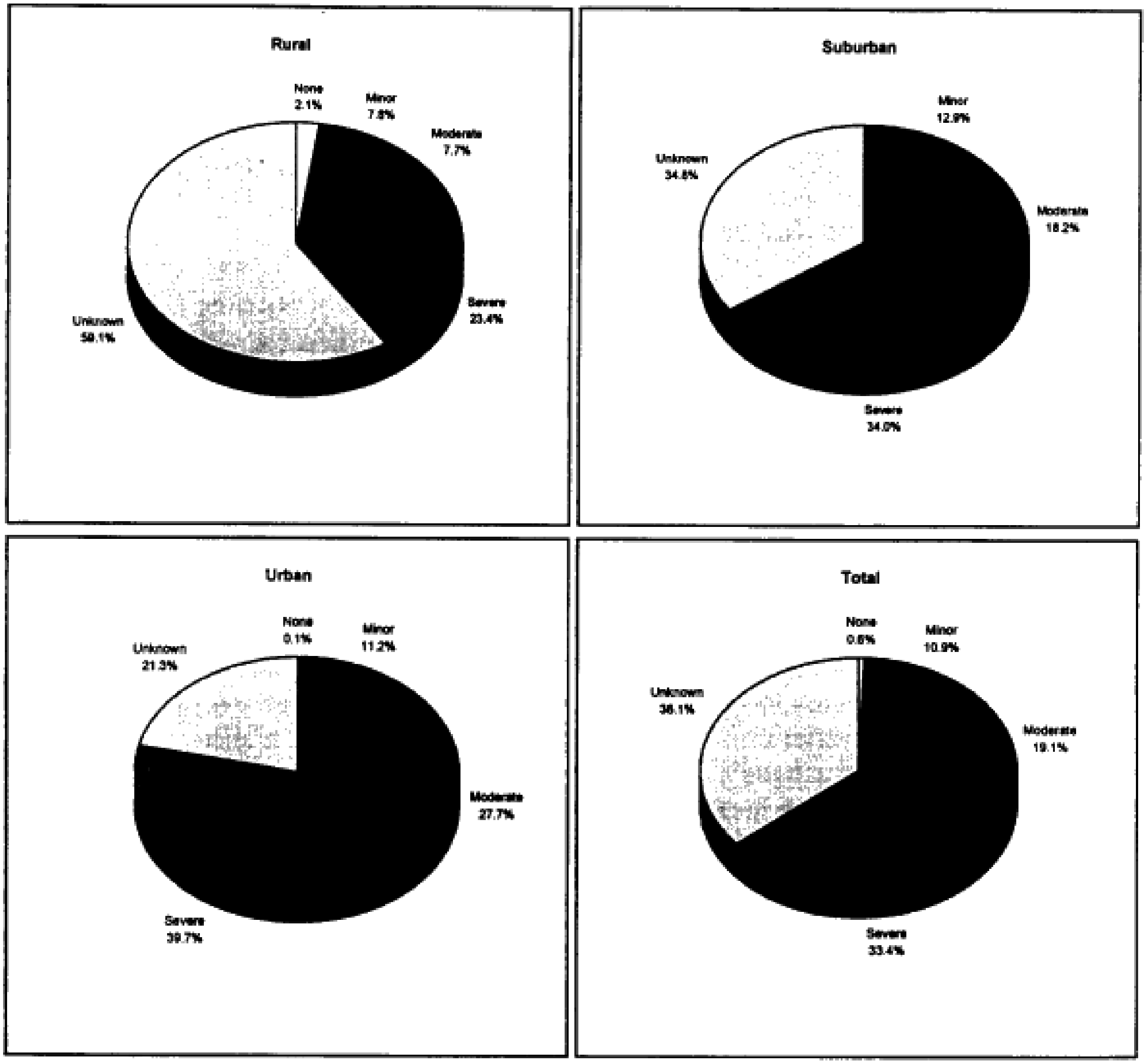
Figures 2-16. Environmental Conditions for Interstate Barrier Crashes

As depicted in figure 2-17, almost 64.0 percent of all interstate barrier crashes result in no occupant injury. Although, approximately 72.0 percent of rural barrier crash occupants are not injured, the majority of fatalities occur in rural crashes. Urban barrier crashes result in less severe injuries as compared to other locations.



Figures 2-17. Occupant Injury Severity for Vehicles Involved in Interstate Barrier Crashes

Where vehicle damage is known, approximately half of interstate barrier crashes result in severe vehicle damage (figure 2-18). The largest proportion of severe vehicle damage occurs in urban locations. Caution should be used in interpreting the results because, overall, 36.1 percent of vehicle damage severity is unknown, and reaches almost 60.0 percent in rural areas.



Figures 2-18. Damage Severity for Vehicles Involved in Interstate BarTier Crashes

Data highlights from tables presented in appendix D are summarized below:

1. Maximum Injury Severity in Vehicle by Surface Condition - The largest proportion of barrier crash fatalities occur on dry pavement. Generally, barrier crashes result in less severe occupant injuries when there are adverse road surface conditions. Over 80.0 percent of barrier crashes that occur on icy pavement do not result in any occupant injuries.

2. Vehicle Damage by Surface Condition - The largest proportion of severe vehicle damage resulting from interstate barrier impacts occurs on dry pavement. The smallest proportion of severe vehicle damage occurs under icy road surface conditions.

3. Injury Severity by Restraint Protection - Almost 75 percent of interstate barrier crashes result in no injuries when restraint systems ara used. The percentage drops to approximately 50.0 percent when restraint systems are not used: More fatal and incapacitating injuries result when restraints are not used (6.6 percent and 10.7 percent, respectively) than when restraint systems are used (0.2 percent and 2.9 percent).

4. Time of Day by Location - Overall, most interstate barrier crashes occur between 3-6 pm, however, the largest proportion of urban barrier crashes occur between midnight - 3 am and between noon - 3 pm in rural locations.

5. Day of Week by Location - The majority of barrier crashes occur on Saturday and the largest proportion (19.6 percent) of these crashes occur on urban interstates.

6. Critical Event Making Crash Imminent - Traveling over the right or left edge of the roadway accounts for approximately 27 percent of interstate barrier crashes. Loss of control due to poor road conditions (e.g., puddle, pothole, ice, etc.) contributes to 16.4 percent of interstate barrier crashes. Almost 12 percent of the barrier crashes involve the encroachment of another vehicle into the principle vehicle's lane. Nearly 6 percent of all interstate barrier crashes involve more than two vehicles. Over 5 percent of barrier crashes can be attributed to loss of control due to excessive speed.

7. Most Harmful Event - For interstate barrier crashes, the event resulting in the most severe property damage or injury is the collision with a guardrail (43.2 percent), followed by collision with a concrete barrier or other longitudinal type barrier (25.9 percent). Other harmful events include collision with a motor vehicle in transport (7.7 percent), collision with a bridge structure (4.6 percent), rollovers (1.4 percent), and collision with impact attenuator/crash cushion.

8. Rollover - Approximately 92 percent of interstate barrier crashes do not result in rollovers. The majority of rollovers that do occur are tripped by guardreils.

9. Impairment - Almost 89.0 percent of drivers involved in interstate barrier crashes are not impaired and 9.0 percent report feeling drowsy or sleepy prior to the crash.

3.2.3.4 Injury Severity and Vehicle Damage Resulting from Barrier Crashes (CDS)

CDS data files are used to gain more accurate details on occupant injury and vehicle damage severity as related to the manner in which barriers are struck by vehicles. Algorithms fo~ calculating delta V information are not appropriate for traffic barrier crashes and consequently are not included in the analysis.

Analysis of the CDS data files included two sets of restraints. In the first set of restraints (which also serve as baseline filters in the next two analyses), the data are limited to accidents involving single vehicle, right/left roadside departures, on roadways with speed limits greater than 80.5 kph (50 mph) (CDS does not code for interstates) and object contacted (highest) limited to concrete traffic barrier, impact attenuator, or other traffic barrier. An assessment of vehicle general area of damage (highest) and type of damage distribution is conducted.

The purpose of the analysis is to determine the manner in which vehicles collide with barriers.

1. Type of Damage Distribution - The majority of vehicles that strike barriers have a wide area of damage (30.7 percent), 18.0 percent have a corner damage distribution and 6.0 percent have sideswipe damage. Type of damage distribution is unknown for 43.2 percent of the vehicles.

2. General Area of Damage - The majodty (50.4 percent) of vehicles involved barrier crashes have frontal damage. Caution should be used in interpreting the results, however, since 43.2 percent of general areas of damage are unknown.

This CDS analysis focuses on barrier crashes resulting in a wide area of deformation on the front of a vehicle. The analysis examines pre-crash events, vehicle restraint usage, and injuries associated with type of barrier impacted.

1. Accident Type - Far more barrier crashes result from left roadside departure (78.2 percent) than from right roadside departure (21.8 percent). The largest proportion of barrier crashes are due to loss of control/traction (56.6 percent left and 10.1 percent right roadside departure).

2. Restraint Protection by Maximum Injury in Vehicle - Far fewer occupants are injured in barrier frontal impacts when vehicle restraint systems are used (33.1 percent) than when they are not used (16.2 percent). Restrained occupants receive more minor injuries (68.4 percent) than unrestrained occupants (52.6 percent) and less serious injuries (1.3 percent) than those who are unrestrained (28.3 percent).

3. Deformation Extent (highest) - Vehicles with a wide area of frontal damage have 37.3 percent extent zone 1 damage and 53.8 percent extent zone 2 damage.

4. Restraint Protection by Maximum Treatment in Vehicle - Major differences between treatment of restrained and unrestrained occupants include the proportion that are hospitalized (3.7 percent and 27.1 percent, respectively), fatalities (0.1 percent and 2.4 percent, respectively) and treatment later (23..6 percent and 0.0 percent, respectively).

5. Maximum Injury in Vehicle by Object Contacted (highest) - In crashes where a concrete barrier is struck, 29.2 percent of the occupants ara not injured, 65.6 percent sustain minor injuries and 2.4 percent have serious injuries. Crash attenuator collisions result in almost 42 percent minor injuries, however, 59.2 percent of resulting injuries are unknown for this group. For occupants in vehicles that collide with other types of traffic barriers (e.g. , guardrails), 13.0 percent are not injured, 44.3 percent receive minor injuries, 4.9 percent have moderate injuries and 36.8 percent are seriously injured.

6. Maximum Treatment in Vehicle by Object Contacted (highest) - The majority of vehicles impact concrete barriers (66.0 percent). Approximately 55.0 percent of occupants involved in frontal impacts with concrete barriers receive no treatment while only 14.0 percent of occupants involved in collisions with other types of barriers (e.g., guardrails) do not require treatment. Significantly fewer concrete barrier crash victims are hospitalized (2.2 percent) or result in fatalities (0.2 percent) as compared to those involved in collisions with other types of traffic barriers (39.8 percent and 1.8 percent, respectively). All crash attenuator collision occupants (1.4 percent of total frontal barrier crashes) are hospitalized.

3.2. 3. 5 Review of Causal Factors for Barrier Related Crashes

Findings of the Indiana Tri-Level study (Treat, et al., 1979) regarding causal factors for single vehicle roadway departure (SVRD) crashes with stationary objects are reviewed in this subsection. The data include all stationary objects (i.e., not limited to barrier crashes) and all roadway types (i.e., not limited to interstates). Despite the fact that the Tri-Level data sample is broader in scope, it seems reasonable to assume that its findings are relevant to a discussion of interstate barrier crashes, as many of the same causal factors are likely to be involved.

According to the Tri-Level study, the largest proportion of SVRD crashes result from human causes (86 percent). Of the direct human causes (85 percent), 20 percent are recognition errors, 58 percent are decision errors, and 22 percent are performance errors. Indirect human causes (physicel, physiological, alcohol impaired) account for 22 percent of SVRD crashes. Environmental causes (e.g., slick roads, ambiance-related conditions) are attributed to 34 percent of SVRD crashes.

3.2.3.6 Conclusions and AHS Implications from Barrier Related Crashes

- Approximately 9.0 percent of interstate crashes are barrier related and they are distributed almost evenly over rural, suburban, and urban locations. AHS barrier crash reduction could occur equally across urban, suburban and rural locations.

- Left roadside departures account for approximately 78.0 percent of barrier crashes that occur on roadways with speed limits greater than 80.5 kph (50 mph). This finding strongly supports the use of barriers in the AHS because, without a barrier between automated and manual lanes, left side road departure vehicles from the manual lanes would intrude into the automated lanes.

- Most barrier crashes occur between 3-6 pm, however, the largest proportion of urban barrier crashes occur between midnight-3 am. An AHS not only has the potential to decrease barrier crash rates during afternoon rush hour traffic, but also during other time periods associated with specific locations (e.g., midnight - 3 a.m. in urban locations).

- The majority of interstate barrier crashes occur during lighted conditions, on dry roads with no adverse weather conditions. Under these conditions, occupant injury and vehicle damage severity associated with barrier crashes should decrease significantly with AHS lat/long control. The degree of improvement for barrier crashes occurring under adverse road and weather conditions (i.e., snow, ice, wet) will depend on the sensitivity of the lat/long system to ambient weather conditions.

- Nearly 50.0 percent of barrier crashes involve loss of control/traction. Close to 30.0 percent of barrier crash types are drive off road and approximately 9.0 percent of barriers are struck in an attempt to avoid a collision. Improved surface quality and maintenance of the AHS highway. and lat/Iong control systems, could eliminate many of these barrier crashes.

- The majority (50.4 percent) of vehicles involved in barrier crashes have frontal damage. Approximately 68.0 percent of all occupants involved in frontal collisions with barrier crash are transported to the hospital. This indicates that in the majority of barrier crashes the resulting occupant injuries warrant medical attention. Time delays and congestion from ambulance response may result.

- The majority of vehicles that strike barriers on roadways with speed limits greater than 80.5 kph (50 mph) have a wide area of damage in the front of the vehicle. (Side impact or sideswipe impacts may be under-represented in the accident data file as resulting injuries/damage are less severe and subsequently are not police reported.) Barrier performance criteria need to be assess in light of AHS requirements.

- Concrete barHers are the most frequently impacted type of barrier system (66.0 percent). Other types of types barrier crashes, including guardrails are struck in 32.7 percent of the crashes and crash attenuators are struck in 1.4 percent of the crashes. Frontal collisions with other types of traffic barriers, such as guardrails, result in more serious injuries (36.8 percent) than with concrete barriers (2.4 percent) or attenuators (0.0 percent). More occupants escape injury (29,2 percent) or receive minor injuries (65.6 percent) in concrete barrier crashes than in crashes with other types of traffic barriers (14.0 percent and 44.3 percent, respectively). This result is counter intuitive as a collision with a rigid barrier system, the concrete barrier, results in less severe injuries than more flexible barrier systems.

- Approximately 86.0 percent of SVRD collisions with stationary objects in the in-depth Tri-Level study are attributed to human causes; the largest factor is decision errors, including excessive speed and improper evasive action.

- Approximately 75.0 percent of restrained occupants of vehicles involved in interstate barrier crashes have no injuries and only 3.0 percent of injuries incurred are incapacitating or fatal. Of the unrestrained occupants, 50.0 percent have no injuries and 17.0 percent have incapacitating or fatal injuries.

Table 2-19. Barrier Safety Issues/Risks for AHS

Issue	Risk	Recommendation
Barrier as roadside obstacle	A struck barrier may cause driver to lose control of vehicle especially at high travel speed, e.g., vault, roll-over, submarine Reduced lane maneuverability Intrusion of impacting vehicle into adjacent lane Wide angle of impact with a rigid barrier increases injury severity	Offset barrier from shoulder by 0.6 or more meters (2 ft) Identify optimal barrier design for AHS application Identify appropriate rigidity of barrier structure
Barrier end as roadside obstacle	A struck barrier end may cause driver to lose control of vehicle especially at high travel speed, e.g., vaulting, roll-over, submarining	Identify optimal barrier end treatment for AHS (e.g., energy attenuators) Increase gore area Continuous barrier design
Maintenance repair time	Excessive down-time in high volume areas	Design barrier for efficient maintenance operation
Barrier accommodation of all vehicle types	High CG vehicles may intrude into space above barrier upon impact	Design barrier to redirect all types of errant vehicles
Site dependent barrier requirements	Ineffective barrier performance	Derive barrier requirements based on unique highway features (e.g., uneven terrain, depressed/elevated highway, embankments, exit ramps)
Snow/ice build-up next to barrier	Snow/ice forms a "ramp effect'	Timely snow removal
Breakdown lane	Presence of breakdown lane increases travel distance to barrier and increases the potential for a wide	Consider potential for wide angle impact in barrier design.

3.2.3.7 Recommendations from Traffic Barrier Crash Analysis

- Develop algorithms for AV calculations to estimate change in velocity for vehicles striking traffic barriers
- Assess the compatibility of enhanced traffic barrier systems with adjoining roadside structures on existing highways
- Assess end treatment performance for angled vehicle impacts on both sides of the terminal and head-on impacts. A barrier terminal located in the gore area of transition lane could sustain these types of impacts
- Investigate use of Highway Safety Information System (HSIS) for barrier crash information

- Assess traffic barrier performance with MVE impacts (heavier weight, high CG)
- Assess traffic barrier performance with high velocity impacts: >96 kph (60 mph)

3.2.4 Roadway Departure Crashes

"Not a collision with a motor vehicle in transport" is the largest category of crash types for interstate crashes. This crash type typically involves a single vehicle that either contacts an object/animal in the roadway or leaves the roadway where it may strike an obstacle, rollover, or travel to a final rest position. Single vehicle interstate departure crashes are both a challenge and an opportunity for an AHS due to the:

- unique AHS causal factors that may lead to roadway departure crashes
- causes and circumstances of interstate departure crashes - designers can try to minimize the occurrence of this crash type due to the frequency of occurrence on interstate highways
- likelihood and consequences of roadway departure vs. barrier impacts for malfunction management and design considerations in light of an active lateral/longitudinal control system
- AHS benefits that can be realized from existing causal factors that can be eliminated by an AHS or that raise flags for potential problem areas (e.g., control loss due to reduced traction).

3.2.4.1 Roadway Departure Crashes Resulting from AHS Unique Situations

Similar to rear-end crashes, an automated highway environment has tremendous potential for eliminating roadway departure crashes due to driver error, vehicle defects, and environmental conditions. Once again, the technology required to remove existing causes of accidents has the potential to fail and create new causal factors. Table 2-20 summarizes scenarios that may lead to AHS departure collisions and the RSCs where these situations occur.

A review of the RSCs reveals unique AHS situations that may lead to AHS roadway departures. Single vehicle roadway departure crashes may result from unmitigated single or multiple fault/hazards that affect lateral control - particularly if a vehicle is in the process of merging from the transition lane to automated lane (I2 configurations) and strikes an automated vehicle. The response of the automated vehicle depends on how quickly the lateral control algorithm can correct the large error term that has been introduced by a lateral impact. The automated vehicles trailing the struck vehicle must now deal with an obstacle in the roadway. An additional concern is whether the impact damages any control or communication equipment in the process.

In addition to the fault/hazard elements that may lead to AHS departure collisions, mixing of manual and automated vehicles poses a unique causal factor for AHS departure crashes. As mentioned in the section on rear-end crashes, manual vehicles have a much greater reaction time than automated vehicles. A manual vehicle trailing an automated vehicle that suddenly brakes has only a few options. The manual vehicle may try to stop in time, which may be unsuccessful and the manual vehicle strikes the automated vehicle, or depending on road conditions, the manual vehicle may skid off the roadway. If the manual vehicle strikes the automated vehicle off center, this may induce rotation into the struck vehicle causing it to depart the AHS. The manual vehicle may also try to swerve around the automated vehicle and successfully avoid a crash or subsequently travel or skid off the roadway.

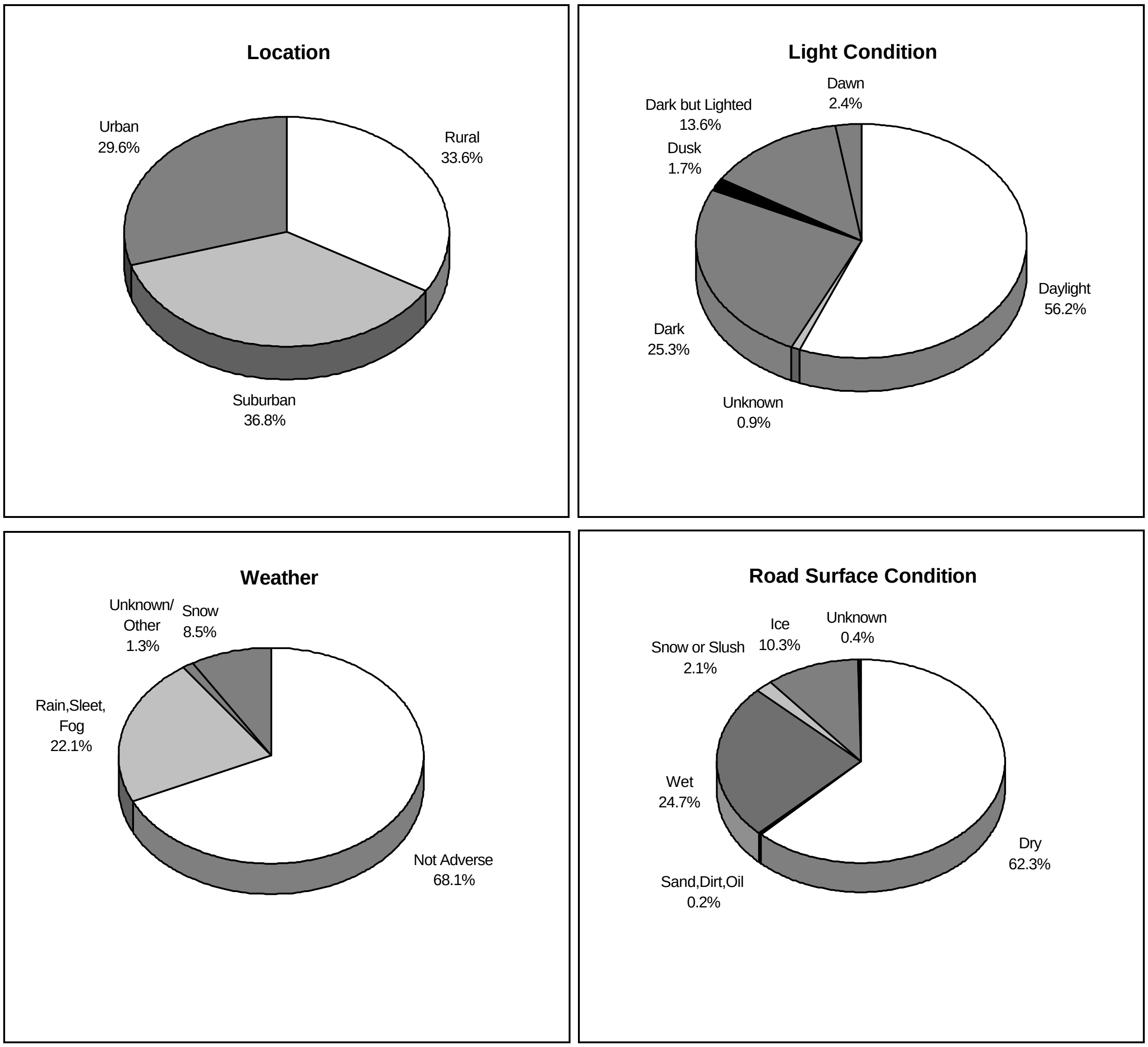
Table 2-20. AHS Scenarios with Roadway Departure Potential (Assumes No Barriers)

Situation => Roadway Departure	Applicable RSCs
Result of attempted corrective actions by a manual vehicle trailing an automated vehicle that suddenly brakes	I1C1
Result of offset rear-end crash due to: manual vehicle trailing an automated vehicle that suddenly brakes or stops	I1C1
Result of side impact due to manual vehicle intruding into automated lane	I2C1, I2C2
Result of malfunction during transition lane maneuvers	I2C1, I2C2
Result of offset rear-end crash due to: lead vehicle deceleration rate > trailing vehicle's maximum deceleration capabilities due to differences in vehicle braking characteristics or insufficient reaction time of trailing vehicle	I1C1,I2C1, I2C2 I3C1, I3C2, I3C3
reduced visibility conditions	I1C1 Sensor dependent for remaining RSCs
system traction degraded due to surface or weather conditions	I1C1 Sensor dependent for remaining RSCs
vehicle sensor, computer, communication or data link failures	I1C1,I2C1, I2C2 I3C1, I3C2, I3C3
roadway sensor, computer, communication or data link failures	I2C1, I2C2 I3C1, I3C2, I3C3
multiple malfunctions occurring simultaneously	I2C1, I2C2 I3C1, I3C2, I3C3
manual backup mode is in effect (particularly if driver is impaired or incapacitated)	I2C1, I2C2 I3C1, I3C2, I3C3
roadway obstacle present or incident occurs	All RSCs
vehicle lateral control and/or actuator failures	All RSCs
sabotage	All RSCs

3.2.4.2 General Characteristics of Run Off Interstate Crashes (GES)

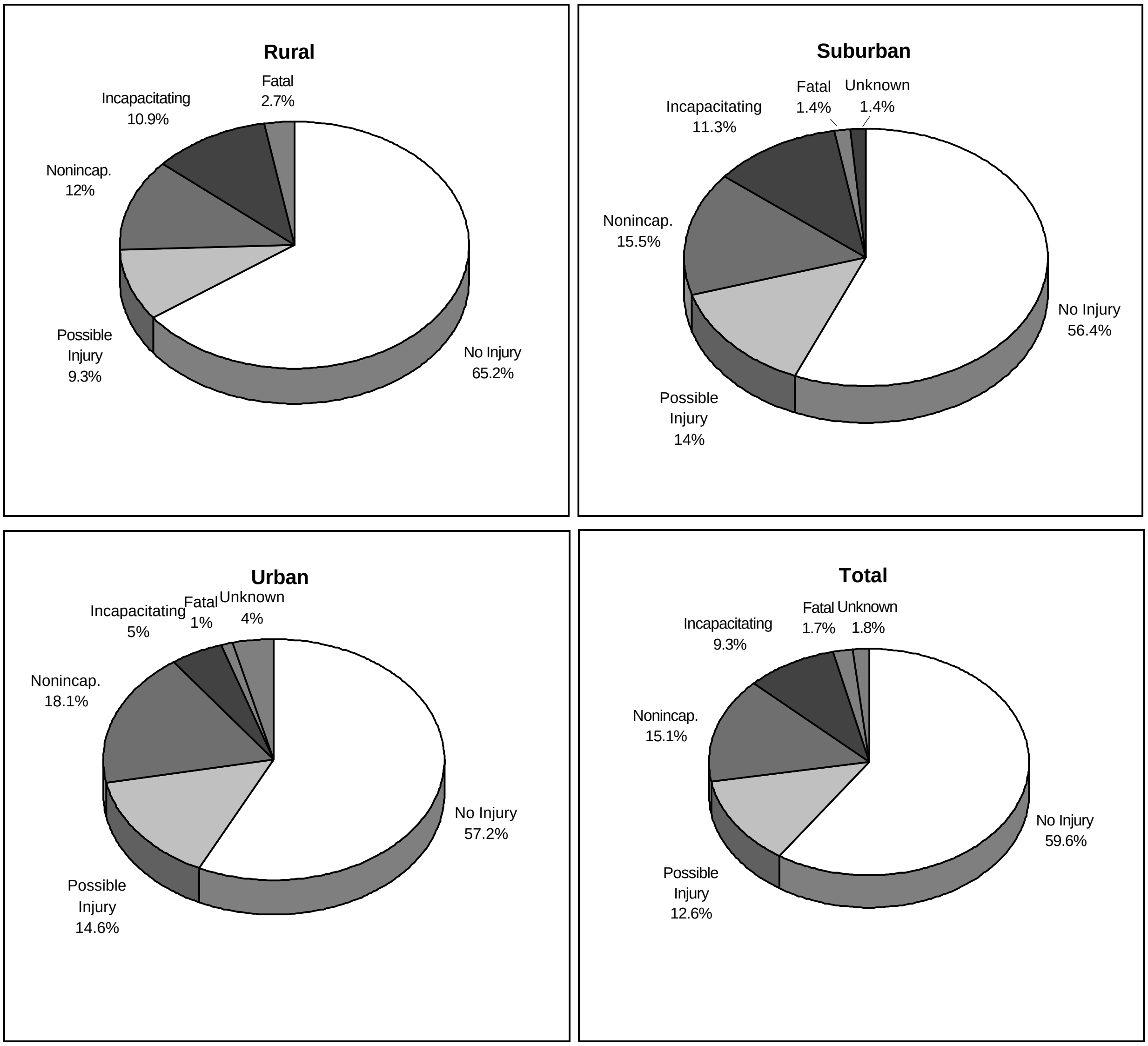
Single vehicle roadway departure collisions are a major portion of the interstate highway accident picture and comprise and even larger proportion of the fatal interstate accident picture. Collisions "not with a motor vehicle in transport" are 42 percent of all interstate accidents, and 70 percent of all fatal interstate accidents. A summary of interstate roadway departure crash characteristics is presented in this section using GES data. Data charts supporting this information are provided in appendix E.

The environmental characteristics for interstate roadway departure crashes are shown in figures 2-19. Interstate roadway departure occurrences are somewhat evenly distributed over rural, suburban and urban areas - with suburban areas having the highest proportion of this crash type. Over two thirds of interstate roadway departures occur under no adverse weather conditions; 22.1 percent occur during rain, sleet, or fog; and 8.5 percent during snow. Road surface conditions are primarily dry (62.3 percent), followed by wet (24.7 percent), icy (10.3 percent), and snow or slush covered (2.1 percent). Over half of interstate roadway departures occur during daylight, 13.6 percent are on dark but lighted roads, and one quarter occur on dark roads.



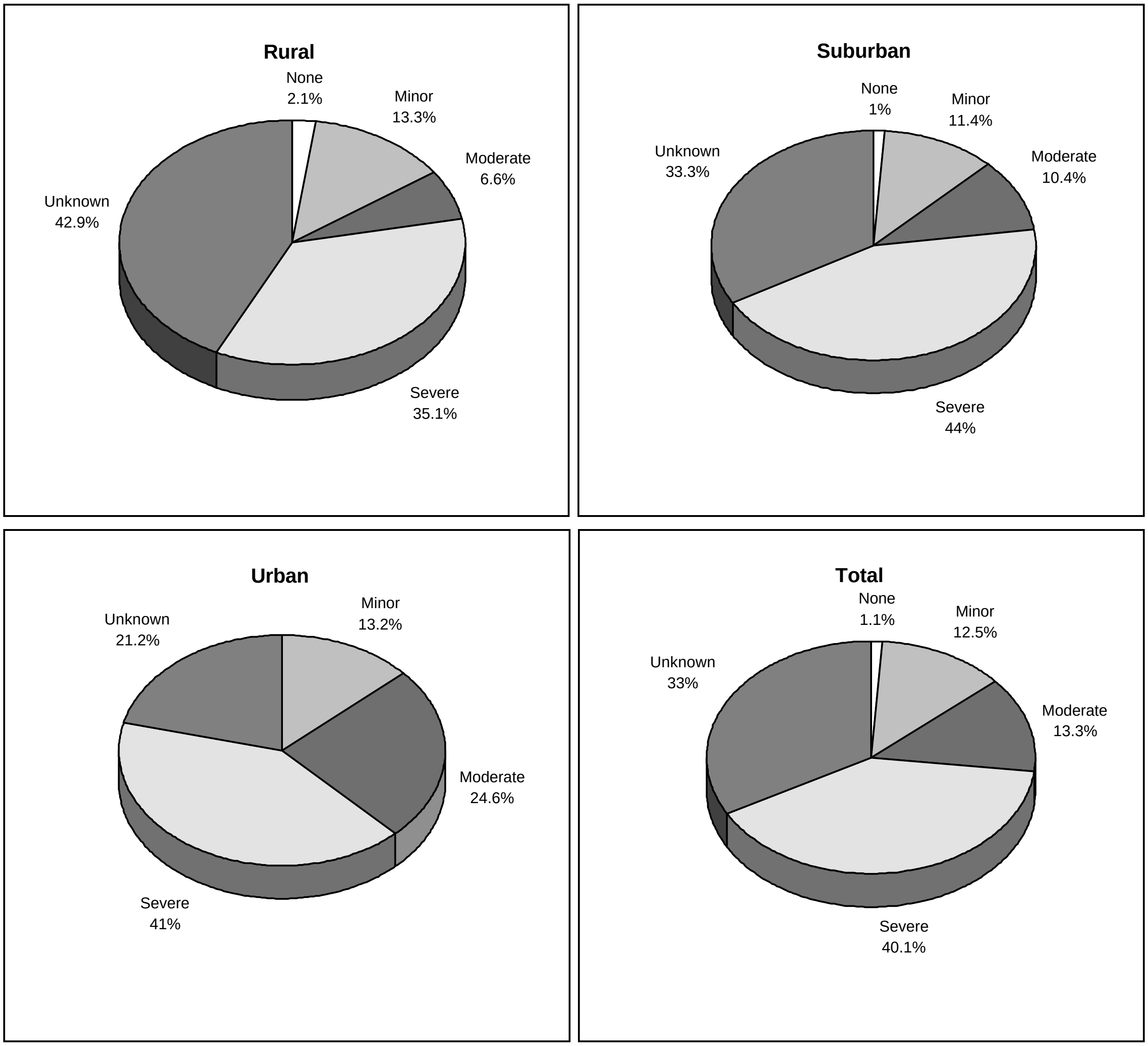
Figures 2-19. Environmental Conditions for Interstate Departure Crashes

Figures 2-20 and 2-21 show the severity of consequences for interstate roadway departure crashes. Rural locations for this crash type have a higher proportion of "no injury" for vehicle occupants than crashes occurring in suburban or urban areas; although rural roadside departures also have the highest occurrence of fatalities. For non-fatal injury crashes, suburban crashes tend to result in more serious injuries than urban or rural crashes. Once again, this information is limited to police reported data and the CDS data presented later is a better source of occupant injury level.



Figures 2-20. Injury Severity by Location for Occupants of Vehicles Involved in Interstate Departure Crashes

For interstate roadway departures where vehicle damage is known, 60 percent of the vehicle damage is severe. Crashes in suburban locations exhibit the highest frequency (43.7 percent) of severe vehicle damage. For departure crashes in urban locations, moderate vehicle damage occurs more often than in rural or suburban locations. Only 1.1 percent of the vehicles departing from the roadway are reported to have no damage (figure 2-21).



Figures 2-21. Vehicle Damage by Location for Interstate Departure Crashes

Data highlights from tables presented in appendix E are summarized below:

1. Injury Severity x Surface Condition: Interstate roadway departure accidents on dry roads result in higher injury levels and greater vehicle damage than on wet, snowy, or icy roads. Crashes on dry roads have the highest frequency of fatal and incapacitating injuries to vehicle occupants. Departures on icy roads tend to result in the lowest maximum injury level for vehicle occupants. These results are due to the higher travel speeds associated with dry road conditions.

2. Injury Severity x Restraint Use: Fatal injuries comprise 1.2 percent of the vehicle occupant injury picture. When some form of restraint system is used the proportion decreases to 0.5 percent; when no restraint system is employed the proportion increases to 6.7 percent. The same trend applies to incapacitating and nonincapacitating injuries. For restrained occupants, 70 percent receive no injury.

3. Vehicle Damage x Surface Condition: Severe vehicle damage occurs most frequently on all road surface conditions. Crashes on dry roads have the highest incidence of severe vehicle damage.

4. Most Harmful Event: The most harmful event for a vehicle departing the interstate is collision with a guardrail or barrier - 38.8 percent of vehicles strike a guardrail or barrier. Rollovers have the next highest frequency of occurrence: 12.2 percent of vehicles departing the roadway rollover. Other objects that are struck (20.9 percent of the time) are trees, culverts, parked motor vehicles and poles or posts.

5. Time of Day x Location: Over 30 percent of interstate roadway departures occur between noon and 6 pm, with peak intervals varying by location: urban - 16.6 percent from midnight to 3am; suburban - 18.3 percent from 3 to 6 pm; and rural - 20.9 percent from noon to 3 pm.

6. Day of Week x Location: Approximately half of interstate roadway departures occur on Friday through Sunday for all three locations. Saturdays are the most likely day for this crash type.

7. Alcohol Involvement x Location: Police reported alcohol involvement accounts for 8.3 percent of roadway departures on interstates. Crashes in urban locations have the highest incidence of alcohol involvement - 15.2 percent. Alcohol involvement occurs in similar proportions for suburban and rural crash locations.

8. Driver Impairment x Location: Nearly 14 percent of drivers involved in interstate roadway departure crashes are reported to be drowsy or sleepy. The problem is low in urban locations (4 percent) and high in rural locations (22.5 percent).

9. Critical Event Making Crash Imminent: Loss of control due to a vehicle related problem or poor road conditions accounts for 38.1 percent of the critical events that make a crash imminent for a vehicle departing the interstate. Traveling over the edge of the roadway describes 39.1 percent of the circumstances leading to the departure related crash.

The GES and CDS data filters used to characterize interstate departure crashes are described in appendix E. Data from the CDS Data Analysis are presented in tabular form in appendix E.

3.2.4.3 Occupant Injury Severity Resulting from Roadway Departure Crashes (CDS)

The single most severe injury level reported for any occupant of a CDS sampled vehicle is presented in table 2-E1. Approximately 70 percent of the maximum occupant injury per vehicle are "no injury" or "minor injury". Critical or untreatable injuries represent 0.8 percent. However, table 2-E2 shows the most intensive treatment given to any vehicle occupant within 30 days of the crash, and this shows 2.5 percent of the vehicles have occupants that died as a result of injuries sustained from the crash.

The single most severe injury level reported for each occupant of a CDS sampled vehicle by restraint use is shown in table 2-E3. Occupants using restraint systems have a much higher frequency of "no injury" resulting from the crash and consistently lower frequencies of minor to untreatable injuries. For this analysis, a restraint system is defined as a functioning passive or active belt system or a deployed airbag.

3.2.4.4 Review of Causal Factors for Roadway Departure Crashes

The majority of single vehicle roadside departure crashes can be described by three categories of first harmful event: rollover, collision with a fixed object, and collision with a parked vehicle.

Data on Single-Vehicle Roadway Departure Crashes (Knipling, 1993) cites causal factor analysis results from the Indiana Tri-Level study (Treat, et al., 1979). The study covers in-depth and on-scene investigations of 153 single vehicle roadside departure crashes. These crashes represent the overall single vehicle roadway departure problem - they are not restricted to interstates. The causal factors are divided into three major categories: vehicle factors, human causes, and environmental causes. The Tri-Level study rated causal factors according to the investigators level of confidence of the factor's role in the crash. The ratings are certain, probable, and possible. Causal factors determined to be certain or probable suggest that 81 to 95 percent of single vehicle roadside departure crashes result from human causes, 18 to 24 percent are from vehicular factors, and 34 to 49 percent are due to environmental causes (see table 2-21). A single crash may have more than one causal factor, therefore, percent totals are greater than 100 percent.

Table 2-21. Causal Factors for Single Vehicle Roadway Departure Crash Types

	Causal Factor		
Crash Type	**Human**	**Vehicular**	**Environmental**
Rollover	95%	24%	49%
Collision with Stationary Object	86%	18%	34%
Collision with Parked Vehicle	81%	24%	43%

3.2.4.5 AHS Implications and Conclusions from Roadway Departure Crashes

- For I2 infrastructures, vehicles that depart the roadway may now intrude into the automated lanes. If barriers are used, they will prevent these vehicles from traveling into the automated lanes, except at entry/exit points. This is a significant concern given the magnitude of this crash type on present day interstates. Single vehicle roadway departure collisions are part of the "collision not with a motor vehicle in transport" category. This group represents 42 percent of all interstate accidents, and 70 percent of all fatal interstate accidents.

- The most harmful event for vehicles departing the interstate is collision with a guardrail or barrier. Guardrail or barrier designs for an AHS should consider the injury producing characteristics of barriers currently in use (see barrier related crashes - section 3.2.3).

- Approximately 85 percent of single vehicle roadway departures are attributed to human causes (with contributing vehicular and environmental causes). Many of the precrash situations are characterized by control or traction loss. Therefore, a high probability exists for this crash type to be prevented by AHS technology. Removal of human causal factors along with vehicle system monitoring and inspection has the potential to significantly reduce the occurrence of this crash type on AHS roadways.

- Restraint systems are effective in reducing injury levels in interstate departure crashes.

- Many interstate departure crashes occur at non-peak travel times. It may not be necessary to impose short gap distances during these travel hours and the potential for vehicles departing the roadway as a result of being struck by another vehicle can probably be greatly reduced.

- Alcohol is a factor in 8.3 percent of interstate departures. Impaired drivers will probably not gain access to the AHS, therefore, these drivers may persist on the non-AHS roads and the frequency of occurrence may persist. This is a particular problem for the I1C1 RSC, where automated vehicles will be traveling with manual vehicles, and for the I2C1 and I2C2 RSCs where manual vehicles will be traveling in lanes next to the AHS. This concern lends support to the argument of separating the manual and automated lanes by installing barriers.

3.2.4.6 Recommendations from Roadway Departure Crash Analysis

- AHS designs need to avoid this crash type - which is essentially a control loss - in any failure mode, due to the overrepresentation of this crash type in the fatal accident picture.

- Causal Factor Analysis for single vehicle departures on interstates should be performed.

- Consideration of AHS unique causal factors for AHS departures is specific to the RSCs. Specific safety analysis will be required when a final configuration - or perhaps one configuration for each urban, suburban and rural locations - is chosen.

- The I1C1 configuration may be the first form of automation. I1C1 has automated lane keeping and this feature will be beneficial in eliminating roadway departures. A drawback to the I1C1 configuration is lane sharing by manual and automated vehicles, which may create crash situations of its own. The pros and cons of an I1C1 configuration show be studied further. This RSC would be the easiest to implement and a postive AHS demonstration would smooth the way for higher and more expensive levels of automation.

- Add algorithms to CRASHPC program for ΔV calculations to estimate change in velocity for vehicles striking a non-deformable object.

3.2.5 Object/Animal in Roadway Crashes

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

This circumstance may remain constant from today's interstates, without extensive measures to exclude these obstacles from the AHS. Crashes involving objects or animals represent 5.2 percent of all interstates crashes. Given the 490,336 million vehicle miles of travel on US Interstates, this equates to a rate of 0.03 incidents per million VMT. Additional events, under non-normal operating conditions, that may lead to "AHS roadway obstacles" or lane blocking incidents are:

- loss of lateral control
- offset rear-end crashes
- rear-end crashes on low traction surfaces (perhaps due to fluid spills)
- lane/change merge crashes
- crashes related to driver impairments

Object/animal related crashes are included in the "Not a collision with a motor vehicle in transport" category in figure 2-4. Depending on the size of the object or animal, these crashes do not necessarily result in high injury levels, but attempts to avoid these obstacles or to control the vehicle trajectory after contact with the obstacle may have more serious consequences. In states where large animals (cows, deer, horses) are common near the roadway, the chance for higher injury levels is much greater. Objects or animals on interstate crashes are examined to:

- envision unique AHS causal factors that may lead to collisions with objects or animals in the roadway.

- determine likelihood and consequences of object/animal collisions for malfunction management and design considerations in light of an active lateral/longitudinal control system.

- estimate AHS benefits that can be realized from eliminating this crash type.

- raise the issue of automated vehicles emulating what the driver does right - how many crashes with objects or animals are avoided by a driver's evasive maneuvers.

3.2.5.1 Object/Animal in Roadway Crashes Resulting from AHS Unique Situations

The object/animal in the roadway problem is probably one of the few factors that may remain constant between present day interstates and future automated highways. One means of eliminating some of the objects in the roadway, is not to allow vehicles carrying unsafe loads admission to the AHS. For RSCs such as the I1C1 configuration with existing highways for its infrastructure, it would be desirable to prevent these vehicle from entering the highway - although this would require regulations and enforcement. Without extensive and costly measures to keep animals out or to prevent objects from falling onto the roadway, the object/animal problem is outside the control capabilities of automation. Most likely, detection, avoidance, and emulating what a manual driver does right, will be available to deal with this problem.

An additional concern with the object/animal in the roadway problem is the sequence of events that may follow a manual or automated vehicle attempting to avoid this situation. The vehicle may be able to successfully maneuver around the object /animal leaving it for the next vehicle to deal with, but at least with automation, other automated vehicles may be warned.

Automated vehicles coming upon the scene will have advance notice that a problem exists. In terms of highway maintenance, a unit could be dispatched to remove the danger. In a less fortunate situation, the first vehicle may strike the object /animal or brake suddenly and perhaps steer to avoid the object/animal. Depending on the surrounding traffic and road surface conditions, a rear-end, lane change or roadway departure collision may ensue. The object/animal in the roadway is a problem for all of the infrastructures and all of the levels of command and control.

3.2.5.2 Characteristics of Interstate Object/Animal in Roadway Crashes

Precrash situations characterized by single driver, forward impact with a stationary object or pedestrian/animal represent 6.0 percent of all interstate crashes and 16.3 percent of all first harmful events for fatal interstate crashes. For interstate fatal crashes, 12.7 percent of the first harmful events are a vehicle striking a pedestrian, 3.6 percent are collisions with objects or animals.

In contrast to most of the other accident types, 57.3 percent of crashes with non-fixed objects on interstates occur during dark lighting conditions. This crash type occurs less frequently in urban locations (11.2 percent) and occurs in most often in suburban locations (50.1 percent) followed by rural locations (38.7 percent).

Interstate object/pedestrian/animal in the roadway crashes typically occur on dry roadways (86.7 percent) with no adverse weather conditions (93.6 percent). Only 6.3 percent of this crash type occur during rain with 9.5 percent on wet roads (figure 2-22).

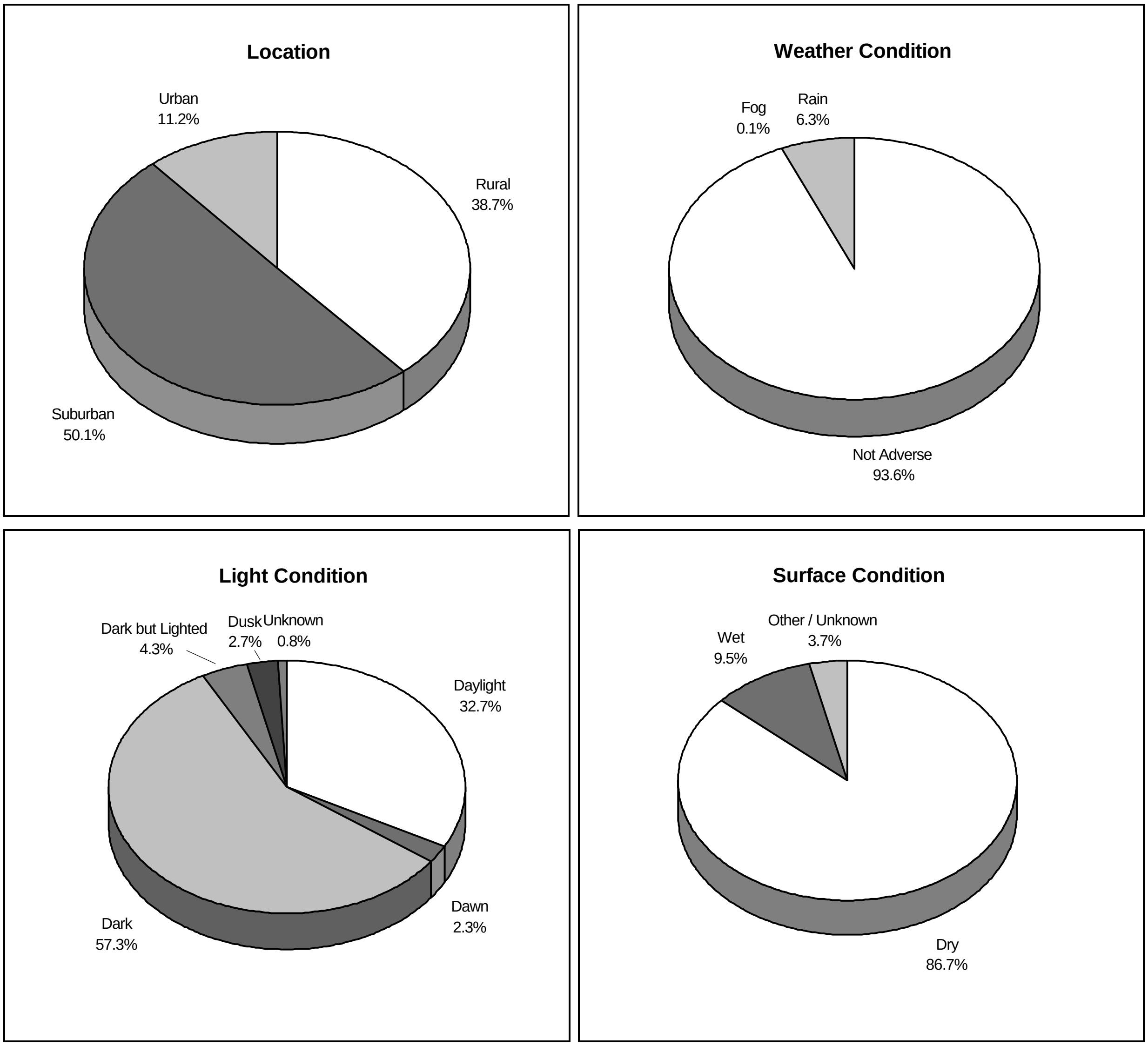


Figure 2-22. Environmental Conditions for Object/Animal in Roadway Crashes

Vehicle damage is more of a factor than occupant injury for crashes with non-fixed objects on interstates. The maximum injury severity for any occupant in the vehicle is shown in figure 2-23. Approximately 96 percent of the collisions result in no injury or only a possible injury. Urban locations have the highest incidence of nonincapacitating injuries and rural locations have the only occurrence of incapacitating injuries.

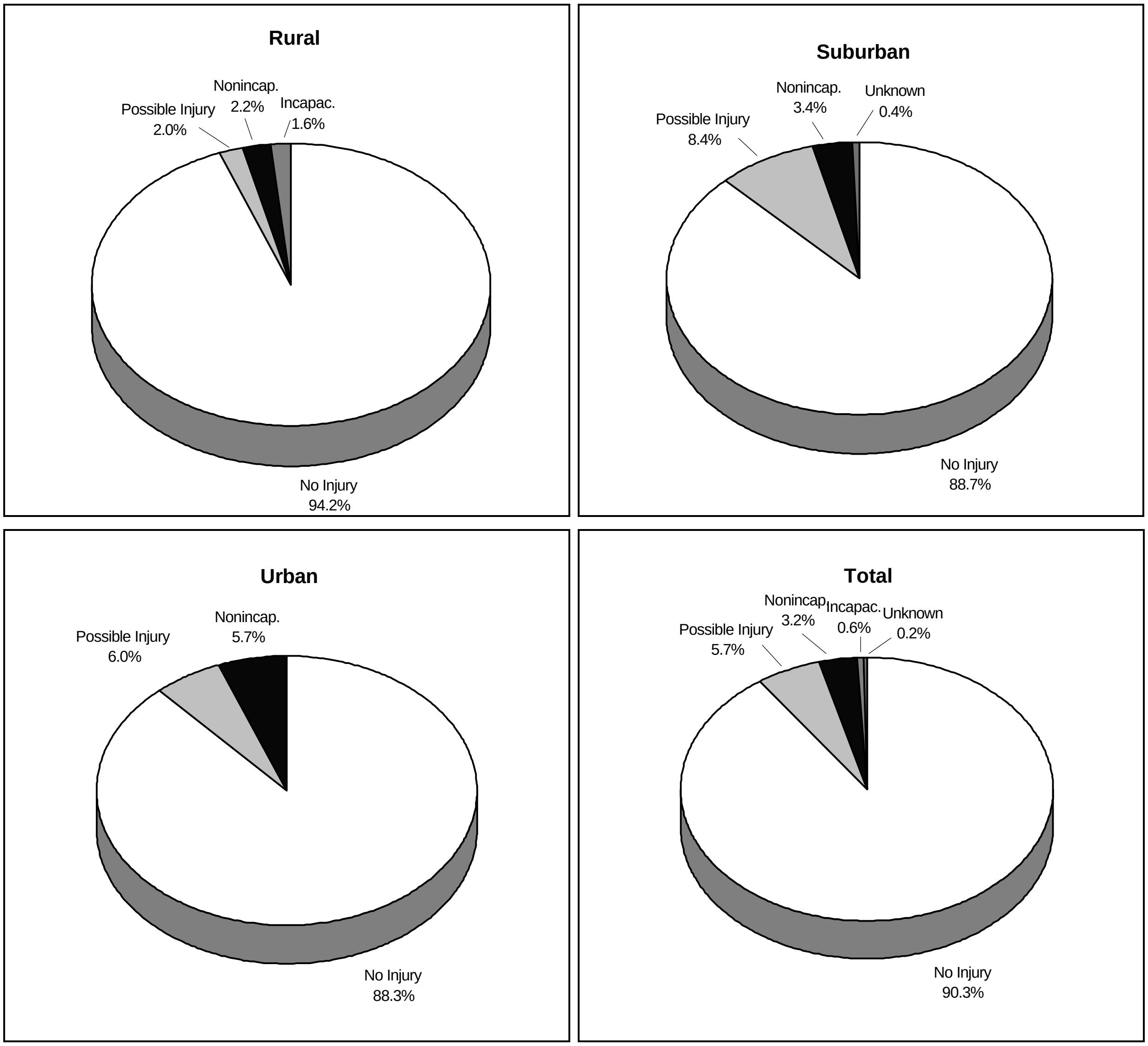


Figure 2-23. Injury Severity for Occupants of Vehicles Involved in Object/Animal in Roadway Crashes

The assessment of vehicle damage severity for this crash type is very limited, nearly half are listed as unknown (figure 2-24). For interstate crashes involving non-fixed objects where vehicle damage is known, 47.4 percent of the vehicle damage is moderate. Crashes in rural areas result mainly in severe vehicle damage (42.5 percent) and crashes in suburban and urban locations exhibit primarily moderate vehicle damage (suburban - 47.6 percent, urban - 59 percent).

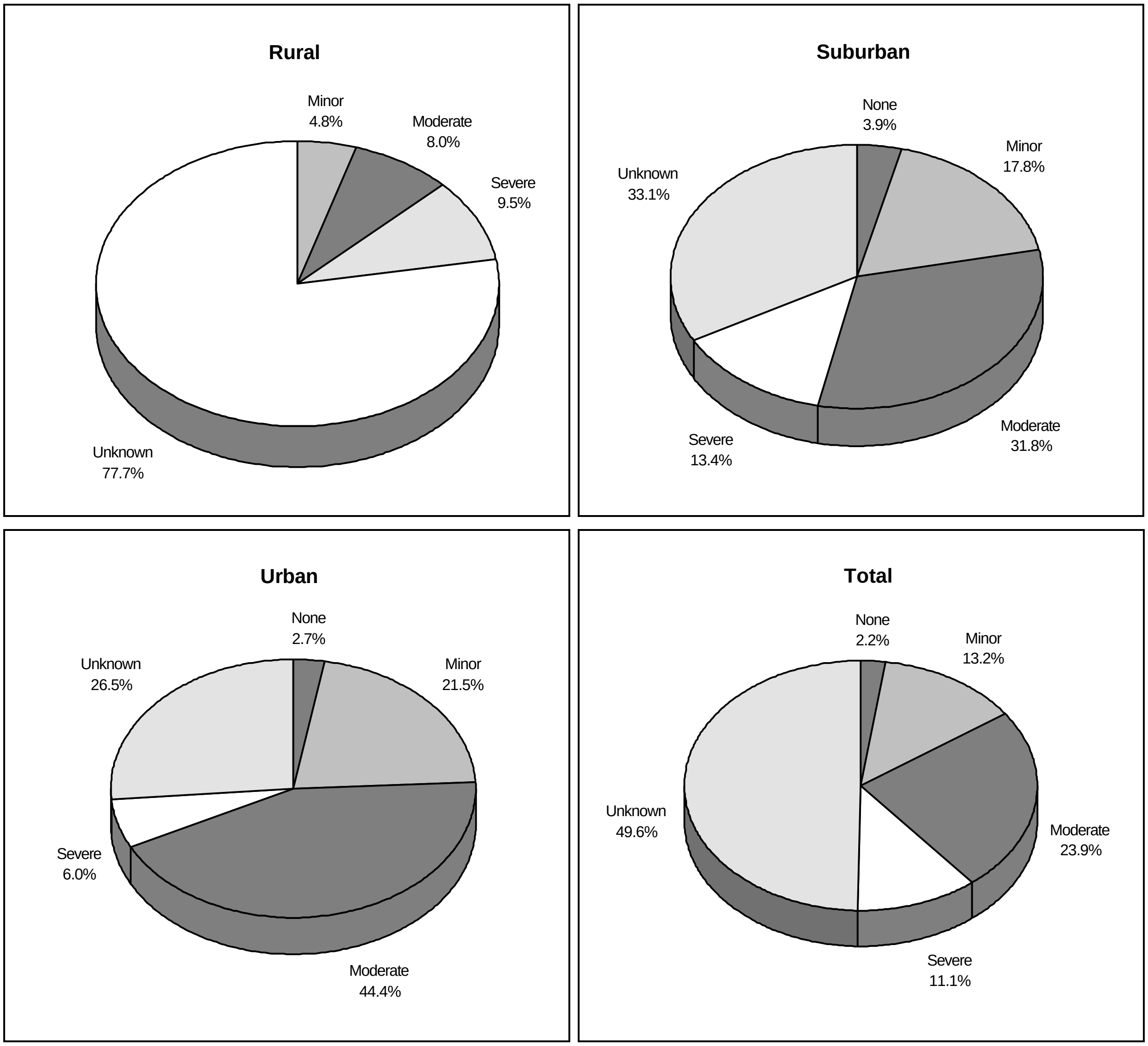


Figure 2-24. Damage Severity of Vehicles Involved in Object/Animal in Roadway Crashes

Data highlights from tables presented in appendix F are summarized below:

1. Maximum Injury Severity in Vehicle x Surface Condition: The higher injury levels occur on dry road surfaces. CDS data is provided below to yield a better estimate of injuries sustained from this crash type.

2. Vehicle Damage x Surface Condition: Crashes on dry roads are most likely to result in moderate to severe vehicle damage and crashes on wet roads mainly result in minor to moderate vehicle damage.

3. Injury Severity x Restraint Use: Restrained occupants are most likely to escape injury when involved in collisions with non-fixed objects on interstates - 94.3 percent incur no injuries. Approximately 22 percent of unrestrained occupants received non-incapacitating injuries compared to 1.9 percent for restrained occupants.

4. Time of Day x Location: Evenings are the most likely time for collisions with non-fixed objects on interstates. Nearly 45 percent of these crashes occur between 6 pm and midnight. The 6-9 pm time slot has the highest frequency of occurrence for all 3 locations.

5. Day of Week x Location: Crashes with non-fixed objects on interstates are somewhat evenly distributed throughout the days of the week, except for Fridays when 20.4 percent of this crash type occurs.

6. Accident Type by Location: The precrash situation in urban locations is characterized by 58.3 percent object in roadway and 41.7 percent pedestrian or animal in the roadway. As congestion decreases, the occurrence of object related crashes decreases and pedestrian/animal crashes increases. For suburban locations, the distribution is 74 percent pedestrian/animal and 26 percent stationary object, for rural locations, it's 83.9 percent animal and 16.2 percent stationary object.

7. Most Harmful Event x Location: In urban crashes, 10 percent involve pedestrians, for suburban crashes 1.8 percent involve pedestrians, and no pedestrians crashes are recorded for rural locations.

8. Number of Vehicles Involved x Location: Most crashes involve one vehicle, except in urban locations, where 37 percent involve 2 vehicles.

9. Alcohol Involvement x Location: Police reported alcohol involvement is not a major factor for interstate object/animal crashes - 0.9 percent of the total are documented as alcohol involved. The proportion is highest for urban locations, but it is still only 2.3 percent.

The GES and CDS data filters used to characterize interstate object/animal in roadway crashes are described in appendix F. Data from the CDS Data Analysis are presented in tabular form in appendix F.

3.2.5.3 Occupant Injury Severity Analysis for Object/Animal in Roadway Crashes (CDS)

CDS data files were examined for passenger car vehicle damage and occupant injury as a result of collisions with objects or animals (pedestrians did not appear in the first object contacted distribution) on roadways with a posted or statutory speed limit greater than 80.5 kph (50 mph). Similar to GES data findings, occupant injuries are low - 97.1 percent are none or minor and 1.7 percent are moderate (table 2-F1). For required medical treatment, most vehicle occupants required no treatment (67 percent), 30.2 percent were transported and released and 1.7 percent needed hospitalization (table 2-F2). There are more occurrences of moderate injuries for unrestrained occupants and more minor injuries for restrained occupants. Frequencies of no injury are similar for restrained and unrestrained occupants (table 2-F3).

Vehicle extent damage is presented in table 2-F4 for passenger cars where the general area of damage is the front and the total damage distribution is wide. For 77.3 percent of the vehicles, residual crush extends into zone 1, and 22.7 percent extend into zone 3. Zone 3 is the highest extent zone recorded for passenger cars involved in object/animal related crashes.

3.2.5.4 AHS Implications and Conclusions from Object/Animal in Roadway Crash Analysis

- The object/animal in the roadway is likely to persist in the AHS environment without costly measures to exclude them - which is highly unlikely for RSCs using existing roadways.

- Collisions with non-fixed objects usually result in low injury levels and minor to moderate vehicle damage. However, collisions resulting from vehicles avoiding obstacles may produce more severe injuries.

- Sensors to detect objects or animals must be able to function in dark lighting conditions.

- Object in the roadway is more of a problem in urban locations than animal in the roadway. The data do not indicate where the objects come from, however, preventing objects falling from other vehicles is an obvious source that should be eliminated.

- Collisions with non-fixed objects in urban locations often involve 2 vehicles. As traffic becomes more congested, the consequences of an object/animal in the roadway increase.

- Fatalities resulting from vehicles striking pedestrians on automated highways will be eliminated as collisions and breakdowns are eliminated along with the need for people to exit their vehicle after such an event.

- Occupant restraints are effective in reducing injuries resulting from this crash type.

3.2.5.6 Recommendations from Object/Animal in Roadway Crash Analysis

- Since excluding objects or animals from the AHS may not be practical for all RSCs, reliable detection devices will be a necessary input to the lateral/longitudinal control systems.

- Breakdown lanes may be useful to provide room for vehicles to avoid large objects or animals in the roadway. In an AHS context, objects may also refer to vehicles involved in a previous crash.

- Further studies are needed to analyze the tradeoff between striking an obstacle or the consequences of attempting to avoid it - particularly if it is moving.

- Sensors to detect objects or animals must be able to function in dark lighting conditions.

- Vehicles with unsafe loads should not be permitted on an AHS for any of the RSCs.

- Physical means of excluding objects/animals on congested roadways may be worth the cost and requires further research.

- Pedestrians are not allowed on existing interstates, yet many fatalities on interstates are the result of a vehicle striking a pedestrian. The origin of these pedestrians is not noted in the data, but the logical conclusion is that these people exit their vehicle after a collision or breakdown. Since vehicle monitoring systems may be flagging vehicles for exit or directing them to breakdown lanes, passengers must not be permitted to exit the vehicle unless staying inside the vehicle poses a greater threat.

- All occupants of automated vehicles must be restrained.

3.2.6 Lane Change/Merge Crashes

Lane change/merge crashes are part of the angle or sideswipe portions of the interstate accident picture (see figure 2-4). Interstate angle and sideswipe crashes represent 20 percent of all interstate accidents, and 9.3 percent of fatal accidents. The RSCs have the AHS lane change maneuver automated in all of the RSCs except for the I1C1 configuration, where the AHS lane change is manually performed. The I2C1 and I2C2 RSCs have the AHS lane(s) adjacent to manual lanes. The driver must still perform the lane change maneuver to enter the transition lane to the AHS. This transition lane is the slow lane for the AHS and the fast lane for the manual traffic. A concern is that a vehicle in the transition lane may be projected onto the AHS by a lateral impact with another vehicle changing from the manual lanes to the transition lane. A study of lane change merge crashes is required to:

- envision unique AHS causal factors that may lead to lane change/merge crashes on an AHS

- understand the causes and circumstances of lane change/merge crashes to aid designers in avoiding the occurrence of this crash type

- estimate benefits of an AHS in terms of eliminating causes of lane change/merge crashes

- raise the issue of the need for barriers on the I2C1 and I2C2 RSCs, given the frequency of this crash type on present day interstates

3.2.6.1 Lane Change/Merge Crashes Resulting from AHS Unique Situations

The lane change/merge scenario will be automated for the all of the RSCs except the I1C1 configuration, where lane change maneuvers are still under manual control. Also, for the I2 infrastructures, a vehicle must still enter the AHS transition lane under manual control. It may be possible for the I2 infrastructures to have their own entrance ramps, but this may not be feasible for all locations due to cost and right-of-way limitations. In addition to the three RSCs still requiring some form of manual merging, consideration must always be given to the rare event of unmitigated single or multiple malfunctions. Table 2-22 summarizes scenarios that may lead to AHS lane change/merge collisions and the RSCs where these situations may occur.

Many of the precrash situations that may lead to a lane change/merge crash type are similar to the single vehicle interstate departure circumstances. The common precrash event is that a vehicle deviates from its lane position - either intended or unintended. The difference is that instead of leaving a lane near the edge of the roadway and traveling off the road, the vehicle departs its lane and enters another lane. If another vehicle is in its path, a collision occurs. Therefore many of the AHS unique scenarios that lead to AHS roadway departures are the same as situations leading to the lane change/merge crash type.

Lane change/merge crashes may result from unmitigated single or multiple fault/hazards that affect lateral control - particularly if a vehicle is in the process of transitioning onto an automated lane (I2 configurations). This failure may be a vehicle based malfunction, in which case, an automated vehicle about to be laterally impacted may have time to avoid the collision. If the failure is a function of roadway commands, there may be time to revert to a vehicle-to-vehicle form of communication - if not, the consequences may be more serious. An additional concern is whether the impact has damaged any control or communication equipment.

Obstacles or animals in the roadway are a problem for all RSCs. In I1C1, automated vehicles still rely on the driver for lane change maneuvers. The driver of an automated vehicle may swerve to avoid striking an obstacle or animal in the roadway and subsequently impact a vehicle in the adjacent lane. Also, a manual vehicle may strike an automated vehicle in this same set of circumstances. In higher level RSCs, the question remains whether the lateral control algorithms will operate at the level of being able to avoid an obstacle or animal in the AHS. This requires sensor technology capable of detecting a problem with sufficient time to change the vehicle's path and the availability of an adjacent lane or breakdown lane that is not already occupied by another vehicle.

Mixing of manual and automated vehicles poses a unique causal factor for lane change/merge crashes. Similar to the circumstances for single vehicle roadway departure collisions, a manual vehicle trailing an automated vehicle that suddenly brakes has potential for several crash types. Due to the difference in reaction times (see rear-end crash types for a more detailed discussion) the manual vehicle has limited options. One of these options is to try to swerve around the automated vehicle and possibly strike another vehicle in an adjacent lane. The I1C1 RSC may have informal "platoons" where a group of automated vehicles link up and travel at shorter gap distances and if possible, higher speeds. A vehicle changing lanes into an informal platoon may result in more than a two vehicle collision.

Offset rear-end crashes that induce rotation into the struck vehicle may result in the struck vehicle changing lanes and striking another vehicle. In the I1C1 RSC this may be an automated vehicle being struck by a manual vehicle. In the I2 infrastructures the transition lanes may be prone to mixing of automated and manual vehicles where offset rear-end crashes may occur. Also in the I2 infrastructure configurations, a vehicle striking a barrier that is redirected back into the automated or transition lane may be involved in a low to large angle impact with another vehicle.

Table 2-22. AHS Scenarios with Lane Change/Merge Crash Potential

Situation => Lane Change/Merge Crash	Applicable RSCs
Result of attempted corrective actions by a manual vehicle trailing an automated vehicle that suddenly brakes	I1C1
Result of offset rear-end crash due to: manual vehicle trailing an automated vehicle that suddenly brakes or stops	I1C1
Result of side impact due to manual vehicle intruding into automated lane	I2C1, I2C2
Human error during merge into transition lane from manual lane	I2C1, I2C2
Result of unmitigated malfunction during transition lane maneuvers	I2C1, I2C2
Result of offset rear-end crash due to: lead vehicle deceleration rate > trailing vehicle's maximum deceleration capabilities due to differences in vehicle braking characteristics or insufficient reaction time of trailing vehicle	I1C1,I2C1, I2C2 I3C1, I3C2, I3C3
reduced visibility conditions	I1C1 Sensor dependent for remaining RSCs
system traction degraded due to surface or weather conditions	I1C1 Sensor dependent for remaining RSCs
vehicle sensor, computer, communication or data link failures	I1C1,I2C1, I2C2 I3C1, I3C2, I3C3
roadway sensor, computer, communication or data link failures	I2C1, I2C2 I3C1, I3C2, I3C3
multiple malfunctions occurring simultaneously	I2C1, I2C2 I3C1, I3C2, I3C3
manual backup mode is in effect (particularly if driver is impaired or incapacitated)	I2C1, I2C2 I3C1, I3C2, I3C3
roadway obstacle present or incident occurs	All RSCs
vehicle lateral control and/or actuator failures	All RSCs
sabotage	All RSCs

3.2.6.2 Characteristics of Interstate Lane Change/Merge Crashes

Lane change/merge crashes are generally classified as angle or sideswipe collisions. Interstate angle and sideswipe crashes represent 20 percent of all interstate accidents, and 9.3 percent of fatal accidents. Crashes where the angle of impact is large, as in side impacts, tend to produce more serious injuries than crashes where the impact angle is low - lane change/merge collisions. An overview of interstate lane change/merge crash characteristics is presented in this section.

Figures 2-25 presents the environmental characteristics for lane change/merge crashes on interstates. Similar to the general rear-end crash picture, lane change/merge crashes on interstates mainly occur in urban and suburban areas on dry roadways, with natural or artificial lighting and no adverse weather conditions. As congestion increases, the incidence of this crash type also increases. Degraded road surface and weather conditions do not seem to increase the likelihood of this crash type.

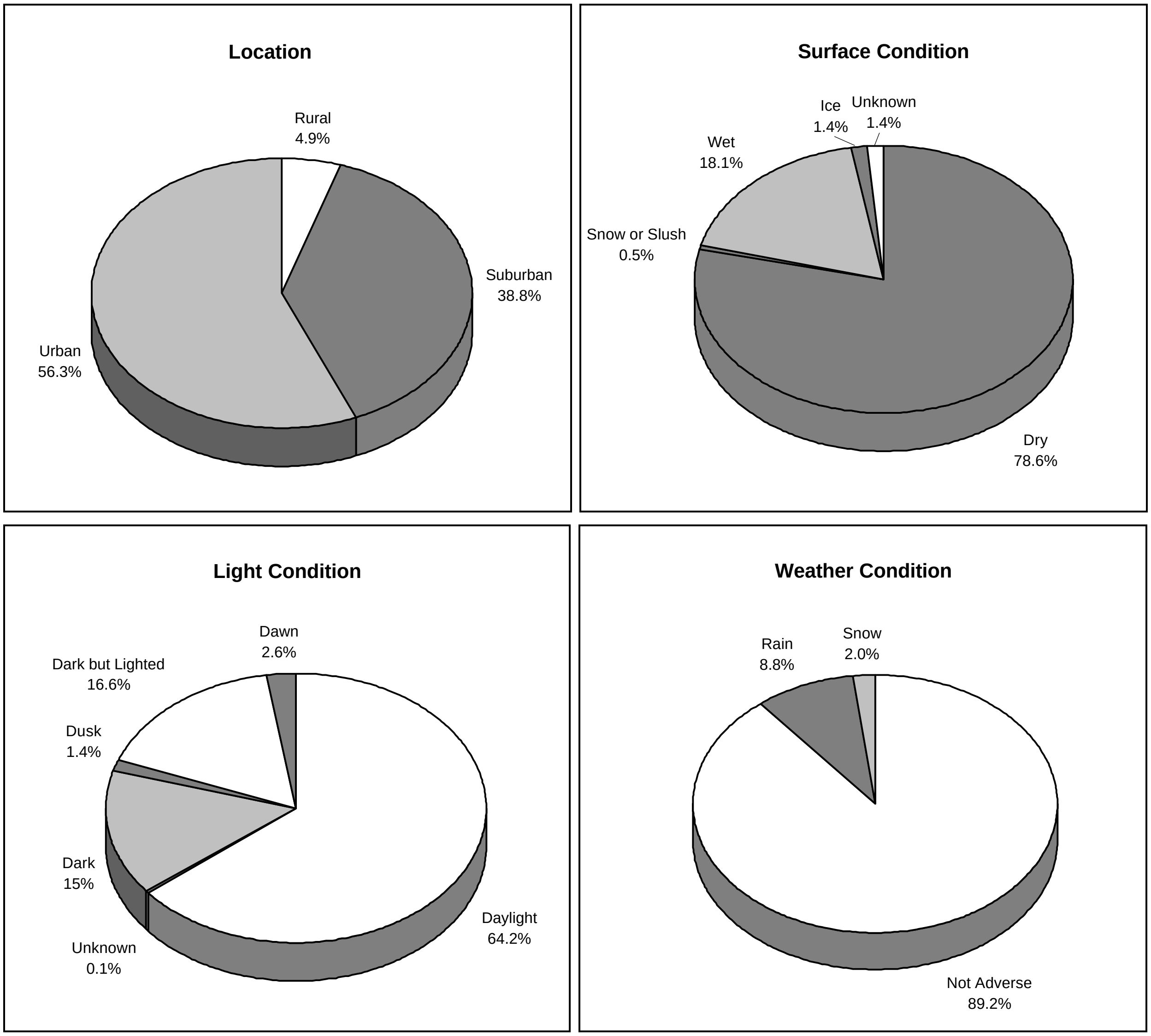


Figure 2-25. Environmental Conditions for Lane Change/Merge Interstate Crashes

Lane change/merge collisions on interstates are reported as resulting in no injury to involved vehicle occupants in 71 percent of the collisions (figure 2-26). Crashes occurring in rural locations have the highest frequency of no injury (83 percent) and the highest frequency of incapacitating injuries (1.5 percent).

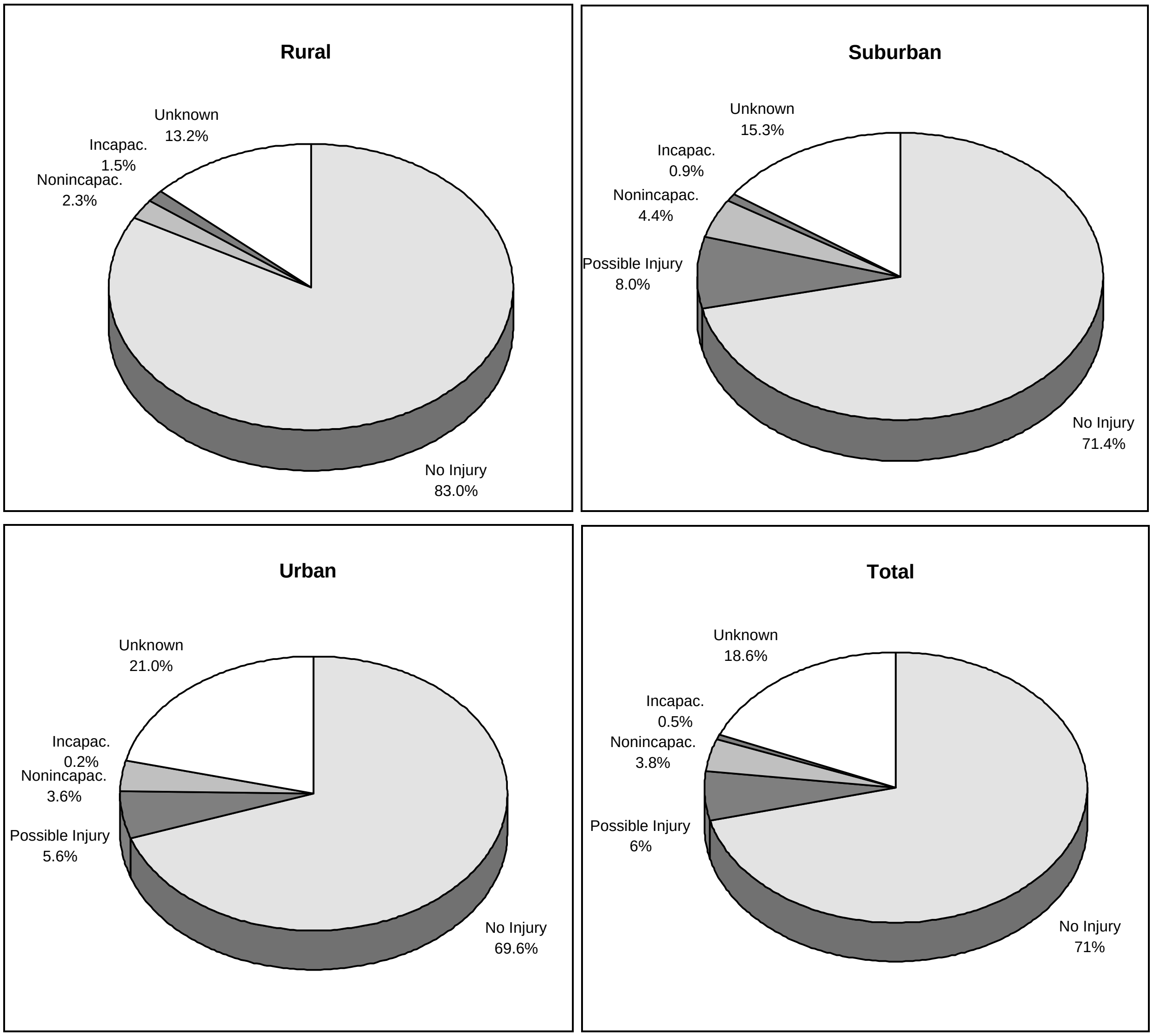


Figure 2-26. Injury Severity for Occupants of Vehicles Involved in Lane Change/Merge Interstate Crashes

Minor to moderate vehicle damage describes the known damage severity for vehicles involved in interstate lane change/merge crashes (figure 2-27). These two categories represent 78.4 percent of the vehicle damage descriptions from these collisions. Vehicles involved in this crash type in rural locations primarily incur either minor damage (82 percent) or severe damage (15.3 percent). Urban locations have the highest frequency of severe vehicle damage (18.5 percent).

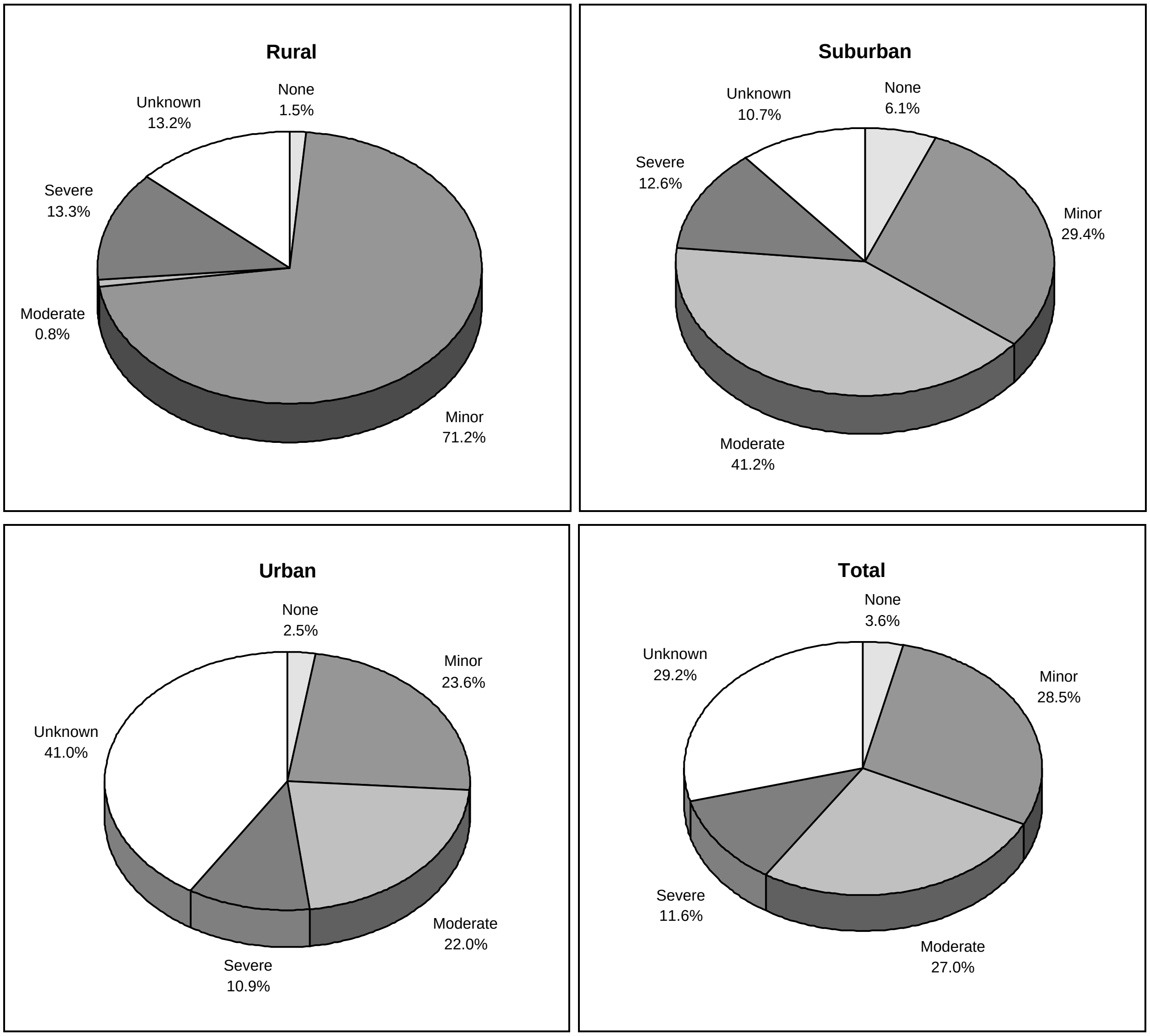


Figure 2-27. Damage Severity for Vehicles Involved in Lane Change/Merge Interstate Crashes

Data highlights from tables presented in appendix G are summarized below:

1. Highest Injury Level in Vehicle x Surface Condition: As road conditions progress from dry to wet to snow/slush to ice, injury severity decreases, indicating that drivers slow down as road conditions worsen, so the impact velocity for crashes on degraded road surfaces is lower (figure 2-G1).

2. Vehicle Damage x Surface Condition: Vehicle damage severity worsens with road surface conditions. Specifically, minor damage drops off and moderate to severe damage increases as road surface conditions degrade. For snow or slush covered roads, all of the vehicles are classified as having severe damage. See figure 2-G2.

3. Injury Severity x Restraint Use: The GES data does not exhibit major differences between the maximum occupant injury per vehicle for restrained versus

unrestrained occupants involved in interstate lane change/merge crashes. The term restrained refers to occupants that are protected either by a belt system or a deployed airbag. There are a lower proportion of incapacitating injuries for restrained occupants. Unfortunately, the fatal injuries fell into the unknown category for restraint use.

4. Time of Day x Location: Interstate lane change/merge crashes are an evening rush hour problem for urban and suburban locations. Nearly 32 percent of the urban crashes occur between 3 and 6 pm, and 37.4 percent of the suburban crashes occur between 3 and 9 pm. In rural locations, the 6 to 9 am time period is the most frequent time for this crash type.

5. Day of Week x Location: Overall, lane change/merge crashes on interstates are somewhat evenly distributed over weekdays. The highest frequency of occurrence in rural locations is on Thursdays and Saturdays (57 percent). Suburban locations have a peak occurrence on Fridays (25.6 percent) and urban locations have the largest proportion of this crash type on Mondays and Tuesdays (39.1 percent).

6. Relation to Junction: The majority of interstate lane change/merge crashes occur in non-interchange areas at non-junctions (80.1 percent). Only 4.2 percent are at entrance/exit ramps.

7. Alcohol Involvement x Location: Rural interstate lane change/merge crashes have a large proportion of police reported alcohol involvement. Approximately 16 percent of these crashes are listed as "alcohol involved" as compared to 0.9 percent for drivers involved in collisions in suburban locations and 2.9 percent in urban locations.

The GES and CDS data filters used to characterize interstate lane change/merge crashes are described in appendix G. Data from the CDS Data Analysis are presented in tabular form in appendix G.

3.2.6.3 Occupant Injury Severity for Lane Change/Merge Crashes (CDS)

The maximum occupant injury severity within each vehicle involved in a same trafficway, same direction, sideswipe/angle collision is shown in table 2-G1. The highest recorded injury level resulting from the collision is critical, although the variable for the most intensive medical treatment for occupants of each vehicle shows 1.1 percent of the vehicles have occupants that died within 30 days of the crash as a result of injuries sustained in the crash (table 2-G2). The discrepancy between injury severity ratings and medical treatment is that very few injuries are actually classified as untreatable, yet injuries rated as AIS serious, severe or critical may result in death.

The majority of vehicles involved in lane change/merge crashes have occupants with their highest injury level rated as minor or moderate (80.6 percent). More than half of the vehicles (57.5 percent) have occupants that were transported to a medical facility, treated, and released. Approximately, nine percent of the vehicles have occupants that require hospitalization.

Severe injuries are the highest injury level for restrained occupants, while critical injuries are the highest injury level for unrestrained occupants. However, restrained occupants suffered higher frequencies of moderate and serious injuries than unrestrained occupants (table 2-G3).

3.2.6.4 Review of Causal Factors for Lane Change/Merge Crashes

Crash causes determined for the Indiana Tri-Level study (Treat, et al., 1979) are cited as part of a study on lane change/merge crashes on all roadways, (Knipling 1993). The Tri-Level statistics describe causal factors associated with 19 lane change/merge crashes. The causal factors defined as certain or probable indicate that 100 percent of the investigated lane change/merge crashes can be attributed to human causes. The primary human causes are recognition errors (mainly improper lookout) and decision errors (false assumptions and improper maneuvers). Ten percent of the cases are cited as having environmental factors that contributed to the crash and no vehicular factors are listed. Knipling notes that in the Tri-Level study, multiple crash causes are often indicated.

3.2.6.5 AHS Implications and Conclusions from Lane Change/Merge Crash Analysis

- Lane change/merge and rear-end crashes make up the majority of vehicle-to-vehicle crash types (as opposed to single vehicle crashes) on interstate highways. These crash types typically occur in congested areas - suburban and urban locations. RSC I1C1 is not likely to reduce the frequency of lane change/merge crashes since manual vehicles are mixed with automated vehicles and automated vehicles still use the driver for lane change maneuvers. RSCs I2C1, I2C2 are the initial configurations that will begin to reduce the occurrence of this crash type. As percent participation increases, drivers that are already transitioned on to the AHS are most likely to be free of this crash type. The I2 transition lanes still pose circumstances where lane change/merge crashes might occur. The greatest concern is for vehicles being struck in the transition lane and pushed into the AHS traffic stream. The separate I3 infrastructures hold the greatest potential for eliminating this crash type.

- Police reported alcohol involvement is a problem associated with this crash type in rural areas. The I1C1 RSC is attractive for rural locations, but the presence of impaired drivers will degrade the benefits.

- Lane change/merge collisions are a commuter's problem. They mainly occur on weekdays during the evening rush hour. This is a target area for AHS prevention, and should produce significant benefits.

- The majority of lane change/merge crashes result in no injury to the vehicle occupants and minor to moderate vehicle damage. Most of these crashes occur at non-interchange, non-junction related areas. The AHS will greatly reduce these crashes, the potential for increase is in transition lanes and at entry/exit locations to the AHS.

- Restraint systems eliminated the occurrence of critical injuries, but did not lower the occurrence of severe and serious injuries, since current restraints are designed primarily to protect against frontal impacts versus side impacts.

- Causal factor analysis of lane change/merge collisions indicates that 100 percent of these crash types have human error as a certain or probable cause for the collision. Environmental factors play a minor role in causes for this crash type. Causal factors such as driver recognition and decision errors are likely to be eliminated by an automated highway system. Environmental factors will be detected by the AHS so that proper judgments can be made.

3.2.6.6 Recommendations from Lane Change/Merge Crash Analysis

- Lane change/merge crashes have been reviewed relative to the RSCs. Detailed safety analysis specific to the configurations selected for AHS implementation must be performed to determine the real potential for eliminating this crash type and the possible creation of new causal factors for this crash type.

- Tradeoffs should be evaluated for costs versus benefits of lower level RSCs (I1C1, or I2C1 where automated vehicles control lane changes) for rural locations in terms of cost and safety, particularly in light of impaired driver involvement for this crash type.

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

- Automated vehicles must have higher levels of side impact protection than vehicles sampled in the 1992 CDS study.

- Effectiveness of vehicles equipped with improved side impact protection (vehicles that already meet 1997 safety standards) in reducing occupant injury levels during side impacts should be studied.

- CDS data set should be expanded to included general descriptive information, or perhaps have a key to link the cases back to their original GES case number to obtain this information.

- Algorithms should be developed to estimated ΔV for side to side collisions.

3.2.7 Driver Impairment Crash Analysis

This section examines the impaired driver crash problem that exists on today's highways and considers the potential for this crash type on an AHS. To determine the frequency and conditions of occurrence regarding interstate impaired driver collisions, various accident data bases are examined. This approach is taken in order to gauge the magnitude of the existing impaired driver hazard and gain an understanding of relevant crash characteristics. This knowledge can be used in the development of an AHS that maximizes driver safety.

An initial analysis of the GES data file is conducted to identify the types of driver impairments that are most frequently involved in crashes. As it will be discussed, the results of the analysis show that, on existing highways, alcohol/drug violators and drowsy/fatigued drivers are major contributors. Subsequently, these two groups of drivers became the focus of the impaired driver assessment.

Older drivers are also considered in the impaired driver analysis. Since the accident data files contain frequency data and the older driver population is proportionately smaller than other age groups, the crash percentage for older drivers appears small (i.e., crash rate for older drivers is not available). Only crash type frequency for older drivers is treated here.

A study of impaired driver crashes is required to:

- understand the causal and situation factors of today's interstate impaired driver crashes to assist AHS designers in developing an infrastructure and implementing technology which serves to reduce the occurrence and severity of this crash type

- envision unique AHS causal factors that may lead to impaired driver crashes on an AHS

- estimate the benefits of an AHS in terms of eliminating causes of driver impaired crashes

- raise the issue of the need for barriers on the I2C1 and I2C2 RSCs, given the frequency of this crash type on present day interstates

- raise the issue of AHS check-in and check-out procedures for the impaired driver

- raise the issue of AHS driver status monitoring and driver alertness (driver in the loop)

3.2.7.1 Interstate Impaired Driver Crashes Resulting from AHS Unique Situations

AHS lat/long control will eliminate driver lane keeping errors that are prevalent for drowsy/fatigued drivers. Driver related causal factors, such as driver misperception and judgment error, can be reduced in frequency.

New causal factors, however, may occur that are unique to the AHS. Unmitigated system failure/malfunctions could create situations where impaired driver crashes will occur. A summary of AHS scenarios and related RSCs are provided in table 2-23.

AHS technology has the potential to eliminate may of the factors that lead to impaired driver crashes, including denying access to some types of impaired drivers. AHS check-in procedures can be implemented to detect the alcohol impaired driver and through this screening process eliminate alcohol impaired crashes from most AHS infrastructures. The alcohol impaired driver will remain a problem on the I1C1 where there is no physical division between automated and manual lanes and automated and manual vehicles travel in the same lane.

The probability of AHS impaired driver collisions increases with the occurrence of unmitigated system failures/malfunctions affecting lat/long control or when manual backup mode is required. The impaired driver may be incapable of any response or may have delayed braking and steering responses. This scenario could result in a barrier impact, rear-end crash or side impact of an adjacent vehicle.

Table 2-23. AHS Scenarios with Impaired Driver Crash Potential

{PRIVATE }Situation ==> Impaired Driver Crash	Applicable RSCs
manual vehicle trailing an automated vehicle that suddenly brakes or stops reaction time for automated vehicle: ~0.3 sec. reaction time for manual vehicle: ~1.7 sec (*) reaction time for impaired driver of manual vehicle: may be > 1.7 or non-existent	I1C1 I2C1 & I2C2 Transition lanes
result of sideswipe or side impact due to: impaired driver of manual vehicle intrudes into automated lane	I1C1
failure of impaired driver to assume manual backup mode in the event of a system failure	I1C1, I2C1, I2C2, I3C1, I3C2, I3C3
improper lane change by manual or automated vehicle	I1C1
improper merge into transition lane	I2C1 & I2C2
reduced visibility conditions	I1C1, I2C1 & I2C2 Transition lanes
system traction degraded due to surface or weather conditions	I1C1, I2C1 & I2C2 Transition lanes
roadway obstacle present or incident occurs	I1C1, I2C1 & I2C2 Transition lanes
check-in, check-out	All RSCs

*Transportation Research Circular 419, March 1994.

3.2.7.2 Characteristics of Impaired Driver Interstate Crashes

According to the 1992 GES data file there were 22,280 vehicles involved in crashes where the driver was impaired. This represents 4.4 percent of total interstate crashes. The inclusion of drivers who are more than 60 years old (32,226) in the impaired driver category, raises this figure to 10.9 percent.

A summary of interstate impaired driver crash characteristics is presented in this subsection. Support graphics for the data can be found in appendix H. Data from the 1992 GES data files are used to provide general information regarding the characteristics of interstate impaired driver crashes.

An initial analysis of the GES data files is conducted to determine the frequency with which impaired drivers are involved in interstate crashes.

1. Violation - Of the drivers involved in interstate crashes, 1.6 percent are charged with alcohol/drug violations. A very small number of drivers are charged with alcohol/drugs and speeding violations (did not exceed 0.0 percent).

2. Impairment - The largest group of impaired drivers are those that report feeling drowsy or sleepy prior to the crash (2.7 percent).

Based on these findings, further analyses are conducted of:

- drivers with alcohol/drug violations
- drowsy/sleepy impaired drivers

3.2.7.3 Characteristics of Interstate Alcohol/Drug Related Crashes

This analysis focuses on the characteristics of alcohol/drug related crashes that occur on interstates. GES data files are used.

As depicted in figure 2-28, most interstate crashes involving alcohol/drug driver violations occur under dark but lighted (44.0 percent) or dark (34.2 percent) conditions. The majority of these crashes occur in urban locations (63.0 percent), on dry roads (85.3 percent) and when there are no adverse weather conditions (93.0 percent).

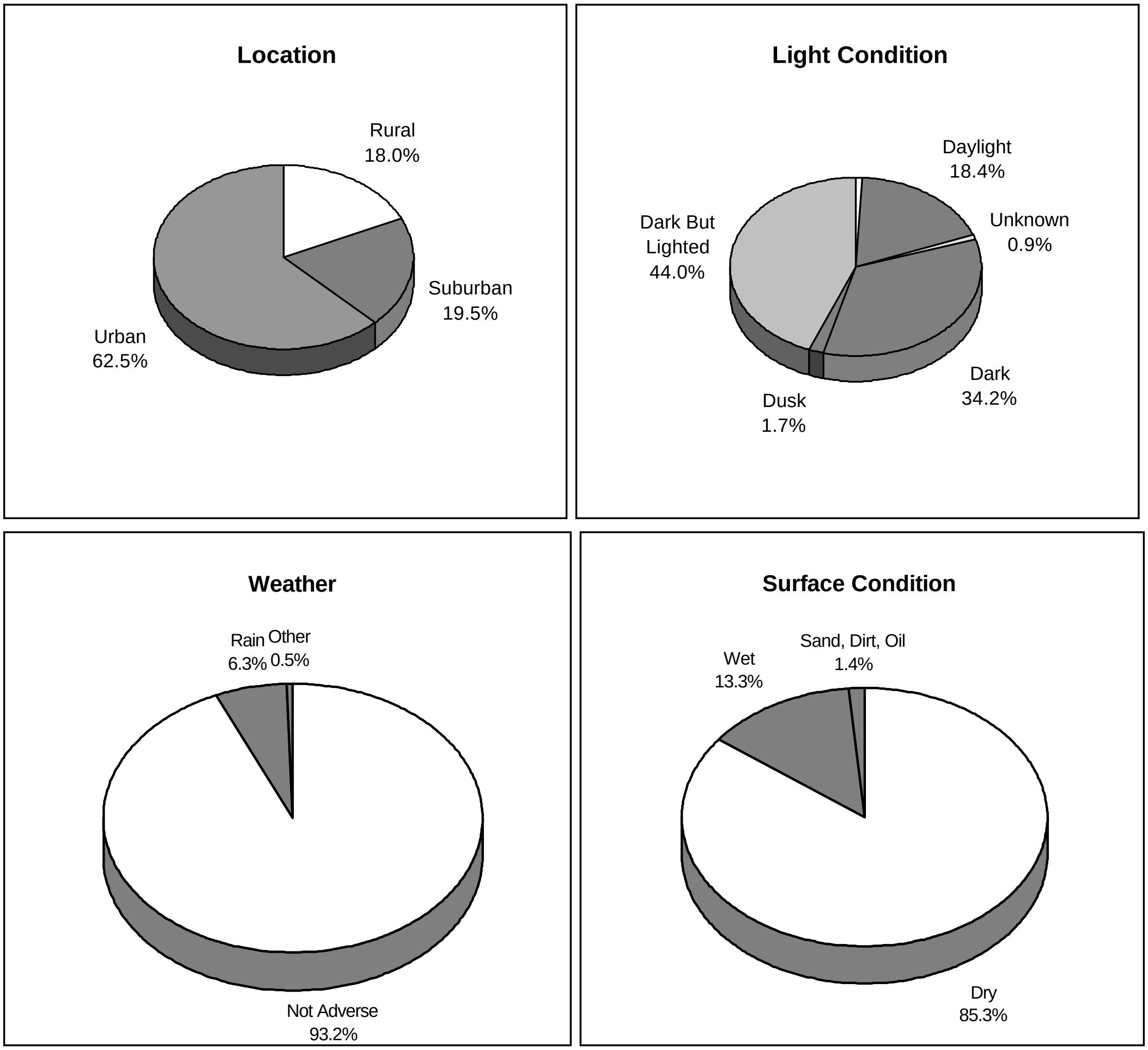


Figure 2-28. Environmental Conditions for Interstate Crashes with Alcohol/Drug Violations Charged to Driver

In the majority of interstate crashes with alcohol/drug violations, occupants are not injured (61.3 percent). Approximately 30.0 percent receive possible or non-incapacitating injuries and 7.5 percent have incapacitating injuries. Most crashes with incapacitating injuries occur in suburban (18.1 percent) locations.

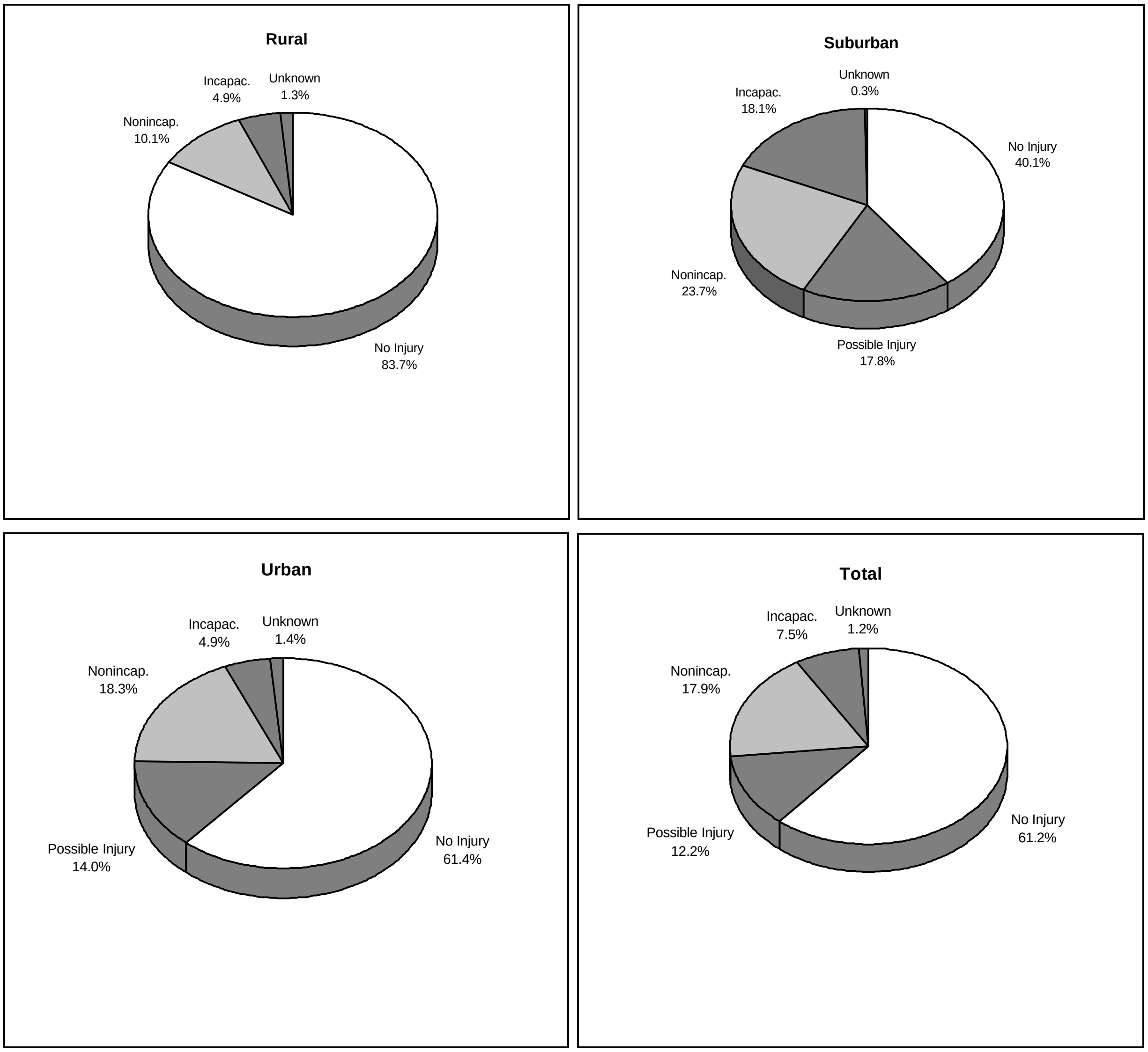


Figure 2-29. Highest Injury Severity for Occupants of Vehicles Involved in Interstate Crashes with Alcohol/Drug Violations Charged to Driver

Of the vehicles involved in alcohol/drug related interstate crashes, 36.5 percent have minor damage, 20.5 percent have moderate damage and 33.8 percent have severe damage. The majority of crashes resulting in severe vehicle damage occur in urban locations.

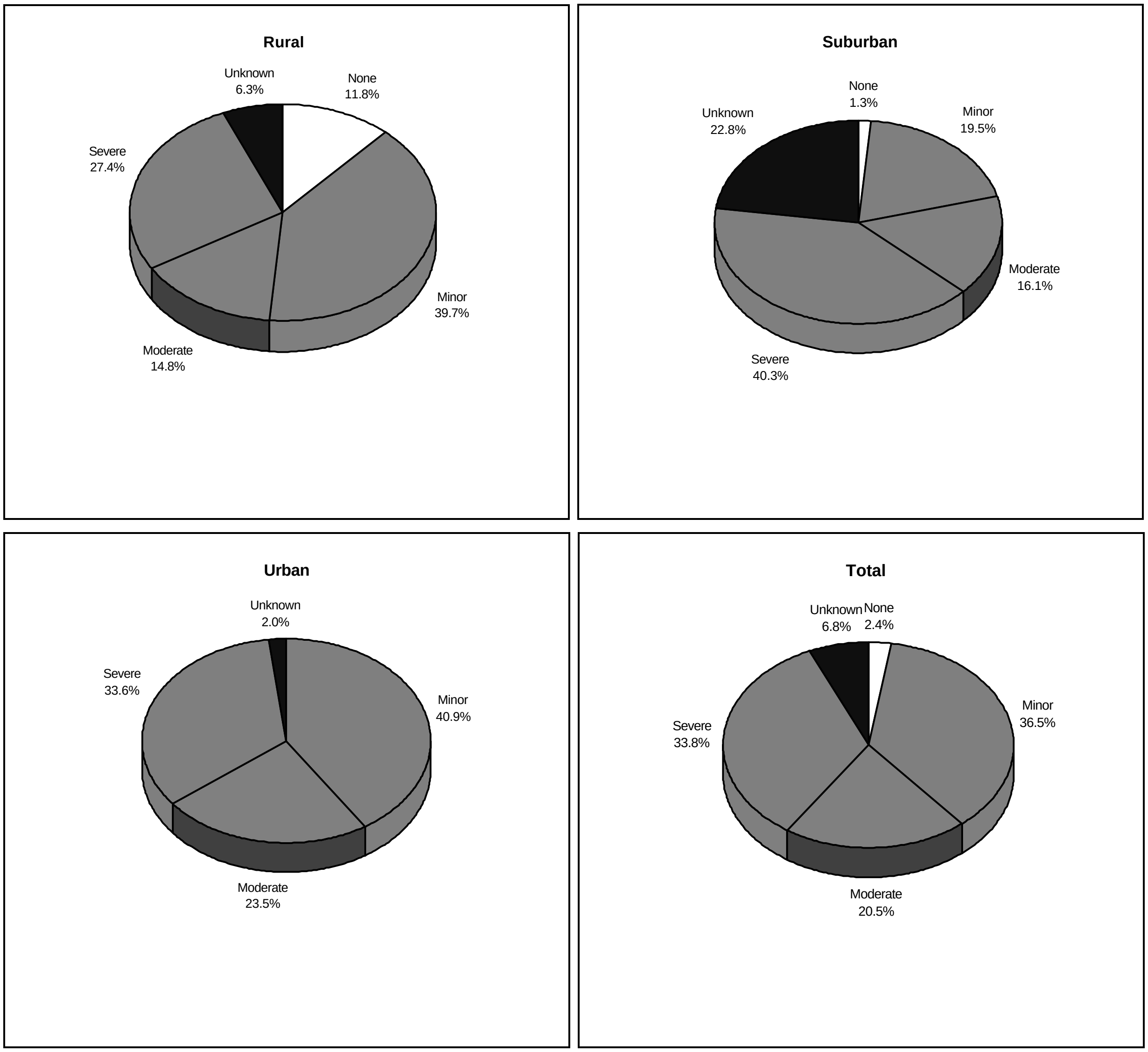


Figure 2-30. Damage Severity for Vehicles Involved in Interstate Crashes with Alcohol/Drug Violations Charged to Driver

Data highlights from tables presented in appendix H are summarized below.

1. Accident Type by Age Group - The majority of interstate crashes involving alcohol/drug violations are rear-end collisions (37.7 percent), single driver roadside departures (30.2 percent; 12.7 percent loss of control and 17.5 percent drive off road) and side swipes (19.4 percent). The majority of single driver roadside departures and sideswipes involve drivers from age 31 to 45 and the majority of rear-end crashes involve drivers from age 21 to 30.

2. Maximum Injury Severity in Vehicle by Roadway Surface Condition - Of the interstate alcohol/drug involved crashes that result in incapacitating occupant injuries (7.5 percent), 95.1 percent occur on dry pavement.

3. Vehicle Damage by Roadway Surface Condition - Of the interstate alcohol/drug involved crashes that result in severe vehicle damage (33.8 percent), 84.9 percent occur on dry pavement.

4. Driver Injury Severity by Vehicle Restraint Protection - For drivers charged with alcohol/drug violations in interstate crashes who use vehicle restraint systems (69.1 percent), 70.2 percent are uninjured, 24.5 percent receive possible or non-incapacitating injuries and 5.3 percent have incapacitating injuries. For drivers not using restraint systems (17.9 percent), only 38.5 percent escape injury, 40.8 percent receive possible or non-incapacitating injuries and 15.5 percent are incapacitated.

5. Time of Day by Location - The most interstate barrier crashes involving alcohol/drug violations occur between 10 pm and midnight (35.6 percent) and between midnight and 3 am (26.1 percent). The majority of these crashes occur in urban areas.

6. Weekday by Location - Most interstate crashes with alcohol/drug violations occur on Saturdays (27.6 percent) and the majority of them occur in urban locations (43.0 percent). The fewest number of crashes occur on Monday (4.9 percent) and Sunday (6.8 percent).

7. Critical Event Making Crash Imminent by Vehicle Role - For vehicles involved in interstate crashes with alcohol/drug violations that initiate the critical pre-crash event, 24.9 percent travel over the edge of the roadway, 21.0 percent are in another vehicle's lane, 9.8 percent lose vehicle control and 6.6 percent encroach into another vehicle's lane.

8. Movement Prior to Critical Event by Vehicle Role - Approximately 71.0 percent of all vehicles involved in interstate crashes with alcohol/drug violations are traveling straight prior to the critical event, 6.6 percent are changing lanes, 3.5 percent are stopped in traffic lane, 2.1 percent are leaving a parked position, and 1.5 percent are negotiating a curve or slowing/stopping in traffic. The majority of movements prior to critical event involve the striking vehicle (61.0 percent).

9. Most Harmful Event by Vehicle Role - The most harmful events for vehicles involved in interstate crashes with alcohol/drug violations include collision with a motor vehicle in transport (59.3 percent), collision with a fixed object (20.1 percent), and rollover (4.6 percent).

10. Number Vehicles Involved by Location - The majority of interstate crashes with alcohol/drug violations involve two vehicles (57.4 percent) or are single vehicle crashes (34.4 percent). Both of these crash types occur most frequently in urban areas (64.8 percent and 50.5 percent, respectively).

11. Age Group - The majority of interstate alcohol/drug violation crashes occur for the 21-30 age group (37.6 percent). For the 31-45 age group, 34.4 percent are charged with alcohol/drug violations, 11.6 percent of 46-60 year olds are charged and 10.7 percent of drivers less than 21 years old are charged.

12. Sex - Male drivers involved in interstate crashes are more frequently charged with alcohol/drug violations (76.4 percent) than females (22.6 percent).

The intent of the analysis is to examine worse case crash characteristics and vehicle behavior for fatal crashes involving alcohol/drug violations. FARS 1992 data files are used.

1. Alcohol Test Results - Interstate alcohol/drug related crash fatalities have the following alcohol test results: 12.5 percent have 0.00 BAC, 1.5 percent have 0.01 to 0.02 BAC, 1.4 percent have 0.03 to 0.04 BAC, 6.6 percent have 0.05 to 0.06 BAC, 1.5 percent have 0.07 to 0.08 BAC, 5.2 percent have 0.09 to 0.10 BAC and 49.0 percent have greater than 0.10 BAC.

2. Drug Test Results - Interstate alcohol/drug related crash fatalities have the following drug test results: 44.1 percent not tested, 14.0 percent no drugs reported, 2.1 percent narcotic, depressant, or stimulant drugs, 2.9 percent cannabinoid drug, 2.2 percent multiple drugs, 34.6 percent unknown.

3. Vehicle Maneuver - Of the vehicles involved in alcohol/drug related fatal interstate crashes, approximately 65.0 percent are going straight prior to the crash, 14.0 percent are negotiating a curve, 10.3 percent are changing lanes or merging, 4.4 percent are passing or overtaking another vehicle and 3.7 percent are maneuvering to avoid an animal/object in the road.

4. Manner of Collision - The manner of collision for the majority of interstate fatal crashes with alcohol/drug violations is not a collision with a motor vehicle in transport (58.5 percent). Head-on collisions occur in 16.7 percent of the crashes, 13.2 percent are rear-end collisions, 5.9 percent are angle impacts, 5.1 percent are sideswipe (same direction) impacts.

3.2.7.4 Characteristics of Interstate Crashes Involving Drowsy Drivers

The analysis is limited to interstate crashes involving drivers who reported feeling drowsy prior to the collision. GES 1992 data files are used.

Most interstate crashes involving drowsy drivers occur under daylight (57.2 percent) or dark (32.6 percent) conditions. The majority of drowsy driver interstate crashes occur in rural locations (46.1 percent) and suburban areas (37.8 percent). Just under 93.0 percent of drowsy driver interstate crashes occur on dry roads and approximately 94.0 percent occur when there are no adverse weather conditions.

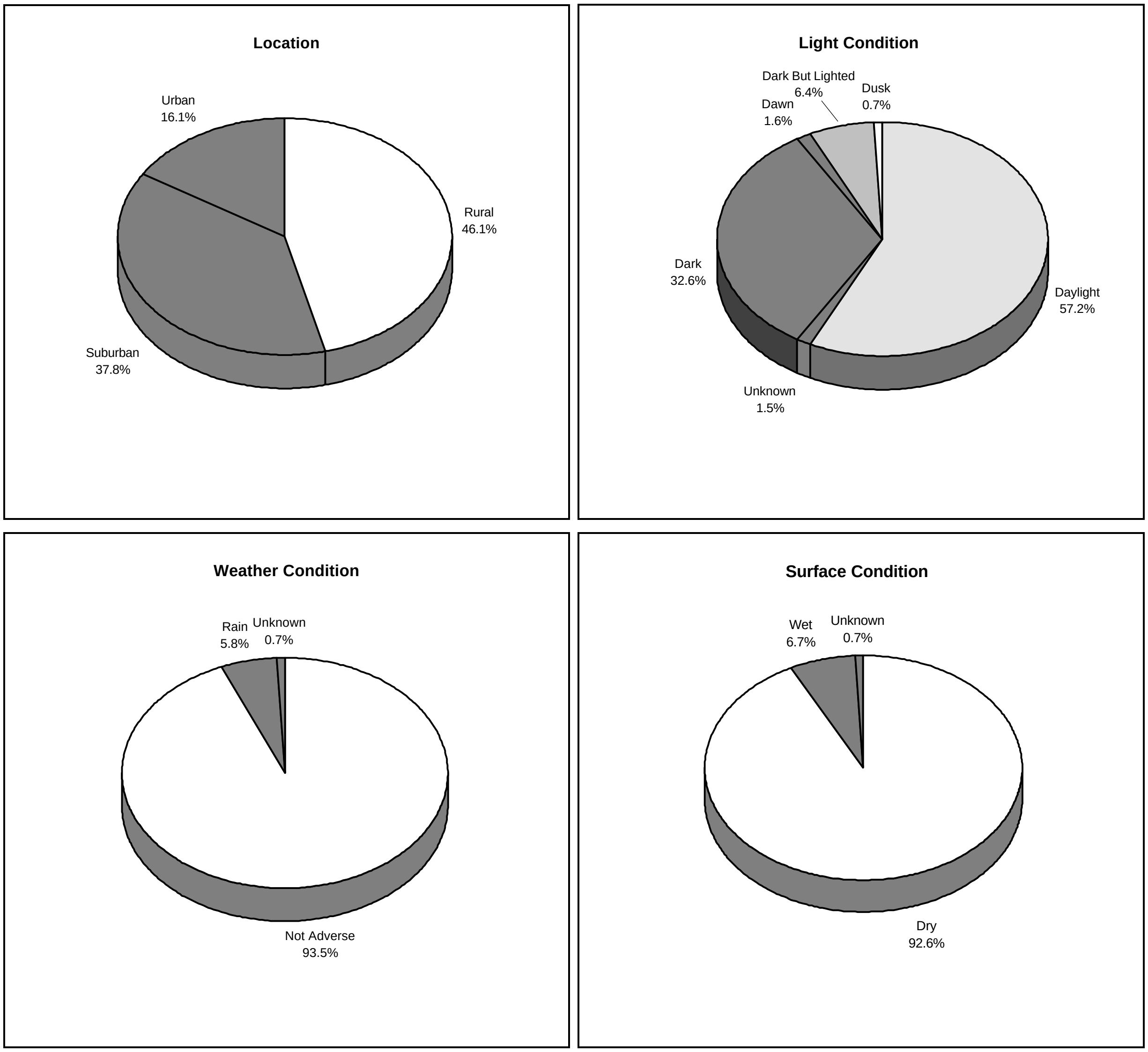


Figure 2-31. Environmental Conditions for Interstate Crashes Where Driver is Drowsy

The majority of occupant of vehicles involved in these crashes are not injured (56.7 percent). Approximately 28.0 percent receive possible or non-incapacitating injuries, 10.5 percent have incapacitating injuries and 4.4 percent are fatalities. Most crashes with incapacitating injuries occur in suburban and rural locations. The majority of fatalities take place in rural locations.

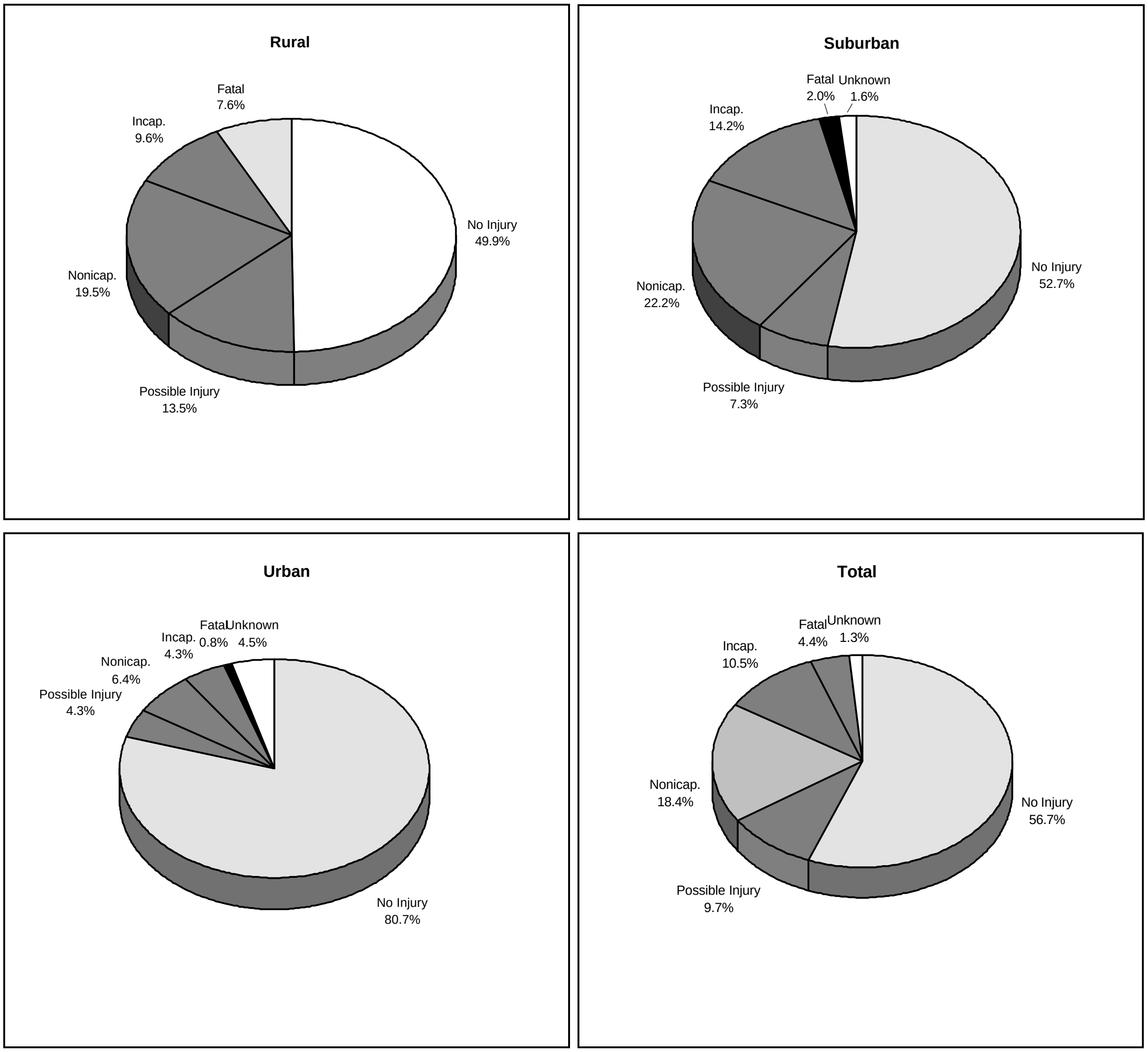


Figure 2-32. Highest Injury Severity for Occupants of Vehicles Involved in Interstate Crashes Where Driver is Drowsy

Of vehicles involved in drowsy driver interstate crashes, 7.7 percent have minor damage, 13.1 percent have moderate damage and 37.4 percent have severe damage (41.6 percent are unknown). The majority of crashes resulting in severe vehicle damage occur in rural locations (41.5 percent).

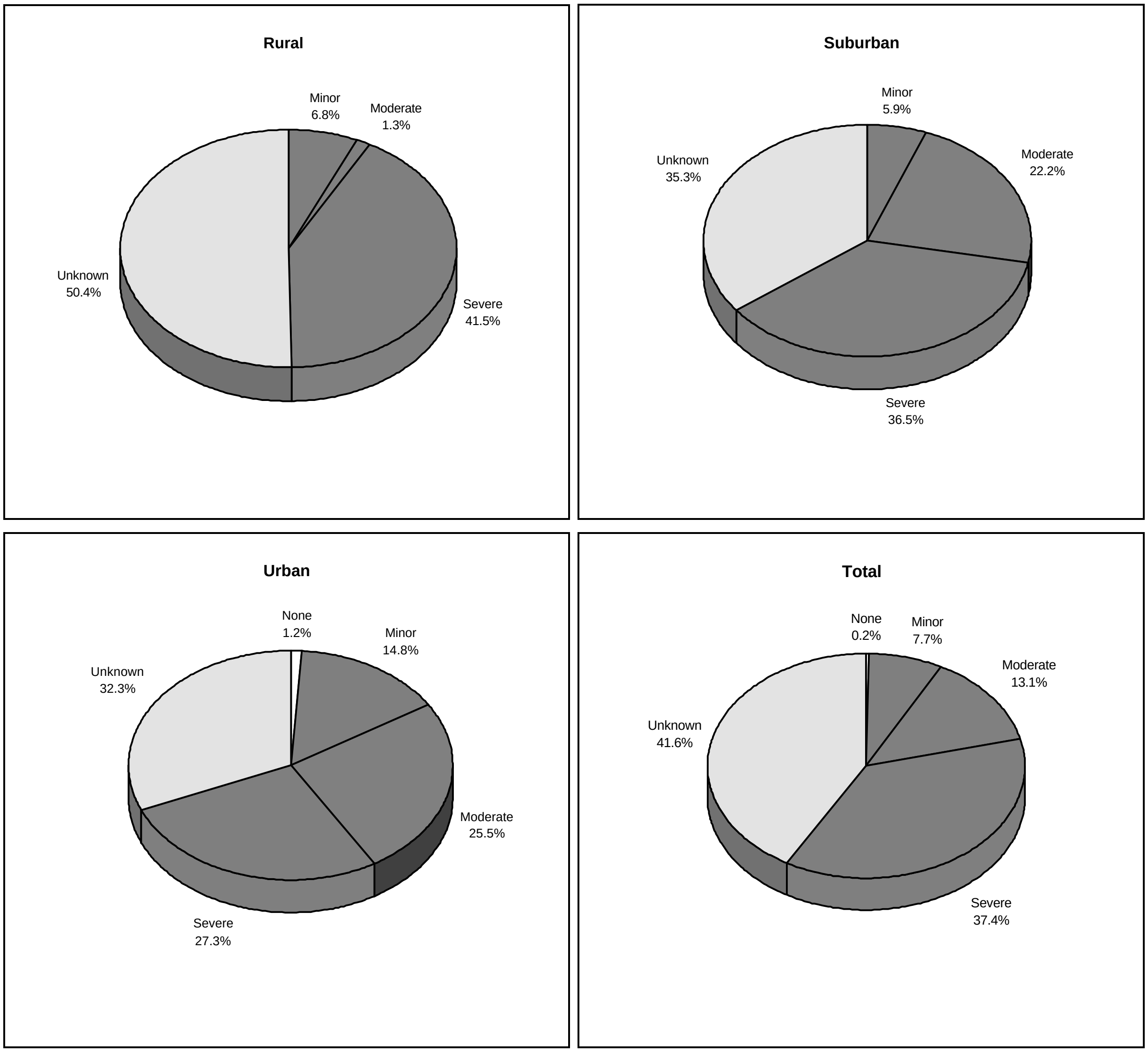


Figure 2-33. Damage Severity for Vehicles Involved in Interstate Crashes Where Driver is Drowsy

Data highlights from tables presented in appendix H are summarized below.

1. Accident Type by Age Group - The majority of interstate crashes involving drowsy drivers are single driver roadside departures (65.6 percent; 22.4 percent loss of control and 42.7 percent drive off road). Right drive off road crashes happen almost twice as often as left drive off road crashes (27.9 percent and 14.8 percent, respectively). Rear-end crashes occur 15.2 percent of the time and 10.8 percent of the crashes are same direction sideswipes. Generally, the majority of single driver roadside departures, rear-end crashes and sideswipes involve drivers from age 21 to 30. Older drivers (i.e., > 60 years old) tend to be involved in right roadside departures and untripped rollovers.

2. Maximum Injury Severity in Vehicle by Roadway Surface Condition - Of the interstate crashes involving drowsy drivers that result in incapacitating occupant injuries (10.5 percent), 97.2 percent occur on dry pavement.

3. Vehicle Damage by Roadway Surface Condition - Of the interstate drowsy driver involved crashes that result in severe vehicle damage (37.4 percent), 88.8 percent occur on dry pavement.

4. Driver Injury Severity by Vehicle Restraint Protection - For drowsy drivers involved in interstate crashes who use vehicle restraint systems (81.3 percent), 62.8 percent are uninjured, 25.9 percent receive possible or non-incapacitating injuries, 6.6 percent have incapacitating injuries and 1.0 percent are fatalities. For drivers not using restraint systems (11.3 percent), 51.9 percent escape injury, 26.0 percent receive non-incapacitating injuries, 17.0 percent are incapacitated and 5.1 percent are fatalities.

5. Most Harmful Event - The most harmful events for drowsy driver interstate crashes include collision with a motor vehicle in transport (26.0 percent), rollover (20.3 percent) and collision with a guardrail (15.7 percent).

6. Time by Location - The most interstate barrier crashes involving drowsy drivers occur between 3 pm and 6 pm (21.2 percent) and between 6 am and 9 am (19.6 percent) and the majority of these crashes occur in rural areas.

7. Weekday by Location - Most interstate crashes involving drowsy drivers occur on Saturdays (18.6 percent) and most of them occur in suburban locations (52.5 percent). The fewest number of crashes occur on Friday (10.4 percent). Overall, the majority of drowsy driver crashes occur in rural locations (46.1).

8. Alcohol by Location - Alcohol involvement is reported by police in approximately 8.0 percent of drowsy driver interstate crashes. The majority of these crashes occur in urban locations (58.4 percent).

9. Number Vehicles Involved by Location - The majority of drowsy driver interstate crashes are single vehicle collisions (73.2 percent) and most of them occur in rural locations (55.5%). About 25.0 percent of the crashes involve two vehicles (57.4 percent) and this crash type occurs most frequently in suburban areas (47.5 percent).

10. Age Group - The majority of interstate drowsy driver crashes occur for the 21-30 age group (30.4 percent). For the 31-45 age group, 27.5 percent report feeling drowsy, 12.6 percent of drowsy drivers are 46-60 year olds, 6.0 percent are ages 61 to 70, 7.4 percent are older than 70 years of age and 15.3 percent of drivers less than 21 years old report feeling drowsy.

11. Sex - Male drivers involved in interstate crashes more frequently report feeling drowsy prior to a crash (81.0 percent) than females (19.0 percent).

The intent of the analysis is to examine worse case crash characteristics and vehicle behavior for fatal drowsy driver interstate collisions. The FARS 1992 data files are used.

1. Alcohol Test Results - Interstate drowsy driver crash fatalities have the following alcohol test results: 40.8 percent have 0.00 BAC, 1.4 percent have 0.01 to 0.02 BAC, 1.1 percent have 0.03 to 0.04 BAC, 1.6 percent have 0.05 to 0.06 BAC, 1.5 percent have 0.07 to 0.08 BAC, 1.5 percent have 0.09 to 0.10 BAC and 6.8 percent have greater than 0.10 BAC (45.1 percent unknown).

2. Drug Test Results - Interstate drowsy driver crash fatalities have the following drug test results: 57.6 percent not tested, 17.5 percent no drugs reported, 0.2 percent depressant drugs, 1.1 percent stimulant drugs, 0.7 percent cannabinoid drug, 0.7 percent multiple drugs, and 22.2 percent unknown.

3. Vehicle Maneuver - Of the vehicles involved in drowsy driver fatal interstate crashes, approximately 84.0 percent are going straight prior to the crash, 11.4 percent are negotiating a curve, 1.3 percent are maneuvering to avoid an animal/object in the road and 1.1 percent are passing or overtaking another vehicle.

4. Manner of Collision - The manner of collision for the majority of interstate fatal crashes with drowsy drivers is not a collision with a motor vehicle in transport (87.7 percent). Rear-end collisions occur in 6.1 percent of the crashes, 3.6 percent are head-on collisions and 1.6 percent are angle impacts.

5. First Harmful Event - By far, the first event producing injury or damage for interstate drowsy driver crashes is vehicle overturns (38.1 percent). Collision with a guardrail is the first harmful event in 16.1 percent of the crashes and collision with a motor vehicle in transport occurs in 9.0 percent of the crashes.

The purpose of this analysis is to examine accident types associated with older driver interstate crashes. The GES 1992 data files are used.

1. Accident Type by Age Group - The majority of 61 to 70 year olds are involved in same way - same direction interstate crashes (61.2 percent; 39.4 percent rear-end, 20.3 percent sideswipe angle) and single driver crashes (23.5 percent; 14.2 percent right roadside departure, 3.7 percent left roadside departure, 6.1 percent forward impact). Drivers greater than 70 years of age are involved in the following crash types: 48.7 percent same way - same direction crashes (25.9 percent rear-end, 22.7 percent sideswipe) and 33.3 percent single driver crashes (15.1 percent right roadside departure, 18.2 percent left roadside departure, 0.0 percent forward impact).

3.2.7.5 Review of Causal Factors

Findings of the Indiana Tri-level study (Treat, et al., 1979) regarding causal factors for impaired driver crashes are reviewed in this subsection. The data include all roadway types (i.e., not limited to interstates) but despite the fact the study is broader in scope, it is assumed that its findings are relevant to the discussion of impaired driver crashes, as many of the same causal factors are likely to be involved.

According to the Tri-Level study, alcohol impairment is the most frequently assessed driver condition implicated as a crash cause (0.5-3.1 percent, definite cause, in-depth investigation) for all severities of police reported crashes. It is found that accident severity (i.e., personal injury and vehicle damage severity) is significantly greater when alcohol impairment is involved. The study stresses that alcohol impaired driver performance concerns are falling asleep and speeding. Other drug impairment is ranked second among driver conditions that are implicated as crash causes (0.2 to 0.5 percent, definite cause, in-depth investigation). Fatigue is ranked as the third highest driver condition for in-depth probable involvement in crash causation (0.0 to 0.2 percent, definite cause, in-depth investigation).

3.2.7.6 AHS Implications and Conclusions from Impaired Driver Crash Analysis

Impaired driver collisions, including alcohol/drug, drowsy/fatigue impaired and older driver, account for 10.9 percent of interstate crashes. The frequency of these collisions can be greatly reduced for most AHS RSCs. This reduction will occur through the use of check-in screening, driver status monitoring, and automated lat/long control. The impaired driver will remain a problem for the I1C1 RSC since there is no physical barrier separation of automated and manual lanes and there is a mix of vehicle control types in the same traffic lane.

Alcohol/Drug Impairment:

- Unlike the majority of other crash types (e.g., rear-end or barrier crashes), most interstate crashes involving alcohol/drug violations occur under dark but lighted (44.0 percent) or dark (34.4 percent) conditions. The majority of these crashes occur in urban locations (63.0 percent) between the hours of 10 pm and midnight (35.6 percent), on dry roads (85.0 percent), under no adverse weather conditions (93.0 percent). Therefore, the greatest AHS reduction of impaired driver crashes will occur in urban areas, during night time hours and good weather conditions.

- Approximately 61.0 percent of alcohol/drug related crashes do not result in occupant injury. Incapacitating injuries occur for 7.5 percent of the occupants and most of these more serious injury producing crashes occur on dry pavement (95.1 percent), in suburban (47.2 percent) and urban (41.1 percent) locations. AHS reduction of crash related injury severity will be the greatest in suburban and urban areas, under dry pavement conditions.

- Approximately 34.0 percent of alcohol/drug related interstate crashes result in severe vehicle damage. Most of these crashes occur in urban locations (62.1 percent) and on dry pavement (84.9 percent). AHS reduction of alcohol/drug related crashes resulting in severe vehicle damage will be the greatest in urban areas, under dry pavement conditions.

- Of those drivers involved in alcohol/drug related interstate crashes who use vehicle restraint systems (69.1 percent), 70.2 percent are uninjured. Only 38.5 percent of unrestrained drivers (17.9 percent unrestrained) escape injury and of those who are injured, nearly three times as many suffer incapacitating injuries (15.5 percent) as compared to restrained drivers (5.3 percent). AHS vehicle occupants will benefit from restraint use.

- Rear-end collision is the most frequently occurring crash type for alcohol/drug impaired drivers (37.7 percent) and drivers who are 21 to 30 years of age are most often involved. Single driver roadside departures (30.2 percent) more frequently involve 31 to 45 year old drivers. Alcohol/drug related rear-end collisions will remain a problem for the I1C1 configuration, however, it is typically a low injury producing crash. Roadside departures may present a more serious problem on an AHS, as it could result in the alcohol/drug impaired driver intruding into the lane containing automated vehicles.

- The majority of alcohol/drug related interstate crashes involve two vehicles (57.4 percent), while 34.5 percent are single vehicle crashes. The fact that two vehicle crashes typify this crash type has implications for an AHS, particularly for the I1C1 RSC and the I2C1 and I2C2 configurations without barriers, where an alcohol/drug impaired driver in a manually vehicle will be able to travel in and intrude into the lane containing automated vehicles.

- About 71.0 percent of vehicles involved in alcohol/drug related interstate crashes are traveling straight prior to the crash. The critical events making the crash imminent include travel over the edge of the roadway (24.9 percent), 21.0 percent are in another vehicle's lane 9.8 percent lose vehicle control and 6.6 percent encroach into another vehicle's lane. The most harmful events for this crash type are collision with a motor vehicle in transport (59.3 percent), collision with a fixed object (20.1 percent) and rollover (4.6 percent). AHS lat/long control will reduce the frequency with which automated vehicles deviate from their lanes and reduce instances of control/traction loss.

- In fatal alcohol/drug related interstate collisions, 49.0 percent of the drivers have greater than 0.10 BAC. In the drug tests conducted, the cannabinoid drug use has the highest frequency (2.9 percent). Determination of an AHS procedure for alcohol and drug testing must be made and a legal BAC level for as AHS must be established.

- The majority of alcohol/drug related interstate crashes involve drivers who are 21 to 30 years of age (37.6 percent) and 31 to 45 years old (34.4 percent). The majority of drivers involved in this crash type are males (76.4 percent).

Drowsy/Fatigued Driver Collisions:

- Most drowsy driver interstate crashes occur during daylight conditions (57.2 percent), in rural locations (37.8 percent), on dry roads (92.6 percent), under no adverse weather conditions (93.5 percent). Alcohol involvement occurs in approximately 8.0 percent of drowsy driver crashes and most of these occur in urban locations. The majority of drowsy driver crashes occur between 3 pm and 6 pm (21.2 percent) and 6 am and 9 am (19.6 percent) in rural areas. The most (peak) drowsy driver crashes occur on Saturdays in suburban areas. These are the conditions under which an AHS will have the greatest impact on safety.

- Approximately 56.0 percent of drowsy driver interstate crash occupants are not injured, 10.5 percent receive incapacitating injuries and 4.4 percent are fatalities. The most severe occupant injuries result from crashes occurring on dry pavement. Most crashes with incapacitating injuries occur in suburban areas and most fatalities occur in rural locations. When vehicle restraint systems are used, fewer occupants are injured and less severe injuries result. Occupants will benefit from the use of restraint systems on an AHS and the greatest reduction in occupant injury severity resulting from drowsy driver crashes will occur in rural and suburban areas.

- Approximately 37.0 percent of drowsy driver interstate crashes result in severe vehicle damage, 88.8 percent of these occur on dry pavement and most occur in rural locations (46.1 percent). The largest AHS reduction in vehicle damage from drowsy driver crashes will occur in rural locations on dry pavement.

- The majority of drowsy driver interstate crashes are single driver roadside departures (65.6 percent) and most of these are drive off road (42.7 percent). Right drive off road crashes happen almost twice as frequently as left drive off road crashes. Generally, the majority of single driver roadside departures, rear-end crashes and sideswipes involve drivers from age 21 to 30. Older drivers (i.e., > 60 years old) tend to be involved in right roadside departures and untripped rollovers. The most harmful events are collision with a motor vehicle in transport (26.0 percent), rollover (20.3 percent) and collision with a guardrail (15.7 percent). AHS lat/long control will reduce the frequency of lane keeping errors, roadside departures and failures to maintain a safe gap distance. The high frequency of roadside departures supports the use of barriers on the AHS.

- Of the vehicles involved in drowsy driver fatal interstate crashes, approximately 84.0 percent are going straight prior to the crash, most crash types are not a collision with a motor vehicle in transport (87.7 percent) and the first harmful event is vehicle overturn (38.1 percent). AHS has the potential to reduce fatalities through lat/long control and driver status monitoring.

- The majority of drowsy driver interstate crashes involve drivers who are 21 to 30 years of age (45.7 percent). Male drivers more frequently report feeling drowsy (81.0 percent) than females (19.0 percent). Young males will benefit most from AHS driver status monitoring.

Older Driver Collisions:

- The majority of older drivers (>60 years old) are involved in same way - same direction interstate collisions (55.0 percent; which includes rear-end and sideswipe crashes) and single driver crashes (28.4 percent; which includes right and left roadside departure and forward impact crashes). Since accident types typical of older driver population involve, for the large part, lane keeping errors and failure to maintain a safe gap distance, older driver performance on an AHS should improve greatly with the benefit of automated lat/long control.

3.2.7.7 Recommendations from Impaired Driver Crash Analysis

- Determine the impact of impaired driver roadside departures on an AHS, particularly for the I1C1 RSC and the I2C1 and I2C2 configurations without barriers

  Determine the check-in procedure for alcohol/drug testing and establish a legal AHS BAC level

- Determine procedure for driver status monitoring and level of driver interaction required

- Determine the type of driver testing which should be conducted before transition to manual control at check-out and the level of driver alertness required

- Determine the effect of driver aging on transition requirements and determine the extent of system compensation required

3.2.8 Mixed Vehicle Crash Analysis

The RSCs depict potential scenarios for an AHS, differentiated by command and control distribution and roadway infrastructures. A separate dimension is vehicle mix. Today's interstates allow passenger cars, vans and light trucks (single vehicle equivalents - SVEs) to share lanes with medium and heavy trucks (multiple vehicle equivalents - MVEs). From a safety point of view, the issue is raised: is it worth providing separate AHS lanes for the two vehicle types. From a performance and throughput perspective, multiple vehicle equivalents will limit the system capabilities. Cost factors and right-of-way limitations may require that roadways accommodate both single and multiple vehicle equivalents, as they do today. An AHS environment will certainly be beneficial in reducing accidents between single and multiple vehicle equivalents, although differences in vehicle performance capabilities must be taken into consideration, not only for acceleration and deceleration capabilities, but also for the ability of a passenger car or light truck to withstand a collision with a medium or heavy truck. Mixed vehicle crashes on today's interstates are examined to:

- envision unique AHS causal factors that may lead to mixed vehicle crashes on an AHS

- understand the causes and circumstances of mixed vehicle crashes to aid designers in avoiding the occurrence of this crash type and determine the frequency of occurrence of mixed vehicle crashes on interstates

- estimate benefits of an AHS in terms of eliminating mixed vehicle crashes

- provide support arguments for weighing the costs of maintaining separate lanes for multiple vehicle equivalents vs. the consequences of mixing them in with single vehicle equivalents.

The CDS data file was scanned for mixed vehicle crashes using the variables for the case vehicle body type and the other vehicle body type. The other vehicle body type was either missing or unknown for most of the applicable cases. Therefore, CDS data analysis was not performed for mixed vehicle type crashes.

The GES data filters used to characterize interstate mixed vehicle type crashes are described in appendix I.

3.2.8.1 Mixed Vehicle Crashes Resulting from AHS Unique Situations

Scenarios leading to mixed vehicle crashes are the same as the AHS unique situations depicted for any of the vehicle-to-vehicle crash types described in the previous sections. Circumstances specific to SVEs and MVEs are noted in table 2-24. The major differences when multiple vehicle equivalents enter the picture are vehicle dynamics and handling capabilities. The lower acceleration rates, longer braking distances add an extra dimension to the problem of safe gap distances. "Tolerable ΔVs" remain the same. However, when a single vehicle equivalent collides with a multiple vehicle equivalent nearly all of the energy from the collision is absorbed by the single vehicle equivalent. The ΔV for the multiple vehicle equivalent is very small.

Table 2-24. AHS Scenarios with Mixed Vehicle Collision Potential

Situation => Mixed Vehicle Collisions	Applicable RSCs
manual multiple vehicle equivalent trailing an automated single vehicle equivalent that suddenly brakes or stops Reaction time for automated vehicle: ~0.3 sec. Reaction time for manual vehicle: ~1.7 sec. (*) Note: greater braking distances are required for MVE	I1C1 I2C1 & I2C2 Transition lanes
MVE changes lanes into automated SVE	I1C1, I2C1 & I2C2 Transition lanes
lead vehicle deceleration rate > trailing vehicle's maximum deceleration capabilities due to differences in vehicle braking characteristics or insufficient reaction time of trailing vehicle	I2C1, I2C2 I3C1, I3C2, I3C3

*(Transportation Research Circular 419, 1994)

3.2.8.2 Characteristics of Interstate Mixed Vehicle Crashes

When a medium or heavy truck is involved in a collision on an interstate, it is usually with a passenger car, van, or light truck. Two vehicle crashes where one vehicle is a passenger car or light truck and the other is a medium or heavy truck represent approximately 10 percent of the crashes on interstates. The predominant manner of collision for mixed vehicle crashes on interstates is a sideswipe - same direction (45.1 percent) followed by nearly equal proportions of rear-end (27.3 percent) and angle (26.3 percent) orientations.

Figure 2-34 presents the environmental characteristics for mixed vehicle type crashes on interstates. Crashes between cars and medium/heavy trucks are primarily an urban problem. 52.6 percent of these crashes occur in urban areas, 37.2 percent are in suburban areas and 10.2 percent are in rural areas. Road surface conditions are generally dry, although 19 percent are on wet roads and 4 percent are on icy roads. Likewise, 83 percent occur under no adverse weather conditions 15.6 percent occur during rain or snow. Lighting is usually daylight or dark but lighted (80.1 percent) and 16.9 percent occur when it is dark.

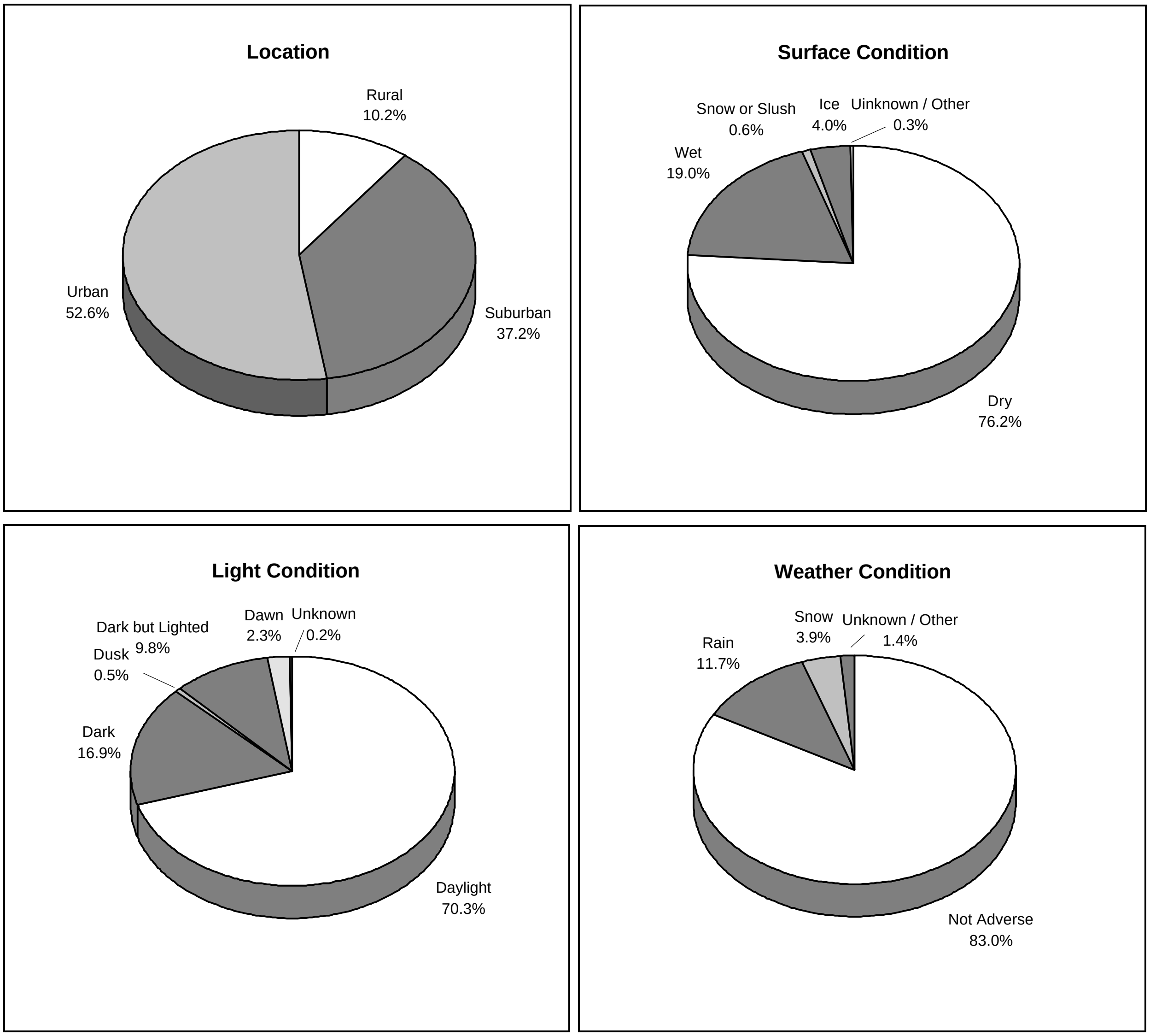


Figure 2-34. Environmental Conditions for Interstate Mixed Vehicle Crashes

As anticipated, occupants of passenger cars and light trucks suffer higher injury levels than passengers of medium/heavy trucks (figure 2-35). The incidence of fatal injuries is low, 0.1 percent, although this is probably a conservative number. Vehicle damage is much higher for the passenger cars and light trucks (figure 2-36). 29.5 percent of the passenger cars and light trucks sustain severe vehicle damage, compared to 3.9 percent for the medium/heavy trucks. All of the sampled passenger cars and light trucks are damaged to some degree, whereas 7.9 of the medium/heavy trucks are listed as having no damage.

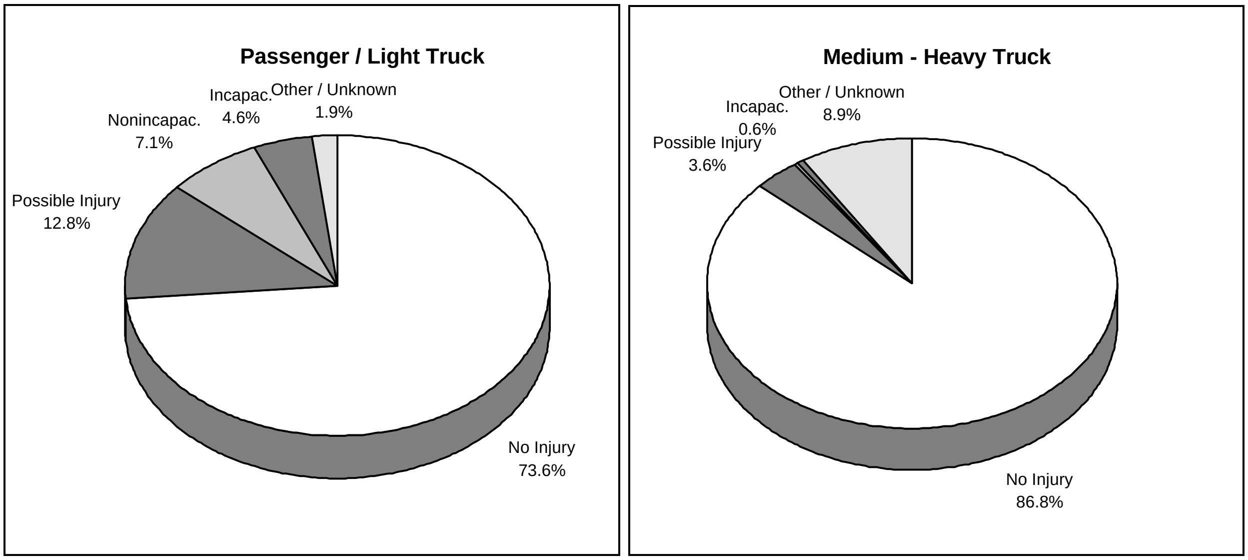


Figure 2-35. Occupant Injury by Vehicle Type for Interstate Mixed Vehicle Crashes

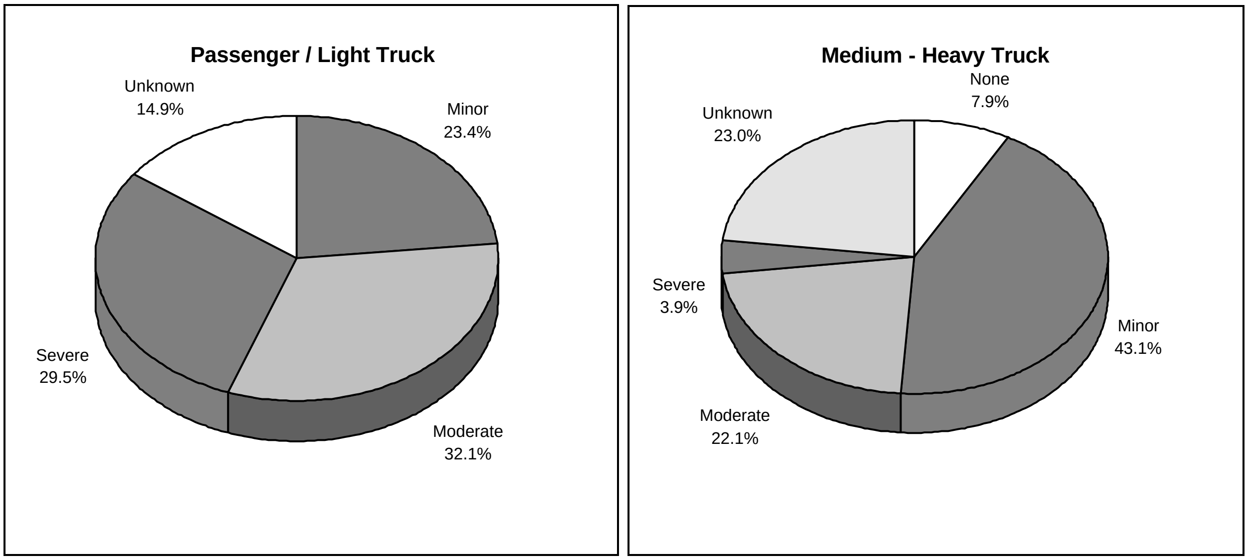


Figure 2-36. Vehicle Damage Severity by Vehicle Type for Interstate Mixed Vehicle Crashes

Data highlights from tables presented in appendix I are summarized below:

1. Time x Location: Mixed vehicle type crashes occur most frequently during the 3 - 6 pm time period. This is the most common time for mixed vehicle crashes in urban and suburban locations. In rural locations, the 9 - noon time slot has the highest frequency of these crashes.

2. Weekday x Location: Monday through Friday are the days when mixed vehicle type crashes are most frequent. Only 13.9 percent of these crashes occur on weekends. In rural locations, Thursdays and Fridays have the highest proportion of mixed vehicle crashes; in suburban locations, Tuesdays through Fridays have the

highest percentages; and in urban locations, Mondays and Tuesdays are most common.

3. Vehicle Role x Vehicle Type: Approximately two thirds of the time, the medium and heavy trucks are the striking vehicle (62.8 percent), and one third of the time they are the struck vehicle.

4. Critical Event x Vehicle Type: Nearly 14 percent of the passengers/light trucks are listed as “in another vehicle’s lane” for the critical event which made the crash imminent, and 15.1 percent of the medium/heavy trucks fall into this category. Encroaching in another vehicle’s lane at a non-junction area describe the critical event for 48.3 percent of the medium/heavy trucks and 15 percent of the automobile/light trucks. Another vehicle encroaching into this vehicle’s lane account for 44.1 percent of the automobile/light truck vehicles and 16.9 percent of the medium/heavy trucks. Drivers of medium/heavy trucks do not appear to see or perceive the presence of the passenger car/light truck vehicles.

5. Alcohol Involvement x Vehicle Type: Drivers of passenger cars and light trucks have a higher frequency of police reported alcohol involvement (3.9 percent) than drivers of medium/heavy trucks (0.1 percent); although the overall level of involvement is low - 2 percent.

6. Injury Severity x Vehicle Type x Restraint Use: Use of restraint systems by occupants of passenger cars and light trucks lowers injury severity levels. For occupants of medium and heavy trucks, the proportions do not change as a function of occupant restraint usage.

3.2.8.3 AHS Implications and Conclusions from Mixed Vehicle Crash Analysis

- Most mixed vehicle crashes occur in urban and suburban areas, only 10 percent occur in rural areas. Thinking in terms of using the I1C1 RSC as a long term AHS configuration, the low incidence of SVE and MVE collisions is a positive argument for a lower cost, rural AHS that can be thought of as a by-product of developing higher level RSCs for more congested areas.

- Mixed vehicle crashes occur during high traffic volume periods - weekdays from 3-6 pm. This is a common time for the majority of crash types and is an excellent opportunity for AHS technology.

- Medium/heavy trucks are usually the striking vehicle, controlled gap distances and lane changes maneuvers would benefit vehicles that require long braking distances. Often in congested areas the problem of following too closely, is created by vehicles that "fill in" the gaps left between a truck and another vehicle.

- The low incidence of police reported alcohol involvement is a plus for the I1C1 configuration for mixed vehicle types.

- The lane change/merge and rear-end crash configurations describe the majority of mixed vehicle crash types - which are likely to be eliminated on an AHS.

- Restraints are effective in reducing injury severity levels for occupants of SVEs.

3.2.8.4 Recommendations from Mixed Vehicle Crash Analysis

- Given the driving skills and training required for drivers of commercial vehicles, these drivers may be good candidates for early I1C1 implementations.
- Analyze safe gap distances for MVEs trailing SVEs, while maintaining 8 and 16 kph (5 and 10 mph) ΔVs. Determine restrictions this places on capacity.
- Occupants of automated vehicles should be restrained.
- Study benefits of I1C1 configuration as a long term rural AHS for mixed vehicle types.

3.3 AHS BENEFITS ANALYSIS

As stated previously, the goal of the AHS, under normal operating conditions, is a collision free driving environment. This assumes full automation and fail-safe malfunction management under any and all circumstances. Given that these assumptions are met, existing studies on accident causal factor analysis allow for a quantification of benefits that may be derived from an AHS. Estimates of the improved accident picture for an AHS were treated separately for each crash type, where data is available. An assessment of the overall safety benefits derived from an AHS is posed as a range of percent reduction in crashes.

The lowest estimate represents elimination of crashes where a vehicle defect, driver impairment or inclement weather may have contributed to the crash. GES data was used to determine these numbers. GES data are from police reports only and do not represent causal factor assessment. The highest estimate is based on removing crash causes that are related to human, vehicle, or environmental factors. This estimate is derived from causal factors analysis performed as part of the Indiana Tri-Level Study.

Table 2-25 shows GES data for vehicle collisions on interstates where vehicle defects, driver impairments or inclement weather may have contributed to the cause of the crash. The numbers are represented as a percent of all interstate collisions for urban, suburban and rural locations. Overall, approximately 31 percent of all interstate collisions are reported by police to have one of these factors present.

Table 2-25. Percent of Interstate Collisions where Vehicle Defects, Driver Impairment, and Inclement Weather are Involved

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

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

The upper estimate of AHS safety improvement is based on data derived from Calspan causal factor analysis of rear-end crashes and the Indiana Tri-Level study. This estimate is based on an assumption that the combination of automated control and vehicle system monitoring/inspection has the potential to remove human and vehicular factors and most (80 percent) of the environmental factors. The data pertains to crashes on all roadways, and is not limited to interstates. A causal factor analysis of interstate crashes is recommended.

Causal factor results from the Indiana Tri-Level Study are shown in table 2-26. Tabulations are based on 420 in-depth investigated accidents where a “certain” rating was applied to the causal factor. A “certain” rating is applied when there is absolutely no doubt as to a factor’s role, and is considered analogous to a 95 percent confidence level. Certain cause of the accident means that, assuming all else remains unchanged, there is no doubt that if the deficient factor had been removed or corrected, the accident would not have occurred.

Table 2-26. Tri-Level Causal Factor Analysis Results

Certain Causes	Causal/Factors
70.7%	Human Causes: recognition errors, decision errors, performance errors, critical non-performances, non-accident /intentional
12.4%	Environmental Factors: view obstructions, slick roads, transient hazards, design problems, control hindrances
4.5%	Vehicular Factors: braking systems, tires & wheels, communications systems, steering systems, body & doors

The causal factor analysis data indicate a potential reduction in crashes of 85 percent. This estimate assumes that human, vehicular and most environmental causes will not be replaced by technology failures.

The range of improvement in terms of rate of vehicle collisions per million vehicle miles traveled (VMT) is presented in table 2-27. Vehicle miles traveled are based on figures for today's interstates, FARS, 1991. The overall range of improvement due to automation is estimated to be 31 to 85 percent. The estimates are based on crash reductions only. No assessment is made of the potential for an increase in the number of vehicles that may be involved in AHS collisions, due to higher speed and shorter headways.

Table 2-27. AHS Safety Improvements

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

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

4.0 CONCLUSIONS

Conclusion and recommendations are provided at the end of the fault hazard analysis section and after each crash type analysis. A discussion of the key items is repeated in this section, followed by a summary table of safety issue and risks.

The fault hazard analysis of AHS operations addressed potential system failures or degradations, and their local and system-wide effects on the AHS. The analysis represented the individual phases of AHS operation as a time sequence of events for each general category of RSC. The main conclusions, after examining system impacts resulting from failure of AHS components, stress the need for system reliability and safety for a successful AHS.

Automated vehicles must have redundant steering and braking systems. The consequences of loss of vehicle control, which are detailed in the sections on individual crash types, emphasize the importance of complete longitudinal and lateral control at all times. Management of other types of faults and hazards is dependent on the integrity of the basic vehicle controllers.

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

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

Role 1, "Brain On, Hands and Feet Off", was assumed for assessment of local and system effects of component failures. Both roles require further examination. Role 1 does not allow the driver to completely relax, but it maintains a very capable and intelligent system component that would be extremely expensive to replace. Research must be conducted to determine reasonable expectations for human drivers as partial controllers or backups for automated systems. Role 2 permits the driver to be completely detached from the system.

This mode eliminates the concept of manual backup and requires studies to determine acceptable AHS-exit criteria for drivers resuming manual control.

The object/animal in the roadway may remain a constant between today's interstates and an AHS. The cost of preventing these elements from entering the AHS emphasizes the need for detection devices. However, even if it is possible to detect an obstacle that truly needs to be avoided, the longitudinal and lateral control systems must be capable of diverting the stream of vehicles, and they must have the room to maneuver the vehicles safely around the obstacle. Also, accident statistics show the number of times a vehicle strikes an object or animal in the roadway. They do not show the number of times a driver successfully maneuvers around an obstacle and still maintains control of the vehicle. Both alternatives are costly and additional work is needed to study of the tradeoffs associated with each strategy.

The RSCs were not developed as evolutionary configurations. However, the consequences of faults and hazards at the higher levels of automation, emphasize the benefits of an evolutionary approach to an AHS. These benefits will be derived in the form of costs, implementation, and ability to gracefully degrade to lower levels of command and control as the more sophisticated designs are developed and implemented. Evolutionary designs may also turn out to be the configuration of choice for specific locations, such as rural areas, where the cost of building separate automated roadways is impractical.

Specific crash types were analyzed to examine the consequences of deviations from the assumptions made to achieve a collision free driving environment. These deviations appear in the form of mixed manual and automated vehicles for the I1C1 RSC and for portions of the I2C1 and I2C2 RSCs. They may also appear as holes in the mitigating strategies prescribed by malfunction management for any RSC or as degradations from safe designs due to cost, implementation, or throughput tradeoffs.

Crash types similar to those on today's interstates will probably become the crash types that occur on an AHS due to a malfunction. The causal factors will be AHS unique, the number of vehicles involved will probably be greater, and the distribution of crash types will vary from today's interstate accident picture. The emphasis is on fail-soft designs that will be geared to the lowest injury producing crash types.

FARS data were used to rank crash types according to risk of a fatal injury. The crash types listed in order of decreasing frequency of fatal injuries are: Non-Collision with a Motor Vehicle in transport, Head-On, Rear-End, Angle, Sideswipe Same Direction, and Sideswipe Opposite Direction. Non-Collision with a Motor Vehicle in transport consists primarily of vehicle rollovers and roadway departures. Head-On and Sideswipe Opposite Direction are extremely low frequency events on interstates.

Rear-end crashes were analyzed in detail since they may be the most frequently occurring AHS crash type, and ΔV estimates for striking and struck vehicles are available in the CDS data file. Occupant injury levels and vehicle damage severities were expressed as a function of ΔV. This analysis led to the safety team's recommendation that ΔVs for rear-end crashes should be limited to 16 kph (10 mph). If the system is not able to ensure straight front-to-back rear-end crashes and potential exists for offset rear-end crashes, this recommendation is lowered to 8 kph (5 mph). The lower number is suggested to prevent a vehicle spinning off from a primary crash into a more severe crash type with a barrier or a vehicle in an adjacent lane. The estimate of "tolerable" ΔVs for AHS rear-end crashes relates directly to safe gap distances between vehicles traveling at high speed with short headways.

Barrier related crashes represent another potential AHS crash type, particularly for RSCs where automated lanes are adjacent to manual lanes. Left roadside departures account for approximately 78 percent of barrier crashes that occur on roadways with speed limits greater than 80.5 kph (50 mph). This finding strongly supports the use of barriers on the AHS since, without a barrier between automated and manual lanes, left side road departure vehicles from the manual lanes will intrude into the AHS. A review of current barrier standards indicates that these guidelines must be examined relative to AHS applications.

An estimate of crashes that may be prevented by an AHS was presented as a range of percent improvement. The lowest estimate represents GES crashes where a vehicle defect, driver impairment, or inclement weather may have contributed to the crash. Only police reported information is included in this estimate. There is no assessment of crash cause. GES data analysis resulted in a 30 percent improvement.

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

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

Table 2-28. Safety Issues and Risks

#	Issue Descriptions	Comments	RSC Impact	Discussed
1	AHS must consider vehicles impaired by a partial or complete loss of braking ability. See Appendix B for brake components that may lead to this failure mode.	Vehicle braking systems should be checked at a biannual AHS inspection. Initial braking systems failure detection should prevent AHS engage. Redundant braking systems should be employed to avoid systems failure and loss of longitudinal control. A breakdown lane would be helpful in alleviating traffic slowdowns. See table 2-10 for individual RSC handling of this problem.	All RSCs Less severe for I3C3	Section 3.1, Appendix B
2	AHS must consider problems caused by a vehicle slowing down due to mechanical breakdown or electrical failure. See Appendix B for a list of electrical/mechanical components that may lead to this failure mode.	Initial detection might prevent AHS from engaging. A breakdown lane would be helpful in alleviating traffic slowdowns. See table 2-10 for individual RSC handling of this problem.	All RSCs Less severe for I3C3	Section 3.1, Appendix B
3	AHS must consider must consider problems caused by sudden vehicle stops due to mechanical breakdown or electrical failure. See table 2-10 for individual RSC handling of this problem.	Note that the vehicle must be removed quickly to avoid serious traffic delays. A breakdown lane would be helpful in alleviating traffic slowdowns. See table 2-10 for individual RSC handling of this problem.	All RSCs Less severe for I3C3	Section 3.1, Appendix B
4	AHS must consider lateral control failure	Initial lateral control systems failure detection should prevent AHS from engaging. Vehicle steering should be checked at the biannual AHS inspection. Redundant steering systems should be employed to avoid a lateral control failure. If possible, the vehicle should be stopped to avoid possible collisions with vehicles in adjacent lanes since vehicle lane keeping ability may be lost. See table 2-10 for individual RSC handling of this problem. A breakdown lane would be helpful in isolating the vehicle.	All RSCs Less severe for I3C3	Section 3.1, Appendix B
5	AHS must consider vehicle performance variations.	AHS should normally be engaged. This is a concern for I2 RSC's with a transition lane between AHS and manual traffic. See table 2-10 for individual RSC handling of this problem.	All RSCs	Section 3.1, Appendix B, Section 3.2.8

Table 2-28. (continued) Safety Issues and Risks

#	Issue Descriptions	Comments	RSC Impact	Discussed
6	AHS must consider actuator failure in AHS steering, braking, and throttle.	Initial detection should prevent AHS from engaging while redundant systems should be employed to avoid loss of AHS steering and braking. The critical issue is the loss of vehicle lateral control whereas the loss of AHS throttle control is the least critical issue. Driver response capabilities become a critical issue if they are insufficient for a given situation and manual backup is required (e.g. maintaining gap distance and lane position). See table 2-10 for individual RSC handling of this problem.	All RSCs	Section 3.1, Appendix B
7	AHS must consider vehicle sensor failure.	Initial detection should prevent AHS from engaging. This becomes a critical issue if vehicle AHS lane keeping and longitudinal control is lost and driver response is inadequate for manual backup. Vehicle lane keeping and longitudinal control could also be affected. See table 2-10 for individual RSC handling of this problem.	All RSCs	Section 3.1, Appendix B
8	AHS must consider vehicle communications failure	Initial detection should prevent AHS from engaging. Vehicle to vehicle and roadway communications could be impaired. This becomes a critical issue if vehicle AHS lane keeping and longitudinal control is lost and driver response is inadequate. See table 2-10 for individual RSC handling of this problem.	I2C1, I2C2, I3C1, I3C2, I3C3	Section 3.1, Appendix B
9	AHS must consider vehicle computer failure.	Initial detection should prevent AHS from engaging. This becomes a critical issue if vehicle AHS lane keeping control is lost and driver response is delayed. Driver response time and performance capabilities in resuming manual control of the vehicle are critical in avoiding major accidents if manual backup is employed. See table 2-10 for individual RSC handling of this problem.	All RSCs	Section 3.1, Appendix B

Table 2-28. (continued) Safety Issues and Risks

#	Issue Descriptions	Comments	RSC Impact	Discussed
10	AHS must consider vehicle data link failure.	Initial detection should prevent AHS from engaging. Vehicle to vehicle and roadway communications could be impaired. This becomes a critical issue if AHS lane keeping and longitudinal control is lost and driver response is inadequate. Note that errors in command messages may cause improper vehicle control and could seriously impact traffic management. See table 2-10 for individual RSC handling of this problem.	I2C1, I2C2, I3C1, I3C2, I3C3	Section 3.1, Appendix B
11	AHS must consider roadway sensor failure.	A roadway failure is more serious in nature as it effects many vehicles at once. A serious failure may require AHS shutdown. In a worst case scenario, drivers may need to resume manual control until system returns on line. Note that the driver response time is critical in avoiding major accidents. I3C3 is most seriously impacted RSC since all vehicle actions could be affected.	I2C1, I2C2, I3C1, I3C2, I3C3	Section 3.1, Appendix B
12	AHS must consider roadway communications failure	A roadway failure is more serious in nature as it affects many vehicles at once. A serious failure may require total AHS shutdown. In a worst case scenario, drivers might need to resume manual control until the system returns on line. Thus, the driver response time is critical in avoiding major accidents. I3C3 is most seriously impacted RSC since all vehicle actions could be affected.	I2C1, I2C2, I3C1, I3C2, I3C3	Section 3.1, Appendix B
13	AHS must consider roadway computer failure	A roadway failure is more serious in nature as it affects many vehicles at once. A serious failure may require total AHS shutdown. In a worst case scenario, drivers might need to resume manual control until the system returns on line. Thus, the driver response time is critical in avoiding major accidents. I3C3 is most seriously impacted RSC since system monitoring and vehicle actions could be affected.	I2C1, I2C2, I3C1, I3C2, I3C3	Section 3.1, Appendix B

Table 2-28. (continued) Safety Issues and Risks

#	Issue Descriptions	Comments	RSC Impact	Discussed
14	AHS must consider roadway data link failure	A roadway failure is more serious in nature as it affects many vehicles at once. A serious failure may require total AHS shutdown. In a worst case scenario, drivers might need to resume manual control until the system returns on line. Thus, the driver response time is critical in avoiding major accidents. I3C3 is most seriously impacted RSC since system monitoring and vehicle actions could be affected.	I2C1, I2C2, I3C1, I3C2, I3C3	Section 3.1, Appendix B
15	AHS must consider roadway obstacles.	Obstacle detection is difficult or impossible to sense electronically making this a roadway operations issue. Note that this may be more of a factor in rural areas. Vehicle damage or collision could result causing traffic slowdown or stoppage. The obstacle must be removed quickly to avoid adverse effects, or vehicles must be directed around obstacle.	All RSCs	Section 3.1, Appendix B, Section 3.2.5
16	AHS must consider environmental incidents or sabotage	This is a roadway operations issue where vehicle damage or collision could result. Traffic slowdown or stoppage is possible. Incident scene response time is crucial in avoiding possible complications to those involved and serious traffic problems.	All RSCs	Section 3.1, Appendix B
17	AHS must consider system traction degradation	AHS engagement is permitted unless conditions are extreme. Note that there is an increased accident potential and the system may adjust vehicle speeds and maneuvers to suit environmental conditions. This may cause a traffic slowdown.	All RSCs	Section 3.1, Appendix B
18	AHS must consider reduced visibility	AHS would permit engagement but speed reduction may be required. The degree of impact is dependent on sensors used for vehicle lane keeping and longitudinal control. This situation may have a greater effect on fully manually controlled vehicles.	All RSCs	Section 3.1, Appendix B
19	AHS must consider crosswinds.	AHS should permit engagement unless conditions are extreme. The degree of impact is dependent on the sensors used for lane keeping control. This results in an intermittent disturbance to lane keeping control.	All RSCs	Section 3.1, Appendix B
20	AHS must consider driver incapacitation.	AHS engage is denied if driver fails the initial check-in test. This might have serious impacts if the AHS roadway system fails and the driver needs to resume manual control of the vehicle.	All RSCs	Section 3.1, Appendix B, Section 3.2.7

Table 2-28. (continued) Safety Issues and Risks

#	Issue Descriptions	Comments	RSC Impact	Discussed
21	AHS must consider driver impairment	AHS engage is not permitted if driver fails initial check-in test. Also, degree of impairment is a factor. Under normal operating conditions there would be minimal to no adverse effects on the I3C3 RSC since the roadway controls all vehicle actions.	All RSCs	Section 3.1, Appendix B, Section 3.2.7
22	AHS must consider driver override.	There should be minimal to no consequences for the I1C1 RSC since the driver is fully engaged and ready to resume manual control. There is an increase in accident potential for the other RSC's as there would be an "intruder" in the system.	All RSCs	Section 3.1, Appendix B
23	AHS must consider non-AHS certified vehicles.	AHS access, transition, or engage would be denied for all of the RSC's.	All RSCs	Section 3.1, Appendix B
24	AHS must consider the effects of control system accuracy, response characteristics, system lags, and data rates on lat/long control.	System lags: sensors, actuator rates, data rates Control system accuracy: sensors, noise, models Response characteristics: vehicle dynamics	All RSCs	Section 3.1, Appendix B
25	AHS must consider software bugs and their effects on lat/long control	Control system outputs may be in error, which could seriously degrade system performance and increase collision potential	All RSCs	Section 3.1, Appendix B
26	AHS must consider sensors affected by roadway power supplies and their effects on lat/long control	Control system inputs/outputs may be in error, which could seriously degrade system performance and increase collision potential	All RSCs	Section 3.1, Appendix B
27	AHS must consider crosstalk and its effect on lat/long control	Control system inputs/outputs may be in error, which could seriously degrade system performance and increase collision potential	All RSCs	Section 3.1, Appendix B
28	AHS must consider lighting/weather effects on sensors, actuators (i.e., sunlight, temperature, humidity, etc.) in relation to lat/long control	Control system inputs/outputs may be affected, which could degrade system performance and increase collision potential	All RSCs	Section 3.1, Appendix B
29	AHS must consider the effect of wet spray from the road on sensors, windshields, headlights	Sensor performance may be affected when coated or dirty.	All RSCs	Section 3.1, Appendix B
30	AHS must consider occupant response to lat/long control (i.e. damping)	Typically, humans are comfortable with 0.7 damping. However, this level of damping may be too low for the control system's response to an impact by another vehicle	All RSCs	Section 3.1, Appendix B

Table 2-28. (continued) Safety Issues and Risks

#	Issue Descriptions	Comments	RSC Impact	Discussed
31	AHS must consider time/distance requirements associated with releasing vehicles from automated control.	Human and vehicle response characteristics require specific time/distance allocations to ensure orderly transitions from automated to manual control. Range of driver steering and braking response times should be identified.	All RSCs	Section 3.2.7
32	AHS must consider the velocity ranges at which transitions may be completed from AHS to non-AHS.	The specific velocity at which the driver is willing to relinquish/assume control vary with the transition area and vehicle response characteristics. Common velocity limits for curves, grades, proximity to barriers should be identified	All RSCs	Section 3.2.7
33	AHS must consider types of driver testing which should be completed before transitions are initiated.	The primary emphasis here relates exit transition areas and the degree of driver alertness (i.e., capability of the driver to assume vehicle control).	All RSCs	Section 3.2.7
34	AHS must consider types of vehicle testing which should be completed before transitions are initiated.	The primary emphasis here relates to entrance transition areas and those vehicle components/systems which are most likely to influence trip safety. Reliability of components for automation systems should be quantified.	All RSCs	Section 3.2.7
35	AHS must consider the effect of transient lighting and weather conditions on transition requirements.	Adverse lighting and weather conditions typically degrade driver performance and can degrade vehicle response characteristics and the operational characteristics of onboard sensing equipment. Driver, vehicle and equipment required characteristics should be identified. Probable ranges of degraded performance should be established	All RSCs	Section 3.2.7
36	AHS must consider the effect of driver inexperience on transition requirements.	Driver response characteristics typically degrade with age. Levels of deterioration that are likely to occur and the extent of system compensation that is required should be identified.	All RSCs	Section 3.2.7
37	AHS must consider the effect of traffic density on transition requirements.	Heavy traffic density in non-AHS lanes adjacent to AHS entry/exit areas will adversely affect or infringe upon AHS traffic	All RSCs	Section 3.2.7
38	AHS must consider the risks of high speed and small headway on lat/long control.	The rear-end crash is the second most common crash type on today's interstates. Interstate rear-end crashes represent 36 percent of interstate accidents, and 12 percent of fatal accidents. Under normal operations, with sound safety practices, the AHS will be a collision free environment. However, in an unmitigated failure mode where vehicles are tightly packed, the rear-end crash will be the most frequent AHS crash type.	I2C1, I2C2, I3C1, I3C2, I3C3	Section 3.1, Appendix B, Section 3.2.2

Table 2-28. (continued) Safety Issues and Risks

#	Issue Descriptions	Comments	RSC Impact	Discussed
39	AHS must consider the risks of a manually operated vehicle trailing an automated vehicle.	Manual vehicles have a much greater reaction time than automated vehicles. Clinical studies have been conducted that showed the reaction time for an automated vehicle is approximately 0.3 seconds; this number may be lowered as sensor and technology improvements are made. Reaction time for a manually operated vehicle is approximately 1.75 seconds, although this is highly dependent on the individual driver.	I1C1	Section 3.1, Appendix B, Section 3.2.2
40	AHS must consider the effect of manual drivers next to automated lanes	Left roadside departures account for approximately 78% of barrier crashes that occur on roadways with speed limits greater than 80.5 kph (50 mph).	I2C1, I2C2	Section 3.1, Appendix B Section 3.2.3
41	Impact severity quantified in terms of delta V and related to occupant injury and vehicle damage provides a basis for determining safe gap distances.	The availability of delta V estimates for striking and struck vehicles involved in rear-end crashes, along with occupant injury and vehicle damage information, provides a means to represent injury levels and damage severity as a function of delta V. This information can be used to establish guidelines for “tolerable” delta Vs for AHS accidents which can then be used to determine safe gap distances between vehicles traveling at high speeds with short headways.	All RSCs	Section 3.2.2
42	All occupants of an automated vehicle should be restrained.	The use of restraints significantly reduces the occurrence of injuries in interstate crashes.	All RSCs	Section 3.2
43	The object/animal in the roadway is likely to persist in the AHS environment without costly measures to exclude them.	The cost of preventing these elements from entering the AHS emphasizes the need for detection devices. Automation is capable of creating a “smart driver” that knows the state of the vehicle, and the limits of the vehicle’s handling capabilities for road and weather conditions, but automation cannot control objects or animals. Therefore, automation must deal with them, particularly on the long stretches of suburban and rural highways where the problem is most significant.	All RSCs	Section 3.2.5
44	Sensors to detect objects or animals must be able to function in dark lighting conditions.	57.3% of crashes with non-fixed objects on interstates occur during dark lighting conditions.	All RSCs	Section 3.2.5

Table 2-28. (continued) Safety Issues and Risks

#	Issue Descriptions	Comments	RSC Impact	Discussed
45	Breakdown lanes may be useful to provide room for vehicles to avoid large objects of animals in the roadway	Accident statistics show the number of times a vehicle strikes an object or animal in the roadway. They do not show the number of times a driver successfully maneuvers around an obstacle and still maintains control of the vehicle. This problem has tremendous implications for an AHS and requires further research.	All RSCs	Section 3.2.5
46	Vehicles with unsafe loads should not be allowed on an AHS	Object in the roadway is more of a problem in urban locations than animal in the roadway. The data do not indicate where the objects come from, however, preventing objects falling from other vehicles is an obvious source that should be eliminated.	All RSCs	Section 3.2.5
47	Automated vehicles require technology that can distinguish between roadway obstacles that must be avoided and those that only appear to pose a threat.	Further studies are needed to analyze the trade-off between striking an obstacle or the consequences of attempting to avoid it - particularly if it is moving. In an AHS context, objects in the roadway may also refer to vehicles involved in a previous crash.	All RSCs	Section 3.2.5
48	Object in the roadway is more of a problem in urban locations than animal in the roadway.	The precrash situation in urban locations is characterized by 58.3 percent object in roadway and 41.7 percent pedestrian or animal in the roadway. As congestion decreases, the occurrence of object related crashes decreases and pedestrian / animal crashes increases. For suburban locations, the distribution is 74 percent pedestrian / animal and 26 percent stationary object, for rural locations, it's 83.9 percent animal and 16.2 percent stationary object.	All RSCs	Section 3.2.5
49	Collisions with non-fixed objects in urban locations often involve two vehicles.	As traffic becomes more congested, the consequences of an object/animal in the roadway increase. The longitudinal and lateral control systems must be capable of diverting the stream of vehicles, and they must have the room to maneuver the vehicles safely around the obstacle.	All RSCs	Section 3.2.5

Table 2-28. (continued) Safety Issues and Risks

#	Issue Descriptions	Comments	RSC Impact	Discussed
50	Pedestrians should not be allowed on an AHS - passengers must not be allowed to exit their vehicles unless remaining inside poses a greater threat.	Pedestrians are not allowed on existing interstates, yet many fatalities on interstates are the result of a vehicle striking a pedestrian. The origin of these pedestrians is not noted in the data, but the logical conclusion is that these people exit their vehicle after a collision or breakdown. Since vehicle monitoring systems may be flagging vehicles for exit or directing them to breakdown lanes, passengers must not be permitted to exit the vehicle unless staying inside the vehicle poses a greater threat.	I2C1, I2C2, I3C1, I3C2, I3C3	Section 3.2.5
51	The I1C1 RSC is attractive for rural locations, but the presence of impaired drivers will degrade the benefits.	Police reported alcohol involvement is a problem associated with the lane change/merge crash type in rural areas. Studies should be performed to assess the trade-offs associated with the I1C1 RSC for rural applications.	I1C1	Section 3.2.6, Section 3.2.7
52	The effectiveness of improved side impact protection in reducing occupant injury levels during side impacts (vehicles that already meet 1997 safety standards) should be evaluated for AHS applications	In interstate lane change/merge crashes, restraint systems eliminated the occurrence of critical injuries, but did not lower the occurrence of severe and serious injuries, since current restraints are designed primarily to protect against frontal impacts versus side impacts.	All RSCs	Section 3.2.6
53	AHS must consider the severity of accidents involving commercial and transit vehicles	Medium / heavy trucks are usually the striking vehicle, controlled gap distances and lane changes maneuvers would benefit vehicles that require long breaking distances.	All RSCs	Section 3.1, Appendix B, Section 3.2.8
54	I1C1 may be a lower cost alternative for rural AHS applications	Most mixed vehicle crashes occur in urban and suburban areas, only 10 percent occur in rural areas. Thinking in terms of using the I1C1 RSC as a long term AHS configuration, the low incidence of SVE and MVE collisions is a positive argument for a lower cost, rural AHS that can be thought of as a by-product of developing higher level RSCs for more congested areas.	I1C1	Section 3.2.8
55	Medium / heavy trucks are usually the striking vehicle, controlled gap distances and lane changes maneuvers would benefit vehicles that require long breaking distances.	Often in congested areas the problem of following too closely is created by vehicles that “fill in” the gaps left between a truck and another vehicle.	All RSCs	Section 3.2.8

Table 2-28. (continued) Safety Issues and Risks

#	Issue Descriptions	Comments	RSC Impact	Discussed
56	Impaired driver collisions, including alcohol/drug, drowsy/fatigue impaired and older driver, account for 10.9 percent of interstate crashes.	The frequency of these collisions can be greatly reduced for most AHS RSCs. This reduction will occur through the use of check-in screening, driver status monitoring, and automated lat/long control. The impaired driver will remain a problem for the I1C1 RSC since there is no physical barrier separation of automated and manual lanes and there is a mix of vehicle control types in the same traffic lane.	All RSCs, particularly important for I1C1	Section 3.2.7
57	The majority of alcohol/drug related interstate crashes involve two vehicles (57.4 percent), while 34.5 percent are single vehicle crashes.	The fact that two vehicle crashes typify the impaired crash type has implications for an AHS, especially for the I2C1 and I2C2 RSCs where an alcohol/drug impaired driver in a manual vehicle will be able to travel in and intrude into the lane containing automated vehicles.	All RSCs, particularly important for I1C1	Section 3.2.7
58	Rear-end collision is the most frequently occurring crash type for alcohol/drug impaired drivers	Single driver roadside departures (30.2 percent) more frequently involve 31 to 45 year old drivers. Alcohol/drug related rear-end collisions will remain a problem for the I1C1 configuration, however, it is typically a low injury producing crash. Roadside departures may present a more serious problem on an AHS, as it could result in the alcohol/drug impaired driver intruding into the lane containing automated vehicles.	All RSCs, particularly important for I1C1	Section 3.2.7
59	Determination of an AHS procedure for alcohol and drug testing needs to be made and a legal BAC level for an AHS needs to be established.	In fatal alcohol/drug related interstate collisions, 49.0 percent of the drivers have greater than 0.10 BAC. In the drug tests conducted, the cannabinoid drug use has the highest frequency (2.9 percent).	All RSCs, particularly important for I1C1	Section 3.2.7
60	AHS Check-in procedures will benefit from existing statistics on drivers and related crash types.	The majority of drowsy driver interstate crashes involve drivers who are 21 to 30 years of age. Male drivers more frequently report feeling drowsy (81.0 percent) than females (19.0 percent). Young males will benefit most from AHS driver status monitoring.	All RSCs.	Section 3.2.7
61	Impaired drivers will probably not gain access to the AHS, therefore, these drivers may persist on the non-AHS roads.	This is a particular problem for the I1C1 RSC, where automated vehicles will be traveling with manual vehicles, and for the I2C2 RSCs where manual vehicles will be traveling in lanes next to the AHS. This concern lends support to the argument of separating the manual and automated lanes by installing barriers.	All RSCs	Section 3.2.3, Section 3.2.7

Table 2-28. (continued) Safety Issues and Risks

#	Issue Descriptions	Comments	RSC Impact	Discussed
62	The use of barriers in the AHS should be considered. Without a barrier between automated and manual lanes, left side road departure vehicles from the manual lanes would intrude into the automated lanes.	Left roadside departures account for approximately 78% of barrier crashes that occur on roadways with speed limits greater than 80.5 kph (50 mph).	All RSCs, particularly important for I2C1 & I2C2	Section 3.2.3, Section 3.2.4
63	Improved surface quality and maintenance of the AHS highway, and lat/long systems, could eliminate many barrier crashes.	Nearly 50% of barrier crashes involve loss of control/traction. Close to 30% of barrier crash types are drive off road and approximately 9% of barriers are struck in an attempt to avoid a collision.	All RSCs, particularly important for I2C1 & I2C2	Section 3.2.3
64	For I2 infrastructures, vehicles that depart the roadway may now intrude into the automated lanes.	If barriers are used, they will prevent these vehicles from traveling into the automated lanes, except at entry/exit points. This is a significant concern given the magnitude of this crash type on present day interstates. Single vehicle roadway departure collisions are part of the "collision not with a motor vehicle in transport" category. This group represents 42 percent of all interstate accidents, and 70 percent of all fatal interstate accidents.	All RSCs, particularly important for I2C1 & I2C2	Section 3.2.3, Section 3.2.4
65	Guardrail or barrier designs for an AHS should consider the injury producing characteristics of barriers currently in use.	The most harmful event for vehicles departing the interstate is collision with a guardrail or barrier.	All RSCs, particularly important for I2C1 & I2C2	Section 3.2.3
66	The high frequency of roadside departures supports the use of barriers on the AHS. The majority of drowsy driver interstate crashes are single driver roadside departures (65.6 percent) and most of these are drive off road (42.7 percent).	Right drive off road crashes happen almost twice as frequently as left drive off road crashes. Generally, the majority of single driver roadside departures, rear-end crashes and sideswipes involve drivers from age 21 to 30. Older drivers (i.e., > 60 years old) tend to be involved in right roadside departures and untripped rollovers. The most harmful events are collision with a motor vehicle in transport (26.0 percent), rollover (20.3 percent) and collision with a guardrail (15.7 percent). AHS lat/long control will reduce the frequency of lane keeping errors, roadside departures and failures to maintain a safe gap distance.	All RSCs, particularly important for I2C1 & I2C2	Section 3.2.3, Section 3.2.4, Section 3.2.7

Table 2-28. (continued) Safety Issues and Risks

#	Issue Descriptions	Comments	RSC Impact	Discussed
67	Barrier as roadside obstacle	A struck barrier may cause driver to lose control of vehicle especially at high travel speed, e.g., vault, rollover, submarine. Barriers: - Reduce lane maneuverability - Prevent intrusion of impacting vehicle into adjacent lane. - create potential for large angle impacts	All RSCs, especially I2C1 & I2C2	Section 3.2.3
68	Barrier end as roadside obstacle	A struck barrier end may cause driver to lose control of vehicle especially at high travel speed, e.g., vaulting, rollover, submarining	All RSCs, especially I2C1 & I2C2	Section 3.2.3
69	Barrier maintenance and repair time should be considered	Excessive down-time in high volume areas may affect public acceptance of AHS	All RSCs, especially I2C1 & I2C2	Section 3.2.3
70	AHS barrier designs should accommodate all vehicle types.	High CG vehicles may intrude into space above barrier upon impact	All RSCs, especially I2C1 & I2C2	Section 3.2.3
71	Site dependent barrier requirements	Barrier performance may be ineffective for specific AHS sites and configurations	All RSCs, especially I2C1 & I2C2	Section 3.2.3
72	Snow/ice forms a “ramp effect” if allowed to build-up next to a barrier	May increase maintenance time and cost	All RSCs, especially I2C1 & I2C2	Section 3.2.3
73	Breakdown lanes and barriers	Presence of breakdown lane increases travel distance to barrier and increases the potential for a wide angle impact	All RSCs, especially I2C1 & I2C2	Section 3.2.3
74	Data from causal factor analysis indicates that 70% of crashes are due to human error, 12% to vehicular factors and 5% to environmental factors.	The combination of automated control and vehicle system monitoring/inspection has the potential to remove 80 to 90 percent of the causal factors cited for rear-end crashes such as driver error and vehicle defects. Clearly, an automated system that can remove driver error from the driving task would be highly successful in reducing the frequency of occurrence of crashes, assuming that the automation system does not replace the driver error causal factors with its own set of unique AHS causal factors.	I3C3	Section 3.3

APPENDIX A SAFETY TASK LITERATURE REVIEW

Al-Deek, H., Ishak, S. and Radwan A. E., "The Potential Impact of Advanced Traveler Information Systems (ATIS) on Accident Rates in an Urban Transportation Network", IEEE-IEE Vehicle Navigation and Information Systems Conference, Ottawa, 0-7803-1235-X/93, 1993.**{**PRIVATE **}**

Summary: The paper presents a method for predicting changes in accident rates resulting from traffic diversion by ATIS in Orlando's Transportation Network. To assess the relationship between traffic congestion and accident rates, accident analysis and modeling are separately conducted on freeways and street arterial. Accident models are then used to construct a risk matrix containing accident rates per million vehicle miles. Risk factors are used to assess the impact on safety of diverting traffic with ATIS. The risk factors vary by type of roadway, traffic intensity, congestion level and vehicle type (ATIS or non-ATIS). The study found that hourly volume and queuing conditions significantly affect the prediction of accident rates on freeways and that there was a correlation between daily accident rate patterns and traffic volume patterns.

Allen, R. Wade, Szostak, Henry T., Rosenthal, Theodore J., "Modeling Driver/Vehicle performance in Emergency Maneuvers", Proceedings of the Human Factors Society, 32nd Annual Meeting - 1988, 1988.

Summary: The combined performance of the driver and vehicle determine whether accidents result from traffic conflicts, road hazards, etc. This paper describes the driver behavior and hazard scenario aspects of a computer simulation which models both vehicle dynamics and driver steering and braking behavior. The technical aspects of the simulation have previously been published. The issue of how much the driver and vehicle contribute to accident involvement is addressed, and antilock brake evaluation is used as an example.

Arem, B. van and Vlist, J.M. van der, "Application of an On-line Procedure for Estimating Capacity Under Prevailing Roadway and Traffic Conditions", IEEE-IEE Vehicle Navigation and Information Systems Conference, Ottawa, 0-7803-1235-X/93, 1993.

Summary: The paper presents a procedure for estimating motorway capacity under prevailing road and weather conditions. Two elements that vary according to prevailing conditions are: 1) the empirical relation between occupancy and intensity; and 2) maximum occupancy achievable under free-flowing conditions. The procedure has potential application for dynamic traffic management systems.

Bender, J. G., Bonderson, L. S., Schmelz, R. E., Thompson, J. F., Benyo, T. R., Miller, D. and Stuart, D., "Systems Studies of Automated Highway Systems, Final Report", General Motors Corporation, FHWA/RD-82/003, July 1982.

Summary: The study identifies and evaluates candidate AHS system concepts and implementation strategies based on potential for successful deployment, and includes AHS trade studies. The recommended system concept is a smart vehicle with self-contained power supply operating on a passive guideway.

Bender, J. G., "An Overview of Systems Studies of Automated Highway Systems", IEEE Transactions on Vehicular Technology, Vol. 40, No. 1, p. 82-99, 0018-9545/91, February 1991.

Summary: The article presents a summary of the factors that influence the design, development and deployment of an IVHS. AHS goals, system concepts and implementation strategies are presented. The system concept recommended is the use of a smart vehicle with self-contained power supply on a passive guideway. An implementation plan and goal evaluation for the recommended concept is presented. Safety aspects of AHS include the elimination of driver error, head-on collisions, angle collisions and run-off-the-road accidents.

Bishop, J. R. , Jr., Alicandri, E., "Status Report on the Automated Highway System Program", Autonomous Unmanned Vehicle Society Annual Meeting, Washington, D.C., June 1993.

Summary: An overview of the DOT AHS program plan is provided.

Bonsall, P., "Assessing the Impacts and Benefits of In-Car Route Guidance Advice via Field Trials", IEEE-IEE Vehicle Navigation and Information Systems Conference, Ottawa, 0-7803-1235-X/93, 1993.

Summary: Bonsall discusses the need to collect more information on user response (human factors issues) during field tests of in-car route guidance systems. A list of field test objectives are identified, as well as measures of effectiveness for system evaluation.

Brehmer, B., "Variable Errors Set a Limit to Adaptation", Ergonomics, Vol. 33, Nos. 10/11, p. 1231-1239, 0014-0139/90, 1990.

Summary: Brehmer hypothesizes that variable error (the variance of the response distribution or within-subjects variability) limits the extent to which a driver can adapt to the traffic environment and is a major cause of accidents. The conclusions of a study conducted by Bjorkman (1963), in which passengers were required to predict the meeting point of their car with an on-coming car, are disputed. Bjorkman found that subjects underestimated the distance to the meeting point when their car was traveling faster than the on-coming car and overestimated the meeting point distance when the on-coming car was traveling faster than their car. It was concluded that subjects made the systematic error of predicting mid-points for meeting-points. Brehmer provides evidence for the

alternative explanation that the imperfect correlation between predicted and actual meeting-points was due to variable error in speed perception. Based on his results, Brehmer suggests that accident rates will depend on the distribution of vehicle speeds. His predictions include: 1) a general regression of all speed judgments toward the mean; thus, errors become greater in size as driving speed moves away from the mean. Accident probability would be expected to be lowest for cars driving at the mean speed and increase with deviation from the mean (Solomon, 1964); 2) accident rates will be higher in traffic environments where the variance of the speed distribution is high (Greenberg, 1964). Brehmer suggests the following safety measure: decrease variability of the traffic environment, e.g., speed limits, separation of different kinds of road users.

Brown, I. D., "Drivers' Margins of Safety Considered as a Focus for Research on Error", Ergonomics, Vol. 33 Nos. 10/11, p. 1307-1214, 0014-0139/90, 1990.

Summary: Brown suggests that field testing is necessary in order to obtain an understanding of driver error. Accident statistics and road side observation do not provide adequate information for estimating the risk level of drivers' errors. These methods of accident assessment are limited in their ability to distinguish between driving task and environmental factors that contribute to error production and factors that prevent or constrain the drivers' ability to implement error correcting actions. According to Brown, research suggests that drivers generally tend to be biased toward inadequate safety margins because they underestimate traffic hazards and/or overestimate their ability to cope safely with hazards. He suggests that inadequate safety margins effects recovery from error in the following ways: 1) limited time available to select and implement the appropriate error correcting actions will increase the likelihood of judgmental error; 2) because drivers tend to overestimate their hazard coping abilities, they may lack the skill needed to recover from an error; and 3) even if the appropriate action is selected and the driver is skilled enough to implement it, there will tend to be insufficient time to implement it. Brown contends that field testing of hypotheses based on theories of driver error is more valid than relying on the subjective assessment of error contributions to accident statistics.

Bryden, J. E. and Bruno, " Movable Concrete Median Barrier Risk Analysis Transportation", N. J. Research Record, Vol. No. 1233, pp. 1-10, WNYC-3-22-6 0901259379, 1989.

Summary: A model was developed to determine the probability that a primary impact on a movable concrete median barrier (MCMB) would interfere with opposing traffic. A model of the traffic and geometric conditions of the Tappan Zee Bridge on the NY State Thruway and the deflection characteristics of the MCMB was developed using a microcomputer spreadsheet.

Calting, I., "PROMETHEUS and DRIVE - European Initiatives", Mobile Information Systems, Chapter 9, Boston, Artech House, p. 273-305, 0920996816, 1990.

Summary: The chapter provides an overview of the European PROMETHEUS and DRIVE programs. Both PROMETHEUS, concentrating on vehicle development and vehicle environment, and DRIVE, concerned with infrastructure, work together to achieve the objective of an integrated system of road traffic. Information regarding the programs' structures, subprograms (e.g., PROMETHEUS consists of PRO-CAR for driver assistance, PRO-NET for vehicle-to-vehicle communication and PRO-ROAD for vehicle to environment communication), workplans and objectives is provided.

Cassisdy, V. highway barrier, Mark VII barrier, "New Steel Highway Barrier Yields on Impact", Modern Metals, Vol. 40, No. 7, p. 12-18, Issue No. 0026-8127, August 1994.

Summary: The International Barrier Corp. (IBC) developed a sand filled, coated coil barrier (called Mark VII), designed for increased energy absorption, that was installed on highways in Toronto and Miami as part of a test program. No test results were available at time of publication.

Chang, G., Chen, C. and Carter, C.C., "Intervention Analysis for the Impacts of the 65 mph Speed Limit on Rural Interstate Highway Fatalities ", Journal of Safety Research, Vol. 24, p. 33-53, 0022-4375/93, 1993.

Summary: Data analysis of highway fatalities was conducted to assess the impact of the 65 mph speed limit. Earlier analyses showed that the increased speed limit had significant initial impacts on fatalities, but the effect decayed after about a one year "learning period". In this study, the states were clustered into groups with similar characteristics to minimize the effects of data aggregation on the results. Large states appeared to be unaffected by the 65 mph speed limit, while small states shown a significant increase in fatalities since the speed limit increase. It is noted that the results are based on only two years post data and the results could change as additional data becomes available.

Chen, Kan, Ervin, Robert D., "Worldwide IVHS Activities:A Comparative Overview", Vehicle Electronics Meeting Society's Needs: Energy, Environment, Safety Society of Automotive Engineers, 92C019, 1992.

Summary: Intelligent Vehicle-Highway Systems (IVHS) has become a global movement in the last five years. Although the original technical research related to IVHS started over twenty years ago in the three regions of North America, Europe, and Japan, the recent programs have become interdisciplinary, intermodal, and dependent on tripartite partnerships among public, private, ad academic organizations in many parts of the world. Due to the different social settings and national characteristics, IVHS programs in various parts of the world have different complementary strengths which can form the basis for international cooperation.

Chira-Chavala, T.Yoo, S.M., "Feasibility Study of Advanced Technology HOV Systems, Volume 1: Phased Implementation of Longitudinal Control Systems", Program on Advanced Technology for the Highway, U.C. Berkeley, 1055-1425, 1992.

Summary: The objectives of this study are as follows:
1) To identify possible scenarios for early deployment of longitudinal control technologies in the highway environment, particularly early deployment of longitudinal control technologies in the highway environment, particularly early deployment of ICC's and advanced longitudinal control systems that are currently researched at the California PATH program.
2) To address some feasibility issues for the identified scenarios, particularly potential impacts on traffic operation, capacity, and safety.

Currently, ICCS's and advanced longitudinal control systems are not in use on the road, and evidence in the literature have only identified possible system concepts. In order to meet the above objectives, this study has to define hypothetical systems for ICCS's and advanced longitudinal control systems for the evaluation purpose. This is accomplished by reviewing prior and related continuing studies.

Colbourn, Christopher J.Brown, Ivan D.Copeman, Alan K., "Drivers' Judgements of Safe Distances in Vehicle Following", Human Factors, 1978, 20(1), 1-11, 1978.

Summary: Driver behavior in the vehicle-following situation, a major source of road accidents, was investigated using a controlled-track experiment. Drivers were found to adopt headways of approximately 2 seconds irrespective of speed of travel, driving experience, or instructed probability of the leading vehicle's stopping. under the optimal conditions used, drivers demonstrated that such headways were more than adequate to avoid tail-end collisions in an emergency situation. The implications of these results for the development of perceptual-motor support devices and the attributions of causes in road accidents are discussed.

Cooper, Peter J., Tallman, Karen Tuokko, HollyBeattie, B. Lynn, "Vehicle Crash Involvement and Cognitive Deficit in Older Drivers", Journal of Safety Research, Vol.24, 0022-4375/93, 1993.

Summary: The driving records of 165 older persons who were e classified as having dementia in a clinic assessment were examined in this study. These records were compared with those of a stratified random sample selected from the population of drivers in British Columbia. The dementia group was found to have been involved in over twice the number of collisions as their controls were during identical time periods. Further, over 80% of the dementia group who experienced a crash event (and who were almost all judged at fault) continued driving for up to 3 years following the event, and during this time over one third of these had at least one more accident.

DeLeys, N.J., Parada, L.O., "Rollover Potential of Vehicles on Embankments, Sideslopes and Other Roadside Features.Volume I, Technical Report", Calspan Corporation, FHWA/RD-86/163, 1986.

Summary: This study examines the interaction of vehicles with various roadside features to determine critical roadside-feature design criteria based on the potential for inducing vehicle rollover. Among the findings are that: (1) different classes of vehicles based on use and/or size exhibit distinct differences in rollover tendencies, and (2) the existing accident data base lacks the information necessary to define the roadside feature geometry and other conditions that caused vehicle rollover. Full-scale tests with an instrumented automobile were performed to verify the HVOSM (Highway-Vehicle -Object Simulation Model) as modified to improve its utility for studying vehicle off-road traversals. The HVOSM was used to predict the dynamic responses of representative small and large cars encountering different roadside-feature configurations, including both tracking and nontracking departures from the roadway. It was concluded that the side-slope of fill embankments should be no steeper than 3:1, and preferably flatter, for fill heights greater than 3 ft (0.9 m) to reduce the likelihood of small-car-roll-over. It is recommended that consideration be given to revising the present AASHTO design criteria for barrier warrants accordingly. It is also shown that the rounding of slope breaks currently recommended by AASHTO further reduces the rollover hazard.

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Elvik, R., "Quantified Road Safety Targets: A Useful Tool for Policy Making?", Accident Analysis and Prevention, Vol. 25., No. 5, p. 569-583, 0001-4575/93, 1993.

Summary: The study compares safety performance between Norwegian counties that set quantified road safety targets to those that only set qualified targets. Counties with quantified safety targets demonstrated a more reduced accident rate as compared to counties without quantified safety targets. Safety performance was best for counties with the highest quantified safety targets. Road safety targets were classified according to degree of quantification, reference outcome, hierarchical structure and level of ambition.

Elias, J., Stuart, D., Sweet, L. and Kornhwuser, A., "Practicality of Automated Highway Systems. Volume II: Technical Design Considerations", Calspan Corporation, FHWA-RD-79-40, November 1977.

Summary: The practicality of AHS is evaluated, in regard to technical and socio-economic impact, for various design concepts. Reasons for deciding that AHS is practical are based on AHS performance in the areas of energy, safety, service and cost. The authors suggest that to achieve a level of safety for AHS that exceeds that of conventional highway systems, AHS should incorporated the following: 1)elimination of driver-related factors in accident causation, e.g.,falling asleep, confusion at exit ramps, alcohol impaired drivers, distraction by other occupants of vehicle, excessive speed and improper driver action; 2)common speed and constant headway operation (one second between vehicles or 3600 mph is mentioned as providing a reasonable level of safety if automated control and braking systems meet certain specifications for improvement); 3) minimal delay in application of braking at the emergency level after potential problem detection; 4) high reliability of critical system elements; 5) fail-safe design of vehicle and roadway controller systems; and 6) pre-acceptance inspection of potential AHS-user at guideway entry. Vehicle factors contributing to accident causes include brake failure, brake imbalance, tire faults and excessive steering freeplay.

Farber, Eugene I., "Human Factors Issues in IVHS", Vehicle Electronics Meeting Society's Needs: Energy, Environment, Safety Society of Automotive Engineers, 92C047, 1992.

Summary: This paper addresses some of the major human factors issues relating to IVHS while focusing on the driver and the vehicle. A major goal in designing IVHS man-machine interfaces is ease-of-use to minimize distracting demands on the driver's attention. These are of particular concern in a number of proposed IVHS applications because of their complexity and uniqueness. Three sets of issues are discussed: (1) traditional "nuts and bolts" human engineering considerations, i.e., the size, type, location and visibility of controls and displays; (2) systems level design concerns relating to the logical and operational characteristics of the man-machine interface (e.g., the information content of the displays and functionality of the system, its various operating modes and the sequence of driver control actions required to access a function; (3) human factors testing and validation of the man-machine interface, including driver/system performance measures, the use of simulators and on-the-road testing, and techniques for measuring workload.

Federal Highway Administration, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements - Volume 2", United States Department of Transportation - Federal Highway Administration, FHWA-T-82-233, December 1982.

Summary: This synthesis is published in two volumes. Each of the 17 safety research subject areas is presented as an individual chapter. Subject areas included in Volume 2 are: construction and maintenance zones; adverse environmental conditions; roadway lighting; railroad-highway grade crossings; commercial vehicles; bicycle ways; pedestrian ways; and speed zoning and control. An overall 17-chapter subject index is included in both volumes of the synthesis for finding specific areas of interest.

Furukawa, Yoshimi, "The Direction of the Future Automotive Safety Technology", Vehicle Electronics Meeting Society's Needs: Energy, Environment, Safety Society of Automotive Engineers, 92C013, 1992.

Summary: The author states that Japan's traffic accident statistics clearly indicates that, in a mixed traffic system, the Mutual Safety Concept provides a highly desirable approach to traffic safety from the standpoint of protecting those individuals who are the most vulnerable in a traffic accident. An important first step in accomplishing the aims of the Mutual Safety Concept, as this paper points out, is the observation of animal group movements in nature, especially their instinctive abilities to sense and avoid dangers. A human's instinctive ability to sense and avoid the danger is impaired when he or she moves in an automobile. The author believes, therefore, that this instinctive function should be built into automobiles as a form of intelligent technology. With this basic concept in mind, this paper describes the necessary capabilities for improving the mutual safety in three capabilities; that is (1) sensing the danger, (2) communication with other traffic elements, and (3) adaption to a changing road environment and traffic conditions. The paper will also introduce technical issues that need to be addressed as well as present expectation for the further developments in electronic technologies that will materialize the technical elements.

Garber, S. and Graham, J. D., "The Effects of the New 65 Mile-Per Hour Speed Limit on Rural Highway Fatalities: A State-By-State Analysis", Accident Analysis and Prevention, Vol. 22, No. 2,p. 137-149, 0001-4575/90, 1990.

Summary: The effects of the new 65 mph speed limit on U.S. rural highway fatalities is examined. Data from 40 states are analyzed using FARS data. The results suggest that the new speed limit has increased fatalities on both rural interstate and rural non-interstate highways in most states, although the effects differ across the states. Median effect for rural interstates for the 40 states was approximately 15% more fatalities and 5% more fatalities for rural non-interstates.

Golob, T. F., Recker, W. W. and Leonard, J. D., "An Analysis of the Severity and Incident Duration of Truck-Involved Freeway Accidents", Accident Analysis and Prevention,Vol. 22, No. 2,p. 137-149, 0001-4575/87, 1987.

Summary: Accident data involving large trucks and combination vehicles on Los Angeles freeways was analyzed according to collision factors, accident severity, incident duration and lane closures. Using log-linear models, the results show significant differences in immediate consequences of truck-related freeway accidents according to collision type. The most severe accident types in terms of injuries and fatalities were the hit-object and broadside collisions. Single-vehicle accidents were more severe than two-vehicle accidents. The longest accident durations were associated with overturned vehicles.

Grandel, J. and Berg, F. A., "Technical Defects in Passenger and Commercial Vehicles - Results of Examinations of Vehicles Involved in Accidents Compared with Results of Periodic, Technical Monitoring of Vehicles", 95120..

Summary: The article presents evidence that vehicle defective structures are dependent on the age of the vehicles. Passenger vehicles experience technical difficulties more frequently and are also more frequently involved in accidents resulting from the defects. This trend was also evident for goods vehicle, busses and semitrailer tractors, but not as age dependent as with passenger vehicles. Defects in trailers and semitrailers appeared not to depend on age. Defects in passenger vehicles, categorized as the cause of an accident, were predominantly found on the brakes and tires.

Green, R. N., German, A., Gorski, A. M., Nowak, E. S., Tryphonopoulos, J. P. and Mason D. F. , "Unsatisfactory Road side Barrier System Performance in Real-World Collisions: Lessons to be Learned", International Congress and Exposition, Detroit, Michigan, Reprinted from p. 194 Vehicle Highway Infrastructure: Safety Compatibility, 870077, February 23-27, 1987.

Summary: The study examines particular accident cases which demonstrate how the omission or misapplication of design criteria lead to failure of roadside barrier systems. The authors cite references stating that 50% of all fatal accidents resulted from single vehicle roadway departures and one-third of single-vehicle, roadside, fixed-object fatal accidents involve guard rails. Thirty percent of single vehicle roadway departure accidents involve roadside collisions on the opposite side of the roadway (this has implications for the end treatment of the downstream ends of barrier systems). A sample of the cases reviewed in the study include the following factors:
1) Snow/ice piled up against a guardrail forming a ramp - the vehicle rode up the ramp, along the top of the barrier and into a concrete abutment. 2) Guardrail placed too low with respect to the level of the highway surface - the vehicle struck the guardrail, rode up on top of the horizontal rail and into a concrete abutment.
3) Misdirection of vehicle traveling at high speed when barrier was struck - the vehicle struck the buried end of the Armco-type guardrail as it approached the

bridge. It rode along the top of the guardrail, became airborne, and struck the concrete bridge wall.
4) Insufficient stiffness of guardrail system approaching bridge and improper guard rail alignment with the bridge rail - the vehicle struck the Armco-type guardrail at a vertical wooden post adjacent to the bridge abutment, displaced the post, penetrated the guard rail system and continued forward, striking a steel post anchored in the bridge abutment.
5) Upstream end of guardrail was not anchored, insufficient stiffness of guardrail system approaching bridge (posts spaced too far apart and rail was not bolted to the bridge) - the vehicle struck the barrier, became pocketed in the guardrail, and spun into a concrete bridge abutment.
6) Insufficient stiffness of guardrail (posts spaced too far apart and rail was only welded lightly to the bridge structure) - the vehicle lost directional control, crossed oncoming traffic lanes, struck and penetrated the guardrail (the support posts gave way and the rail separated from the bridge). The vehicle contracted the concrete base of the bridge, impacted a bridge vertical support pillar and became airborne. It rolled over and came to rest upside down.
7) Unprotected downstream end barrier - the vehicle lost directional control, crossed over to the opposite side of the roadway and moved sideways into the unprotected downstream end of the Armco-type barrier system. The barrier end caused the passenger door hinges and latch to separate and barrier end penetrated the occupant compartment, pushing the passenger door through the compartment to the driver's side of the vehicle.

Other factors that were included in the study included the use of wooden post and rail barriers and chain link fences that are not designed to redirect errant vehicle and unmarked, unprotected bridge abutments. fences)

Gyorki, J. R. (senior editor), "Silicon Sensors Hit the Road", Machine Design,p. 56-60, August 1993.

Summary: The article discusses the increased use of silicon sensors in the automobile industries. Increased use is due to the fact that silicon sensors are smaller, lighter, more accurate than electromechanical counterparts and can be integrated with microprocessors to provide additional intelligence for safety and emission controls. Some examples of future automotive applications include sensors for antilock braking system pressure, tire pressure, engine oil pressure, and exhaust/oxygen.

Hakamies-Blomqvist, Liisa E., "Fatal Accidents of Older Drivers", Accident Analysis and Prevention, Vol. 25, No.1, 0001-4575/93, 1993.

Summary: Fatal accidents of drivers aged 65 or more in Finland in 1984-1989 were compared with those of the statistically safest age group of 26-40 with special emphasis on self-caused accidents. The basic material consisted of 769 multidisciplinary investigated traffic accidents. Older drivers had an overall responsibility ratio [(single + guilty)/total] of .89 versus .61 for the comparison group; in collisions between vehicles this ratio was .87 versus .50. The number of accidents per driver's license increased with age in old drivers. Accidents caused by older drivers were different from those of the comparison group. Old drivers typically collided in an intersection with a crossing vehicle, which they did not notice at all, or saw so late that they did not have enough time to try an avoiding maneuver. Accident characteristics and their implications for safety research and countermeasures are discussed.

Hall, J.W., "Highway Engineering Improvements to Accommodate Older Drivers", ICE 1990 Compendium of Technical Papers, 1990.

Summary: Analyses show that the elderly have crash patterns that differ significantly from those of younger drivers. While it may be that any engineering improvement that reduces crash frequency for all drivers will provide some benefit for the elderly, it is also clear that certain remedial actions provide a differential benefit for elderly drivers. Selection of appropriate countermeasures depends on proper evaluation of accidents. in particular, this study found that routine statistical analyses were insufficient for this task; preparation of collision diagrams was necessary to accurately assess the elderly's crash experience at each location.

This study found that the elderly have a serious problem with situations requiring the assimilation of a substantial amount of information from the driving environment. They also have difficulty in properly assessing the temporal and spacial relationships of other vehicles in the traffic stream. Problems they encounter might be ameliorated through greater use of protected left turn signalization and maintenance of clear sight triangles. There is also a need to provide stronger control of driveway access and egress, including the use of right turn deceleration lanes and the possible prohibition of left turn exiting maneuvers onto major arterials.

Finally, this study has shown that while the elderly have a below average number of accidents per licensed driver, their rate per mile of travel is higher than average.

Hall, Jerry H. (chairman), "Driver Performance Data Book Update - Older Drivers and IVHS", Transportation Research Circular 419 , 0097-8515, 1994.

Summary: This circular is a compilation of summaries of driver performance data from two areas of research: older drivers and intelligent vehicle highway systems (IVHS). The summaries were written in a format similar to the one used in the National Highway Traffic Safety Administration's 1987 Driver Performance Data Book. This circular has the same objective as the Driver Performance Data Book: to provide summaries of research data relevant to understanding driver performance capabilities and limitations that can influence crash prevention. Both documents are intended to provide users with a quick overview of available data on a particular topic and a reference to use for finding more detailed information.

Research was identified for selection based on the following criteria: 1.) The research must contain quantitative data on older driver behavior or performance or focus on behavior or performance of drivers of any age when using vehicle or roadway-based advanced technology devices. Theoretical analyses, basic research, or analyses of accident statistics unrelated to driver behavior or performance would not be included.

2.) The study should have implications for motor vehicle design or highway/traffic control design.
3.) The data should not have been collected as part of a pilot test with very few subjects.
4.) The data should have been collected after 1986 or should have been a major effort not included in the 1987 Driver Performance Data Book.
5.) The research should have been of high quality, using appropriate experimental design and controls.
In the older driver area, relevant research was difficult to find because many studies did not have older drivers specifically mentioned in the title or abstract. Instead, these studies included older drivers as subjects along with younger subjects in order to obtain data more representative of the driving population. Where possible it was tried to identify and summarize the data in these studies. In the IVHS area, three types of data were sought: 1) basic information on performance (e.g. reaction times, decision times) that would be useful in evaluating possible IVHS technologies; 2) measures of driver performance using specific IVHS technologies; and 3) measures of driver performance using IVHS devices. IVHS is a relatively new area and because of the proprietary nature of the technology, the latter type of data may not be available to the public domain.

Heller, M. and Huie, M., "Vehicle Lateral Guidance using Vision Passive Wire and Radar Sensors", IEEE-IEE Vehicle Navigation and Information Systems Conference, p. 503-508, 0-7803-1235-X/93, 1993.

Summary: The paper reviews work that has been conducted to evaluate various methods that can be used for vehicle lateral guidance. Experiments were conducted using vision, passive wire and radar sensors on a common steering controller platform. Test procedures and results are discussed.

Hitchcock, A., "Intelligent Vehicle/highway System Safety: Multiple Collisions in Automated Highway Systems", Transportation Research Board 73rd Annual Meeting, Washington, D. C., 940201, 1994.

Summary:

Hitchcock, A., "An Example of Quantitative Evaluation of AVCS Safety", Pacific RIM Conference , 1993.

Summary: A method is provided for evaluating the effects of various AVCS design features on safety. To demonstrate that methodology, the influence of a lane divider on safety in analyzed for a postulated one-automated lane AHS 12 mile length of freeway. It is estimated that without the divider, for secondary accidents (vehicle from collision in manual lane intrudes into automated lane), 4-5 additional deaths per year would occur for the 12 mile section of freeway, and 0.4 additional deaths per year would occur with divider. Hitchcock suggests that the methodology can be used to model other accident types in an automated system, if the nature and frequency of initiating events or failures is specified.

Hitchcock, A., "Methods of Analysis of IVHS Safety", PATH Research Report Institute of Transportation Studies , University of California, Berkeley, UCB-ITS-PRR-92-14, 1993.

Summary: The report provides an overview of PATH IVHS research and contains a bibliography of articles on the safety of IVHS. The objective of the program was to define and demonstrate methods to assure and evaluate the safety of IVHS. Two example systems were used for demonstration. The first system had one automated lane on a freeway with other lanes dedicated to manual controlled vehicles, with most of the intelligence contained in the infrastructure. The second system had several automated lanes, with intelligence primarily in the vehicle. Both of the systems are platoon designs and safety issues regarding the use of platoons are discussed. Architecture of the systems is discussed in terms of a 6 level model: Level 0 - physical level describes how vehicular motions are affected by vehicle controls; Level 1- regulatory level includes vehicle-borne control systems; level 2 - platoon is concerned with platoon maneuvers formation and dissolution; Level 3 - link level concerned with the organization of platoon formation, choice of lane and exit point; Level 4 - network level includes general route-choice control, speed and spacing parameters; and Level 5 - law concerned with legal AHS policy. System specifications and fault tree analyses are discussed for the example systems. Some conclusions drawn from the work include: 1) it is possible to design a reasonably safe automated highway (safety vs. cost trade-off); 2) complete specification and fault tree analysis are identified as techniques that can be used to assure and verify conformity of design to a safety criterion.

Hitchcock, A., "Fault Tree Analysis of a First Example Automated Freeway", PATH Research Report Institute of Transportation Studies , University of California, Berkeley, UCB-ITS-PRR-91-14, 1993.

Summary: See Hitchcock (1992) for background used for the fault tree analysis.

Hitchcock, A. , "Use of NASS Data for Evaluation of AVCS Devices", PATH Research Report Institute of Transportation Studies , University of California, Berkeley, UBC-ITS-PWP-91-3, 1993.

Summary: Data from the 1986 National Accident Sampling System (NASS) are evaluated regarding whether sufficient information is provided to determine whether an IVHS device present in any of the vehicles could have affected the course of an accident. The IVHS devices and results are as follows:
1) forward night vision - NASS provides minimal evaluative information about this device
2) a forward object detection device - NASS data would be useful here
3) a "blind spot" warning - NASS data would be useful here
4) a red light warning - a proper assessment would require a more selective choice of cases

5) a vehicle status indicator - NASS files do not contain very much data about vehicle condition that is relevant to crash avoidance; the condition of steering and brakes is not reported
6) a driver status indicator - NASS is not useful here
7) a rollover threshold warning - very few relevant cases were found. Rollover almost always is initiated by an event which occurs after the driver has lost control and, therefore, use of the device may be limited.

It was concluded that NASS data is useful for evaluation of AVCS when drivers' choices are limited to a straight course at an appropriate speed. NASS has little value for evaluating vehicle status indicators. NASS maps are very useful.

Hitchcock, A. , "Notes from a Talk on Standards and IVHS Safety", PATH Research Report Institute of Transportation Studies , University of California, Berkeley, UCB-ITS-PWP-91-3, 1993.

Summary: The paper discusses the needs for IVHS standards and codes. Based on system safety practices and standards used in U.S. and European industries, three issues relevant to IVHS are identified:
1) hazard analysis and safety-critical subsystem - relevant standards include procedural standards which describe analytic process, linking of management and documentation to design and maintenance, including update/new requirements and other process and procedural standards specifying methods for using analytic tools used in the analysis (risk analysis, failure mode and effect analysis, and fault tree analysis);
2) design, verification, and validation of safety-critical software - relevant standards include communication protocols, formal verification of software code;
3) configuration management - relevant standards are those that describe the process of how different actors (contractors, manufactures, etc) are advised of activities of the others and how this is managed and documented.
Lists of standards relevant to IVHS are provided in the Appendix. A major difference that distinguishes industrial systems and IVHS, however, is that is no single owner responsible for the IVHS as a whole system. This multiple ownership will influence standards and the procedures used to certify compliance with standards.

Hitchcock, A. , "A First Example Specification of an Automated Freeway", PATH Research Report Institute of Transportation Studies , University of California, Berkeley, UCB-ITS-PRR-91-3, 1993.

Summary: Background for this report is provided in Methods for Analysis of IVHS Safety: Final Report of PATH MOU 19 (Hitchcock, 1992a). This report presents a formal specification for an automated freeway with vehicles in platoons. The objective of this work is to define a technique of safety analysis for automated freeway systems. The criterion used to define a hazard in that two or more faults must occur simultaneously and independently before hazards can arise. The following areas are discussed:
1) Control system - the automated freeway system is divided into blocks approximately 1 mile long with one entrance and exit. Each vehicle

communicates with roadside "iterators" (asynchronous controllers) that have various functions (e.g., the block transfer controller passes control from block to block; vehicle presence detectors provide data which allows the system to track vehicle movements and identities.)
2)Physical layout - the system contains one automated lane (AL) located on the leftmost lane of the freeway and separated from the other lanes by a fence containing off-gates and on-gates. The gates allow access to and from the transition lane (TL). Both the AL and TL centerlines have lateral guidance references with a turning-point marker on the AL at the off-gate and at the on-gate on the TL. Chicanes, sensors that observe vehicle motion, ensure vehicle control devices are functioning properly.
3) System architecture - the system architecture is described in Varaiya and Shadover 1991. Only the link, platoon and regulatory layers are discussed in this report. Each layer is composed of modules. A single link module operates over one or more complete blocks. The platoon layer is composed of a number of interlinked, asynchronous controllers and each controller contains several modules. Each block contains one set of controllers and the controllers communicate with other controllers, vehicle presence detectors and vehicles on AL and TL. The platoon, regulatory and physical layers are the safety-critical subsystem. The link layer, outside the safety-critical subsystem, communicates information about the desired speed and configuration of vehicles and platoons only with the platoon layer. The link layer manages the formation of vehicles into platoons, entrance of vehicles into AL and exiting from AL.
4) Vehicle controllers - vehicles contain a lateral-control system, a longitudinal control system, a communication system and a self-monitor. A vehicle on the AL develops a fault if it wanders excessively, does not respond to messages from the aliter (vehicle control obturator for vehicles on AL), looses speed or looses contact with the vehicle ahead or reports itself as faulty.

Message structure, system and vehicle modes, roadside controllers and system operation are also discussed.

Hitchcock, Anthony, "Methods of Analysis of IVHS Safety", Program on Advanced Technology for the Highway, U.C. Berkeley, UCB-ITS-PRR-91-13, 1991.

Summary: This paper is a compilation of notes from a talk on standards and IVHS safety. Safety criterion is defined by stating that an accident occurs when 1) one or more components has failed, and is not behaving in the way specified by the designer, 2) the designer has made an error, and a situation has arisen in which proper operation of the system leads to a breach of the specification, and 3) the specification is in error, and actions which meet the letter of specification fail to meet its intention - that casualties will not occur. The paper also states that however "fail-safe" a design is made, catastrophes cannot be made mathematically impossible. A lesser safety criterion must therefore be made express. In practice making the criterion more rigorous will incur a cost in system performance. The paper proposes a logical process of design and subsequent verification which will ensure that the safety criteria are met, and that if changes to the design are made, the need for reverification is minimized.

Hsu, A, Sachs, S, Eskafi, F. and Varaiya P., "The Design of Platoon Maneuvers for IVHS", University of California at Berkeley, PATH Research Report, UCB-ITS-PRR-91-6 ISBN 0-87942-566-0, 1993.

Summary: The control hierarchy for merging and splitting platoons and changing lanes presented in the article consists of a link layer controller, a platoon layer, a regulation layer, and a physical layer. Only platoon merging is considered in detail and a communication architecture for a platoon merge maneuver is described.

The platoon layer of the control hierarchy contains the state information, i.e., car ID, highway name, lane number, section number, platoon number target size, target speed, car position in platoon, platoon size, platoon speed, flag indicating when car is already engaged in a maneuver. The merge maneuver design protocol includes: 1) a flow diagram/algorithm of the necessary actions of the platoon and regulation layers of the hierarchy in implementing a merge of vehicle A and B; 2) interpreting the actions as a synchronization of message exchange of two separate state machines; 3) detailing protocol as inter acting state machines in a formal language (COSPAN); and 4) verifying if the protocol behaviors are acceptable.

Johnston, Robert A.DeLuchi, Mark A.Sperling, Daniel Craig, Paul P., "Automated Urban Freeways: Policy Research Agenda", Journal of Transportation Engineering, 0733-947X, 1990.

Summary: Population growth, continuing suburbanization, and higher labor-force participation rates, combined with a virtual halt in new freeway construction, have led to rapid increases in traffic congestion in the U.S. This congestion is costly; for example, the cost of highway congestion in the Los Angeles region is estimated to be $3.6 billion per year. Roughly half of this congestion is estimated to be caused by incidents, and 63% is on freeways. In the future, planners project that congestion will increase dramatically and that the proportion of delay on surface streets will increase, as congestion spreads. Automated freeways have been proposed as a solution to urban traffic congestion. Paper describes the staged development of automated urban freeways and then suggests a series of research topics related to the major policy issues of road capacity, air quality, noise, safety and liability, cost and equity, privacy, and organizational complexity. These difficult questions should be resolved before public acceptance for the technology is sought. Policy research on these matters should be carried out before or at the same time as the technology is being developed.

King, P.J., Balmer, L. Burnham, J., Locket, F. P., Barber, P. A. and Richardson, M. J. , "Autonomous Intelligent Cruise Control - A Review and Discussion", IEEE-IEE Vehicle Navigation and Information Systems Conference, Ottawa, 1993.

Summary:

Knipling, Ronald R.Yin, Hsiao-Ming, "IVHS/Crash Avoidance CountermeasureTarget Crash Problem Size Assessment and Statistical Description Report #1: Introduction Report #2: Problem Size and Descriptive Statistics Report #3: Problem Size Assessment: All Crashes", Office of Crash Avoidance Research National Highway Traffic Safety Administration U.S. Department of Transportation, 1991.

Summary: This document presents problem size assessments and statistical crash descriptions for a series of defined crash types. The crash types are the "target crashes" of various high-technology Intelligent Vehicle Highway system crash avoidance countermeasures. Target crash problem sizes are assessed using such measures as number of crashes, number and severity of injuries, number of fatalities, crash involvement rate (per 100 million vehicle miles of travel), and crash involvement likelihood (e.g., annual number of involvements per 1,000 vehicles). Crashes are described statistically primarily in terms of the conditions under which they occur (time, day, weather, roadway type, etc.) and, when data are available, in terms of possible contributing factors.

The overall "problem definition/countermeasure technology assessment" process consists of the following seven elements:

1.) Describe crash problems amenable to reduction through the application of countermeasure technologies.
2.) Quantify current crash problem sizes.
3.) Assess countermeasure technology, capabilities, and mechanisms of action to identify candidate vehicle-based solutions to these crash problems.
4.) Assess and describe relevant roadway environmental, vehicle, and driver factors affecting potential countermeasure effectiveness.
5.) Model target crash scenarios and countermeasure action to predict effectiveness and identify critical countermeasure functional requirements to ensure effective performance.
6.) Derive benefits estimates based on the potential effectiveness of identified countermeasures in preventing and/or reducing the severity of target crashes.
7.) Identify specific priority technological, human factors, or other R&D issues to be resolved to ensure that the countermeasures potential is reached.

Knipling, Ronald R., Yin, Hsiao-Ming, "IVHS/Crash Avoidance CountermeasureTarget Crash Problem Size Assessment and Statistical Description Report #7: Lane Change/Blind Spot Crashes", Office of Crash Avoidance Research National Highway Traffic Safety Administration U.S. Department of Transportation, 1991.

Summary: Lane change/blind spot crashes are the target crashes of lateral near-object detection systems. Such systems detect the presence of a vehicle in the driver "blind spot" of a vehicle making a lane change or similar maneuver. Near-object detection systems are likely to be effective only in crashes involving low to moderate closing speeds.

Lane change/blind spot crashes consist of two major subtypes:

- Sideswipe or angle crashes in which one vehicle was changing lanes
- Rear-end crashes where the lead (struck) vehicle was changing lanes.

For the purposes of this analysis, the two subtypes have been aggregated (but they may be disaggregated if future analyses require it).The primary crash problem size assessment is based on 1989 GES and FARS data. For each

data source, estimates are provided for all vehicle types, passenger vehicles (automobiles, light trucks, vans), and combination-unit trucks.

Knipling, Ronald R., Yin, Hsiao-Ming, "IVHS/Crash Avoidance CountermeasureTarget Crash Problem Size Assessment and Statistical Description Report #11: Rear-end Crashes", Office of Crash Avoidance Research National Highway Traffic Safety Administration U.S. Department of Transportation, 1991.

Summary: Rear-end crashes are the target crashes of numerous countermeasure concepts. These countermeasure concepts include the following:
1.) Prevent "tailgating," perhaps by warning the following driver that he/she is following too closely.
2.) Provide an earlier warning of lead vehicle stopping
3.) Provide a more salient warning of lead vehicle stopping and/or stationary
4.) Provide automatic braking in the following vehicle, which may involve partial braking (as in adaptive "smart" cruise control) or full braking to a stop.

The different countermeasures outlined above have slightly different, though overlapping, target crash groups. To accommodate the different possible target crash groups, three "levels" of rear-end crashes are quantified using 1989 GES and FARS data:
1.) All rear-end crashes
   - All vehicle types
2.) All rear-end crashes occurring on a roadway (and thus are likely to be addressed by warning devices)
   - All vehicle types
   - Passenger vehicle as striking vehicle
   - Passenger vehicle as struck vehicle
   - Combination -unit truck as striking vehicle
   - Combination-unit truck as struck vehicle
3.) Rear-end crashes occurring on a roadway in which the lead vehicle maneuver just prior to the crash was slowing or stopping in traffic lane (a narrower definition consistent with the crash scenario assumed by most rear-end crash countermeasures)
   - All vehicle types
   - Passenger vehicle as striking vehicle
   - Passenger vehicle as struck vehicle
   - Combination-unit truck as striking vehicle
   - Combination-unit truck as struck vehicle

Knipling, Ronald R., Yin, Hsiao-Ming, "IVHS/Crash Avoidance CountermeasureTarget Crash Problem Size Assessment and Statistical Description Report #13: Intersection Crossing Path Crashes", Office of Crash Avoidance Research National Highway Traffic Safety Administration U.S. Department of Transportation, 1991.

Summary: Intersection crossing path crashes are the target crashes of advanced technology communications/processing systems that would "read" planned driver actions at intersections based on communications with vehicles, and then warn one or both drivers of an imminent conflict. For example, if two

vehicles were approaching the intersection from opposite directions and one was intending to turn left, the system might calculate the expected movement paths of the two vehicles in relation to the intersection signaling timing and geometry, and in relation to each other. The system would warn the turning vehicle if the planned turn were unsafe due to the expected presence of the other vehicle, or perhaps usurp driver control of the vehicle and initiate automatic braking and/or steering.

Since the envisioned countermeasure would likely involve cooperative communication between vehicle sand existing (though modified) intersection traffic control devices (e.g., traffic lights), it is likely that only crashes occurring at intersections with traffic lights (as opposed to stop or yield signs) are applicable. Thus, the first problem size assessment presented here is for crashes at signalized intersections . The second problem size assessment presented is for the larger problem of all intersection crashes.

Knipling, Ronald R., Yin, Hsiao-Ming, "IVHS/Crash Avoidance CountermeasureTarget Crash Problem Size Assessment and Statistical Description Report #19: Single Vehicle Off-the -Road Crashes", Office of Crash Avoidance Research National Highway Traffic Safety Administration U.S. Department of Transportation, 1991.

Summary: Single vehicle off-the-road crashes are the target crashes of a variety of countermeasures, most intended primarily to simply "keep the vehicle on the road". The primary crash problem size assessment is based for all vehicle types, passenger vehicles (automobiles, light trucks, vans), and combination-unit trucks. This report presents problem size estimates for all one-vehicle crashes where the first harmful event occurs either:
- On the shoulder/parking lane
- Off the roadway/shoulder/parking lane
- On the median

Knipling, Ronald R., Yin, Hsiao-Ming, "IVHS/Crash Avoidance CountermeasureTarget Crash Problem Size Assessment and Statistical Description Report #19: Single Vehicle Off-the -Road Crashes", Office of Crash Avoidance Research National Highway Traffic Safety Administration U.S. Department of Transportation, 1991.

Summary: These crashes, unique to heavy vehicles, are the target crashes of near-object detection systems. Such a system, if installed on a truck, would detect the presence of a vehicle or fixed object (e.g., utility pole, parked vehicle) on the right side of the truck during the turning maneuver. Such systems are likely to be effective only in crashes involving low to moderate closing speeds. The primary crash problem size assessment is based on 1990 GES and FARS data. For each data source, estimates are provided for combination-unit trucks and single-unit trucks.

Knipling, Ronald R., Yin, Hsiao-Ming, "Lane Change/Merge: Problem Size Assessment and Statistical Description", Office of Crash Avoidance Research National Highway Traffic Safety Administration U.S. Department of Transportation, 1993.

Summary: This document presents problem size assessments and statistical crash descriptions for lane change/merge (LCM) crashes and two key subtypes of the LCM crashes. The LCM crashes are a potential "target crash" of the technology Intelligent Vehicle Highway System (IVHS) crash avoidance countermeasures. To elucidate potential countermeasure applicability, the LCM crash is divided into two types: angle/sideswipe and rear-end LCM crashes. The emphasis of this report is on the angle/sideswipe LCM crashes. This subclass is likely to be most amenable to prevention of the obstacle detection system. Principal data sources are the 1991 General Estimates System (GES) and Fatal Accident Reporting System (FARS). LCM crash problem size is assessed using such measures as number of crashes, number and severity of injuries, number of fatalities, crash involvement rate, and crash involvement likelihood. Problem size statistics are provided for four vehicle type categories: all vehicles, passenger vehicles (i.e., cars, light trucks, light vans), combination-unit trucks and medium/heavy single-unit trucks. Angle/sideswipe LCM crashes are described statistically primarily in terms of the conditions under which they occur (e.g., time of day, weather, roadway type) and, when data are available, in terms of possible contributing factors.

Knipling, R.R.Ironer, M.Hendricks, D.L.Tijerina, L.Everson, J.Allen, J.C.Wilson, C., "Assessment of IVHS Countermeasures for Collision Avoidance: Rear-end Crashes", National Highway Traffic Safety Administration U.S. Department of Transportation, DOT HS 807 995, 1993.

Summary: This report describes an analysis of the application of Intelligent Vehicle Highway System (IVHS) technology to the reduction of rear-end crashes. The principle countermeasure concept examined is a headway detection (HD) that would detect stopped of slower-moving vehicles in a vehicle's travel path. The report is organized to correspond to the major steps of the project methodology:

1. Quantify baseline target crash problem size and describe target crash characteristics.
2. Describe, analyze, and model target crash scenarios to permit understanding of principal crash causes, time and motion sequences, and potential interventions.
3. Assess countermeasure technology and mechanisms of action to identify candidate solutions.
4. Assess relevant human factors and other (e.g., environmental, vehicle) factors affecting crash scenario and potential countermeasure functional requirements.
5. Model countermeasure action to predict effectiveness and identify critical countermeasure functional requirements.
6. Identify specific priority technological, human factors, and other R&D issues to be resolved. Case reconstructions and modeling indicate that most rear-end crashes are due to driver inattention, and that this inattention can in theory be addressed successfully by the HD countermeasure concept and available radar technologies.

Kraus, J.F., Anderson, C. L., Arzemanian, S., Salatka, M., Hemyari, P., and Sun, G., "Epidemiological Aspects of Fatal and Severe Injury Urban Freeway Crashes", Accident Analysis and Prevention, Vol. 25, No. 3, p. 229-239, 0001-4575/93, 1993.

Summary: Two types of frequently occurring freeway accidents were examined with respect to physical features (design) of the freeway. The two accident types were: 1) a rear-end impact by a moving vehicle with one stopped or slowed in a traffic lane; and 2) a vehicle that leaves the roadway and road shoulder and impacts with a barrier or obstacles off the roadway. Fatal/severe injuries were highest for off-road crashes as compared to in-lane crashes. There was a higher rate of in-lane crashes in freeway segments without a left shoulder. Off-road collisions occurred more frequently in the absence of a right shoulder and on freeways with two or three lanes.

McDevitt, C.F., "Recent Innovations in Traffic Barriers and Other Roadside Safety Appurtenances", Transportation Forum, Vol. 2, No. 2, p. 12-23 , 0826-8193, September 1985.

Summary: The roadside safety devices reviewed in the article include the following:
1) Guardrails - a) The three beam guardrail (three corrugations) was designed to minimize the problems that occurred with the W-beam. With the W-beam, a mounting height of 12 " was found to be critical: mounting too low allowed vehicles to vault or rollover the barrier; mounting too high permitted vehicle bumpers /wheels to snag on the support posts. Both the W-beam and the three beam were found to have posts that rotated backwards on impact and the attached rail would form a ramp that allowed vehicles to vault over the barrier. Therefore, the three beam barrier was modified so that the rail disconnects from the posts during impact. Other improvements include design changes to minimize bumper/wheel snagging and reduce impact forces on front wheel and vehicle suspension systems. The modified three beam has been designed so that the rail moves upward on impact which works to prevent high CG vehicles from rolling over the barrier. Tests have shown that the modified three beam was able to redirect a 3,200 lb intercity bus traveling at 59 mph with 15 degree impact angle.

b) The self-restoring barrier (SERB) guardrail or tubular three beam consists of two three beams welded together, mounted on posts with a hinged pivot bar and held away from the posts by a steel cable. Upon impact the SERB deflects backward and upward and returns to its original position after vehicle deflection. This guardrail system is also designed with break away posts for heavy vehicle impacts. It can redirect a 40,000 lb intercity bus traveling 60 mph with an impact angle of 15 degrees.

2) Bridge Rails - There are 4 service level bridge rails. Service level 1 is used on secondary or local roads with low speed travel. Level 2 is a general service level and higher service level rails are used for locations with severe geometric conditions, heavy traffic areas, and heavy vehicle traffic areas. Service level 1 bridge rail may consist of a three bean rail mounted on breakaway wooden or steel posts. This type of rail has some ability to redirect heavy vehicles (e.g., 20,000 lb school bus, 45 mph, 7 degree impact angle). The tubular three beam

retrofit railing and the New Jersey concrete safety shape bridge parapets, both high service level bridge rails, are able to redirect 20,000 lb school buses at 40 mph and 15 degree impacts. SERB bridge rail, also a high service level rail, deflects a few inches backward when impacted and is able to redirect errant vehicles so they are parallel to the rail. The ultra-tall wall is used in areas where a vehicle cannot be permitted to penetrate and it prevents vehicles from rolling over the top of the barrier. To protect bridge trusses, retrofit railings have been developed that include three beam, aluminum thru-beam, box beam and W-beam rail systems
3) Median Barriers - The F shape and New Jersey concrete safety shape barriers (32" height) reduce the likelihood of rollover upon impact with the barrier. They serve to turn and redirect errant vehicles by lifting the vehicle on the lower slope of the barrier and reducing the friction forces between the vehicle tires and the road surface. The General Motors shape barrier is no longer used due to a problem with rollovers. The tall wall barrier (42" height), similar in profile to the New Jersey barrier, is capable of redirecting 80,000 tractor-trailers. Impact forces are distributed along the barrier through longitudinal reinforcing steel and closed loop stirrups. The moveable concrete median barrier is composed of 2.5 ft New Jersey or F shape barrier segments hinged together. Other median barriers include the International Barrier Corporation (IBM) sand filled steel bin barrier and soil-mounted and structure-mounted SERB median barriers.
4) Guardrail Terminals - The turned-down W-beam guardrail end, called the "Texas Twist", was developed to eliminate vehicles becoming speared with rail ends. However, the turned-down end of the rail (25 ft length) formed a ramp that launched impacting light weight vehicles. The controlled releasing terminal (CRT) is designed so that the W-beam guardrail releases from the support posts and can be ridden down by light vehicles. An advantage of the CRT is that it has a straight rather than a flared terminal and requires minimal space. The safe end treatment (SENTRE) terminal is designed so that there is minimal penetration of the impacting vehicle by the W-beam rail end while the breakaway slipbase posts slide along a cable and redirect the vehicle away from the terminal. Energy from the impact is also absorb by sand filled containers mounted on the posts.

McLellan, David R.Ryan, Joseph P.Browalski, Edmund S.Heinricy, John W., "Increasing the Safe Driving Envelope - ABS, Traction Control and Beyond", Vehicle Electronics Meeting Society's Needs: Energy, Environment, Safety Society of Automotive Engineers, 92C014, 1992.

Summary: This paper discusses the use of active control strategies in automobiles. Antilock Brake Systems (ABS) and Acceleration Slip Regulation (ASR) or Track Control have shown a great deal about active safety and provided encouragement to the vision described in the paper. ABS/ASR work by measuring the rotational spin-down or spin-up (slip) of the tires and apply control strategies that limit the "slip" to the 5-15% range. Yaw stability is a by-product of this strategy because the tire develops lateral and longitudinal forces together. By controlling the longitudinal slip of the tire contact patch, significant and useful lateral forces can be available for stability and control. ABS provides repeatable straight stops in the shortest possible distance under most

conditions. These stops are shorter than locked wheel stops. They are accomplished without loss of steering control or flatspotting. Steering maneuvers that can be accomplished within the driving envelope (limit corning , evasive maneuver, etc.) without breaking can also be accomplished under ABS breaking. ASR controls the spin-up of the tire as much as ABS controls the spin-down. ASR hardware and intervention strategies are different from ABS and also may differ between FWD and RWD because of the different aspects of drive wheel spin presented by FWD and RWD cars; however, they all select among control subsystems of engine management (spark, fuel, throttle) and brake intervention (right and left wheels controlled separately and together). The paper then leads to the next possible level of active control strategies, e.g. mechanical-electronic systems that enhance driver control without requiring decisions or actions on the part of the driver. An assessment of the sensors, hardware and strategies that can accomplish this is then presented.

Miller, M. A., Bresnock, A., Lechner E. H. and Shladover, S. E., "Highway Automation: Regional Mobility Impacts Assessment", Transportation Research Board n Annual Meeting, Washington, D.C., 930522, January 1993.

Summary: The paper presents a comparison of mobility between automated and non-automated roadways with a highway automation network scenario. Performance measures used included vehicle miles traveled, vehicle hours traveled, vehicle hours of delay and average speed. The results indicate that automated roadways demonstrated a significant improvement in mobility on freeways, arterial and freeway on- and off-ramps.

Nelson, J.R., Spitzer, F. and Stewart, S., "Experiences Gained in Implementing an Economical, Universal Motorist Information System", IEEE-IEE Vehicle Navigation and Information Systems Conference, Ottawa, 0-7803-1235-X/93, 1993.

Summary: An overview of the design and implementation of an ATIS is provided.The ATIS provides information on approximately 1,000 kilometers of Toronto's highways. The ATIS is infrastructure free and operates with an ATMS (COMPASS). The Traffic and Road Information System (TRIS) architecture is provided.

Peters, J. I., Mammano, F. J., Dennard D. and Inman V. W., "TravTek Evaluation Overview and Recruitment Statistics", IEEE-IEE Vehicle Navigation and Information Systems Conference, Ottawa, 0-7803-1235-X/93, 1993.

Summary: The article provided an overview of the TravTek (Travel Technology) system and a description of the operational field tests that were currently being conducted to evaluate the system. The tests include naturalistic field studies, controlled field experiments, debriefing interview and questionnaire studies, network modeling and safety studies, architecture evaluation and global evaluation. No test results are provided.

Pierowicz, J., Parada, L., Hendricks, D., Bollman, E., Lloyd, M., Weissman, S., Scheifflee, T., and Page, J., "Intersection Collision Avoidance Using IVHS CountermeasuresTask 1: Draft Interim Report", Calspan Corporation, 8149-1, 1994.

Summary: The analysis conducted in Task 1 of this program developed a picture of what types of crashes occur at intersections, how these crashes occur, and why these crashes occur. From this analysis a number of conclusions were drawn:

1. The intersection collision problem is serious. Intersections rank second in locations where vehicle fatalities occur.
2. Intersection crashes are caused primarily by driver perception failures. The second most common cause is deliberate driver action to violate the traffic control device.
3. Any countermeasure that is designed to prevent intersection crashes must address both the Faulty Perception and the Deliberate Driver Action causal factors.
4. A sensory enhancement system that could alert the driver to the presence of other vehicles in the proximity of the intersection could be effective in dealing with the driver perceptive failure crashes. This system should be able to recognize those vehicles that pose a threat to the vehicle in which the countermeasure is installed. The system should also be able to, at minimum, present the driver with information regarding threat vehicle direction.
5. The deliberate driver action causal factor will require developing an active countermeasure, that is, a system with authority to override the driver inputs and to steer or apply brakes to avoid the collision. At this point, the degree of system authority required is unknown. The clinical analysis results showed that the timing between the two vehicles in an intersection crash is critical. The collision may be avoided by disrupting this timing through limited braking or steering. This idea will be investigated further in future tasks. The application of an active countermeasure may be resisted by the public. If this type of system is required to prevent intersection crashes legislation may be required.

Reed, Thomas B., "Discussing Potential Improvements in Road Safety: A Comparison of Conditions in Japan and the United States to Guide Implementations of Intelligent Road Transportation Systems", IVHS Issues and Technology, SAE, 921558, 1992.

Summary: The potential impact of Intelligent Road Transportation Systems (Advanced Road Traffic Systems in Japan; Intelligent Vehicle-Highway Systems in the United States) on road safety is discussed through comparison of road transportation in Japan and the United States. The resulting insights show that IRTS should 1) focus on regional needs, emphasize road safety, and respond flexibly to uncertainty in accident trends in order to reduce the magnitude of the road safety issue, 2) adapt to roadway architecture and traffic conditions, be perceived as effective and automatic, and handle any detrimental higher order system s effects in order to be effective, and 3) be compelling, receive government support, and manage uncertainty from counter vailing marketplace trends in order to gain market penetration. The potential safety benefit of

eliminating alcohol from roadways is identified as greater than the analogous benefit of IRTS. These insights should help ensure that IRTS adequately addresses road safety issues.

Roberts, James F., "Roadside Design Guide", Task Force for Roadside Safety of the Standing Committee on Highways Subcommittee on Design, 1988.

Summary: This design guide has been prepared to update, consolidate and expand information contained in existing publications and policy statements which pertain to safer roadside design. Additionally, information has been taken from numerous research reports, technical advisories, and individual state reports that have not previously been widely distributed to the highway community. This document is intended to provide guidance not only of direct use to engineers, but also to highway construction and maintenance personnel. Chapter 2 explains in general terms how a benefit/cost approach may be used to assist the highway engineer in choosing between alternative design options in cases where the most effective design treatment is not obvious. Chapter 3 re-emphasizes the clear zone concept and addresses roadside slope and drainage structure treatments that may lessen the danger to a motorist who leave the roadway. Chapter 4 includes information on sign and luminary supports, and other significant roadside features that are normally installed within highway rights-of-way. Chapters 5,6,7 and 8 provide updated and expanded information on the selection, location, and design of roadside barriers, median barriers, bridge railings and crash cushions, respectively.

Rockwell International Science Center, "Potential Payoffs from IVHS: A Framework for Analysis - Appendix C", CA PATH Program, Institute of Transportation Studies, University of California at Berkely, PATH Research Report, UCB-ITS_PRR-92-8, August1992.

Summary:

Saxton, L., "Automated Control - Cornerstone of Future Highway Systems", IVHS Review, Intelligent Vehicle-Highway Society of America,p. 1-16, Summer 1993.

Summary: The article provides an overview of the emergence of AHS as a solution for highway transportation demands. Examples of AHS operational benefits include:
1) immunity to distracting events - traffic safety will increase because visual distractions (e.g., disabled vehicle on the shoulder, not physically interfering with traffic) will not interrupt traffic flow ;
2) weather related traffic effects - AHS standardized operating conditions will increase traffic volume and safety by eliminating disparity in individual driving speeds and disruption in traffic flow caused by adverse weather;
3) uniform driving performance - AHS will provide uniform/standardized speeds, headways, lane changing, merging, etc., thus, increasing traffic volume and safety ;

4) increased capacity - estimated 3000-4000 vph per lane for early generation systems;
5) lane widths and right of way (ROW) - AHS standardized operation will allow narrower lane widths and geometrically efficient ramp designs while increasing traffic safety;
6) environmental air quality performance - achieved through stable traffic flow, AHS monitoring of vehicle engine performance and emissions, and potential use of electrically powered vehicles; and
7) other features - higher operating speeds (80 to 100 mph) with increased traffic safety and reduced time to destination.

Other AHS design goals include: dual mode (manual and automated)AHS vehicles; fully automated vehicles; and retrofit capability allowing manually controlled vehicles to be retrofitted with an AHS control module.

Saxton, L., "Automated Highway System - Considerations for Success", IEEE, IEEE-80CH16601-4 1980, 1980.

Summary: The paper discusses the benefits of AHS in areas of energy safety and environment. Energy issues include the use of petroleum alternatives, such as electrically-powered vehicles. Safety issues include a discussion of the human, environmental and vehicle related accident causes. Environmental benefits include the reduction of vehicle emissions and a reduced right of way and lane width requirements. AHS goals are discussed and a design concept utilizing a passive guideway is presented. The use of barriers on the passive guideway would serve to: 1) proved a fixed side wall reference for a vehicle lateral control system; 2) restrain vehicle movement during failure of vehicle lateral control system; 3) prevent intrusion of manual vehicles into automated lanes; 4) provide design, construction and maintenance practices consistent with those used currently.

Sheridan, B. T., "Human Factors of Driver-Vehicle Interaction in the IVHS Environment", Center for Transportation Studies, Massachusetts Institute of Technology, Dot Hs 807 737, June 1991.

Summary: The report provides a review of human factors issues associated with IVHS. Mental workload, driver errors and warnings are considered with regard to ADIS and AVCS. Possible future research using simulator tasks to measure driver performance/workload under IVHS conditions is suggested and models useful for planning experiments are discussed.

The following steps are presented in considering the impacts of IVHS on driver safety: 1) identify the functions that will probably be added by IVHS; 2) perform a task analysis in terms of driver sensory, cognitive and motor requirements for each function; 3) assess if the sensory, cognitive motor requirements exceed human capabilities/ workload limits and in regard to age, education, culture and physical handicap; 4) evaluate how exceeding driver capabilities/workload limits are likely to translate into errors/accidents.

Simulator experiments are presented for each of the following IVHS functions: 1)pre-trip and en route navigation; 2) dynamic announcement of impending collision, intersection, required turn or display of surrounding traffic; 3) safety status indication/warning of vehicle or driver; 4) general communications with off-highway locations, other vehicles; 5) automatic control.

Simonsson, S., "Car-Following as a Tool in Road Traffic Simulation", IEEE-IEE Vehicle Navigation and Information Systems Conference, Ottawa, 0-7803-1235- X/93, 1993.

Summary: A new car-following model is presented along with an overview of car-following theory. It is based on the hypothesis that a driver reacts to stimuli in the surrounding traffic by selecting an acceleration or deceleration proportional to two components the difference between the driver's preferred time gap and the actual time gap, and the difference between the driver's preferred speed and the actual speed. Mimic, a microscopic simulation model, contains the following key components: a road system, a terrain model, a structures model, a vegetation model, a vehicle-driver-unit model, the traffic flow, a car-following model, a gap-acceptance model, an overtaking model, and modules for input and output of data. Mimic is appropriate for large road networks, including roads and intersections of arbitrary geometrical design. Mimic is part of ESCORT, a knowledge-based expert system for estimating road user impacts and environmental effects of road traffic.

Staplin, Loren, Lococo, Kathy, Sin, Sim, "Traffic Maneuver Problems of Older Drivers: Final Technical Report", KETRON Division of the Bionetics Corporation, FHWA-A-RD-92-092, 1993.

Summary: This project includes a literature review and accident analysis that supported the hypothesis that age differences in motion perception capabilities represent a likely source of difficulty for specific traffic maneuver problems experienced by older drivers. A feasibility study was performed to evaluate the most appropriate apparatus for use in later driving simulation tests planned in this research. Two sets of experiments were subsequently conducted. In the first experiment, drivers in three age groups -- 18-55, 56-74, and 75+ years of age -- estimated the time-to-collision (TTC) of an approaching vehicle, from both stationary and moving perspectives. The conflict vehicle approached at varying speeds, and was removed from the view of the test subject at varying times/distances relative to the subject. In the second experiment, drivers viewed a dynamic roadway scene containing an approaching conflict vehicle. The subjects' task was to judge the "last safe moment to proceed" with a particular traffic maneuver in relation to the conflict vehicle, to determine a gap judgment measure. Both the TTC and the gap judgment measures were obtained under laboratory conditions using simple stimulus presentation methodologies in a driving simulator. Limited controlled field validation data were also obtained for both types of dependent measures, using the same test sample. Recommendations for countermeasures to accommodate older driver difficulties with turning maneuvers at intersections were developed consistent with the results of these studies.

Stevens, W. B., "The Automated Highway System (AHS) Concepts Analysis", Mitre, Mc Lean, Virginia, MTR 93W000123, August 1993.

Summary: The report presents AHS operational goals, AHS functional characteristics for vehicles, roadway infrastructure and command and control, and AHS design concepts. Concept definition factors include vehicle class, roadway infrastructure interaction, power source, lateral control strategy and vehicle control strategy.

Terhune, K. W. , "Contributions of Vehicle Factors and Roadside Features to Rollover in Single-Vehicle Crashes - Task 2 of Project "Crash Avoidance Research - Stability and Control", Calspan Corporation, DOT HS 807 735, March 1991.

Summary: Using NASS single vehicle accident data, the study investigated the role of vehicle factors and roadside features in causing rollovers. Sideslopes and ditches were found to be the roadside features with the highest rollover rates. Various types of rollovers are discussed. Those related to barrier/curb/guardrail are trip-over, flip-over, climb-over, and bounce-over. Percent rollovers, given feature contact were (approximated) 10% - curb, 15% - guardrail, 15% - divider and 16% - wall.

Terhune, Kenneth W., Ph.D., "A Study of Light Truck and Passenger Car Rollover and Ejection in Single-Vehicle Crashes", Calspan Corporation, 7636, 1988.

Summary: This report follows up previous Calspan research revealing that, while light trucks protect their occupants about as well as cars do in single-vehicle crashes, light trucks had substantially higher rollover and ejection rates than cars. The new research sought to determine (a) the roles of driver, environment, and vehicle factors in the rollovers of light trucks and (b) how occupants are ejected from light trucks. Studied were pickups, vans, and utility vehicles from model years 1979-1986, using data from the 1980-1985 files of the National Accident Sampling System (NASS). To provide additional details about roadsides, rollovers, and ejections, a special clinical file was created by coding from 487 hard-copy NASS cases. In controlling for driver and environmental factors, light truck overturn rates remained higher than car rates, with utility vehicle rates distinctly the highest. Compared to cars, light trucks exhibited more precrash lateral skidding, more on-road rollovers, and more tripping-type rollovers. Occupant ejections were the highest in utility vehicles, somewhat higher in pickups than in cars, and about the same in vans as in cars. Controlling for crash severity indicated that ejections were highly injurious to occupants. Structural failures associated with ejection were doors opening, windows and windshields breaking, and in the case of utility vehicles, roof failures. It was concluded that vehicle factors appear to play a role in elevated light truck overturn rates, and that ejection is preeminently a utility vehicle problem. Recommendations for research and countermeasures were given.

Terhune, Kenneth W., Ph.D., "Contributions of Vehicle Factors and Roadside Features to Rollover in Single-Vehicle Crashes.Task 2 of Project "Crash Avoidance Research -Stability and Control"", Calspan Corporation, 7888-1, 1991.

Summary: This study examined single-vehicle crashes from the National Accident Sampling System (NASS) to suggest how vehicle factors and roadside features interact in generating rollovers. Due to the exploratory nature of the of the study and the small numbers in the subsamples, the data were analyzed in unweighted form. Consequently, the study should be viewed as heuristic: the results cannot be generalized and taken as representative of the national population of cars and light trucks in accidents. Findings were: (1) Roadside features with the highest rollover rates of contacting vehicles were sideslopes and ditches; (2) Vehicle factors were related to overturn rates mainly with the most hazardous roadside features; (3) The combined data for the cars and light trucks of the sample indicate that the overturn rates were inversely related to the stability factors; the separate data did not have this general trend, but reliability of the stability factor data may have been a problem; (4) Wheelbase was inversely related to rollover rates ; (5) When controlling for wheelbase and stability factor, light trucks had substantially higher overturn rates; and (6) Wheelbase and vehicle type were related to precrash vehicle modes (skidding, spinning, etc.), which in turn were related to rollover rates. Recommendations include the need for reliable stability factor data.

Tongue B. H., Yang, Yean-Tzong and White, M. T., "Platoon Collision Dynamics and Emergency Maneuvering I: Reduced Order Modeling of a Platoon for Dynamical Analysis", Institute of Transportation Studies, University of California at Berkeley, PATH Research Report, UBC-ITS-PRR-91-15, August, 1991.

Summary: An operational model of vehicle platoon dynamics under emergency conditions was developed and the platoon's dynamic behavior under non-nominal, or emergency conditions was evaluated. A non-linear reduced order model (ROM)was developed from an accurate and high order mode. Regression analysis, based on the least-squares algorithm, was applied to the response of a full order model in order to determine the reduced order vehicle model. Preliminary results have shown that the reduced order model provides an accurate response match with the original model. A platoon model has been developed and preliminary simulations of platoon dynamics have been performed in which system parameters, e.g., sampling time, desired headway, vehicle spacing and road grades, were varied. A detailed literature review is included.

Transportation Builder, "As Drivers Age... Visual Cues Must Change", Transportation Builder, p. 12-13, November - December 1990.

Summary: The article presents information regarding physical and mental aging characteristics and impacts on driving performance. Physiological changes include decreased night vision, decreased retinal function and diminished ability to perceive contrast. Due to changes in cognitive abilities, older drivers require more time (25-35% increase) to process visual information.

Bigger, brighter signs, better maintained and wider pavement markings, and simplified intersections were recommended.

Treat, J. R., "A Study of Precrash Factors Involved in Traffic Accidents ", HSRI Research Review (University of Michigan Highway Safety Research Institute), Vol. 10, No. 6/Vol. 11, No. 1, p. 1-35, May-June/July-August 1980.

Summary: Results regarding vehicular factors of the accident investigation are provided under article #31s of this data base. This article also included human direct causes of accidents. Recognition errors (perception (e.g., improper look-out), comprehension and delays) and decision errors (e.g., excessive speed) were the most commonly identified problems. Other human errors included inattention, improper evasive action, internal distraction, improper driving technique, inadequate defensive driving technique, false assumption, improper maneuver and overcompensation. Human conditions/states (i.e., physical, physiological and experiential factors) including fatigue, driver experience and alcohol impairment were also considered, with alcohol impairment the most frequently recorded problem. Environmental factors including roadway design and condition, visibility and other precrash factors external to driver and vehicle, were identified as definite causes in 12.4% of the accidents. Highway-related factors were predominately reported as problems, followed by slick roads and ambience-related factors.

Vehicle system improvements (state-of the art for production vehicles) were assessed to evaluate safety benefits. The improvements included radar-warning, radar-actuated, and antilock braking systems. The assessment focused on whether the improved vehicle systems would have enabled the crashes to be avoided. Four-wheel antilock braking combined with radar-actuated braking systems were reported as most promising. Also considered beneficial were improved brake lights and vehicle-lifetime braking components.

Treat, J. R. and Romberg, R., "Tri-Level Study: Modification Task 1: Final Report on Potential Benefits of Various Improvements in Vehicle Systems in Preventing Accidents or Reducing Their Severity", Indiana University Institute for Research in Public Safety , DOT-HS-805 094, June, 1977.

Summary: In-depth case reports were reviewed in order to assess if various vehicle systems improvement would serve to prevent or reduce the severity of accidents. The vehicle improvements and percent of possible benefits are as follows:

-vehicle lifetime brake components (5.5%) -pad/lining wear indicator (2.1%)
-underinflation warning device (2.6%) -improved wet traction tires (3.1%)

Treat, J.R. and Stansifer, R. L., "Vehicular Problems as Accident Causes - An Overview of Available Information", International Automotive Engineering Congress and Exposition, Detroit, 770117, February/March 1977.

Summary: This accident investigation focused on the role of vehicular factors in accident causation. It was found that vehicular degradations, maladjustments, and failures were identified as definite causes in 4.5% of the accidents investigated and either definite of probable causes in 12.6% of the accidents. Most commonly identified causes were problems with brakes and tires. Included within the category of brake system problems, gross system failure (front and/or rear) accounted for more than half of the brake problems recorded. Gross brake system failures included brake hose failures, wheel cylinder failures, master cylinder failures and adjustment mechanism loss or failure. The average mileage for vehicles (with working odometers) that experienced gross brake failures was 65,991. The most commonly identified tire and wheel problems were inadequate tread depth and improper inflation (predominately under inflation). Ranking third and fourth, respectively, as vehicular causes were communications systems (lights, signals glazed surfaces, related vision hardware- wipers, washers and defrosters) and the steering system (excessive freeplay or binding, freezing or locking). Other vehicular factors included body and doors (opening pre-crash,power train and exhaust (loss of power, hesitation), suspension problems, and driver seating and controls.

Human factors were identified as definite causes of 70.7% of the accidents and environmental factors (including slick roads) were identified as definite causes of 12.4% of the accidents.

Treat, J. R., Tumbus, N. S., MacDonald, S. T., Shinar, D., Hume, R. D. Mayer, R. E., Stansifer, R. L. and Castellar, N. J., "Tri-Level Study of the Causes of Traffic Accidents, Volume I: Casual Factors Tabulations and Assessments", Indiana University Institute for Research in Public Safety , DOT-HS-805 085, March 1977.

Summary: The tri-level study included accident data collection from: 1)police reports and other baseline data files; 2)on-site accident investigation; and 3) in-depth accident investigation. The in-depth team identified human factors as a probable cause in 92.6% of accidents investigated; environmental factors as probable causes in 33.8% of the accidents; and vehicular factors as probable causes in 12.6% of the accidents. Improper lookout, excessive speed, inattention, improper evasive action and internal distraction were the major human causes of accidents. View obstruction and slick roads were major environmental causes of accidents. Brake failure, inadequate tread depth, side-to-side brake imbalance, under-inflation, and vehicle related vision obstructions were major vehicular causes of accidents.

Treat, J. R., Tumbus, N. S., MacDonald, S. T., Shinar, D., Hume, R. D. Mayer, R. E., Stansifer, R. L. and Castellar, N. J., "Tri-Level Study of the causes of Traffic Accidents, Volume II: Special Analyses", Indiana University Institute for Research in Public Safety , DOT-HS-805 086, March 1977.

Summary: A continuation of the research presented in Volume I, Volume II includes an analysis of the relationship between driver vision, knowledge, psychological make-up, etc. and accident involvement. Accident involvement was found to be related to vision (particularly poor dynamic visual acuity) and personality (particularly poor personal and social adjustment). Driving task knowledge did not appear to be related to accident involvement.

Treat, J. R., Tumbus, N. S., MacDonald, S. T., Shinar, D., Hume, R. D. Mayer, R. E., Stansifer, R. L. and Castellar, N. J., "Tri-Level Study of the Causes of Traffic Accidents, Executive Summary", Indiana University Institute for Research in Public Safety , DOT-HS-805 099, May 1979.

Summary: The report provides a summary of Volume I and II (see articles #34s and #35s).

Treat, J. R., "A Study to Determine the Relationship Between Vehicle Defects and Crashes", Indiana University Institute for Research in Public Safety , DOT-HS-800 661, November 1977.

Summary: The report describes the methodology for conducting the Tri-Level Study of the Causes of Traffic Accidents (see articles # 34s and # 35s).

Tsao, H. S. J., Hall R. W., Shladover, S. E., Placher, T. A. and Levitan, L. J., "Human Factors Design of Automated Highway Systems: First Generation Scenarios", PATH, University of California, FHWA-RD-93-123, 1993.

Summary: This report provides a human factors functional analysis of AHS. Seven operational scenarios are presented which vary on the following dimensions: 1) the degree to which automated and manual traffic is separated; 2) the rules for vehicle following and spacing, and 3) the level of automation in traffic flow control. AHS human factors issues addressed are: (driving task) transition from manual to automated driving mode; normal automated driving mode - separation of vehicles, speed and speed variability, ride quality, movement between lanes; emergency response mode and transition from automated to manual driving mode; (AHS infrastructure task) diversity of vehicles on the automated highway; physical separation of automated and manual vehicles; separation among different types of automated vehicles, lane barriers and width; lane additions/reductions and merging/dividing.

Tsao, H. S., Hall, R. W., and Shladover, S. E., "Design Options for Operating Automated Highway Systems", IEEE-IEE Vehicle Navigation and Information Systems Conference, Ottawa, 0-7803-1235-X\93, 1993.

Summary: The design options for a fully automated AHS that are presented. The major dimensions of the design options are: 1) separation of traffic; 2) transitions between manual and automated driving; 3) normal automated driving; and 4) failures and emergency response. Six AHS scenarios are presented that vary according to the following attributes: 1) separation of automated traffic from manual traffic; 2) separation among automated traffic; and 3) vehicle following rule.

Tsao, H. S. and Hall, R. W., "Probabilistic Model and a Software Tool for AVCS Longitudinal Collision/Safety Analysis ", PATH Working Paper Institute of Transportation Studies , University of California, Berkeley, UCB-ITS-PWP-93-2, June 1993.

Summary: A probabilistic model is used to compare the safety consequences associated with platooning and free-agent vehicle-following rules. The assumptions of the model are:
1) two vehicles are moving on a straight lane at a common speed prior to failure
2) the failed vehicle decelerates at a constant but random rate
3) the following vehicle decelerates at a constant but random rate after a reaction delay (if it has not already collided with the failed vehicle)
4) the two rates are possibly correlated.

Input parameters are:
1) length of gap between the two vehicles,
2) common speed prior to failure
3) reaction delay of the following vehicle
4) bivariate joint distribution of the deceleration rates of the two vehicles.

Output includes probability of a collision and the probability distribution of the relative speed at collision time.

It is demonstrated that the free-agent vehicle-following rule implemented with a potential technology of fast and accurate emergency deceleration, under some reasonable conditions, can avoid collisions and allow high freeway capacity previously thought possible only under the platooning rule. The model can be used in any context where a vehicle needs to decelerate abruptly, e.g., deceleration for object in the road, or to analyze an initial collision when longitudinal vehicle control is used, e.g., autonomous intelligent cruise control.

Tsugawa, S., "Japanese IVHS Looks to 2014 and Beyond", IVHS Review, Intelligent Vehicle-Highway Society of America, p. 51-64, Summer 1993.

Summary:

Ullman, G. , " Delineation of Concrete Safety Shaped Barrier", Transportations Research Record, Vol. 1160, p. 97-1041, WNYC-3-23-6, 090125937, 1988.

Summary: The study examined the influence of 5 different delineation treatments for concrete safety shaped barriers on lane distributions and vehicle lateral distances from the barrier. Its objectives were to determine: 1) how different delineator types, spacings and mounting positions on the barrier affect nighttime traffic in the lane adjacent to the barrier; 2) driver preference and perception of the delineator treatments; 3) how visibility/brightness of delineator types deteriorate over time. The delineator types included: 1) a round acrylic cube-corner reflector; 2) a small plastic bracket covered with high intensity sheeting; and 3) a cylindrical tube covered with high intensity reflective sheeting. Top and side barrier mounting and spacing at 50 and 200 ft. were included in the study. It was found that delineation treatment had no effect on traffic operations. Side-mounted cube-corner reflectors spaced at 50 ft. were rated the brightest and most effective treatment by subjects. The cube-corner reflectors also maintained more of their original visibility over time as compared to reflective sheeting. Side-mounted delineators lost visibility faster than top-mounted delineators. Top-mounted cube-corner delineators spaced no greater than 200 ft. apart were recommended for use.

Ullman, Gerald L., Dudek, Conrad L., "Delineation of Concrete Safety Shaped Barriers", Transportation Research Record 1160, #1160, 1988.

Summary: In this paper, the results of a study of five delineation treatments for concrete safety shaped barriers are presented. These treatments were tested along a lighted urban freeway in Houston, Texas. A low-light video camera and time-lapse video recorder were mounted above each treatment to record nighttime traffic next to the barrier before and after the treatments were installed. Nighttime subjective evaluations were conducted when the treatments had been in place for several months and had become dirty. Study researchers also measured the visibility distances of the treatments at periodic intervals after delineation installation. The results showed that the treatments had little effect in lane distributions and vehicle lateral distances from the barrier. Subjects rated the side-mounted cube-corner lenses at 50-ft spacings as the brightest and most effective treatment of those studied. However, lane straddling rates may have increased slightly next to this treatment. Visibility data showed that the cube-corner lenses lost less of their original visibility over time than did reflective sheeting. Also, side-mounted delineation was found to become dirty and lose its visibility faster than top-mounted delineation. On the basis of the measurements taken, top-mounted cube-corner delineators at spacings no greater than 200 ft were recommended for delineating concrete safety shaped barriers.

Vovak, Robert J., "Diagnosis of Safety System Faults", Vehicle Electronics Meeting Society's Needs: Energy, Environment, SafetySociety of Automotive Engineers, 92C055, 1992.

Summary: Automotive electronics engineers are designing system controllers to provide more assistance in diagnosing complex safety systems. Antilock Braking Systems (ABS), Traction Control (T/C), and Passive Restraint systems are becoming more prevalent on today's vehicles. The electronic controllers for these systems often are called upon to interact with other electronic controllers on the vehicle making diagnosis of system problems more challenging for the design engineer. In addition, development, manufacturing, and service areas of the automotive industry are requesting that he design engineer provide their respective areas with more diagnostic features and capabilities. This paper will discuss the types of system faults that must be addressed with safety systems and the systems interactions encountered when addressing these faults. It will touch upon some of the benefits the electronics design engineer can provide to the development, manufacturing, and service areas. Included through the paper are future diagnostic features possible for these safety systems.

Wang, Jing-Shiarn, Knipling, Ronald R., "Single Vehicle Roadway Departure Crashes: Problem Size Assessment and Statistical Description", Department of Transportation Highway Safety Final Report, 1993.

Summary: This document presents problem size assessments and statistical crash descriptions for single vehicle roadway departure (SVRD) crashes. The SVRD crashes, associated with more fatalities than any other accident types, are a major "target crash" of high-technology Intelligent Vehicle Highway System (IVHS) crash avoidance countermeasures. Principal data sources are the 1991 General Estimates System (GES) and Fatal Accident Reporting System (FARS). SVRD crash problem size is assessed using such measures as number of crashes, number and severity of injuries, number of fatalities, crash involvement rate, and crash involvement likelihood. Problem size statistics are provided for five vehicle type categories: all vehicles, passenger vehicles (i.e., cars, light trucks, light vans), combination-unit trucks, medium/heavy single-unit trucks and motorcycles. SVRD crashes are described statistically primarily in terms of the conditions under which they occur (e.g., time of day, weather, roadway type, relation to junction) and, when data are available, in terms of possible contributing factors.

Zhang, W., "Analysis for Establishing Target Safety Levels for IVHS"..

Summary: A method for the quantitative evaluation of IVHS safety is examined. The methodology establishes a basis for setting target safety levels in the design of safety-critical IVHS components. It also provides a means of specifying safety criteria for automatic controlled vehicles (ACV) based on predefined target safety levels. An IVHS safety level is based on severity and frequency criterion. Severity criterion specifies the margin between acceptable hazards and catastrophic/critical hazards and can be determined by the costs and impacts of the accidents that may result from the hazards. Severity criterion can be determined by the number of fatalities/injuries and/or number of vehicles involved in an accident. Frequency criterion specifies the acceptable occurrence rate of catastrophic and critical hazards. A number of safety criteria are defined in the article and the quantitative influence of criteria on the target safety level of ACV and IVHS are assessed. System reliability is also evaluated.

Zhang, W., "Vehicle Health Monitoring for AVCS Malfunction Management", IEEE-IEE Vehicle Navigation and Information Systems Conference, Ottawa, 0-78-1235-X/93, 1993.

Summary:

Zhang, Wei-Bin, "Vehicle Health Monitoring for AVCS Malfunction Management", IEEE-IEE Vehicle Navigation and information Systems Conference, Ottawa-VNIS 1993, 0-7803-1235-X, 1993.

Summary: This paper discusses vehicle health monitoring as related to malfunction management. It addresses the needs and the functions for vehicle inspection, performance monitoring and failure detection/diagnosis. It identifies the safety critical functions of an AVCS and the major functional components which perform the safety critical functions using failure mode effects and criticality analysis. The requirements for a monitoring system regarding detection time, fail-safe characteristics and self-diagnosis capability for monitoring devices are examined. Potential monitoring techniques are investigated.

It is concluded that health monitoring is a vitally important function for a safety-critical system or components. A system or component cannot be identified and used as a safety critical system/component if its functions cannot be completely monitored by a health monitoring system that meets the requirement specifications provided in this paper.

, "IVHS Safety Assessment Lateral/Backing Near-Object Detection Systems Preliminary Review Draft", Office of Crash Avoidance Research National Highway Traffic Safety Administration, 1990.

Summary: This report describes and applies an analytical methodology for assessing the potential benefits of crash avoidance countermeasures. The assessment of potential benefits is essential in order to prioritize and guide federally-funded research and development on these countermeasures. The particular countermeasure concept under examination in this report is the Lateral/Backing Near-Object Detection System (L/B NODS), which is conceived as a countermeasure against lateral movement (e.g., lane change) and backing-related "encroachment" crashes.

APPENDIX B FAULT HAZARD ANALYSIS TABLES

Table 2-B1. Fault/Hazard Analysis for RSC I1C1

RSC I1C1 Assumptions:

- **AHS engage required**
- **Check-in internal to vehicle required for AHS engage**
- **Existing Highway**
- **Manual Entry/Exit (not considered part of AHS operations)**
- **Transition to AHS possible only from left lane**
- **Highway role - Advisory**
- **Automatic longitudinal and lane keeping**
- **Speed and spacing commands set by the driver**
- **Manual lane change**
- **Driver will be alerted upon detection of failure**

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
1	**Controllers**					
1.1	Brakes: Master Cylinder Breakdown Hydraulic Leak Vacuum Leak Reduced Brake Contact Friction	Check - In Lat / Long Check - Out	Exceed a preset limit for the pressure gradient between the braking systems Partial or complete loss of hydraulic braking and reduced braking capability	Vehicle will not engage AHS Partial or complete loss of controlled braking results in impaired longitudinal control, reduced headway, possible impact with the leading vehicle and traffic slowdown	3E - 2E III	Vehicle braking systems would be checked at the biannual AHS inspection Redundant braking systems should be used to minimize failure risk Driver may be responsible for corrective action (emergency brake is still available)
1.1a	Ineffective Emergency Brake (when needed)	Check - In Lat / Long Check - Out	No backup brakes Partial loss of longitudinal control, no brakes	Vehicle will not engage AHS No backup longitudinal control resulting in possible impact with the leading vehicle and traffic slowdown	4E - 1E II	Driver is responsible for corrective measures Two braking failures are assumed
1.1b	AHS Braking Actuators (stuck valve, loss of hydraulic fluid, etc.) Sensors Electronics	Check - In Lat / Long Check - Out	Partial or complete loss of AHS controlled braking	Vehicle will not engage AHS Partial or complete loss of AHS controlled braking may result in reduced headway, possible impact with the leading vehicle and traffic slowdown	2E II	Driver is responsible for corrective measures Disengage AHS and resume manual control

Table 2-B1. (continued) Fault/Hazard Analysis for RSC I1C1

No.	Component Failure	System Phase	Hazard Description: Local Effect	Hazard Description: System Effect	Risk	Remarks
1	**Controllers (cont.)**					
1.2	Steering: Reduced Hydraulic Assist Broken Mechanical Link (tie rod, ball joints, etc.)	Check - In Lat / Long Check - Out	Reduced to no steering capability Partial or total loss of vehicle lateral control	Vehicle will not engage AHS Partial or total loss of vehicle lateral control affects lane keeping ability and reduces / eliminates driver's ability to maneuver laterally and avoid obstacles. May result in collisions and a major traffic slowdown	2E - 1E IV - I	Driver is responsible for corrective measures Redundant steering systems should be employed to avoid the failures
1.2a	AHS Steering Actuators (stuck valve, loss of hydraulic fluid, etc.) Sensors Electronics	Check - In Lat / Long Check - Out	Reduced to no AHS steering Partial or total loss of AHS lane keeping control	Vehicle will not engage AHS Partial or total loss of AHS lane keeping control	2E III	Driver is responsible for corrective measures Disengage AHS and resume manual control
1.3	Throttle Wide Open Throttle (WOT) Ineffective Throttle	Check - In Lat / Long Check - Out	Inability to maintain speed / acceleration Partial loss of longitudinal control	Vehicle will not engage AHS Impairment or loss of longitudinal control may result in reduced headway and collision with the leading / trailing vehicle and traffic slowdown	3E - 2E IV - II	Driver is responsible for corrective measures Braking could augment longitudinal control
1.3a	AHS Throttle Actuators (stuck valve, loss of hydraulic fluid, etc.) Sensors Electronics	Check - In Lat / Long Check - Out	AHS throttle ranging from wide opened to closed Partial loss of AHS longitudinal control	Vehicle will not engage AHS Impairment or loss of AHS longitudinal control could result in reduced headway and impact with the leading / trailing vehicle and traffic slowdown	2E III - II	Driver is responsible for corrective measures Disengage AHS and resume manual control Braking could augment longitudinal control
2	**Drive Train**					
2.1	Engine: Timing Belt Mechanical Breakdown (hydraulic lifters, cam shaft, piston assembly, etc.)	Check - In Lat / Long Check - Out	Reduced to complete loss of engine power Impaired longitudinal control	Vehicle will not engage AHS Impairment or loss of longitudinal control could result in reduced headway and impact with the leading / trailing vehicle and traffic slowdown	4E - 2D IV - II	Driver is responsible for corrective measures Braking and steering are still available for manual control The vehicle would be able to coast

Table 2-B1. (continued) Fault/Hazard Analysis for RSC I1C1

No.	Component Failure	System Phase	Hazard Description Local Effect	System Effect	Risk	Remarks
2	**Drive Train (cont.)**					
2.2	Transmission: Mechanical Breakdown (hydraulic pumps, clutch discs, etc.)	Check - In Lat / Long Check - Out	Reduced ability to control speed, wheels may lock Possible impaired longitudinal and lateral control	Vehicle will not engage AHS Impairment or loss of vehicle control could result in reduced headway and impact with the leading / trailing / adjacent vehicle and major traffic slowdown	2E IV - II	Driver is responsible for corrective measures Braking and steering are still available for manual control A serious issue if the drive wheels lock
2.3	Drive Axle: Constant velocity joints on front drive wheels Broken Axle Mechanical Breakdown (gears, bearings, etc.)	Check - In Lat / Long Check - Out	Loss of longitudinal and / or lateral control	Vehicle will not engage AHS Impairment or loss of vehicle longitudinal and / or lateral control could result in reduced headway and impact with the leading / trailing / adjacent vehicle and major traffic slowdown	2E - 1E II - I	Driver is responsible for corrective measures Braking and steering are still available for manual control A serious issue if the drive wheels lock
3	**Suspension System**					
3.1	Shock Absorbers: Mechanical Wearout	Check - In Lat / Long Check - Out	No serious effect on steering or speed control	AHS could still be engaged	4C	Vehicle occupant discomfort for extreme maneuvers.
3.2	Springs	Check - In Lat / Long Check - Out	Reduced steering control	Vehicle will not engage AHS Impaired lateral control affects lane keeping ability and manual lateral maneuvers, possible traffic slowdown	4D IV	Driver is responsible for corrective measures Vehicle suspension would be checked at the biannual AHS inspection
3.3	Wheels: Detached	Check - In Lat / Long Check - Out	Loss of speed and steering control	Vehicle will not engage AHS Impaired lateral and longitudinal control could result in a collision and a possible major traffic slowdown	1E II - I	Driver is responsible for corrective measures Detached wheel may collide with neighboring vehicles Creation of a roadway lane obstacle

Table 2-B1. (continued) Fault/Hazard Analysis for RSC I1C1

No.	Component Failure	System Phase	Hazard Description: Local Effect	Hazard Description: System Effect	Risk	Remarks
3	**Suspension System (cont.)**					
3.4	Tires: Extreme loss of air pressure Severely out of balance Rear Blowout Front Blowout	Check - In Lat / Long Check - Out	Reduction / loss of steering, reduced speed control	Vehicle will not engage AHS Impairment or loss of lateral control and reduced longitudinal control could result in reduced headway, possible collision and a major traffic slowdown	4A - 1C IV - I	Driver is responsible for corrective measures Self - healing tires may be on the market when AHS is implemented
4	**Cooling and Lubricating**					
4.1	Cooling System: Slow to sudden loss of coolant from radiator, hoses, and water pump Water pump or drive belt breakdown	Check - In Lat / Long Check - Out	Engine overheat or seize - need to stop vehicle	Vehicle will not engage AHS Could result in reduced headway, possible collision with the trailing vehicle and a major traffic slowdown	2C - 1D IV - II	Driver is responsible for corrective measures An exit within one mile may allow time for the vehicle to exit the highway and avoid traffic problems A stalled vehicle must be removed quickly to avoid more serious problems
4.2	Heater: Slow loss of coolant from heater core, valve, hoses	Check - In Lat / Long Check - Out	Possible engine overheat	Vehicle will not engage AHS Could result in reduced headway, possible collision and a traffic slowdown	2C IV - II	Driver is responsible for corrective measures An exit within one mile may allow time for the vehicle to exit the highway and avoid traffic problems A stalled vehicle must be removed quickly to avoid more serious problems
4.2a	Heater core leak causing vapors to condense on windows Defrost Inadequate	Check - In Lat / Long Check - Out	Reduced Visibility	Vehicle may not allow AHS engage May affect manual lateral maneuvers and cause a traffic slowdown	4D - 2B III	Driver is responsible for corrective measures The AHS sensors used may be impacted by reduced visibility

Table 2-B1. (continued) Fault/Hazard Analysis for RSC I1C1

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
4	**Cooling and Lubricating (cont.)**					
4.3	Lubricating System: Very low oil level Sudden loss of oil due to damaged oil filter, pan, cooler	Check - In Lat / Long Check - Out	Engine overheat or seize - need to stop vehicle	Vehicle will not engage AHS Could result in reduced headway, possible collision with the trailing vehicle and a major traffic slowdown	3B - 1D IV - I	Driver is responsible for corrective measures An exit within one mile may allow time for the vehicle to exit the highway and avoid traffic problems A stalled vehicle must be removed quickly to avoid more serious problems
5	**Fuel / Air System**					
5.1	Fuel Pump, Filters, Tank: Fuel leakage from fuel line, gas tank, and fuel pump Broken Fuel Pump Out of Fuel	Check - In Lat / Long Check - Out	Loss of speed control to a stopped vehicle	Vehicle will not engage AHS Loss of longitudinal control could result in reduced headway, possible impact with the trailing vehicle and a traffic slowdown	4D - 2B IV - II	A fuel leak could result in a stalled vehicle A fuel capacity over 20 % is required for AHS engage A stalled vehicle must be removed quickly to avoid more serious problems
5.2	Fuel Injectors or Carburetor: Fuel or air restriction in carburetor or fuel injection system	Check - In Lat / Long Check - Out	Reduced speed control	Vehicle will not engage AHS Impaired longitudinal control could result in reduced headway, possible impact with the trailing vehicle and a traffic slowdown	3C III - II	Driver is responsible for corrective measures
5.3	Emission System: PCV or evaporative emissions control not functioning properly	Check - In Lat / Long Check - Out	Slight reduction in engine power	Negligible	4C IV - III	AHS could still be engaged

Table 2-B1. (continued) Fault/Hazard Analysis for RSC I1C1

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
6	**Electrical System**					
6.1	Loss of Ignition Power: Reduced ignition capability due to damaged spark plugs, coil wires, distributor, etc.	Check - In Lat / Long Check - Out	Partial or complete loss of speed control to a stalled vehicle	Detection would prevent AHS engage Impaired or complete loss of longitudinal control may result in reduced headway, impact with the trailing vehicle or traffic slowdown and delays	4C - 2D IV - II	Driver is responsible for corrective measures May be unable to restart vehicle Braking and steering are still available to coast to the breakdown lane if possible
6.2	Charging system: Electrical Short Circuit Gradual battery discharge from breakdown in alternator, belts, regulator, wires, etc.	Check - In Lat / Long Check - Out	Gradual loss of electric power and possible fire	Dash light would alert driver or driver may detect problem and inform system May result in eventual loss of control and could result in a major collision and traffic slowdown	2E - 2C III - I	Loss of electrical power will effect all vehicle systems A stalled vehicle must be removed quickly to avoid more serious problems
6.3	Lighting System: Broken: bulbs, wires, blown fuses	Check - In Lat / Long Check - Out	Driver's monitoring ability reduced	Dash light activates when circuit is interrupted May affect driver's ability to resume manual control	4C IV	May effect vision based guidance systems
7	**Exhaust System**					
7.1a	Muffler Falls Off	Check - In Lat / Long Check - Out	Obstacle on the roadway	Obstacle on the roadway could slow traffic flow or cause vehicle damage collision	3C III-I	Roadway operations issue
7.1b	Exhaust Gas Leakage into the Vehicle	Check - In Lat / Long Check - Out	Hazardous conditions for vehicle occupants.	Carbon monoxide sensor in vehicle gives signal to alert driver Could affect driver's control ability and monitoring function	2E III - I	Driver could be incapacitated and unable to properly control the vehicle
7.2	Turbo Wearout	Check - In Lat / Long Check - Out	Reduced engine performance	Minimal effect	4D IV	AHS engage permitted

Table 2-B1. (continued) Fault/Hazard Analysis for RSC I1C1

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
7	**Exhaust System (cont.)**					
7.3	Emissions: Restrictions in: Catalytic Converter Oxygen Sensor Air Injection EGR	Check - In Lat / Long Check - Out	Reduced engine performance	Vehicle check engine light illuminates Minimal to significant reduction in longitudinal control, possible reduced headway, traffic slowdown.	4D - 3D IV - II	Vehicle may stall at low velocities or idle speeds Loss of EGR may have more serious impacts
8	**Auxiliary Systems**					
8.1	Windshield Wipers not Functioning	Check - In Lat / Long Check - Out	Reduced visibility	Driver could inform system if vehicle diagnostics do not detect the problem Impaired visibility may affect driver's manual lateral control maneuvers and cause a traffic slowdown or possible collision	3C IV - III	Weather conditions would be a major factor Sensors mounted inside the passenger compartment may be affected
8.2	Air Conditioning Non-Functional	Check - In Lat / Long Check - Out	Occupant discomfort	None	4C	AHS engage permitted
9	**Communication**					
9.1	Loss of Power Bad / Corroded Wires Aging or inoperative electronic components Degraded performance of encoder, transmitter or receiver Faulty Ground	Check - In Lat / Long Check - Out	Degradation or loss of communication with other vehicles and / or roadway	Traffic management capability degraded or lost	II - I	Not applicable for this RSC

Table 2-B1. (continued) Fault/Hazard Analysis for RSC I1C1

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
10	**Sensors**					
10.1	Bad Wires or Connectors Mechanical Failures: Misalignment of sensors, stuck sensors, sensor electrical failure, etc. Calibration Changes Faulty Ground	Check - In Lat / Long Check - Out	Sensor performance ranging from degraded - intermittent - none	Vehicle will not engage AHS Vehicle lane keeping and longitudinal control could be affected, may result in a traffic slowdown or collision	III - II	Manual control is still available to the driver
11	**Vehicle Control Computer**					
11.1	CPU not cycling I/O not functioning or degraded Software Failure	Check - In Lat / Long Check - Out	Lane keeping and longitudinal control commands degraded, faulty, or missing	Vehicle will not engage AHS Vehicle lane keeping and longitudinal control could be affected, may result in a traffic slowdown or collision	III - II	Manual control is still available to the driver
12	**Data Link**					
12.1	Loss of Message Bits	Check - In Lat / Long Check - Out	Command and status messages received by the vehicle may be faulty	Vehicle will not engage AHS Could seriously impact traffic management	II - I	Not applicable for this RSC
13	**Roadway Control**					
13.1	Computer CPU not cycling I/O not functioning or degraded Software Failure	Check - In Lat / Long Check - Out	Partial or total loss of roadway to vehicle communications	Partial or total loss of system monitoring ability could result in major collisions and AHS shut down	I	Not applicable for this RSC

Table 2-B1. (continued) Fault/Hazard Analysis for RSC I1C1

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
13	**Roadway Control (cont.)**					
13.2	Data Link Loss of Message Bits	Check - In Lat / Long Check - Out	Command and status messages received by the vehicle may be faulty	Errors in command messages may cause improper vehicle control and impact traffic management	I	Not applicable for this RSC
13.3	Communications Loss of Power Bad / Corroded Wires Aging or inoperative electronic components Degraded performance of encoder, transmitter or receiver Faulty Ground	Check - In Lat / Long Check - Out	Degradation or loss of communication between vehicles and roadway	Traffic management capability could be degraded or lost	I	Not applicable for this RSC
13.4	Sensors Bad Wires or Connectors Mechanical Failures: Misalignment of sensors, stuck sensors, sensor electrical failure, etc. Calibration Changes Faulty Ground	Check - In Lat / Long Check - Out	Roadway sensor performance ranging from degraded - intermittent - none	Roadway lateral and longitudinal control may be impaired, incorrect or eliminated and seriously impact traffic management	I	Not applicable for this RSC
14	**Vehicle Dynamics / Characteristics**					
14.1	Variations in Acceleration, Braking Traction	Check - In Lat / Long Check - Out	Greater time / distance required for vehicles to reach cruise speed, decelerate, or maneuver laterally	Traffic slowdown and increased collision potential	3A IV	AHS engage permitted System would be limited by least common denominator

Table 2-B1. (continued) Fault/Hazard Analysis for RSC I1C1

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
15	**Road Conditions**					
15.1	Wet Snow or slush ice Sand, dirt, oil, etc.	Check - In Lat / Long Check - Out	Reduced to variations in traction	Traffic slowdown Curves and lateral maneuvers may increase collision potential, speed reduction might be required	3A - 3C IV - I	AHS engage permitted Vehicle speed and spacing may be set based on the roadway advisory
15.2	Uneven Snow Accumulation	Check - In Lat / Long Check - Out	External disturbance to vehicle's lateral and longitudinal control maneuvers	Traffic slowdown due to reduced lane keeping ability. Lane change and longitudinal control abilities may be degraded	3B III - II	AHS engage permitted Vehicle speed and spacing may be set based on the roadway advisory
15.3	Pavement Surface Irregularities (ruts, potholes, grates, puddles, etc.) Traveling over edge of roadway	Check - In Lat / Long Check - Out	External disturbance to vehicle's lateral and longitudinal control maneuvers	Temporary impairment of vehicle maneuverability resulting in traffic slowdown or possible collisions	3C IV - III	May delay AHS engage until the vehicle is stable
16	**Atmospheric**					
16.1	Light Condition: Dark Dark but lighted Dawn or dusk Glare (reflected bright sunlight, headlights)	Check - In Lat / Long Check - Out	Reduced visibility and / or glare	May require speed reduction	3A IV - III	AHS engage permitted Degree of impact is dependent on the sensors used for lane keeping and longitudinal control
16.2	Weather Rain Sleet Snow Fog Rain & Fog Sleet & Fog Other (smog, smoke, blowing dust, hail, etc.) Thunderstorm / Lightning Whiteout	Check - In Lat / Long Check - Out	Reduced visibility, traction and possible degraded sensor performance	Impairment of lane keeping longitudinal control could result in possible collisions and a major traffic slowdown	3A - 3B IV - I	AHS engage permitted unless the conditions are extreme Degree of impact is dependent on the sensors used for lane keeping and longitudinal control

Table 2-B1. (continued) Fault/Hazard Analysis for RSC I1C1

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
16	**Atmospheric (cont.)**					
16.3	Crosswind	Check - In Lat / Long Check - Out	External disturbance to vehicle's lateral motions	Intermittent disturbance to lane keeping control	3B IV - III	AHS engage permitted unless the conditions are extreme Degree of impact is dependent on the sensors used for lane keeping and longitudinal control
17	**Incidents**					
17.1	Blockage due to accident stalled vehicle on roadway Non-Motorist	Check - In Lat / Long Check - Out	Lane(s) blocked	Traffic slowdown, stoppage or possible collisions	3B - 2C III - I	AHS engage request is at the driver's discretion Roadway operations issue
17.2	Roadway Sabotage	Check - In Lat / Long Check - Out	Damage to vehicles and / or roadway	Traffic slowdown, stoppage or possible collisions	3D - 1E III - I	AHS engage request is at the driver's discretion Roadway operations issue
18	**Obstacles**					
18.1	Objects on Roadway (tires, mufflers, etc.) Objects thrown / fallen from leading vehicle Blockage due to animal(s), fallen tree(s), rock(s)	Check - In Lat / Long Check - Out	Obstacle in roadway, possible blocked traffic lane(s)	Traffic slowdown, stoppage or possible collisions	3B - 1E IV - I	AHS engage request is at the driver's discretion Roadway operations issue May be more of a factor in rural areas
19	Driver					
19.1	Improper Command Initiation / Control Commands	Check - In Lat / Long Check - Out	Inappropriate response to system requests Improper speed / headway requests and lateral inputs	Fail check - in / check -out tests Possible minor to major traffic slowdown or collisions	2C - 2D IV - I	AHS engage is not permitted Need to disengage system and bring vehicle to a controlled stop

Table 2-B1. (continued) Fault/Hazard Analysis for RSC I1C1

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
19	**Driver**					
19.2	Driver Impaired by: Drugs / Alcohol Illness, fatigue, drowsiness, etc. Distracted by passengers, instruments, etc. Slow reflexes Driver improperly responds to system requests	Check - In Lat / Long Check - Out	Driver's ability to monitor system and properly respond is degraded Vehicle lateral control maneuvers and decisions are impacted	Fail check - in / check - out tests Major collision potential, possible traffic slowdown or stoppage	3C - 2C III - I	AHS engage is not permitted Degree of impairment is a factor
19.3	Driver: Unconscious Asleep Unresponsive Unable to assume control	Check - In Lat / Long Check - Out	Driver's ability to monitor system and properly respond is lost Vehicle lateral control maneuvers and decisions are lost	Fail check - in / check - out tests Major collision potential, possible traffic slowdown or stoppage	3D - 2C II - I	AHS engage is not permitted Need to bring vehicle to a controlled stop
19.4	Deliberate Override of System	Check - In Lat / Long Check - Out	No effect	No effect	4D IV	
19.5	Non-AHS Certified Driver	Check - In Lat / Long Check - Out	Driver unfamiliar with AHS system	Vehicle will not engage AHS	3D III	

Table 2-B2. Fault/Hazard Analysis for RSC I2C1 and I3C1

RSC I2C1, I3C1

Assumptions:

General:

- **AHS engage required**
- **Vehicle check-in required for AHS engage**
- **Automated Entry / Exit**
- **Highway role - Advisory**
- **Automatic longitudinal and lane keeping (vehicle controlled)**
- **Driver / Vehicle determined speed and spacing**
- **Automated lane change**
- **Driver will be alerted upon detection of failure**
- **Break down lane included on AHS**

I2C1 :

- **Separated AHS lane(s)**
- **Transition to AHS through transition lane; Conventional freeway access / egress**

I3C1 :

- **Dedicated Highway**
- **Transition to AHS from non-AHS roads through AHS entry / exit ramps**

No.	Component Failure	System Phase	Hazard Description: Local Effect	Hazard Description: System Effect	Risk	Remarks
1	**Controllers**					
1.1	Brakes: Master Cylinder Breakdown Hydraulic Leak Vacuum Leak Reduced Brake Contact Friction	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Exceed a preset limit for pressure gradient between the redundant braking systems Fail check-in test Partial or complete loss of hydraulic braking The driver is informed Vehicle moves to the breakdown lane or off AHS	Vehicle may be unable to continue safe AHS operation Vehicle gives 'no go' signal for AHS Impaired longitudinal control may result, reduced headway, possible impact and traffic slowdown Surrounding traffic is notified	4E- 3E III	Vehicle braking systems would be checked at biannual AHS inspection The emergency brake is still available Redundant braking systems should be employed to avoid systems failure and loss of longitudinal control Non-AHS travel affected

Table 2-B2. (continued) Fault/Hazard Analysis for RSC I2C1 and I3C1

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
1	**Controllers (cont.)**					
1.1a	Ineffective Emergency Brake (when needed)	Check - In AHS Entry Lat / Long Check - Out AHS Exit	No backup brakes in addition to primary braking systems failures Fail check-in Loss of vehicle control The driver is informed Vehicle moves to the breakdown lane or off AHS	Vehicle may be unable to continue safe AHS operation Vehicle gives 'no go' signal for AHS Possible impact with the leading vehicle and major traffic slowdown Surrounding traffic is notified	4E-1E II	Total braking failure is assumed Non-AHS travel is affected
1.1b	AHS Braking Actuators (stuck valve, loss of hydraulic fluid, etc.) Sensors Electronics	Check - In AHS Entry Lat / Long Check - Out AHS Exit	AHS controlled braking failure Fail check-in Partial or complete loss of AHS controlled braking The driver is informed Vehicle moves to the breakdown lane, off AHS	Vehicle may be unable to continue safe AHS operation Vehicle gives 'no go' signal for AHS Possible impact with the leading vehicle and major traffic slowdown Surrounding traffic is notified	2E II	In i2 it may be possible to disengage AHS and assume manual control in non-AHS lanes
1.2	Steering: Reduced Hydraulic Assist Broken Mechanical Link (tie rod, ball joints, etc.)	Check - In AHS Entry Lat / Long Check - Out AHS Exit	reduced steering capability to no steering Fail check-in Reduced steering to no steering The driver is informed Vehicle moves to the breakdown lane or off AHS	vehicle may be unable to continue safe AHS operation Vehicle gives 'no go' signal for AHS reduces / eliminates ability to maneuver laterally and avoid obstacles, may affect traffic flow Surrounding traffic is notified, vehicle may be stopped	2E-1E IV-I	Lane keeping is also affected Will not affect manual traffic in an I3 configuration and may require the use of barriers between AHS and non-AHS lanes in I2 to avoid spill over effects Redundant steering systems should be used to avoid component failure

Table 2-B2. (continued) Fault/Hazard Analysis for RSC I2C1 and I3C1

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
1	**Controllers (cont.)**					
1.2a	AHS Steering Actuators (stuck valve, loss of hydraulic fluid, etc.) Sensors Electronics	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced to no AHS steering Fail check-in Non-functional AHS steering The driver is informed Vehicle moves to the breakdown lane or off AHS	Vehicle may be unable to continue safe AHS operation Vehicle gives 'no go' signal for AHS Impairment or loss of lane keeping ability Surrounding traffic is notified, vehicle may be stopped	2E III-I	In I2 it may be possible to disengage AHS and assume manual control in non-AHS lanes
1.3	Throttle Wide Open Throttle (WOT) Ineffective Throttle	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Inability to maintain speed / acceleration Fail check-in Longitudinal control is impaired The driver is informed Vehicle moves to the breakdown lane or off AHS	Vehicle may be unable to continue safe AHS operation Vehicle gives 'no go' signal for AHS Reduced headway, impact with the leading vehicle traffic slowdown & delays Surrounding traffic is notified	3E- 2E IV-II	Braking could augment longitudinal control Vehicle could be made to coast so driver could steer to breakdown lane. Redundant systems would be used
1.3a	AHS Throttle Actuators (stuck valve, loss of hydraulic fluid, etc.) Sensors Electronics	Check - In AHS Entry Lat / Long Check - Out AHS Exit	AHS throttle ranging from wide open to closed Fail check-in Impaired AHS longitudinal control The driver is informed Vehicle moves to the breakdown lane or off AHS	Vehicle may be unable to continue safe AHS operation Vehicle gives 'no go' signal for AHS Reduced headway or possible impact with the leading / trailing vehicle Surrounding traffic is notified	2E III-II	In i2 it may be possible to disengage AHS and assume manual control in non-AHS lanes Braking could augment longitudinal control

Table 2-B2. (continued) Fault/Hazard Analysis for RSC I2C1 and I3C1

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
2	**Drive Train**					
2.1	Engine: Timing Belt Mechanical Breakdown (hydraulic lifters, cam shaft, piston assembly, etc.)	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced to complete loss of engine power Fail check-in Impaired vehicle control The driver is informed Vehicle moves to the breakdown lane or stops	Vehicle may be unable to continue safe AHS operation Vehicle gives 'no go' signal for AHS Reduced headway, impact with trailing vehicle, traffic slowdown & delays Surrounding traffic is notified	4E-2D IV-II	Braking and steering still available for manual control, vehicle would be able to coast Lateral control issue if wheels lock, may need barriers in I2 configuration to avoid spill over effects Stalled vehicle must be removed quickly to avoid major delays and increased accident potential
2.2	Transmission: Mechanical Breakdown (hydraulic pumps, clutch discs, etc.)	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced ability to control speed Fail check-in Impaired vehicle control The driver is informed Vehicle moves to the breakdown lane or stops	Vehicle may be unable to continue safe AHS operation Vehicle gives 'no go' signal for AHS Possible traffic slowdown or collision Surrounding traffic is notified	2E IV-II	Braking and steering still available for manual control Stalled vehicle must be removed quickly to avoid major delays and increased accident potential Loss of lateral control might require the use of barriers for I2 configurations to avoid spill over effects
2.3	Drive Axle: Constant velocity joints on front drive wheels Broken Axle Mechanical Breakdown (gears, bearings, etc.)	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Vehicle control affected Fail check-in Loss of speed and / or steering control. The driver is informed Vehicle moves to the breakdown lane or stops	Vehicle may be unable to continue safe AHS operation Vehicle gives 'no go' signal for AHS Reduced headway, impact with trailing / adjacent vehicle could seriously impact traffic Surrounding traffic is notified	2E-1E II-I	Loss of lateral control might require the use of barriers in an I2 configuration to avoid spill over effects Braking and / or steering may still available for manual control Possibility of blocked traffic lanes, vehicle must be removed quickly

Table 2-B2. (continued) Fault/Hazard Analysis for RSC I2C1 and I3C1

No.	Component Failure	System Phase	Hazard Description: Local Effect	Hazard Description: System Effect	Risk	Remarks
3	**Suspension System**					
3.1	Shock Absorbers: Mechanical Wearout	Check - In AHS Entry Lat / Long Check - Out AHS Exit	No serious effect on steering or speed control.	No system effect, AHS could still be engaged	4C	Vehicle occupant discomfort for extreme maneuvers
3.2	Springs	Check - In	Reduced steering control	Vehicle may be unable to continue safe AHS operation	4D IV-I	Vehicle may become stable at lower velocities, it might be possible to exit the manual system rather than sit in the AHS breakdown lane
		AHS Entry	Fail check-in	Vehicle gives 'no go' signal for AHS		
		Lat / Long	Reduced steering control	Impairs lane keeping ability and lateral control, may affect traffic flow		Loss of lateral control might require the use of barriers in an i2 configuration to avoid spill over effects
		Check - Out	The driver is informed	Surrounding traffic is notified		
		AHS Exit	Vehicle moves to the breakdown lane or off AHS			
3.3	Wheels: Detached	Check - In	loss of vehicle control	Vehicle may be unable to continue safe AHS operation	1E II-I	Detached wheel may collide with neighboring vehicles
		AHS Entry		Vehicle gives 'no go' signal for AHS		Creation of roadway lane obstacle
		Lat / Long	Loss of steering and speed control	Could result in a collision and seriously impact traffic flow		
		Check - Out	The driver is informed	Surrounding traffic is notified		
		AHS Exit	vehicle moves to the breakdown lane or stops			

Table 2-B2. (continued) Fault/Hazard Analysis for RSC I2C1 and I3C1

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
3	**Suspension System (cont.)**					
3.4	Tires: Extreme loss of air pressure Severely out of balance Rear Blowout Front Blowout	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduction in vehicle control Fail check-in Reduction / loss of steering - reduced speed control The driver is informed Vehicle moves to the breakdown lane or off AHS	Vehicle may be unable to continue safe AHS operation Vehicle gives 'no go' signal for AHS Affects lane keeping ability, lateral control, and headway could result in a collision and seriously impact traffic flow Surrounding traffic is notified	4A-1C IV-I	Driver may be able to repair vehicle and continue AHS travel It be possible to exit the system if the problem is minor and an exit is reasonably close Self-healing tires are a possibility
4	**Cooling and Lubricating**					
4.1	Cooling System: Slow to sudden loss of coolant from radiator, hoses, and water pump Water pump or drive belt breakdown	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Engine overheat or seize - need to stop vehicle Fail check-in Impaired lateral / longitudinal control The driver is informed Vehicle moves to the breakdown lane or off AHS	Vehicle may be unable to continue safe AHS operation Vehicle gives 'no go' signal for AHS Could result in a major traffic slowdown or collision Surrounding traffic is notified	2C-1D III-I	An exit within one mile, may allow the vehicle to exit and avoid serious traffic problems Sufficient time may be available to remove vehicle from the system Loss of lateral control might require the use of barriers in an I2 configuration to avoid spill over effects

Table 2-B2. (continued) Fault/Hazard Analysis for RSC I2C1 and I3C1

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
4	**Cooling and Lubricating (cont.)**					
4.2	Heater: Slow loss of coolant from heater core, valve, hoses	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Possible engine overheat Fail check-in Possible engine overheat The driver is informed Vehicle moves to the breakdown lane or off AHS	Vehicle may be unable to continue safe AHS operation Vehicle gives 'no go' signal for AHS Possible traffic slowdown and/or collision Surrounding traffic is notified	2C IV-II	Sufficient time may be available to remove vehicle from the system
4.2a	Heater core leak causing vapors to condense on windows Defrost Inadequate	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced visibility	Severity may be insufficient to prevent AHS access Impaired visibility may affect lateral maneuvers and cause traffic slowdown	4D-2B III	Sensors may be affected by reduced visibility (technology dependent)
4.3	Lubricating System: Very low oil level Sudden loss of oil due to damaged oil filter, pan, cooler	Check - In AHS Entry Lat / Long Check - Out AHS Exit	engine overheat or seize - need to stop vehicle Fail check-in Impaired vehicle longitudinal / lateral control The driver is informed Vehicle moves to the breakdown lane or off AHS	Vehicle may be unable to continue safe AHS operation Vehicle gives 'no go' signal for AHS Could result in a major traffic slowdown or impact with the trailing vehicle Surrounding traffic is notified	3B-1D IV-I	Sufficient time may be available to remove vehicle from the system Loss of lateral control might require the use of barriers in an I2 configuration to avoid spill over effects An exit within one mile, may allow the vehicle to exit and avoid serious traffic problems

Table 2-B2. (continued) Fault/Hazard Analysis for RSC I2C1 and I3C1

No.	Component Failure	System Phase	Hazard Description: Local Effect	Hazard Description: System Effect	Risk	Remarks
5	**Fuel / Air System**					
5.1	Fuel Pump, Filters, Tank: Fuel leakage from fuel line, gas tank, and fuel pump Broken Fuel Pump Out of Fuel	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Speed control degradation to stalled vehicle Fail check-in Loss of speed control to stopped vehicle The driver is informed Vehicle moves to the breakdown lane or off AHS	Vehicle may be unable to continue safe AHS operation Vehicle gives 'no go' signal for AHS Reduced headway or possible impact with the trailing vehicle and traffic delays Surrounding traffic is notified	4D - 2B IV-III	Fuel leak could cause gradual depletion and result in a stalled vehicle. Vehicles need >20% fuel capacity for AHS access Braking and steering still available for manual control Effects may be less severe if sufficient time is available to remove vehicle from the system
5.2	Fuel Injectors or Carburetor: Fuel or air restriction in carburetor or fuel injection system	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced speed control Fail check-in Reduced speed control The driver is informed Vehicle moves to the breakdown lane or off AHS	vehicle may be unable to continue safe AHS operation Vehicle gives 'no go' signal for AHS Impaired longitudinal control resulting in a possible major traffic slowdown Surrounding traffic is notified	3C IV-III	Braking and steering still available for manual control
5.3	Emission System: PCV or evaporative emissions control not functioning properly	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Slight reduction in engine power	Negligible	4C IV-III	AHS could still be engaged

Table 2-B2. (continued) Fault/Hazard Analysis for RSC I2C1 and I3C1

No.	Component Failure	System Phase	Hazard Description: Local Effect	Hazard Description: System Effect	Risk	Remarks
6	**Electrical System**					
6.1	Loss of Ignition Power: Reduced ignition capability due to damaged spark plugs, coil wires, distributor, etc.	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Loss of speed control or stalled vehicle Fail check-in Partial or complete loss of speed control to stalled vehicle The driver is informed Vehicle moves to the breakdown lane or off AHS	Vehicle may be unable to continue safe AHS operation Vehicle gives 'no go' signal for AHS Reduced headway, impact with trailing vehicle or traffic slowdown & delays Surrounding traffic is notified	4C - 2D IV-II	Manual braking and steering still available for manual control Driver may be unable to restart vehicle
6.2	Charging system: Electrical Short Circuit Gradual battery discharge from breakdown in alternator, belts, regulator, wires, etc.	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Gradual loss of electrical power possible fire Possible loss of vehicle control	Could have dash warning light, vehicle would inform surrounding traffic of problem May result in eventual loss of control and could result in major collision and serious impact on traffic flow	2E-2C III-I	Loss of electrical power will affect all the vehicle AHS systems Sufficient time may be available to remove vehicle from the system Loss of lateral control might require the use of barriers in an i2 configuration to avoid spill over effects
6.3	Lighting System: Broken: bulbs, wires, blown fuses	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Driver's monitoring ability reduced	Light would alert driver when circuit is broken May affect ability to resume manual control	4C IV	Might impact vision based systems
7	**Exhaust System**					
7.1a	Muffler Falls Off	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Obstacle on the roadway	Obstacle on the roadway could slow traffic flow or cause vehicle damage / collision	3C IV-II	Roadway operations issue
7.1b	Exhaust Gas Leakage into the Vehicle	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Hazardous conditions for vehicle occupants	Carbon monoxide sensor would alert driver Could affect driver's lane change decisions and monitoring function	2E III-I	Driver could be incapacitated and unable to resume manual control when needed

Table 2-B2. (continued) Fault/Hazard Analysis for RSC I2C1 and I3C1

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
7	**Exhaust System (cont.)**					
7.2	Turbo Wearout	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced engine performance.	Minimal effect	4D IV	AHS access permitted.
7.3	Emissions: Restrictions in: Catalytic Converter Oxygen Sensor Air Injection EGR	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced engine performance.	Check engine light would come on Minimal to significant reduction in longitudinal control	4D- 3D IV-II	AHS access permitted except for EGR which may have more than a minimal effect, vehicle speed may be a factor Vehicle may stall at low velocities or at idle speeds
8	**Auxiliary Systems**					
8.1	Windshield Wipers not Functioning	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced visibility	Driver could inform system if vehicle doesn't detect problem Impaired visibility may affect vehicle control and cause a traffic slowdown	3C IV-III	Weather conditions would be a factor sensors mounted inside passenger compartment may be affected
8.2	Air Conditioning Non-Functional	Check - In AHS Entry Lat / Long Check - Out AHS Exit	vehicle occupant discomfort	none	4C	AHS access permitted vehicle may need to exit from system quickly

Table 2-B2. (continued) Fault/Hazard Analysis for RSC I2C1 and I3C1

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
9	**Communication**					
9.1	Loss of Power Bad / Corroded Wires Aging or inoperative electronic components Degraded performance of encoder, transmitter or receiver Faulty Ground	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Degradation or loss of communication with other vehicles and / or roadway	Traffic management capability could be degraded or lost Possible out of control vehicle may cause serious traffic impacts	II-I	Vehicle speed and spacing may be adversely affected Initial detection would prevent AHS access. On line loss might pose more serious problems
10	**Sensors**					
10.1	Bad Wires or Connectors Mechanical Failures: Misalignment of sensors, stuck sensors, sensor electrical failure, etc. Calibration Changes Faulty Ground	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Sensor performance ranging from degraded to none or intermittent	Vehicle gives 'no go' signal for AHS Vehicle lane keeping and longitudinal control affected, may result in major traffic slowdown	III-II	Initial detection would prevent AHS access. On line loss might pose more serious problems
11	**Vehicle Control Computer**					
11.1	CPU not cycling I/O not functioning or degraded Software Failure	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Longitudinal and lane keeping control commands degraded, faulty or missing	Vehicle gives 'no go' signal for AHS Reduced or loss of AHS control could result in major collision and seriously impact traffic flow	III-I	Initial detection would prevent AHS access. On line loss might pose more serious problems

Table 2-B2. (continued) Fault/Hazard Analysis for RSC I2C1 and I3C1

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
12	**Data Link**					
12.1	Loss of Message Bits	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Command and status messages received by the vehicle may be faulty	Errors in command messages may cause improper vehicle control and could severely impact traffic management	II-I	Loss of data link could have a severe impact. Initial detection would prevent AHS access. On line loss might pose more serious problems
13	**Roadway Control**					
13.1	Computer CPU not cycling I/O not functioning or degraded Software Failure	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Partial or total loss of communications between roadway & vehicle	Loss of roadway advisory could result in a major collision and seriously impact traffic flow	I	AHS may need to be shutdown Manual control still available Vehicle to vehicle communication may be available for vehicle based traffic management
13.2	Data Link Loss of Message Bits	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Command and status messages received by the vehicle may be faulty	Loss of roadway advisory could result in a major collision and seriously impact traffic flow	I	AHS may need to be shutdown Manual control still available Vehicle to vehicle communication may be available for vehicle based traffic management
13.3	Communications Loss of Power Bad / Corroded Wires Aging or inoperative electronic components Degraded performance of encoder, transmitter or receiver Faulty Ground	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Degradation or loss of communication between vehicles and roadway	Loss of roadway advisory could result in a major collision and seriously impact traffic flow	I	AHS may need to be shutdown Manual control still available Vehicle to vehicle communication may be available for vehicle based traffic management

Table 2-B2. (continued) Fault/Hazard Analysis for RSC I2C1 and I3C1

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
13.4	Sensors Bad Wires or Connectors Mechanical Failures: Misalignment of sensors, stuck sensors, sensor electrical failure, etc. Calibration Changes Faulty Ground	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Sensor performance ranging from degraded to none or intermittent	Loss of roadway advisory could result in a major collision and seriously impact traffic flow	I	AHS may need to be shutdown Manual control still available Vehicle to vehicle communication may be available for vehicle based traffic management
14	**Vehicle Dynamics / Characteristics**					
14.1	Variations in Acceleration, Braking Traction	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Greater time / distance required for vehicles to reach cruise speed or stop	Traffic slowdown or increased collision potential	3A IV	AHS access permitted System will be limited by least common denominator
15	**Road Conditions**					
15.1	Wet Snow or slush ice Sand, dirt, oil, etc.	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced traction or variations in traction	Traffic slowdown, curves & lateral maneuvers may increase collision potential, speed reduction may be required	3A-3C IV-II	AHS access permitted Vehicle speed & spacing may be based on roadway advisory
15.2	Uneven Snow Accumulation	Check - In AHS Entry Lat / Long Check - Out AHS Exit	External disturbance to vehicle's lateral maneuvers	Traffic slowdown due to reduced lane keeping capability, lane changing ability and degraded longitudinal control	3B III-II	AHS access permitted Vehicle speed & spacing may be based on roadway advisory
15.3	Pavement Surface Irregularities (ruts, potholes, grates, puddles, etc.) Traveling over edge of roadway	Check - In AHS Entry Lat / Long Check - Out AHS Exit	External disturbance to vehicle's lateral & longitudinal maneuvers	Temporary impairment of maneuvering capability resulting in possible traffic slowdown or impact	3C IV-III	Delay AHS access until vehicle is stable - I2 I3 configuration might need to be shut down if the roadway surface becomes unsafe to vehicle and its occupants

Table 2-B2. (continued) Fault/Hazard Analysis for RSC I2C1 and I3C1

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
16	**Atmospheric**					
16.1	Light Condition: Dark Dark but lighted Dawn or dusk Glare (reflected bright sunlight, headlights)	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced visibility and / or glare	May require speed reduction	3A IV-III	AHS access permitted Impact dependent on sensors used for longitudinal and lane keeping control
16.2	Weather Rain Sleet Snow Fog Rain & Fog Sleet & Fog Other (smog, smoke, blowing dust, hail, etc.) Thunderstorm / Lightning Whiteout	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced visibility, traction and possible degraded sensor performance	Possible reduction in longitudinal & lane keeping control, may result in traffic slowdown and increased collision potential	3A- 3B IV-II	AHS access permitted unless conditions are extreme Impact dependent on sensors used for longitudinal and lane keeping control
16.3	Crosswind	Check - In AHS Entry Lat / Long Check - Out AHS Exit	External disturbance to vehicle's lateral motion	Intermittent disturbance to lane keeping control	3B IV-III	AHS access permitted unless conditions are extreme Impact dependent on sensors used for longitudinal and lane keeping control
17	**Incidents**					
17.1	Blockage due to accident stalled vehicle on roadway Non-Motorist	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Lane(s) blocked	Traffic slowdown or stoppage and possible vehicle collision	3B- 2C III-I	AHS access request at driver's discretion Roadway operations issue
17.2	Roadway Sabotage	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Damage to vehicles, roadway, sensors, etc.	Traffic slowdown / stoppage or possible vehicle and / or system damage / collision	3D- 1E III-I	AHS access request at driver's discretion Roadway operations issue

Table 2-B2. (continued) Fault/Hazard Analysis for RSC I2C1 and I3C1

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
18	**Obstacles**					
18.1	Objects on Roadway (tires, mufflers, etc.) Objects thrown / fallen from leading vehicle Blockage due to animal(s), fallen tree(s), rock(s)	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Obstacle in roadway possible lane blockage	Possible traffic slowdown / stoppage, vehicle damage or collision	3B- 1E IV-I	AHS access request at driver's discretion Roadway operations issue - may be more or a factor in rural areas
19	**Driver**					
19.1	Improper Command Initiation / Control Commands	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Inappropriate response to system requests Vehicle lateral and longitudinal control could be impacted Inappropriate response to system requests	Fail check - in tests Possible minor to major traffic slowdown & delay or collision Fail check - out tests	2C- 2D IV-I	AHS access is not permitted Poses serious problems since driver is partly responsible for lane change decisions
19.2	Driver Impaired by: Drugs / Alcohol Illness, fatigue, drowsiness, etc. Distracted by passengers, instruments, etc. Slow reflexes Driver improperly responds to system requests	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Driver ability to monitor system & respond degraded Driver ability to initiate commands, respond to system, and assume manual control degraded Driver ability to monitor system & respond degraded	Fail check - in tests Possible minor to major traffic slowdown & delay or collision Fail check - out tests	2C- 3C III-I	AHS access is not permitted Degree of impairment is a factor Manual control of vehicle and lane change decisions on the AHS may be affected
19.3	Driver: Unconscious Asleep Unresponsive Unable to assume control	Check - In AHS Entry Lat / Long Check - Out AHS Exit	No response Driver is unable to interact with system or resume manual control	Fail check-in test Major collision potential, traffic slowdown/stoppage Fail check-out test	2C- 3D II-I	AHS access denied Need to bring the vehicle to a controlled stop and try to wake the driver
19.4	Deliberate Override of System	Check - In AHS Entry Lat / Long Check - Out AHS Exit	No effect	Vehicle to vehicle communication may reduce adverse impacts if traffic can adjust to situation	4D IV	

Table 2-B2. (continued) Fault/Hazard Analysis for RSC I2C1 and I3C1

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
19	**Driver (cont'd.)**					
19.5	Non-AHS Certified Driver	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Driver unfamiliar with AHS system	Detection should prevent AHS access	3D III	

Table 2-B3. Fault/Hazard Analysis for RSC I2C2 and I3C2

RSC I2C2, I3C2

Assumptions:

General:

- **AHS engage required**
- **Vehicle check-in required for AHS engage**
- **Automated Entry/Exit**
- **Highway role -Commands speed and spacing**
- **Automated longitudinal and lane keeping (vehicle controlled)**
- **Roadway determined speed and spacing**
- **Automated lane change**
- **Driver has monitor role - will be alerted upon detection of failure**
- **Break down lane included on AHS**

I2C2 :

- **Separated AHS lane(s)**
- **Transition to AHS through transition lane; Conventional freeway access / egress**

I3C3 :

- **Dedicated Highway**
- **Transition to AHS from non-AHS roadways through AHS entrance ramps**

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
1	**Controllers**					
1.1	Brakes: Master Cylinder Breakdown Hydraulic Leak Vacuum Leak Reduced Brake Contact Friction	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Large pressure difference between braking systems Fails check-in test Partial or complete loss of braking capability AHS inspection invalid Vehicle moves to breakdown lane	Possible vehicle braking system failure Vehicle gives 'no go' signal for AHS Possible impact with the leading vehicle, traffic slowdown Traffic informed of problem and adjusted Vehicle may suggest driver stop	3E- 2E III	Vehicle brake systems are checked at the biannual AHS inspection, redundant systems should be employed to avoid this Emergency brake may still be available Unsafe vehicle may be prevented from AHS and non-AHS travel Severity of problem on AHS lanes reduced since braking is not required as often as in manual traffic

Table 2-B3. (continued) Fault/Hazard Analysis for RSC I2C2 and I3C2

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
1	**Controllers (cont.)**					
1.1a	Ineffective Emergency Brake (when needed)	Check - In AHS Entry Lat / Long Check - Out AHS Exit	No backup brakes in addition to primary braking systems failure Failed check-in test Loss of vehicle control AHS inspection invalid Vehicle moves to breakdown lane	No control of vehicle Vehicle gives 'no go' signal for AHS No backup longitudinal control resulting in a possible impact with the leading vehicle and major traffic slowdown possibility Traffic informed of problem and adjusted Crew dispatched to remove vehicle from AHS	4E- 1E II	AHS and non-AHS travel are affected vehicle system may suggest that the driver should stop
1.1b	AHS Braking Actuators (stuck valve, loss of hydraulic fluid, etc.) Sensors Electronics	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Partial or complete loss of AHS controlled braking Fails check-in test Partial or complete loss of AHS controlled braking Manual braking available, AHS inspection invalid Vehicle moves to break-down lane or off of AHS	Impairment of AHS longitudinal control Vehicle gives 'no go' signal for AHS Possible impact with the leading vehicle and major traffic slowdown traffic informed of problem and adjusted to required vehicle response	2E III	Travel on non-AHS roadways unaffected Manual control on non-AHS roads still possible
1.2	Steering: Reduced Hydraulic Assist Broken Mechanical Link (tie rod, ball joints, etc.)	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced steering capability to no steering Failed vehicle check-in test Reduced steering to no steering and partial or total loss of vehicle control AHS inspection invalid Vehicle would stop or move to break down lane if possible	Out of control vehicle could result Vehicle gives 'no go' signal for AHS Lateral control is reduced/ eliminated vehicle ability to maneuver affected, may affect traffic flow, possible collision Traffic informed of problem and adjusted for vehicle response	2E- 1E II-I	Redundant systems should be employed for lateral control This is a serious issue for AHS since lane keeping and longitudinal control could be lost. I2 configurations might require barriers to avoid spill over effects into manual traffic Stopped vehicle blocking lane must be removed - response time is critical

Table 2-B3. (continued) Fault/Hazard Analysis for RSC I2C2 and I3C2

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
1	**Controllers (cont.)**					
1.2a	AHS Steering Actuators (stuck valve, loss of hydraulic fluid, etc.) Sensors Electronics	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced to no AHS steering Fails check-in test Non-functional AHS steering AHS inspection invalid Vehicle could stop or move to the breakdown lane	Detection of AHS steering failure would prevent AHS engage Vehicle gives 'no go' signal for AHS Impairment or loss of lane keeping ability, possible collision and traffic slowdown Traffic informed of problem and adjusted for vehicle response	2E III	Non-AHS travel is permitted unless manual actuators are affected Manual control of vehicle is possible A serious issue since lane keeping and longitudinal control could be lost. I2 configurations might require barriers to avoid spill over effects into manual traffic
1.3	Throttle Wide Open Throttle (WOT) Ineffective Throttle	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Inability to maintain speed / acceleration Failed vehicle check-in test Inability to maintain speed / acceleration AHS inspection invalid Vehicle moves to breakdown lane	Possible hazard - loss of vehicle control Vehicle gives 'no go' signal for AHS Reduced headway or impact with the leading vehicle possible traffic slowdown & delays Traffic informed of problem and adjusted	3E- 2E IV-III	For WOT, vehicle engine might be turned off to allow vehicle to coast to the breakdown lane Condition may affect further non-AHS travel Braking could augment longitudinal control
1.3a	AHS Throttle Actuators (stuck valve, loss of hydraulic fluid, etc.) Sensors Electronics	Check - In AHS Entry Lat / Long Check - Out AHS Exit	AHS throttle ranging from wide open to closed Vehicle fails check-in test AHS throttle ranging from wide open to closed AHS inspection invalid, manual throttle may be available Manual throttle control might be assumed to remove vehicle from AHS	No AHS longitudinal control Vehicle gives 'no go' signal for AHS Reduced headway or possible impact with the leading / trailing vehicle, traffic slowdown Braking available for backup longitudinal control Traffic informed of problem and adjusted	2E III-II	Manual control of vehicle is unaffected Braking could augment longitudinal control if primary systems affected Engine might be turned off so vehicle could coast in the event of WOT

Table 2-B3. (continued) Fault/Hazard Analysis for RSC I2C2 and I3C2

No.	Component Failure	System Phase	Hazard Description Local Effect	System Effect	Risk	Remarks
2	**Drive Train**					
2.1	Engine: Timing Belt Mechanical Breakdown (hydraulic lifters, cam shaft, piston assembly, etc.)	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced to complete loss of engine power Vehicle fails check-in test Impaired vehicle control AHS inspection invalid Vehicle directed to the breakdown lane	Possible disabled vehicle Vehicle gives 'no go' signal for AHS Reduced headway, impact with trailing vehicle or traffic slowdown & delays Traffic informed of problem and adjusted	4E-2D IV-II	Braking and steering still available, vehicle would be able to coast A minor problem may allow time for the vehicle to exit AHS and avoid traffic problems Possible loss of lateral control might require the use of barriers for the I2 configuration
2.2	Transmission: Mechanical Breakdown (hydraulic pumps, clutch discs, etc.)	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced ability to control speed Vehicle fails check-in test Impaired vehicle control AHS inspection invalid Vehicle directed to the breakdown lane	Possible stooped vehicle Vehicle gives 'no go' signal for AHS Reduced headway, impact with trailing vehicle or traffic slowdown & delays Traffic informed of problem and adjusted	2E IV-II	Braking and steering still available for manual control Vehicle may be able to exit AHS if a minor problem occurs Possible loss of lateral control might require the use of barriers for the I2 configuration
2.3	Drive Axle: Constant velocity joints on front drive wheels Broken Axle Mechanical Breakdown (gears, bearings, etc.)	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Loss of speed and / or steering control Vehicle fails check-in test Loss of vehicle control AHS inspection invalid Vehicle directed to the breakdown lane	Possible disabled vehicle Vehicle gives 'no go' signal for AHS Reduced headway, impact with trailing / adjacent vehicle and traffic slowdowns Traffic informed of problem and adjusted	2E-1E II-I	Braking and / or steering may still available The vehicle must be removed quickly to avoid further traffic ramifications Since vehicle lateral control may be impacted, I2 configurations may need barriers to avoid spill over effects into manual traffic

Table 2-B3. (continued) Fault/Hazard Analysis for RSC I2C2 and I3C2

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
3	**Suspension System**					
3.1	Shock Absorbers: Mechanical Wearout	Check - In AHS Entry Lat / Long Check - Out AHS Exit	No serious effect on steering or speed control	No system effect, AHS could still be engaged	4C	Vehicle occupant discomfort for extreme maneuvers
3.2	Springs	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced steering control vehicle fails check-in test Lateral control impaired AHS inspection invalid Vehicle may slow and move to breakdown lane	Possible vehicle loss of control Vehicle gives 'no go' signal for AHS Impaired lane keeping ability and lateral control may affect traffic flow, possible collision Traffic informed of problem and adjusted	4D IV	Vehicle may be safe at low speeds so driver can get to AHS exit Since vehicle lateral control may be impacted, I2 configurations may need barriers to avoid spill over effects into manual traffic
3.3	Wheels: Detached	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Loss of steering and speed control Fail check-in test Loss of steering and speed control AHS inspection invalid Vehicle may be directed to the breakdown lane	Loss of vehicle control Vehicle gives 'no go' signal for AHS Could result in a collision and seriously impact traffic flow Traffic informed of problem and adjusted	1E II-I	Detached wheel may collide with neighboring vehicles Creation of roadway lane obstacle which system might direct traffic around Tow vehicle / clean up crew response may affect severity of consequences

Table 2-B3. (continued) Fault/Hazard Analysis for RSC I2C2 and I3C2

No.	Component Failure	System Phase	Hazard Description: Local Effect	Hazard Description: System Effect	Risk	Remarks
3	**Suspension System (cont.)**					
3.4	Tires: Extreme loss of air pressure Severely out of balance Rear Blowout Front Blowout	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduction / loss of steering - reduced speed control Vehicle fails check-in test Reduction / loss of steering - reduced speed control Vehicle would move to break down lane	Possible loss of vehicle control Vehicle gives 'no go' signal for AHS Affects vehicle dynamics, could result in a collision and seriously impact traffic Traffic informed of problem and adjusted	4A-1C IV-I	Vehicle may be able to assume AHS travel if repairs can be made Self-healing tires may be possible
4	**Cooling and Lubricating**					
4.1	Cooling System: Slow to sudden loss of coolant from radiator, hoses, and water pump Water pump or drive belt breakdown	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Engine overheat or seize - need to stop vehicle Fails check-in test Vehicle control impaired AHS inspection invalid Vehicle may move to breakdown lane or stop	Possible stopped vehicle Vehicle gives 'no go' signal for AHS Could result in major traffic slowdown or impact with the trailing vehicle Traffic informed of problem and adjusted Exit within one mile is needed for vehicle to exit AHS	2C-1D III-I	Sufficient time may be available to remove vehicle from highway
4.2	Heater: Slow loss of coolant from heater core, valve, hoses	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Possible engine overheat Vehicle fails check-in test Possible engine overheat AHS inspection invalid Vehicle moves to breakdown lane or stops	Possible vehicle failure Vehicle gives 'no go' signal for AHS Possible traffic slowdown and/or collision Traffic informed of problem and adjusted if necessary	2C IV-III	Initial detection would prevent AHS access Sufficient time may be available to remove vehicle from highway A minor problem may allow time for the vehicle to exit and avoid adverse traffic impacts

Table 2-B3. (continued) Fault/Hazard Analysis for RSC I2C2 and I3C2

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
4	**Cooling and Lubricating (cont.)**					
4.2a	Heater core leak causing vapors to condense on windows Defrost Inadequate	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced visibility	Severity may be insufficient to prevent AHS engage Minimal to none, possible slowdown Driver may have reduced visibility for manual transition	4D-2B III	Initial detection would prevent AHS access Sensors may be affected by reduced visibility (technology dependent)
4.3	Lubricating System: Very low oil level Sudden loss of oil due to damaged oil filter, pan, cooler	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Engine overheat or seize - need to stop vehicle Fails check-in test Possible loss of vehicle control AHS inspection may become invalid Vehicle moves to breakdown lane or stops	Possible vehicle break down Vehicle gives 'no go' signal for AHS Could result in major traffic slowdown or impact with the trailing / adjacent vehicle Traffic informed of problem and adjusted	3B-1D IV-I	Initial detection would prevent AHS access Sufficient time may be available to remove vehicle from highway Since vehicle lateral control may be impacted, i2 configurations may need barriers to avoid spill over effects into manual traffic
5	**Fuel / Air System**					
5.1	Fuel Pump, Filters, Tank: Fuel leakage from fuel line, gas tank, and fuel pump Broken Fuel Pump Out of Fuel	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Loss of speed control to stopped vehicle Fails vehicle check-in test Loss of speed control to stopped vehicle AHS inspection may become invalid Vehicle moves to breakdown lane or stops	Possible stalled vehicle Vehicle gives 'no go' signal for AHS Reduced headway or possible impact with the trailing vehicle, traffic slowdown Surrounding traffic notified and adjusted	4D - 2B IV-III	Fuel leak could cause gradual depletion and result in a stalled vehicle. Braking and steering still available for manual control Effects may be less severe if vehicle can be removed from highway quickly 20% fuel tank capacity needed for AHS access

Table 2-B3. (continued) Fault/Hazard Analysis for RSC I2C2 and I3C2

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
5	**Fuel / Air System (cont.)**					
5.2	Fuel Injectors or Carburetor: Fuel or air restriction in carburetor or fuel injection system	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced speed control Fails check-in test Impaired longitudinal control AHS inspection invalid Vehicle moves to breakdown lane or stops	Possibility of stalled vehicle Vehicle gives 'no go' signal for AHS A possible major traffic slowdown Surrounding traffic notified and adjusted	3C IV-III	Initial detection would prevent AHS access Braking and steering still available for manual control
5.3	Emission System: PCV or evaporative emissions control not functioning properly	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Slight reduction in engine power Vehicle may stall at idle speeds Vehicle may stall at idle speeds Possibility of stalled vehicle	Negligible May slow traffic entering AHS May slow exiting AHS traffic	4C IV-III	AHS could still be engaged
6	**Electrical System**					
6.1	Loss of Ignition Power: Reduced ignition capability due to damaged spark plugs, coil wires, distributor, etc.	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Partial or complete loss of speed control Fails check-in test Partial or complete loss of speed control to stalled vehicle AHS inspection invalid Vehicle moves to breakdown lane or stops	Possible stalled vehicle Vehicle gives 'no go' signal for AHS May result in reduced headway, impact with trailing vehicle or traffic slowdown & delays Surrounding traffic notified and adjusted	4C - 2D IV-III	Initial detection would prevent AHS engage Manual braking and steering still available for manual control Driver may be unable to restart vehicle Tow vehicle response time crucial

Table 2-B3. (continued) Fault/Hazard Analysis for RSC I2C2 and I3C2

No.	Component Failure	System Phase	Hazard Description: Local Effect	Hazard Description: System Effect	Risk	Remarks
6	**Electrical System (cont.)**					
6.2	Charging system: Electrical Short Circuit Gradual battery discharge from breakdown in alternator, belts, regulator, wires, etc.	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Gradual loss of electrical power possible fire Fails check-in test Vehicle control impaired AHS inspection invalid Vehicle moves to breakdown lane or stops	Possible stalled vehicle Vehicle gives 'no go' signal for AHS May result in eventual loss of control and could result in major collision and traffic slowdown Surrounding traffic notified and adjusted	2E-2C III-I	Initial detection would prevent AHS engage Loss of electrical power will affect all the vehicle AHS systems such as controllers, communication, etc. Sufficient time may be available to remove the vehicle from the highway.
6.3	Lighting System: Broken: bulbs, wires, blown fuses	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Driver's monitoring ability reduced Driver's monitoring ability reduced AHS inspection invalid Driver visibility may be affected	Dash light would inform driver May effect driver's ability to resume manual control	4C IV	Initial detection might prevent AHS engage Driver may need to stop the vehicle and make repairs May affect non-AHS travel
7	**Exhaust System**					
7.1a	Muffler Falls Off	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Obstacle on the roadway	Obstacle on the roadway could slow traffic flow or cause vehicle damage / collision Based on driver decision, system may direct vehicle traffic around object.	3C IV-II	Initial detection would prevent AHS engage Roadway operations issue Roadway clean up response may reduce adverse system effects

Table 2-B3. (continued) Fault/Hazard Analysis for RSC I2C2 and I3C2

No.	Component Failure	System Phase	Hazard Description: Local Effect	Hazard Description: System Effect	Risk	Remarks
7	**Exhaust System (cont.)**					
7.1b	Exhaust Gas Leakage into the Vehicle	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Hazardous conditions for vehicle occupants. Driver may be incapacitated Driver may be unable to resume manual control	Vehicle carbon monoxide sensor would alert driver, may lower windows Could affect driver's lane change decision ability and monitoring function. Vehicle may stop so the driver can be treated	2E III-I	Initial detection would prevent AHS engage and warn the vehicle occupants Non-AHS travel would be affected May require emergency team response. Traffic informed of problem and adjusted to situation if driver is incapacitated
7.2	Turbo Wearout	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced engine performance	Minimal effect	4D IV	AHS engage permitted.
7.3	Emissions: Restrictions in: Catalytic Converter Oxygen Sensor Air Injection EGR	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced engine performance Vehicle may stall at low/ idle speeds Reduced engine performance AHS inspection may be invalid	Check engine light would alert driver AHS entry may be delayed by stalled vehicle Minimal to significant reduction in longitudinal control AHS exit may be delayed	4D- 3D IV-II	AHS engage permitted except for EGR which may have more than a minimal effect (vehicle speed may be a factor) Vehicle may stall at low velocities or at idle speeds
8	**Auxiliary Systems**					
8.1	Windshield Wipers not Functioning	Check - In AHS Entry Lat / Long Check - Out AHS Exit	AHS inspection may be invalid Poor visibility may effect manual travel	Driver could inform vehicle systems if vehicle incapable of detection	3C IV-III	Initial detection would prevent AHS engage Weather conditions would be a factor sensors mounted inside passenger compartment may be affected Driver may need to stop and make repairs before safe travel can be resumed

Table 2-B3. (continued) Fault/Hazard Analysis for RSC I2C2 and I3C2

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
8	**Auxiliary Systems (cont.)**					
8.2	Air Conditioning Non-Functional	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Vehicle occupant discomfort	None	4C	AHS engage permitted vehicle may need to exit from system quickly
9	**Communication**					
9.1	Loss of Power Bad / Corroded Wires Aging or inoperative electronic components Degraded performance of encoder, transmitter or receiver Faulty Ground	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Degradation or loss of communication with other vehicles and / or roadway Fails vehicle check-in test Driver may have to assume manual control AHS inspection invalid Driver moves the vehicle to breakdown lane or off AHS	Unresponsive vehicle seen as "intruder" and traffic adjusted accordingly to prevent major incidents. Vehicle gives 'no go' signal for AHS Surrounding traffic notified, adjusted	II-I	Initial detection would prevent AHS engage Driver may need to resume manual control if the vehicle is unresponsive to the system commands
10	**Sensors**					
10.1	Bad Wires or Connectors Mechanical Failures: Misalignment of sensors, stuck sensors, sensor electrical failure, etc. Calibration Changes Faulty Ground	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Sensor performance ranging from degraded to none or intermittent Fails vehicle check-in test Vehicle AHS inspection invalid Driver moves the vehicle to breakdown lane or off AHS	Manual control still available, system evokes "intruder" response Vehicle gives 'no go' signal for AHS Vehicle lane keeping and longitudinal control affected, may result in major traffic slowdown Traffic informed of problem and adjusted	III-II	Initial detection would prevent AHS engage Driver may need to resume manual control if the vehicle is unresponsive to the system commands

Table 2-B3. (continued) Fault/Hazard Analysis for RSC I2C2 and I3C2

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
11	**Vehicle Control Computer**					
11.1	CPU not cycling I/O not functioning or degraded Software Failure	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Longitudinal and lane keeping control commands degraded, faulty or missing AHS inspection invalid Driver moves the vehicle to breakdown lane or off AHS	Possible uncontrolled vehicle, "intruder" response evoked Vehicle gives 'no go' signal for AHS Reduced or loss of AHS control could result in major collision and seriously impact traffic flow Traffic informed of problem and adjusted	III-II	Initial detection would prevent AHS engage Non-AHS travel unaffected Driver may need to resume manual control if the vehicle is unresponsive to the system commands
12	**Data Link**					
12.1	Loss of Message Bits	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Command and status messages received by the vehicle may be faulty. Fails vehicle check-in test AHS inspection invalid Driver moves the vehicle to breakdown lane or off AHS	If the vehicle becomes unresponsive to roadway commands, it becomes an "intruder" and traffic is adjusted accordingly to avoid major incidents, driver may need to assume control and remove vehicle from AHS Vehicle gives 'no go' signal for AHS Traffic informed of problem and adjusted	II-I	Loss of data link could have a severe impact, initial detection would prevent AHS engage. Driver may need to resume manual control if the vehicle is unresponsive to the system commands. Errors in command messages may cause improper vehicle control and could severely impact traffic management

Table 2-B3. (continued) Fault/Hazard Analysis for RSC I2C2 and I3C2

No.	Component Failure	System Phase	Hazard Description: Local Effect	Hazard Description: System Effect	Risk	Remarks
13	**Roadway Control**					
13.1	Computer CPU not cycling I/O not functioning or degraded Software Failure	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Partial or total loss of communications between roadway & vehicle Driver must be alert and ready to assume manual control of the vehicle	Partial or total loss of system monitoring and traffic management capability would require total system shut down Roadway would be unable to control vehicles	I	Driver may need to resume manual control of the vehicle, response time is critical in avoiding major incidents Communication may still available, system could revert to C1 or vehicle based control
13.2	Data Link Loss of Message Bits	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Command and status messages. received by the vehicle may be faulty Driver must be alert and ready to assume manual control of the vehicle	Errors in command messages may cause improper vehicle control and would require AHS shut down Roadway would be unable to control vehicles	I	All vehicles might be denied access to AHS until system is repaired Communication may still available, system could revert to c1 or vehicle based control. Driver may need to resume manual control of the vehicle, response time is critical in avoiding major incidents
13.3	Communications Loss of Power Bad / Corroded Wires Aging or inoperative electronic components Degraded performance of encoder, transmitter or receiver Faulty Ground	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Degradation or loss of communication between vehicles and roadway Driver must be alert and ready to assume manual control of the vehicle	Traffic management capability could be degraded or lost	I	Communication may still available, system could revert to c1 or vehicle based control. Driver may need to resume manual control of the vehicle, response time is critical in avoiding major incidents

Table 2-B3. (continued) Fault/Hazard Analysis for RSC I2C2 and I3C2

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
13	**Roadway Control (cont.)**					
13.4	Sensors Bad Wires or Connectors Mechanical Failures: Misalignment of sensors, stuck sensors, sensor electrical failure, etc. Calibration Changes Faulty Ground	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Sensor performance ranging from degraded to none or intermittent Driver must be alert and able to assume manual control of the vehicle.	Lateral and longitudinal control may be impaired,	I	May require total system shutdown - communication may still available, system could revert to c1 or vehicle based control. Driver may need to resume manual control of the vehicle, response time is critical in avoiding major incidents.
14	**Vehicle Dynamics / Characteristics**					
14.1	Variations in Acceleration, Braking Traction	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Greater time / distance required for vehicles to reach cruise speed or stop	System may adjust headway / speed accordingly to avoid major incidents	3A IV	AHS engage permitted System will be limited by least common denominator
15	**Road Conditions**					
15.1	Wet Snow or slush ice Sand, dirt, oil, etc.	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced traction or variations in traction	Traffic slowdown, curves & lateral maneuvers may increase collision potential, speed reduction may be required	3A-3C IV-I	AHS engage permitted Roadway set vehicle speed & spacing
15.2	Uneven Snow Accumulation	Check - In AHS Entry Lat / Long Check - Out AHS Exit	External disturbance to vehicle's lateral maneuvers	Traffic slowdown due to reduced lane keeping capability, lane changing ability and degraded longitudinal control	3B III-II	AHS engage permitted Roadway set vehicle speed & spacing
15.3	Pavement Surface Irregularities (ruts, potholes, grates, puddles, etc.) Traveling over edge of roadway	Check - In AHS Entry Lat / Long Check - Out AHS Exit	External disturbance to vehicle's lateral & longitudinal maneuvers	Roadway may adjust vehicle speed and headway to avoid major incidents if surface irregularities exist.	3C IV-I	May require system shutdown until roadway is repaired

Table 2-B3. (continued) Fault/Hazard Analysis for RSC I2C2 and I3C2

No.	Component Failure	System Phase	Hazard Description Local Effect	System Effect	Risk	Remarks
16	**Atmospheric**					
16.1	Light Condition: Dark Dark but lighted Dawn or dusk Glare (reflected bright sunlight, headlights)	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced visibility and / or glare	May require speed reduction	3A IV-III	AHS engage permitted Impact dependent on sensors used for longitudinal and lane keeping control
16.2	Weather Rain Sleet Snow Fog Rain & Fog Sleet & Fog Other (smog, smoke, blowing dust, hail, etc.) Thunderstorm / Lightning Whiteout	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced visibility, traction and possible degraded sensor performance	Possible reduction in longitudinal & lane keeping control, may result in traffic slowdown to avoid increased collision potential	3A- 3B IV-I	AHS engage permitted unless conditions are extreme Impact dependent on sensors used for longitudinal and lane keeping control May affect non-AHS travel
16.3	Crosswind	Check - In AHS Entry Lat / Long Check - Out AHS Exit	External disturbance to vehicle's lateral motion	Intermittent disturbance to lane keeping control Roadway will adjust to environmental conditions	3B IV-I	AHS engage permitted unless conditions are extreme Impact dependent on sensors used for longitudinal and lane keeping control
17	**Incidents**					
17.1	Blockage due to accident stalled vehicle on roadway Non-Motorist	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Lane(s) blocked	Traffic slowdown or stoppage and possible vehicle collision Based on driver decision, roadway may direct traffic around accident / obstacle if possible	3B- 2C III-I	If severe, may require system shutdown Roadway operations issue Roadway control would prevent “rubbernecking” and possibility for more incidents
17.2	Roadway Sabotage	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Damage to vehicles, roadway, sensors, etc.	Traffic slowdown / stoppage or possible vehicle damage / collision	3D- 1E III-I	System shutdown may be required, roadway operations issue Damaged vehicle would be denied AHS access

Table 2-B3. (continued) Fault/Hazard Analysis for RSC I2C2 and I3C2

No.	Component Failure	System Phase	Hazard Description: Local Effect	Hazard Description: System Effect	Risk	Remarks
18	**Obstacles**					
18.1	Objects on Roadway (tires, mufflers, etc.) Objects thrown / fallen from leading vehicle Blockage due to animal(s), fallen tree(s), rock(s)	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Obstacle in roadway possible lane blockage	Possible traffic slowdown / stoppage, vehicle damage or collision Based on driver decision, roadway may adjust traffic around obstacle	3B-1E IV-I	Possibility of complete system shutdown Roadway operations issue - may be more or a factor in rural areas
19	**Driver**					
19.1	Improper Command Initiation / Control Commands	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Inappropriate response to system requests Driver monitor status and decisions would be impacted, may be unable to resume manual control	Fail check - in tests, lane change decisions may be impaired May park vehicle Fail check - out tests, traffic informed of problem and adjusted Driver is not allowed to assume manual control of vehicle, vehicle may be stopped	2C-2D IV-II	AHS engage not permitted Response teams would be dispatched to stopped vehicle to determine driver alertness. Driver may be unable to assume manual control of the vehicle leading to severe consequences if manual control must be assumed on AHS.
19.2	Driver Impaired by: Drugs / Alcohol Illness, fatigue, drowsiness, etc. Distracted by passengers, instruments, etc. Slow reflexes Driver improperly responds to system requests	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Driver ability to monitor system & respond degraded Driver ability to monitor system & respond degraded, driver may lose AHS operating license	Fail check - in tests, lane change decisions affected. Vehicle could stop Fail check - out tests, traffic informed of problem and adjusted Vehicle may be stopped	2C-3C IV-II	Degree of impairment is a factor Driver unable to assume manual control of vehicle (could have serious accident potential) Further non-AHS travel may not permitted, vehicle could be stopped and response crews dispatched to determine driver impairment
19.3	Driver: Unconscious Asleep Unresponsive Unable to assume control	Check - In AHS Entry Lat / Long Check - Out AHS Exit	No response Driver unable to interact with system or assume manual control Drive may lose AHS license	Fail check-in test, lane change decisions impaired Possible system override moves vehicle to break-down lane or off of AHS traffic informed of problem and adjusted to fit response	2C-3D IV-II	Vehicle may be stopped and response teams dispatched Possibility for incident if catastrophic failure of vehicle or system occurs and manual control must be assumed

Table 2-B3. (continued) Fault/Hazard Analysis for RSC I2C2 and I3C3

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
19	**Driver (cont.)**					
19.4	Deliberate Override of System	Check - In AHS Entry Lat / Long Check - Out AHS Exit	NA driver would assume manual control of vehicle	NA if AHS functioning properly, vehicle would be treated as an intruder and vehicles notified so traffic can adjust accordingly to avoid incident	4D IV-I	driver would be responsible for removing vehicle from AHS traffic lanes and getting off at the next available exit. sudden vehicle stoppage may cause major incident.
19.5	Non-AHS Certified Driver	Check - In AHS Entry Lat / Long Check - Out AHS Exit	driver unfamiliar with AHS system		3D IV	vehicle is not permitted to enter AHS.

Table 2-B4. Fault/Hazard Analysis for RSC I3C3

RSC I3C3 Assumptions:

- **AHS engage required**
- **Vehicle check-in required for AHS engage**
- **Dedicated Highway**
- **Automated Entry/Exit**
- **Transition to AHS from non-AHS roadways through AHS entrance ramps**
- **Highway role - Commands individual vehicle actions**
- **Automated longitudinal and lane keeping (vehicle controlled)**
- **Roadway determined speed and spacing requirements**
- **Automated lane change**
- **Driver has monitor role - will be alerted upon detection of failure**
- **Break down lane included on AHS roadway**

No.	Component Failure	System Phase	Hazard Description: Local Effect	Hazard Description: System Effect	Risk	Remarks
1	**Controllers**					
1.1	Brakes: Master Cylinder Breakdown Hydraulic Leak Vacuum Leak Reduced Brake Contact Friction	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Exceed a preset limit for the pressure gradient between the braking systems Fails Check - In test Partial or complete loss of hydraulic braking and reduced braking capability AHS inspection invalid, system with higher pressure is used	Vehicle braking systems failure Vehicle gives 'no go' message for AHS access Possibility of impact with the leading vehicle The vehicle is directed to the breakdown lane or off the AHS	4E-3E III	Vehicle braking systems would be checked at the biannual AHS inspection Emergency brake may still be available Redundant braking systems should be employed to minimize failure risk Loss of vehicle braking systems is less of a concern on AHS since braking isn't required as often as with manual driving
1.1a	Ineffective Emergency Brake (when needed)	Check - In AHS Entry Lat / Long Check - Out AHS Exit	No backup brakes in addition to primary braking systems failure Fails check-in test Loss of vehicle control AHS inspection invalid	Catastrophic vehicle braking system failure Vehicle gives 'no go' message for AHS access No backup longitudinal control resulting in possible impact with the leading vehicle Vehicle directed to breakdown lane	4E-1E II	Vehicle may be prevented from further AHS and non - AHS travel extremely rare , vehicle would lose all braking capabilities, may be less of a concern on AHS where braking is not required as often Two braking failures are assumed

Table 2-B4. (continued) Fault/Hazard Analysis for RSC I3C3

No.	Component Failure	System Phase	Hazard Description Local Effect	System Effect	Risk	Remarks
1	**Controllers (Cont.)**					
1.1b	AHS Braking Actuators (stuck valve, loss of hydraulic fluid, etc.) Sensors Electronics	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Partial or complete loss of AHS controlled braking Fails check-in test Partial or complete loss of AHS controlled braking AHS inspection invalid	AHS longitudinal control impaired Vehicle gives 'no go' message for AHS access Possible impact with lead vehicle, traffic slowdown, longitudinal control might be adjusted with throttle Vehicle directed to breakdown lane or off of AHS at next exit	2E II	Impacts reduced while on AHS since braking is not required as often as on manual highways
1.2	Steering: Reduced Hydraulic Assist Broken Mechanical Link (tie rod, ball joints, etc.)	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Impaired to no vehicle lane keeping and lateral control Failed vehicle check-in test Reduced steering to no steering, partial or total loss of vehicle lateral control AHS inspection invalid	Steering failure of vehicle extremely critical Vehicle gives 'no go' message for AHS access Lane keeping ability and lateral maneuver ability impairment may cause impact with vehicles in adjacent lanes. Vehicle would be slowed to a stop or directed off AHS	2E- 1E IV-I	Steering failure would have the greatest impact on AHS, vehicle must be able to maintain lane keeping ability Redundant lateral control systems should be used on AHS equipped vehicles Vehicle steering systems would be checked at the biannual AHS inspection
1.2a	AHS Steering Actuators (stuck valve, loss of hydraulic fluid, etc.) Sensors Electronics	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced to no AHS steering Failed check-in test Non-functional AHS steering AHS inspection invalid	Vehicle may be unable to maintain AHS lane tracking Vehicle gives 'no go' message for AHS access Impairment or loss of lateral control Vehicle may be slowed to a stop to avoid incident, redundant system might prevent failure	2E III	This is the most critical vehicle failure on AHS since vehicle lateral control and lane keeping ability are affected Manual control of vehicle may still be available for non-AHS travel

Table 2-B4. (continued) Fault/Hazard Analysis for RSC I3C3

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
1	**Controllers (Cont.)**					
1.3	Throttle Wide Open Throttle (WOT) Ineffective Throttle	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Vehicle longitudinal control is impaired Failed vehicle check-in test Inability to maintain speed / acceleration AHS inspection invalid	Vehicle may be unable to maintain longitudinal control, headway affected Vehicle gives 'no go' message for AHS access Reduced headway, impact with the leading / trailing vehicle and possible traffic slowdown & delays Braking available for backup longitudinal control, vehicle directed to breakdown lane	4E-2E IV-III	Initial detection would prevent AHS access Braking could augment longitudinal control Loss of longitudinal control is less critical on AHS roads than with manual traffic Traffic would be adjusted for vehicle with a throttle control failure to be directed to the breakdown lane
1.3a	AHS Throttle Actuators (stuck valve, loss of hydraulic fluid, etc.) Sensors Electronics	Check - In AHS Entry Lat / Long Check - Out AHS Exit	AHS throttle ranging from wide open to closed Failed vehicle check-in test Impaired AHS longitudinal control AHS inspection invalid	Longitudinal control of vehicle may be impaired Vehicle gives 'no go' message for AHS access Could result in reduced headway or possible impact with the leading / trailing vehicle. Vehicle directed to breakdown lane	2E III-II	Manual control of vehicle may be unaffected Braking could augment longitudinal control if primary systems affected
2	**Drive Train**					
2.1	Engine: Timing Belt Mechanical Breakdown (hydraulic lifters, cam shaft, piston assembly, etc.)	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced to complete loss of engine power Failed vehicle check-in test Impaired vehicle longitudinal control AHS inspection invalid	Possible stalled vehicle Vehicle gives 'no go' message for AHS access May result in reduced headway, impact with trailing vehicle or traffic slowdown & delays Vehicle could be able to coast to breakdown lane	4E-2D IV-II	Braking and steering still available for vehicle to coast to breakdown lane A minor problem may allow time for vehicle to exit AHS and avoid adverse traffic impacts Lateral control affected if wheels lock

Table 2-B4. (continued) Fault/Hazard Analysis for RSC I3C3

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
2	**Drive Train (cont.)**					
2.2	Transmission: Mechanical Breakdown (hydraulic pumps, clutch discs, etc.)	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced ability to control speed Failed vehicle check-in test Impaired longitudinal control AHS inspection invalid	Possible stopped vehicle Vehicle gives 'no go' message for AHS access Could result in a major traffic slowdown / possible collision The vehicle is directed to the breakdown lane	2E IV-II	Braking and steering available for vehicle to maneuver to breakdown lane A minor problem may allow time for vehicle to exit AHS and avoid adverse traffic impacts Lateral control affected if wheels lock
2.3	Drive Axle: Constant velocity joints on front drive wheels Broken Axle Mechanical Breakdown (gears, bearings, etc.)	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Loss of speed and / or steering control Failed vehicle check-in test Reduced vehicle lateral / longitudinal control AHS inspection invalid	Possible loss of vehicle control Vehicle gives 'no go' message for AHS access Could result in reduced headway, impact with trailing vehicle or vehicle in adjacent lane and seriously impact traffic flow. The vehicle is directed to breakdown lane or stopped	2E-1E II-I	A minor problem may allow time for vehicle to exit AHS and avoid adverse traffic impacts Lateral control affected if wheels lock
3	**Suspension System**					
3.1	Shock Absorbers: Mechanical Wearout	Check - In AHS Entry Lat / Long Check - Out AHS Exit	No serious effect on steering or speed control.	No system effect	4C	AHS could still be engaged Vehicle occupant discomfort for extreme maneuvers
3.2	Springs	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced steering control. Failed vehicle check-in test Impaired lateral control AHS inspection invalid	Possible loss of vehicle lateral control Vehicle gives 'no go' message for AHS access Impaired lane keeping ability and lateral control, may affect traffic flow Vehicle directed to breakdown lane	4D IV-II	Vehicle suspension systems would be checked at biannual AHS inspection

Table 2-B4. (continued) Fault/Hazard Analysis for RSC I3C3

No.	Component Failure	System Phase	Hazard Description: Local Effect	Hazard Description: System Effect	Risk	Remarks
3	**Suspension System (cont.)**					
3.3	Wheels: Detached	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Loss of steering and speed control Failed vehicle check-in test Impaired vehicle control AHS inspection invalid	Loss of vehicle control / roadway debris Vehicle gives 'no go' message for AHS access Could result in a collision and seriously impact traffic flow. Vehicle stopped or directed to breakdown lane	1E II-I	Detached wheel may collide with neighboring vehicles Creation of roadway lane obstacle which system would direct traffic around
3.4	Tires: Extreme loss of air pressure Severely out of balance Rear Blowout Front Blowout	Check - In AHS Entry Lat / Long Check - Out AHS Exit	reduction / loss of steering - reduced speed control Failed vehicle check-in test Impaired vehicle control	Possible loss of vehicle control Vehicle gives 'no go' message for AHS access Affects lane keeping ability, lateral control, and headway, could result in a collision and a traffic slowdown Vehicle directed to breakdown lane	4A- 1C IV-I	Possibility of self-healing tires may make this a minor issue when AHS is employed Could seriously affect lateral control of the vehicle if a blowout occurs at high velocities If the vehicle is stopped and repairs are made, further AHS travel is permitted
4	**Cooling and Lubricating**					
4.1	Cooling System: Slow to sudden loss of coolant from radiator, hoses, and water pump Water pump or drive belt breakdown	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Engine overheat or seize - need to stop vehicle Failed vehicle check-in test Possible loss of vehicle lateral / longitudinal control AHS inspection invalid	Possible vehicle failure, loss of control Vehicle gives 'no go' message for AHS access Could result in traffic slowdown and impact with the trailing or adjacent vehicle. Vehicle directed to breakdown lane	2C- 1D III-I	Sufficient time may be available to remove vehicle from highway Lateral control affected if wheels lock A minor problem may allow time for the vehicle to exit the AHS and avoid adverse traffic impacts

Table 2-B4. (continued) Fault/Hazard Analysis for RSC I3C3

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
4	**Cooling and Lubricating (cont.)**					
4.2	Heater: Slow loss of coolant from heater core, valve, hoses	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Possible engine overheat Failed vehicle check-in test Possible engine failure, loss of control AHS inspection invalid	Possible stalled vehicle Vehicle gives 'no go' message for AHS access Possible traffic slowdown and / or collision Vehicle directed to breakdown lane	2C IV-III	Sufficient time may be available to remove vehicle from highway A minor problem may allow time for the vehicle to exit the AHS and avoid adverse traffic impacts
4.2a	Heater core leak causing vapors to condense on windows Defrost Inadequate	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced visibility	Severity may be insufficient to prevent AHS access Minimal to none, possible slowdown	4D-2B III	Sensors may be affected by reduced visibility (technology dependent) The driver may have reduced visibility for manual transition
4.3	Lubricating System: Very low oil level Sudden loss of oil due to damaged oil filter, pan, cooler	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Engine overheat or seize - need to stop vehicle Failed vehicle check-in test Possible loss of vehicle control AHS inspection may become invalid	Possible engine failure Vehicle gives 'no go' message for AHS access Possible traffic slowdown or impact with the trailing / adjacent vehicle Vehicle directed to breakdown lane	3B-1D IV-I	Sufficient time may be available to remove vehicle from highway A minor problem may allow time for the vehicle to exit the AHS and avoid adverse traffic impacts Lateral control affected if wheels lock
5	**Fuel / Air System**					
5.1	Fuel Pump, Filters, Tank: Fuel leakage from fuel line, gas tank, and fuel pump Broken Fuel Pump Out of Fuel	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Loss of speed control to stopped vehicle Failed vehicle check-in test Longitudinal control impaired AHS inspection may become invalid	Possible stalled vehicle Vehicle gives 'no go' message for AHS access Reduced headway or possible impact with the trailing vehicle Vehicle directed to breakdown lane or off at the next AHS exit	4D - 2B IV-III	Initial detection of less than 20% full fuel tank would prevent AHS engage Braking and steering still available for vehicle control Effects may be less severe if vehicle can be removed from highway quickly

Table 2-B4. (continued) Fault/Hazard Analysis for RSC I3C3

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
5	**Fuel / Air System (cont.)**					
5.2	Fuel Injectors or Carburetor: Fuel or air restriction in carburetor or fuel injection system	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced speed control Failed vehicle check-in test Impaired longitudinal control AHS inspection invalid	Possibility of stalled vehicle Vehicle gives 'no go' message for AHS access Possible traffic slowdown Vehicle is directed to the breakdown lane or off AHS	3C IV-III	Vehicle would be able to coast Braking and steering still available
5.3	Emission System: PCV or evaporative emissions control not functioning properly	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Slight reduction in engine power Vehicle may stall at idle speeds	Negligible May slow traffic entering AHS May slow exiting AHS traffic	4C IV-III	AHS could still be engaged
6	**Electrical System**					
6.1	Loss of Ignition Power: Reduced ignition capability due to damaged spark plugs, coil wires, distributor, etc.	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Loss of speed control to stalled vehicle Failed vehicle check-in test Longitudinal control impaired AHS inspection invalid	Possible stalled vehicle Vehicle gives 'no go' message for AHS access Reduced headway, impact with trailing vehicle or traffic slowdown & delays Vehicle directed to breakdown lane or off AHS	4C - 2D IV-II	Braking and steering still available Driver may be unable to restart vehicle Vehicle able to coast
6.2	Charging system: Electrical Short Circuit Gradual battery discharge from breakdown in alternator, belts, regulator, wires, etc.	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Gradual loss of electrical power possible fire AHS inspection invalid	Dash light illuminates or the driver may be able to sense problem and inform system May result in eventual loss of control, collision and traffic slowdown Vehicle directed to the breakdown lane	2E-2C III-I	loss of electrical power will affect all the vehicle AHS systems Sufficient time and vehicle control may be available to remove the vehicle from the highway.

Table 2-B4. (continued) Fault/Hazard Analysis for RSC I3C3

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
6	**Electrical System (cont.)**					
6.3	Lighting System: Broken: bulbs, wires, blown fuses	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Driver's visibility and monitoring ability affected	dash light would inform driver May affect driver's ability to resume manual control once off AHS	4C IV	May affect non-AHS travel, vehicle may be stopped if driver unable to safely resume control
7	**Exhaust System**					
7.1a	Muffler Falls Off	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Obstacle on the roadway	Obstacle on the roadway could slow traffic or cause vehicle damage / collision System may direct vehicle traffic around object	3C IV-II	Roadway operations issue Roadway clean up response may reduce adverse system effects
7.1b	Exhaust Gas Leakage into the Vehicle	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Hazardous conditions for vehicle occupants Driver incapacitated	Carbon monoxide sensor would alert driver, may lower windows Could affect driver's control capability and monitoring function Vehicle would be removed from AHS at next exit Vehicle could be stopped so its occupants could be treated	2E IV	Non-AHS travel would be affected driver may be unable to resume manual control May require emergency team response
7.2	Turbo Wearout	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced engine performance	Minimal effect	4D IV	AHS engage permitted.

Table 2-B4. (continued) Fault/Hazard Analysis for RSC I3C3

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
7	**Exhaust System (cont.)**					
7.3	Emissions: Restrictions in: Catalytic Converter Oxygen Sensor Air Injection EGR	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced engine performance Impaired longitudinal control AHS inspection may be invalid	Check engine light would alert driver AHS entry may be delayed Minimal to significant reduction in longitudinal control	4D- 3D IV-II	AHS engage permitted except for EGR which may have more than a minimal effect (vehicle speed may be a factor) Vehicle may stall at low velocities or at idle speeds
8	**Auxiliary Systems**					
8.1	Windshield Wipers not Functioning	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Driver visibility reduced AHS inspection may be invalid	Driver could alert AHS if vehicle can not sense problem Vehicle may be stopped if safe non-AHS travel isn't possible	3C IV-III	Weather conditions would be a factor sensors mounted inside passenger compartment may be affected Poor visibility may affect non-AHS travel
8.2	Air Conditioning Non-Functional	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Vehicle occupant discomfort	None	4C	AHS engage permitted vehicle may need to exit from system quickly
9	**Communication**					
9.1	Loss of Power Bad / Corroded Wires Aging or inoperative electronic components Degraded performance of encoder, transmitter or receiver Faulty Ground	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Degradation or loss of communication with other vehicles and / or roadway Failed vehicle check-in test Driver may have to assume manual control AHS inspection invalid	Unresponsive vehicle seen as "intruder" and traffic adjusted accordingly to prevent major incidents. Vehicle gives 'no go' message for AHS access Driver responsibility to remove vehicle from AHS traffic lanes, may result in traffic slowdown	II-I	Driver may have to assume manual control if vehicle unresponsive to AHS commands, could impact traffic management

Table 2-B4. (continued) Fault/Hazard Analysis for RSC I3C3

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
10	**Sensors**					
10.1	Bad Wires or Connectors Mechanical Failures: Misalignment of sensors, stuck sensors, sensor electrical failure, etc. Calibration Changes Faulty Ground	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Sensor performance ranging from degraded to none or intermittent Failed vehicle check-in test Vehicle AHS inspection invalid	Surrounding traffic notified of problem and "intruder" response is initiated so vehicle can safely exit AHS Vehicle gives 'no go' message for AHS access Vehicle lane keeping and longitudinal control affected, may result in traffic slowdown Driver may need to direct the vehicle to the break-down lane and off AHS	III-II	System would adjust traffic so vehicle could get to breakdown lane Driver may have to assume manual control if vehicle unresponsive to AHS commands
11	**Vehicle Control Computer**					
11.1	CPU not cycling I/O not functioning or degraded Software Failure	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Vehicle control commands degraded, faulty or missing Failed vehicle check-in test AHS inspection invalid	Roadway initiates "intruder" response and adjusts traffic so vehicle can safely exit AHS Vehicle gives 'no go' message for AHS access Reduction or loss of AHS control could result in collision and impact traffic	III-II	Driver may have to assume manual control if vehicle unresponsive to AHS commands
12	**Data Link**					
12.1	Loss of Message Bits	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Command and status messages received by the vehicle may be faulty Failed vehicle check-in test Driver must be alert and able to assume manual control of the vehicle AHS inspection invalid	Roadway initiates "intruder" response and adjusts traffic so the vehicle can safely exit AHS Vehicle gives 'no go' message for AHS access Possibility for traffic slowdown and collision	II-I	Driver may have to assume manual control and remove the vehicle from AHS Errors in command messages may cause improper vehicle control and impact traffic management

Table 2-B4. (continued) Fault/Hazard Analysis for RSC I3C3

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
13	**Roadway Control**					
13.1	Computer CPU not cycling I/O not functioning or degraded Software Failure	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Partial or total loss of communications between roadway & vehicle Driver must be alert and ready to assume manual control of the vehicle	Partial or total loss of system monitoring and traffic management capability, system may need to be shutdown roadway would be unable to control vehicles	I	Vehicle to vehicle communication still available, system could revert to C2 or C1 control Vehicles may be denied AHS entry until the system is repaired Manual control available to driver, response time is critical
13.2	Data Link Loss of Message Bits	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Command and status messages received by the vehicle may be faulty Driver must be alert and ready to assume manual control of the vehicle	Errors in command messages may cause improper vehicle control and could require AHS shut down Roadway might be unable to control vehicles	I	All vehicles could be denied access to AHS until system is repaired Vehicle to vehicle communication still available, system could revert to C2 or C1 control Driver response time is critical in avoiding major incidents
13.3	Communications Loss of Power Bad / Corroded Wires Aging or inoperative electronic components Degraded performance of encoder, transmitter or receiver Faulty Ground	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Degradation or loss of communication between vehicles and roadway Driver must be alert and ready to assume manual control of the vehicle	Traffic management capability could be degraded or lost, system may need to be shutdown Roadway may be unable to control vehicles	I	All vehicles could be denied access to AHS until system is repaired Vehicle to vehicle communication still available, system could revert to C2 or C1 control Driver response time is critical in avoiding major incidents.

Table 2-B4. (continued) Fault/Hazard Analysis for RSC I3C3

No.	Component Failure	System Phase	Hazard Description: Local Effect	Hazard Description: System Effect	Risk	Remarks
13	**Roadway Control (cont.)**					
13.4	Sensors Bad Wires or Connectors Mechanical Failures: Misalignment of sensors, stuck sensors, sensor electrical failure, etc. Calibration Changes Faulty Ground	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Sensor performance ranging from degraded to none or intermittent Driver must be alert and able to assume manual control of the vehicle.	Traffic management capability could be degraded or lost, system may need to be shutdown Roadway may be unable to control vehicles	I	All vehicles may be denied AHS access until system is repaired Vehicle to vehicle communication still available, system could revert to C2 or C1 control Manual control still available, driver response time is critical
14	**Vehicle Dynamics / Characteristics**					
14.1	Variations in Acceleration, Braking Traction	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Greater time / distance required for vehicles to reach cruise speed or stop	System may adjust headway / speed accordingly to avoid major incidents.	3A IV	AHS engage permitted System will be limited by least common denominator
15	**Road Conditions**					
15.1	Wet Snow or slush ice Sand, dirt, oil, etc.	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced traction or variations in traction	Traffic slowdown Curves & lateral maneuvers may increase collision potential, speed reduction may be required	3A-3C IV-I	AHS engage permitted Individual vehicle actions are controlled by the roadway
15.2	Uneven Snow Accumulation	Check - In AHS Entry Lat / Long Check - Out AHS Exit	External disturbance to vehicle's lateral maneuvers	Traffic slowdown due to reduced lane keeping capability, lane changing ability and degraded longitudinal control	3B III-II	AHS engage permitted Individual vehicle actions are controlled by the roadway
15.3	Pavement Surface Irregularities (ruts, potholes, grates, puddles, etc.) Traveling over edge of roadway	Check - In AHS Entry Lat / Long Check - Out AHS Exit	External disturbance to vehicle's lateral & longitudinal maneuvers	Roadway may adjust vehicle speed, headway, and lateral maneuvers to avoid major incidents	3C IV-I	May require system shutdown until roadway is repaired

Table 2-B4. (continued) Fault/Hazard Analysis for RSC I3C3

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
16	**Atmospheric**					
16.1	Light Condition: Dark Dark but lighted Dawn or dusk Glare (reflected bright sunlight, headlights)	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced visibility and / or glare	None-minimal	3A IV	AHS engage permitted Impact dependent on sensors used for longitudinal and lane keeping control May affect non-AHS travel
16.2	Weather Rain Sleet Snow Fog Rain & Fog Sleet & Fog Other (smog, smoke, blowing dust, hail, etc.) Thunderstorm / Lightning Whiteout	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Reduced visibility, traction and possible degraded sensor performance	Possible reduction in longitudinal & lane keeping control, may result in traffic slowdown to avoid increased collision potential	3A- 3B IV-II	AHS engage permitted unless conditions are extreme Impact dependent on sensors used for longitudinal and lane keeping control May affect non-AHS travel
16.3	Crosswind	Check - In AHS Entry Lat / Long Check - Out AHS Exit	External disturbance to vehicle's lateral motion	Intermittent disturbance to lane keeping control Roadway control will adjust to environmental conditions	3B IV-I	AHS access is permitted unless the conditions are extreme Impact dependent on sensors used for longitudinal and lane keeping control
17	**Incidents**					
17.1	Blockage due to accident stalled vehicle on roadway Non-Motorist	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Lane(s) blocked	Traffic slowdown or stoppage and possible vehicle collision Roadway may direct traffic around accident / obstacle if possible	3B- 2C III-I	If severe, may require system shutdown Roadway operations issue Roadway control of vehicle would prevent “rubbernecking” and possibility for more incidents
17.2	Roadway Sabotage	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Damage to vehicles, roadway, sensors, etc.	Traffic slowdown / stoppage or possible vehicle damage / collision Damaged vehicle would be prohibited from entering AHS	3D- 1E III-I	System shutdown may be required Roadway operations issue

Table 2-B4. (continued) Fault/Hazard Analysis for RSC I3C3

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
18	**Obstacles**					
18.1	Objects on Roadway (tires, mufflers, etc.) Objects thrown / fallen from leading vehicle Blockage due to animal(s), fallen tree(s), rock(s)	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Obstacle in roadway possible lane blockage	Possible traffic slowdown / stoppage, vehicle damage or collision Roadway may adjust traffic around obstacle	3B- 1E IV-I	Possibility of complete system shutdown Roadway operations issue - may be more or a factor in rural areas
19	**Driver**					
19.1	Improper Command Initiation / Control Commands	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Inappropriate response to system requests The driver's AHS license may be revoked	Fail check - in tests Initial detection would prevent AHS access The vehicle may be directed to the breakdown lane and stopped Fail check - out tests The driver may not be allowed to resume manual control of vehicle	2C- 2D IV-II	AHS engage not permitted Non-AHS travel could be affected. Driver may be unable to assume manual control of the vehicle affecting AHS only if roadway or vehicle control systems failed and the driver is needed to control the vehicle.
19.2	Driver Impaired by: Drugs / Alcohol Illness, fatigue, drowsiness, etc. Distracted by passengers, instruments, etc. Slow reflexes Driver improperly responds to system requests	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Driver's ability to monitor system & respond is degraded The driver's AHS license may be revoked	Fail check - in tests Initial detection would prevent AHS access The vehicle would be directed to the breakdown lane and stopped Fail check - out tests	3C - 2C IV-II	Degree of impairment is a factor Driver unable to assume manual control of vehicle Further non-AHS travel may not be permitted
19.3	Driver: Unconscious Asleep Unresponsive Unable to assume control	Check - In AHS Entry Lat / Long Check - Out AHS Exit	No response Driver unable to interact with system or assume manual control The driver's AHS license may be revoked	Fail check-in test Initial detection denies vehicle AHS access Fail check-out test	3D - 2C IV-II	Vehicle stopped Emergency response teams may be dispatched to vehicle Possibility for incident if failure of vehicle or system occurs and manual control must be assumed

Table 2-B4. (continued) Fault/Hazard Analysis for RSC I3C3

	Component	System	Hazard Description			
No.	**Failure**	**Phase**	**Local Effect**	**System Effect**	**Risk**	**Remarks**
19	**Driver (cont.)**					
19.4	Deliberate Override of System	Check - In AHS Entry Lat / Long Check - Out AHS Exit	NA Driver would assume manual control of vehicle	NA If AHS functioning properly, vehicle would be treated as an "intruder " and system would adjust traffic accordingly to avoid incident	4D IV-I	The driver would be responsible for removing vehicle from AHS traffic lanes and getting off at the next available exit. Sudden vehicle stoppage may cause major incident
19.5	Non-AHS Certified Driver	Check - In AHS Entry Lat / Long Check - Out AHS Exit	Driver unfamiliar with AHS	Vehicle is not permitted AHS access	3D IV	

APPENDIX C

1.0 DATA FILES AND FILTERS TO DEFINE REAR-END CRASHES

Data from the 1992 GES data files provide general information about the characteristics of rear-end crashes. The scope of the analysis is limited to rear-end crashes on interstate highways by the variable restrictions:

INT_HWY = 1	(crash occurred on an interstate highway)
MAN_COL = 1	(orientation of vehicles in collision is "rear-end")
BODY_TYP < 90	(excludes off road vehicles, snowmobiles, farm equipment, etc.)

All tabulations represent GES weighted estimates.

CDS data are used to describe straight front-to-back rear-end collisions in terms of occupant injury and vehicle damage relative to ΔV. Data from the CDS files are not restricted to interstate accidents since this variable is not available in the CDS data set. Interstate rear-end crashes are similar to rear-end crashes on all roadways in that they are characterized by both lead vehicle moving and lead vehicle stationary situations. The dynamics of 6 o'clock / 12 o'clock rear-end crashes are similar regardless of roadway type since the primary parameter of interest is the force (due to the change in velocity) acting on the vehicle and its occupants and not total velocity. Therefore, broadening the scope to non-interstate accidents does not degrade the analysis.

The following restrictions are imposed on the data files to obtain a clean set of straight front-to-back rear-end collisions involving a wide area of contact between two passenger vehicles (as opposed to the striking vehicle's front bumper catching the rear fender of the struck vehicle and riding up the side of the car). Additional restrictions are imposed to ensure that injuries are not the result of extraneous events such as vehicle rollover or fire.

$20 \leq$ ACCTYPE ≤ 43	(accident type is rear-end or forward impact)
TDD1 = 'W'	(type of damage distribution is wide)
ΔVTOTAL < 99	(delta V is known)
OBJCONT1 < 3	(first object contacted is other vehicle in crash)
OBJCON2A = missing	(no other object was contacted)
ROLLOVER = 0	(vehicle did not rollover after rear-end impact)
FIRE = 0	(vehicle did not catch fire after rear-end impact)
BODYTYPE < 10	(other vehicle was a passenger car)
GAD1 = 'B' OR 'F'	(general area of damage was "back" or "front")

All CDS frequencies represent weighted estimates.

2.0 STATISTICS FOR REAR-END CRASHES

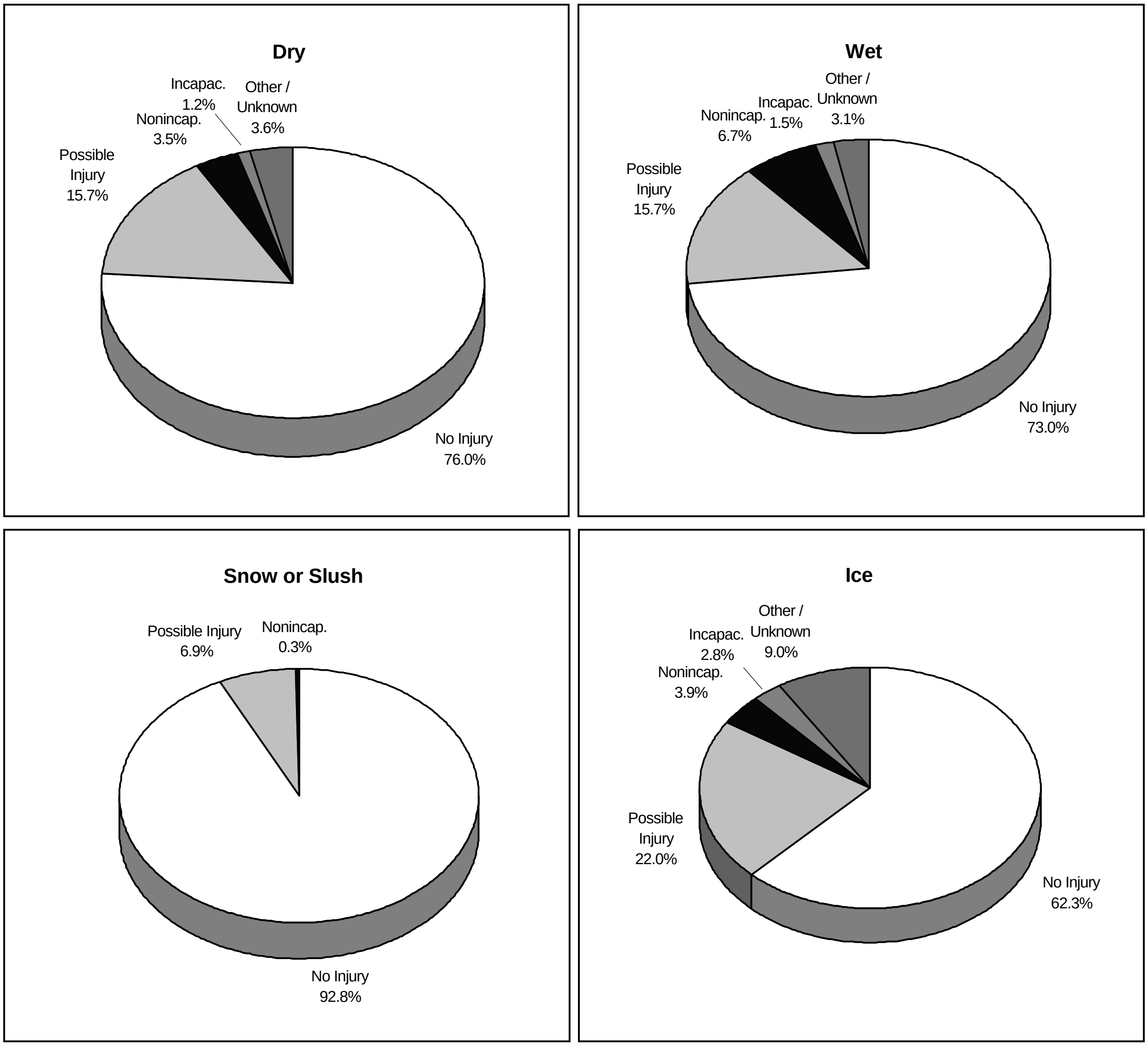


Figure 2-C1. Injury Severity by Road Surface Condition for Occupants of Vehicles Involved in Interstate Rear-End Crashes

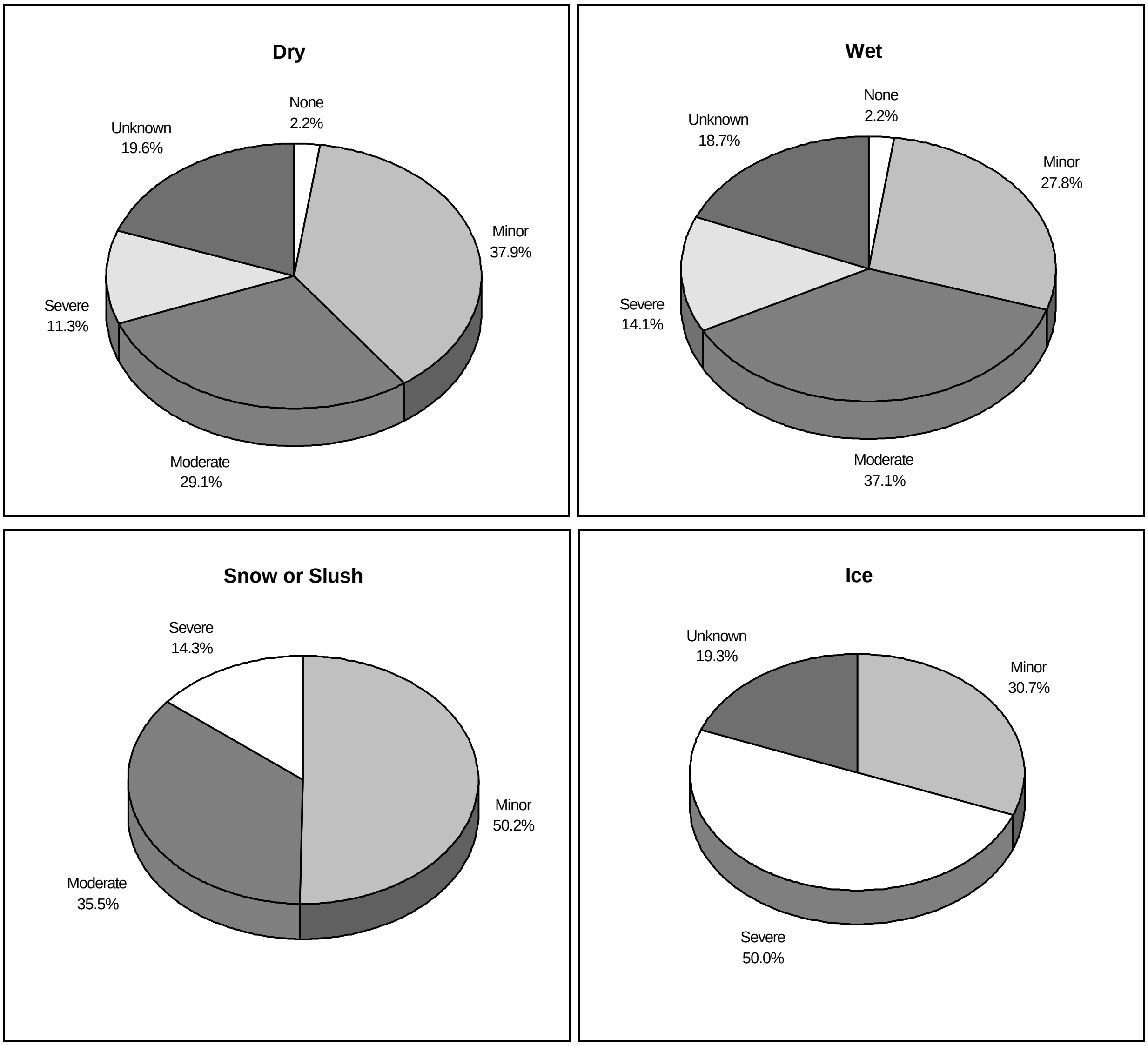


Figure 2-C2. Vehicle Damage by Road Surface Condition for Occupants of Vehicles Involved in Interstate Rear-End Crashes

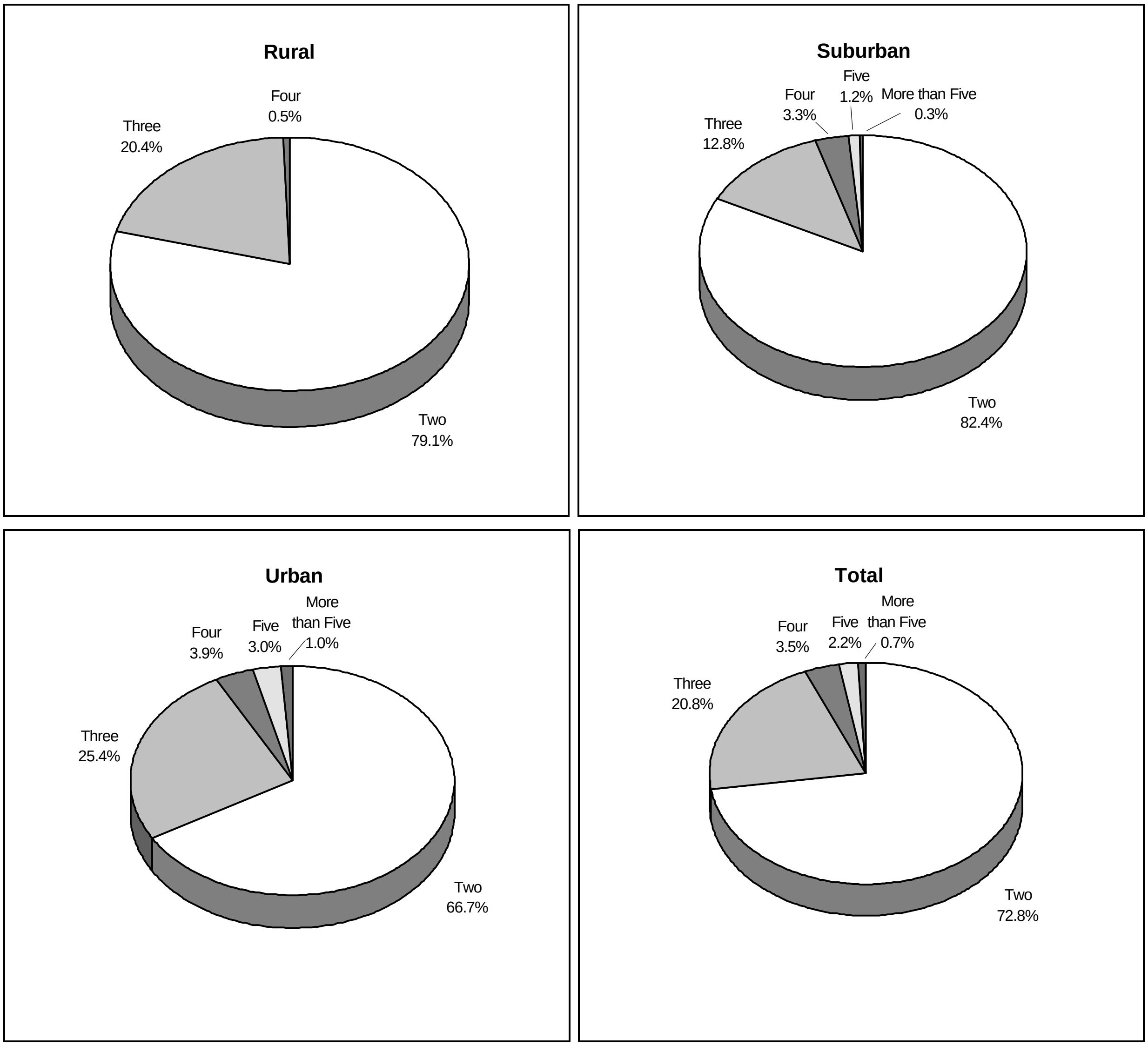


Figure 2-C3. Number of Vehicles Involved by Location in Interstate Rear-End Crashes

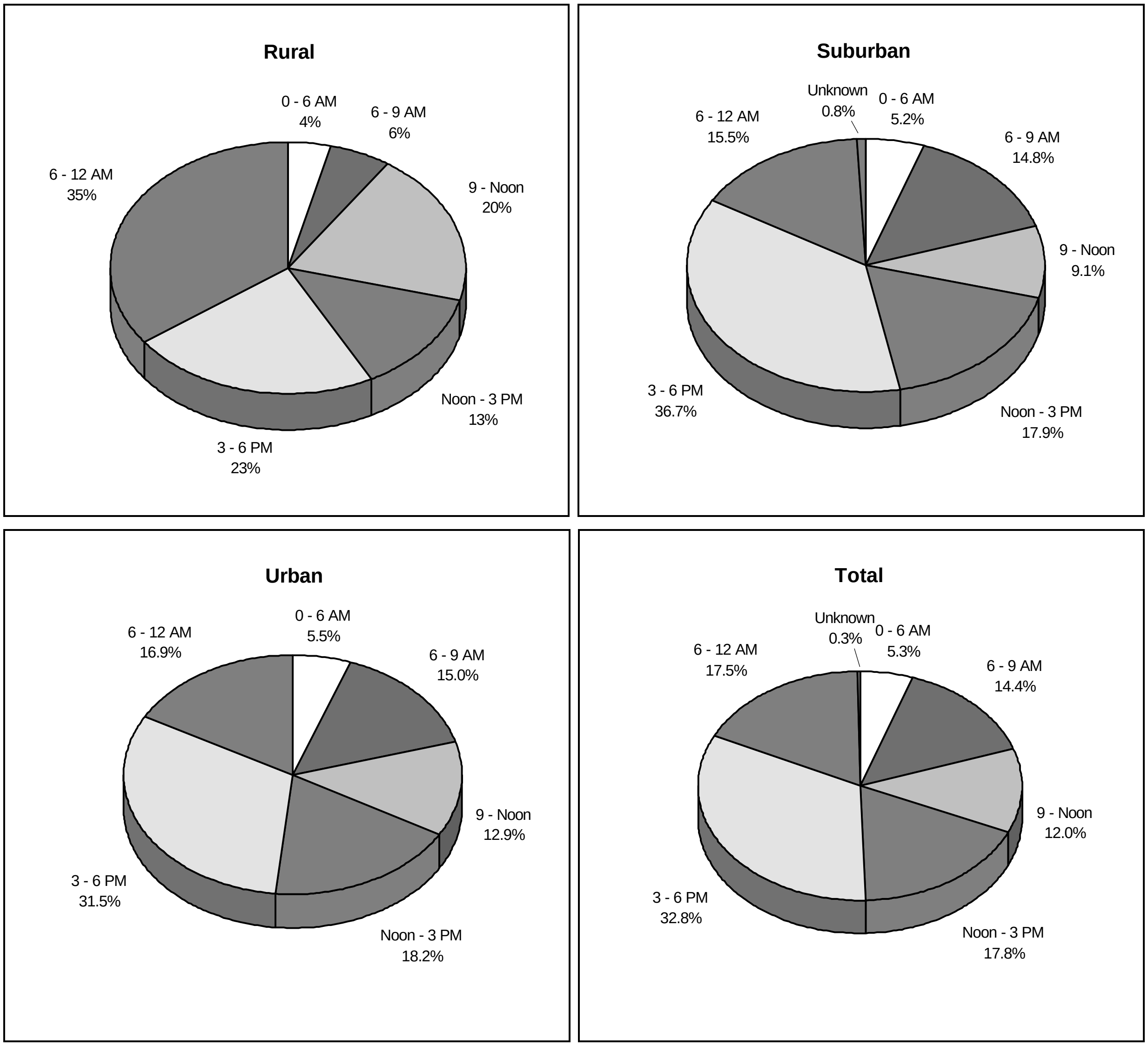


Figure 2-C4. Time of Day for Interstate Rear-End Crashes

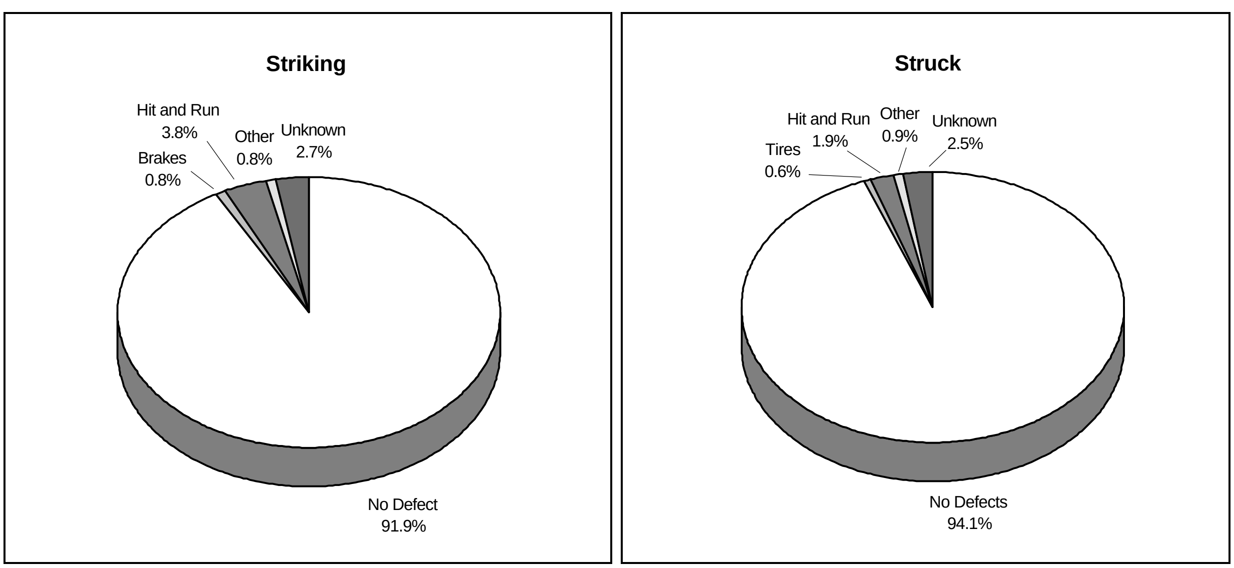


Figure 2-C5. Defects That May Have Contributed to Cause of Crash for Vehicles Involved in Interstate Rear-End Crashes

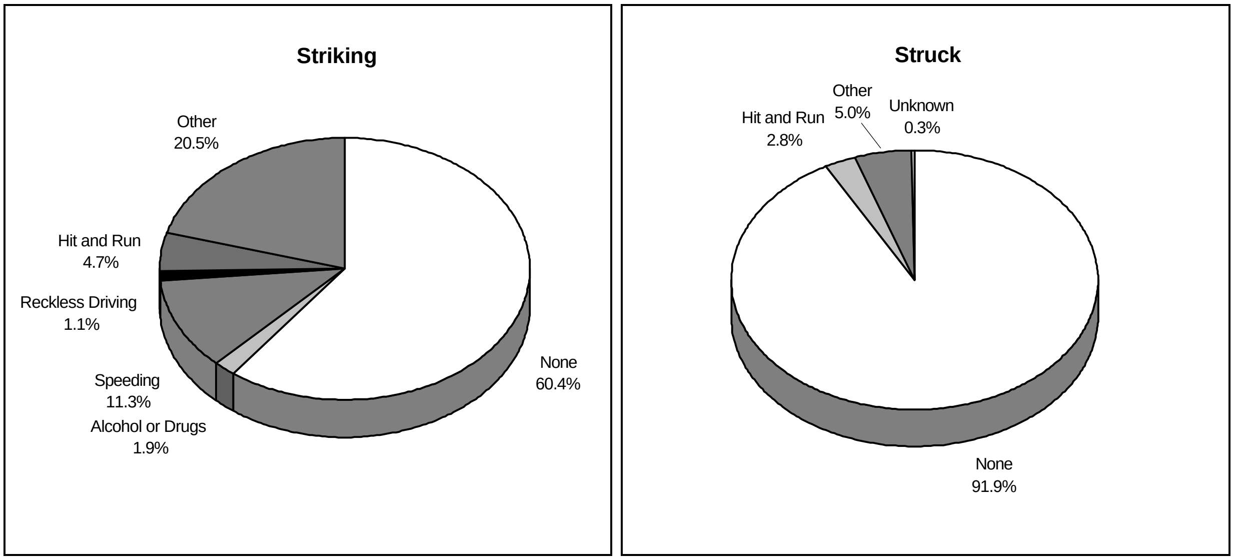


Figure 2-C6. Violations Charged to Drivers of Vehicles Involved in Interstate Rear-End Crashes

APPENDIX D

1.0 BARRIER CHARACTERISTICS AND IMPACT PERFORMANCE

There are three basic types of longitudinal barriers: roadside barriers or guardrails, median barriers and bridge rails. Each barrier type is discussed in the following sections. Discussions on barrier end treatments, barrier selection criteria and barrier related rollover crashes are also presented.

1.1 ROADSIDE BARRIERS OR GUARDRAILS

Impacts with roadside obstacles are responsible for 30 percent of all highway fatalities per year (AASHTO, 1989). Roadside barriers are designed to protect vehicles from roadside hazards, e.g., embankments or roadside obstacles. Barriers are located on the outer edge of the shoulder and when barriers or walls are used, the shoulder width is increased to offset the barrier from the shoulder by 2 feet or more. The shoulder width allows the driver to safely make corrective, return-to-the-road maneuvers. For automated lanes, when vehicle lateral movement is automatically controlled, shoulder width requirements may decrease. However, other considerations, such as snow removal/storage, and vehicle encroachment for mechanical failure or lateral obstacle avoidance movement, may mandate how narrow a shoulder can be used.

Barriers are intended to be continuous, as opposed to segmented, as the barrier end itself becomes a roadside obstacle for the driver. Barrier end treatment is a critical issue that must be resolved if barriers are used to separate manual and automated lanes, particularly when transition lanes are considered. Drivers, traveling at high speeds, must be adequately protected from impacting with barrier ends while attempting to merge onto the automated lanes.

Other highway design features that must be considered in determining AHS barrier use include: depressed freeways with retaining walls or bridge piers that either have an integral concrete barrier shape or are offset from the outer edge of the shoulder and are protected by a barrier; elevated freeways on embankments with decked medians that help to prevent a vehicle from entering the median and dropping off the embankment; and ramp exits from elevated freeways with large gore areas to allow for corrective driving maneuvers and for the placement crash cushions or other devices in front of the parapet and rail. Research will be required to determine the appropriate barrier characteristics (e.g., barrier height and rigidity) and gore area size for vehicles on the automated highway that will travel at higher speeds and, upon impact, could exceed the design limits of today's barrier systems. This is particularly true for MVEs.

Guardrail Design - The thrie beam guardrail (three corrugations) was designed to minimize the problems that occurred with W-beam guardrails. The W-beam guardrail, so named because of its "W" shape, is a flexible barrier system. With the W-beam, a mounting height of 12 in. was found to be critical: mounting too low allowed vehicles to vault or rollover the barrier; mounting too high permitted vehicle bumpers/wheels to snag on the support posts. Both the W-beam and the thrie beam were found to have posts that rotated backwards on impact and the attached rail would form a ramp that allowed vehicles to vault over the barrier. Therefore, the thrie beam barrier was modified so that the rail disconnects from the posts during impact. Other improvements include design changes to minimize bumper/wheel snagging and reduce impact forces on front wheel and vehicle suspension systems. The modified thrie beam has been designed so that the rail moves upward on impact which works to prevent high CG vehicles from rolling over the barrier. Tests have shown that the modified thrie beam was able to redirect a 32,000 lb. intercity bus traveling at 59 mph with 15 degree impact angle.

The self-restoring barrier (SERB) guardrail or tubular thrie beam consists of two thrie beams welded together, mounted on posts with a hinged pivot bar and held away from the posts by a steel cable. Upon impact the SERB deflects backward and upward and returns to its original position after vehicle deflection. The self-restoring aspect of this barrier system is attractive from a maintenance perspective. The SERB guardrail is also designed with break away posts for heavy vehicle impacts. It can redirect a 40,000 lb. intercity bus traveling 60 mph with an impact angle of 15 degrees.

The design limits of the thrie beam and the SERB may be exceeded by MVEs contacting the barriers at increased speeds. Based on available data, it appears that these barriers could prove adequate for single vehicle equivalents (SVEs).

A summary of common roadside barriers and their impact performance is provided in Table 2-D1.

Roadside barrier and bridge alignment - Roadside barriers are aligned with the bridge rails to prohibit the possibility of a vehicle striking the barrier and then striking the bridge rail or the curb. Research will be required to determine if current methods of connecting the roadside barrier and bridge rail is sufficient to safely redirect impacting vehicles traveling at higher rates of speed.

Table 2-D1. Roadside Barriers

TYPE	CHARACTERISTICS	IMPACT PERFORMANCE*
FLEXIBLE SYSTEMS:		
3-Strand Cable	3/4" steel cables, spaced 3-4" apart on weak posts, top cable height 27-30"	Redirects 1,800-4,500 lb. vehicles; 7-11 ft. deflection Advantages: low cost, low deceleration forces, open design prevents snow accumulation along roadway; Disadvantages: long lengths of barrier must be repaired after impact, greater deflection distance required, reduced effectiveness on curves
W-Beam (Weak Post)	W-shaped beam rail installed on weak posts, mounted symmetrically around one bolt, top of railing height is 30"	Redirects 1,800-4,000 lb. vehicles, 7.3 ft. deflection; Advantages: may retain some effectiveness after minor crash less lateral deflection than cable system; Disadvantages: somewhat vulnerable to vaulting or underride caused by incorrect mounting height or irregular approach terrain
Thrie Beam (Weak Post)	Same as W-Beam except that thrie beam is used, mounted by alternating upper and lower bolts on adjacent posts to prevent twisting, top of railing height is 33"	Redirects 1,800-4,500 lb. vehicles, 6.3 ft. deflection Advantages: accommodates greater range of vehicle sizes, less vulnerable to vaulting and underride, accommodates greater range of vehicle sizes; Disadvantages: somewhat vulnerable to vaulting or underride caused by incorrect mounting height
SEMI-RIGID SYSTEMS:		
Box Beam	6"x 6" steel tube mounted on steel posts, posts near point of impact designed to break away, top of railing height is 27"	Redirects 1,800-4,000 lb. vehicles, 4.8 ft. lateral deflection, field tests indicate that 4,500 lb. vehicles can be redirected; Disadvantages: somewhat vulnerable to vaulting or underride caused by incorrect mounting height or irregular approach terrain; failed to keep 4,640 lb. van upright
Blocked-Out W-Beam (Strong Post)	W-beam blocked-out from wood /steel posts, top of railing height is 27"	Redirects 1,800-4,500 lb. vehicles, 2.1-2.9 lateral deflection; Advantages: block-out reduces vehicle snagging and vaulting by maintaining rail height during initial crash; may remain functional after moderate crash; less lateral deflection; most commonly used barrier system; Disadvantages: upper limit 25 deg. angle of impact with van and school bus, failure due to rolling of the vehicle

Table 2-D1. (continued) Roadside Barriers

TYPE	CHARACTERISTICS	IMPACT PERFORMANCE*
SEMI-RIGID SYSTEMS (continued):		
Blocked-Out Thrie Beam (Strong Post)	Thrie-beam blocked-out from wood/steel posts (stronger version of the blocked-out W-beam), top or railing height 32-35"	Redirects 1,800-4,380 lb. vehicles, assumed to meet 4,500 lb. vehicle, lateral deflection 1.5-3.3 ft.; Advantages: less lateral deflection, less prone to damage during a crash, higher rail mounting increases ability to redirect larger vehicles
Modified Thrie Beam	Thrie-beam guardrail modified for heavy vehicles, during an impact the modified spacer block keeps rail face vertical while posts move backwards and raises the height of the rail during impact	Redirects 1,800-32,000 lb. vehicles, 2.9 ft. lateral deflection for 32,000 lb. bus (60 mph, 14 deg.); Advantages: modified design raises height of rail during impact, therefore, lowering the potential of vehicle roll-over; repair costs are lower as compared to other metal beam barrier systems because minimal damage results during low impact crashes, it remains functional during moderate to severe crashes and does not require immediate repair; easier to install and maintain than the W-beam/rubrail system
Self-Restoring Barrier (SERB) Guardrail (experimental)	Tubular thrie beam rail mounted on 8" x 8" wood posts by steel pivot bars and cables, rail deflects backwards and up during impact and returns to original position, top of rail height is 33"	Redirects 1,800-40,000 lb. vehicles, 2.5-3.9 ft. lateral deflection; Advantages: high performance barrier, designed to be maintenance free for most impacts, able to redirect large vehicles, minimizes occupant injury Disadvantages: high cost (twice the cost of concrete safety shape barrier) limits application to select locations (i.e., locations with high frequency of crashes and bridges)
Steel-Backed Wood Rail	6" x 10" wood rail, backed with steel plate, mounted on wood posts, aesthetic/rustic appearance, top of rail height is 27"	Railing is able to redirect 1,800 lb. vehicle (50 mph, 20 deg.) and 4,500 lb. vehicle (50 mph, 25 deg.); Advantages: aesthetic appearance; Disadvantages: appropriate only for limited impact range

Table 2-D1. (continued) Roadside Barriers

TYPE	CHARACTERISTICS	IMPACT PERFORMANCE*
RIGID SYSTEMS:		
Concrete Safety Shape	Sloped front, vertical back face; because this barrier is more susceptible to overturn than the concrete median barrier (CMB) (due to vertical as opposed to sloped back face) it typically contains reinforcing steel and has an enhanced footer; standard top of barrier height is 32" but 42", 64", and 90" high barriers have been constructed	32" New Jersey shape barrier redirects 1,800-4,500 lb. vehicles and 45,000 lb. buses during moderate impacts; 42" barrier redirects 80,000 lb. tractor -trailers (52 mph, 15 deg.); greater than 42" barriers are recommended to minimize overturning of high CG vehicles: Advantages: low cost, low maintenance, effective performance Disadvantages: during high speed, large angle impacts, vehicles can become airborne and reach the top of the barrier; and high CG vehicles may overturn intruding into the space above the barrier - the solution of increasing barrier height to counteract these problems includes a box beam retrofit installed at the top of the barrier and ultra tall wall 90” height, concrete safety shape
Stone Masonry Wall	Concrete core with stone and mortar facing, top of barrier height is 24"	Redirects 1,800 lb. vehicle (60 mph, 15 deg.) and 4,300 lb. vehicle (60 mph and 25 deg.); 27" barrier height currently being tested; Advantages: aesthetic appearance Disadvantages: more costly, limited range of performance

(from AASHTO, Roadside Design Guide, 1989)

* Current standard test criteria:
1) 1800 lb. vehicle impacting at 60 mph and 15 deg. to evaluate occupant risk; and
2) 4500 lb. vehicle impacting at 60 mph and 25 deg to assess structural integrity of barrier

1.2 MEDIAN BARRIERS

Median barriers are intended to prohibit a vehicle from intruding into the on-coming lane of traffic. They are generally used when median width is narrow and traffic volume is high or historically where there has been a high frequency of cross-over accidents. A summary of median barrier characteristics is provided in Table 2-D2.

Selection of the type of median barrier is based on the requirements of the site. Maximum barrier deflection should be less than one-half the width of the median width and should redirect the vehicle in the direction consistent with traffic flow. The use of cable, W-beam on weak posts and box-beam barrier systems should only be used on sites with flat medians, and not for stepped medians (i.e., a median between lanes at different elevations). The use of non-deflective, rigid median barriers (e.g., concrete barrier with sloped face) is generally limited to highways with narrow medians where a low impact angle is expected. High center of gravity vehicles (e.g., tractor-trailers) may intrude into the space above the median barrier (up to 10 feet above the top of the barrier) when it is struck at high speeds or large angles of impact. Sight distance on horizontal curves must be considered when determining the appropriate type of median barrier for use. AHS lat/long control will prevent automated vehicles from contacting barriers during normal operation, however, barrier contact could occur under some conditions of system failure. More likely, however, is the potential barrier collision or over-ride by manual vehicles, including MVEs, that could intrude into automated lanes.

Median Barriers on partial control access highways - The use of median barriers on multi-lane highways with partial control of access can create problems in that they limit space available for return-to-the-road maneuvers, limit the accommodation of crossing and left turns. In fact, while median barriers decrease the occurrence of cross-median crashes, accident frequency typically increases due to limited return-to-the-road maneuvering space (AASHTO, 1989). Vehicle lateral control, however, will alleviate the problem of crashes due to lane deviation. Installation of barriers on highways with partially controlled access is based on an analysis of characteristics, such as, number of crossovers, alignment, sight distance, design speed, traffic volume, median width, and accident history. Highways without full access control can increase safety by limiting the number of conflict points (e.g., intersections), separating conflict areas, reducing maximum deceleration requirements and removing turning vehicles or queues for portions of the through traffic lanes (AASHTO, 1989). These considerations may become more important if an evolutionary approach to AHS is taken and existing roadways are used to service both manual and automated vehicles.

Raised Medians - Raised medians without median barriers will not prevent cross-median collisions on high speed highways. Disadvantages associated with raised medians with curbs include:

1) striking a median may cause the driver to lose control of the vehicle;
2) unless fixed-source lighting/adequate delineation is provided, raised medians are difficult to discern under low visibility/dark conditions;
3) on-coming headlights cast shadows that obscure the curb and adjacent lane; and
4) prohibit use as refuge for disabled vehicles.

Barrier curbs should not be used on high speed roadways, but, if under special circumstances, barrier or mountable curbs are used, they should be located at the outer edge of the shoulder. If the AHS is initiated on existing roadways, modification of roadway structures, such as curbs, will need to be considered.

Table 2-D2. Median Barriers

TYPE	CHARACTERISTICS	IMPACT PERFORMANCE
FLEXIBLE SYSTEMS:		
3-Stand Cable	Flexible system; one of the three cables installed on opposite side of posts than the others; should be used only if area can accommodate 11 ft. deflection; top cable height may reach 33"	Redirects 1,800-4,500 lb. vehicles; 7-11 ft. deflection Advantages: low cost, low deceleration forces, open design prevents snow accumulation along roadway; inexpensive Disadvantages: long lengths of barrier must be repaired after impact, greater deflection distance required, reduced effectiveness on curves
W-Beam (Weak Post)	7 ft. deflection distance; sensitive to height variations and should not be used on irregular terrain (likelihood or vaulting or submarining barrier increases); recommended mounting height is 33"	Redirects 1,800-4,000 lb. vehicles, 7.3 ft. deflection; Advantages: may retain some effectiveness after minor crash to its rigidity, less lateral deflection than cable system; Disadvantages: somewhat vulnerable to vaulting or underride caused by incorrect mounting height or irregular approach terrain
SEMI-RIGID SYSTEMS:		
Box Beam	8X6" steel tubes; deflection distance is 7 ft.; suitable for flat terrain; top of railing height is 30"	- Redirects 1,800-4,000 lb. vehicles, 4.8 ft. lateral deflection , field tests indicate that 4500 lb. vehicles can be redirected ; Disadvantages: somewhat vulnerable to vaulting or underride caused by incorrect mounting height or irregular approach terrain; failed to keep 4,640 lb. van upright
Blocked-Out W-Beam (Strong Post)	2-4 ft. deflection distance; typically used in 10 ft. wide medians; 30" mounting height	- Redirects 1,800-4,500 lb. vehicles, 2.1-2.9 lateral deflection; Advantages: block-out reduces vehicle snagging and vaulting by maintaining rail height during initial crash; may remain functional after moderate crash; less lateral deflection; most commonly used barrier system; Disadvantages: upper limit 25 deg. angle of impact with van and school bus, failure due to rolling of the vehicles

Table 2-D2. (continued) Median Barriers

TYPE	CHARACTERISTICS	IMPACT PERFORMANCE
SEMI-RIGID SYSTEMS:		
Blocked-Out Thrie Beam (Strong Post)	Increased depth of beam allows median barrier to handle a larger range of vehicle sizes than the roadside barrier; also can be modified with spacer blocks for increased performance	Redirects 1,800-4,380 lb. vehicles, assumed to meet 4,500 lb. vehicle, lateral deflection 1.5-3.3 ft.; Advantages: less lateral deflection, less prone to damage during a crash, higher rail mounting increases ability to redirect larger vehicles
Self Restoring Median Barrier (experimental)	A thrie beam rail is attached to each side of two trusses and hung on posts	Redirects 1,800-40,000 lb. vehicles, 2.5-3.9 ft. lateral deflection; Advantages: high performance barrier, designed to be maintenance free for most impacts, able to redirect large vehicles, minimizes occupant injury; recommended for use in areas where large vehicles traveling at high speeds are likely to impact the barrier; light weight makes it suitable for use on bridges Disadvantages: high cost (twice the cost of concrete safety shape barrier) limits application to select locations (i.e., locations with high frequency of crashes)
Sand-Filled Median Barrier (Mark VII)	Consists of continuous, free-standing, steel panels filled with sand; top of barrier height 42"	Redirected vehicles up to 20,000 lb. school bus; severe impacts will cause the barrier to be displaced laterally; Advantages: less severe impact consequences than rigid barrier Disadvantages: high initial cost and high maintenance cost

Table 2-D2. (continued) Median Barriers

TYPE	CHARACTERISTICS	IMPACT PERFORMANCE
RIGID SYSTEMS:		
Concrete Safety Shape or Concrete Median Barrier (CMB)	Sloped front and back face; may be slip-formed, pre-cast or cast in place; various footing and reinforcement techniques are used, longitudinal support near the top of the barrier limits the size and travel distance of concrete fragments that can occur with severe impacts; top of barrier height is typically 32 " with 42" and taller used for sites with high volume of large trucks or severe roadway geometry	32" New Jersey shape barrier redirects 1,800-4,500 lb. vehicles and 45,000 lb. buses during moderate impacts; 42" barrier redirects 80,000 lb. tractor -trailers (52 mph, 15 deg.); greater than 42" barriers are recommended to minimize overturning of high CG vehicles: Advantages: low cost, low maintenance, effective performance Disadvantages: during high speed, large angle impacts, vehicles can become airborne and reach the top of the barrier; and high CG vehicles may overturn intruding into the space above the barrier - the solution of increasing barrier height to counteract these problems includes a box beam retrofit installed at the top of the barrier
Earth Beam	Land form heights over 10 ft. and slope rates greater than 2:1 are not recommended; typically used to shield bridge piers	No test data available; should not be used in high angle impact areas; Advantages : Low cost, low maintenance Disadvantages: Limited application; only a limited portion of the beam is capable of redirecting an impacting vehicle

(from AASHTO, Roadside Design Guide, 1989)

* Current standard test criteria:
1) 1800 lb. vehicle impacting at 60 mph and 15 deg. to evaluate occupant risk; and
2) 4500 lb. vehicle impacting at 60 mph and 25 deg to assess structural integrity of barrier

1.3 BRIDGE RAILINGS

Unlike other types of longitudinal barriers that are set in or on the ground, bridge railings are structural extensions of the bridge. Bridge rails serve to guide traffic movement and prevent the travel of errant vehicles over the edge of the structure.

Bridge Rail Design - There are 4 service level bridge rails. Service level of a highway is determined by its traffic volume and vehicle travel speed. Service level 1 is used on secondary or local roads with low speed travel. Level 2 is a general service level and higher service level rails are used for locations with severe geometric conditions, heavy traffic areas, and heavy vehicle traffic areas. The tubular thrie beam retrofit railing and the New Jersey concrete safety shape bridge parapets, both high service level bridge rails, are able to redirect 20,000 lb. school buses at 40 mph and 15 degree impacts (McDevett, 1985). SERB bridge rail, also a high service level rail, deflects a few inches backward when impacted and is able to redirect errant vehicles so they are parallel to the rail. To protect bridge trusses, retrofit railings have been developed that include thrie beam, aluminum tru-beam, box beam and W-beam rail systems.

The ultra-tall wall (92 in. height) is used in areas where a vehicle cannot be permitted to penetrate and it prevents vehicles from rolling over the top of the barrier. The ultra-tall wall has successfully redirected an 80,000 lb. gasoline tank truck traveling at 53 mph with a 15 degree angle. This type barrier may be appropriate for MVE application, however, sight distance issues need to be considered, along with the potential ramifications of high speed impacts with a rigid barrier system.

1.4 BARRIER END TREATMENTS

Roadside barrier end treatment - The ends of barriers need to be treated in such a manner that they do not become fixed roadside obstacles. The turned-down W-beam guardrail end, called the "Texas Twist", was developed to prevent vehicles from being speared with rail ends. However, it is no longer used as it was found that the turned-down end of the rail (25 ft length) formed a ramp that launched impacting light weight vehicles. End treatments should be designed to have redirectional characteristics identical to the roadside barrier, which means the end must be adequately anchored. Today's barrier end treatment typically includes burying, covering with a mound of earth, flaring the end back, and placing crash cushions or break away cable terminals at barrier ends.

Examples of barrier end treatments include the controlled releasing terminal (CRT), designed so that the W-beam guardrail releases from the support posts and can be ridden down by light vehicles. An advantage of the CRT is that it has a straight rather than a flared terminal and, therefore, requires less space. The safe end treatment (SENTRE) terminal allows minimal penetration of the impacting vehicle by the W-beam rail end while the breakaway slipbase posts slide along a cable and redirect the vehicle away from the terminal. Energy from the impact is also absorbed by sand filled containers mounted on the posts.

The CRT and SENTRE terminals have safely redirected 1,800 lb. and 4,500 lb. vehicles traveling at 60 mph (McDevett, 1985). Research will be required to determine if these terminals would successfully pass tests with vehicles traveling at higher rates of speed. Also, terminal performance requirements for heavier weight MVEs impacts needs to be examined. A summary of end treatments is provided in Table 2-D3.

A barrier end treatment, designed so that is can be impacted on both sides of the terminal, will be required for AHS infrastructure I2 to shield both sides of transition lane barrier ends. Further, as crash-test data are unavailable for barrier end treatments using large vehicles, research will be necessary to determine performance requirements of barrier end treatments for MVEs.

Median barrier end treatment - The same considerations discussed for roadside barriers apply to the treatment of median barrier ends (see Table 2-D4).

Bridge railing end treatment - When interfacing the end of a bridge railing with a roadside barrier, the same degree of rigidity should be maintained between the systems so that the barrier does not "pocket" or "snag" the vehicle. Crash cushions are frequently used to protect exposed bridge rail ends. The presence of a curb at the ends of the bridge structure also impacts the bridge railing design that is used, as vaulting can occur when a vehicle strikes a curb.

Table 2-D3. Roadside Barrier End Treatments

TYPE	CHARACTERISTICS	IMPACT PERFORMANCE
Breakaway Cable Terminal (BCT)	37.5 ft. length, rounded metal end attached to strong or weak post; when struck head-on, the first 2 posts fracture, permitting the rail to bend away from the impacting vehicle; curved flare is essential for effective performance; can be adapted for thrie-beam barrier; top of rail height is 27"	Designed to minimize spearing and rollover; successfully crash-tested with 2,250 and 4,500 lb. vehicles, but too stiff for 1,800 lb. vehicles; attempts at retrofit unsuccessful
Eccentric Loader BCT (experimental)	37.5 ft. length, fabricated steel lever nose inside corrugated steel pipe; two layout designs, 4 ft. and 1.5 ft. off-set from tangent line of guardrail, are used; top of rail height is 27"	4 ft. off-set design successfully tested with 1,800 and 4,500 lb. vehicles; 1.5 ft. off-set design performance was marginal
Turned-Down Guardrail Terminal	25 ft. standard length (50-75 ft. also used), attached to W-beam or thrie beam railing, designed to collapse on impact; original designs had problems with vaulting and rolling; design variations (e.g., weaker post bolts, fastening clips) to weaken the terminal have not performed satisfactorily; flaring terminal end reduces potential for rollover and for capturing impacting vehicles	Successfully crash tested with 2,250 and 4,500 lb. vehicles; no conventional design can accommodate 1,800 lb. vehicle
Controlled Releasing Terminal (CRT) (experimental)	96 ft. length, C-rail used in turned-down section, allowing small tires of light vehicles to pass over the terminal without getting captured; adapted with blockouts and bend away attachments; complex design using wood and steel posts; will attach to W-beam or thrie beam railings; top of rail height is 27"	Successfully tested with 1,800 and 4,500 lb. vehicles; redirection begins where C-rail is at full height (1st post) but vehicle may travel along the barrier for some distance before exiting, therefore, requiring a larger recovery area (free of obstacles) that other terminals
Vehicle Attenuating Terminal (VAT) (experimental)	Consists a three stage system of slotted W-beam elements, breakaway wood posts and a cable anchorage system; depends on severity of impact; 27” top of rail height	Successfully tested with 1,800 lb. vehicle (60 mph) and 4,500 lb. vehicle (60 mph); maintenance requirements are higher because system is complex and requires many parts, however many parts can be reused after an impact

Table 2-D3. (continued) Roadside Barrier End Treatments

TYPE	CHARACTERISTICS	IMPACT PERFORMANCE
Crash-Cushion Attenuating Terminal (CAT) (experimental)	Modified VAT design; can be struck from right or left side; appropriate for semi-rigid median barrier terminal or in narrow gore areas or as an attentuator for rigid barriers or fixed obstacles if additional transition section is used; 44 ft. length	Successfully tested with 1,800 and 4,500 lb. vehicles, for one- and two-sided impacts and head-on impacts
SENTRE (experimental)	System combines guardrail redirection and impact attenuation; the system is mounted on a concrete pad and consists of telescoping thrie beam fender panels, slip-base support posts, and sand-filled plastic containers; can be mounted parallel to roadway or flared with 4 ft. offset; 23 ft. length; top of rail height is 32"	Successfully tested with 1,800 and 4,500 lb. vehicles for both parallel and 4 ft. offset installation; maintenance requirements higher because system is complex and requires many parts, however many parts can be reused after an impact
TREND (experimental)	Designed specifically to shield rigid barrier ends or fixed objects; has redirective and attenuative properties; same design as SENTRE except a steel tension strap connects the TREND posts to the rigid barrier and serves to redirect vehicles impacting the side of the terminal;	Successfully tested with 1,800 and 4,500 lb. vehicles, suitable for use in areas with limited space
3-Strand Cable Terminal	Barrier specific designs; best performing design comprised of steel posts and cable flared back at full height to 3.5 ft. offset, then turned down and anchored to a concrete block	Successfully tested with 1,800 and 4,500 lb. vehicles; less complex design
Anchored in Backslope	Barrier terminated in backslope; appropriate for rigid and semi-rigid barriers; barrier height, flare rate and approach terrain must be considered	Limited testing performed; with a shallow grade, a 27" W-beam rail, flared at 13:1, it was found that a 4,500 lb. vehicle (60 mph ,25 deg) vaulted the barrier on impact. However, when the rail was raised to a constant height throughout the flare, the system successfully redirected 1,800 and 4,500 lb. vehicles (60 mph, 20 deg); low maintenance
Earth Mound	Barrier end is covered with and earth berm; construction must be transversable; appropriate for rigid and semi-rigid barrier ends	No crash testing conducted; low maintenance

(from AASHTO, Roadside Design Guide, 1989)

Table 2-D4. Median End Treatment

TYPE	CHARACTERISTICS	IMPACT PERFORMANCE
Flared	Must be located at a distance from the roadway that does not present a hazard; appropriate flare rate must be used, positive end anchorage	• Only used when located away from approaching traffic (unlikely to be impacted) • The higher the flare rate the greater the angle of impact • Flaring increases the potential for vehicles to be redirected back into or across the roadway
Tapered	Intended to prevent spearing and high deceleration of impacting vehicles used only in areas where it is unlikely to be impacted or in low level speed areas.	• Can cause impacting vehicle to become airborne or overturn
Flared & Tapered	Used only in areas where it is unlikely to be impacted.	• Can cause impacting vehicle to become airborne or overturn.
Earth Beam	Same design principle as tapered end treatment; should not be used where impacting vehicle could enter opposing traffic	• No redirectional capabilities
Anchored in Back Slope	Similar to earth beam, only back slope already exists	• Redirectional capabilities questionable
Shielded (Crash Cushions)	Space limitations restrict crash cushion types that can be used, e.g., GREAT - 2 ft. wide, can be used in narrow medians; Sand Barrels are used in wider medians	• Redirectional capabilities

1.5 BARRIER SELECTION CRITERIA AND AHS CONSIDERATIONS

The criteria used to select an appropriate barrier for a particular highway site are provided in Table 2-D5. The criteria are considered in the context of AHS performance requirements.

Table 2-D5. Selection Criteria For Barriers

Criteria	Comments	AHS Considerations
Performance capability	Barrier must be structurally able to contain and redirect design vehicle	Increased performance capability required for higher velocity impacts and MVEs
Deflection	Barrier deflection should not exceed deflection space	-Minimal deflection space for lane dividers -Gore areas may need to be increased to accommodate higher velocity impacts
Site conditions	Distance from traveled way (too great a distance may rule out using a rigid barrier due to wide angle impact potential); Slope approaching barrier (if steeper than 10:1 a flexible barrier should be used); Narrow grade and shoulder widths (deeper embedment, closer post spacing or soil plates may be needed)	Increased travel distance to barrier with breakdown lane may increase potential for large angle impact
Compatibility	Barrier must be compatible with end treatments and other adjacent barrier systems (e.g., bridge railings)	Tests of compatibility between new/upgraded barrier systems and adjoining bridge rails or end treatments will be necessary
Cost	High performance barriers are more costly	High performance barriers may be required for high velocity impacts and MVEs

Table 2-D5. (continued) Selection Criteria For Barriers

Criteria	Comments	AHS Considerations
Maintenance: Routine	Routine maintenance typically standard across systems for time and cost	Barrier systems requiring less routine maintenance will result in less AHS down time
Collision	Flexible or semi-rigid systems typically require significantly more post-crash maintenance than rigid or high performance barriers	Existing flexible and semi-rigid barriers do not appear capable of redirecting vehicles traveling at higher speeds or MVEs/high CG vehicles
Material storage	Using similar systems requires less storage	Minimal storage is preferable for AHS
Simplicity	Simpler designs are easier to repair properly and less costly	High performance barriers tend to have more complex designs. A low maintenance, high performance system is preferred for AHS
Aesthetics	Barrier designs for environmentally sensitive locations.	-AHS greater traffic volume increases the importance of noise containment -Appearance may be an issue in some locations
Environmental factors	Drifting snow/sand, restriction of driver's sight distance may influence barrier selection. Snow plow blades may tear metal rails and loosen hardware. Corrosive urban environment may cause rapid deterioration of railing.	-Taller barriers required for high CG vehicles may create sight distance problems for smaller vehicles -Snow build-up next to solid barrier systems, such as the Concrete Safety Shape -Corrosive environment should be considered in barrier performance evaluation
Field experience	Monitoring of barrier performance is necessary to identify problems that require an alternate barrier system	Monitoring of new/upgraded/existing barrier systems will be needed to assess ability to meet AHS requirements

(From AASHTO, Roadside Design Guide, 1989)

1.6 BARRIER RELATED ROLLOVER CRASHES

Rollover crashes generally involve single vehicle crashes where the vehicle has departed from the road. Terhune (1988, 1991) investigated the role of roadside features in vehicle rollovers using single vehicle crash data from the National Accident Sampling System (NASS). Some of the roadside features included in the study are dividers, bridge rails guard rails, and curbs. The likelihood of a rollover when contacted by road-departing vehicles are as follows:

Table 2-D6. Rollover Likelihood Given Roadside Feature Contact

Road side Feature	Likelihood of Rollover Given Feature Contact (percent, approx.)
Curb	10
Guard rail	13
Divider	13
Bridge rail	15
Wall	17

Six of the rollover categories used to classify rollover crashes in the study can be seen in Table 2-D7 (from Terhune, 1991).

Table 2-D7. Attributed Causes of the Main Rollover Types

	{PRIVATE }ROLLOVER TYPE			
{PRIVATE }ATTRIBUTED CAUSE	Tripover	Flipover	Fallover	Other Type
Curb	1.60%	0.00%	0.00%	0.00%
Bridge rail	0.00%	0.00%	0.00%	4.20%
Guard rail	0.80%	0.00%	0.00%	4.20%
Divider	0.00%	3.10%	3.80%	4.20%
Wall	0.00%	0.00%	3.80%	0.00%
Total Rollovers	247	32	26	24

According to AASHTO (1989), it has been found that crash potential can be reduced by rounding at the shoulder and at the toe of an embankment slope, e.g., the likelihood of a vehicle becoming airborne is reduced with rounded slopes.

2.0 DATA FILES AND FILTERS TO DEFINE TRAFFIC BARRIER CRASHES

Interstate Barrier Crash Characteristics (GES)
Variable restrictions:
{PRIVATE }

EVENT1 >32,<37	(first harmful or injury producing event limited to collision with an impact attenuator/crash cushion, bridge structure (bridge pier/abutment/parapet end/rail), and concrete traffic barrier or other longitudinal barrier type)
INT_HWY = 1	(crash occurred on an interstate highway)

Manner of Collision with Barrier (CDS)
Variable Restrictions:

{PRIVATE }ACC_TYPE <11	(single driver, right/left roadside departure)
OBJ_CONT1 >53 <57	(concrete traffic barrier, impact attenuator or other traffic barrier (including guardrails))
SPLIMIT > 50 mph	(speed limit constrained to greater than 50 mph)

Occupant Injury and Vehicle Damage Severity for Barrier Crashes Resulting in Frontal Damage (CDS)
Variable restrictions:

{PRIVATE }ACC_TYPE <11	(single driver, right/left roadside departure
OBJ_CONT1 >53 <57	(concrete traffic barrier, impact attenuator or other traffic barrier (including guardrails))
TDD1 = W or E	(type of damage distribution limited to wide or corner impact area)
GAD1 = F	(general area of damage limited to front)
SPLIMIT > 50 mph	(speed limit constrained to greater than 50 mph)

Injuries and Crash Events Associated with Wide Frontal Damage in Barrier Crashes (CDS)
Variable restrictions:

{PRIVATE }ACC_TYPE < 11	(single driver, roadside departure)
OBJ_CONT1 = 54-56	(concrete traffic barrier, impact attenuator or other traffic barrier (including guardrails))
TDD1 = W	(type of damage distribution limited to wide impact area)
GAD1 = F	(general area of damage limited to front)
SPLIMIT > 50 mph	(speed limit constrained to greater than 50 mph)

3.0 STATISTICS FOR BARRIER CRASHES (GES)

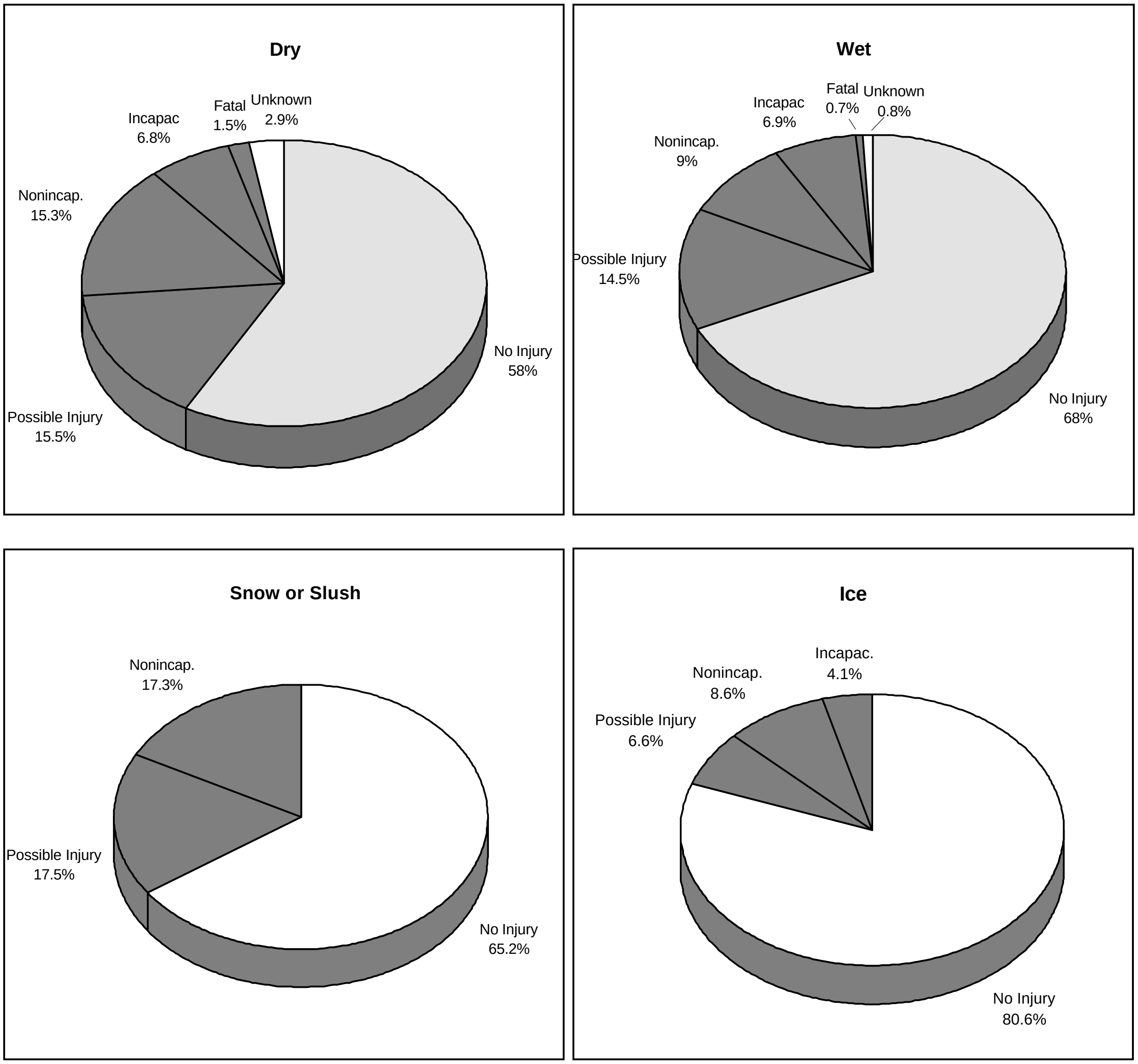


Figure 2-D1. Injury Severity by Road Surface Condition for Occupants of Vehicles Involved in Interstate Barrier Crashes

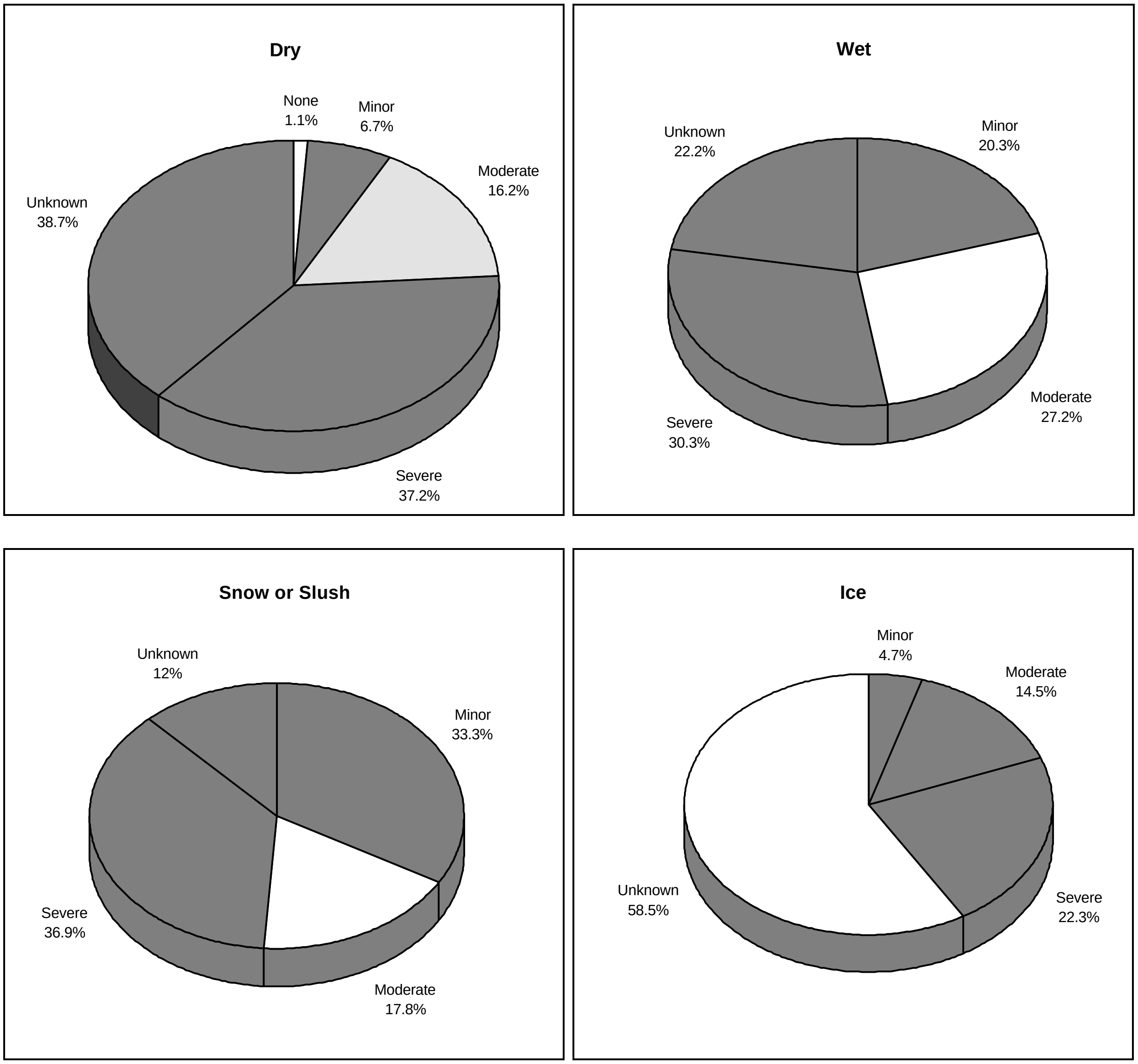


Figure 2-D2. Vehicle Damage by Road Surface Condition for Vehicles Involved in Interstate Barrier Crashes

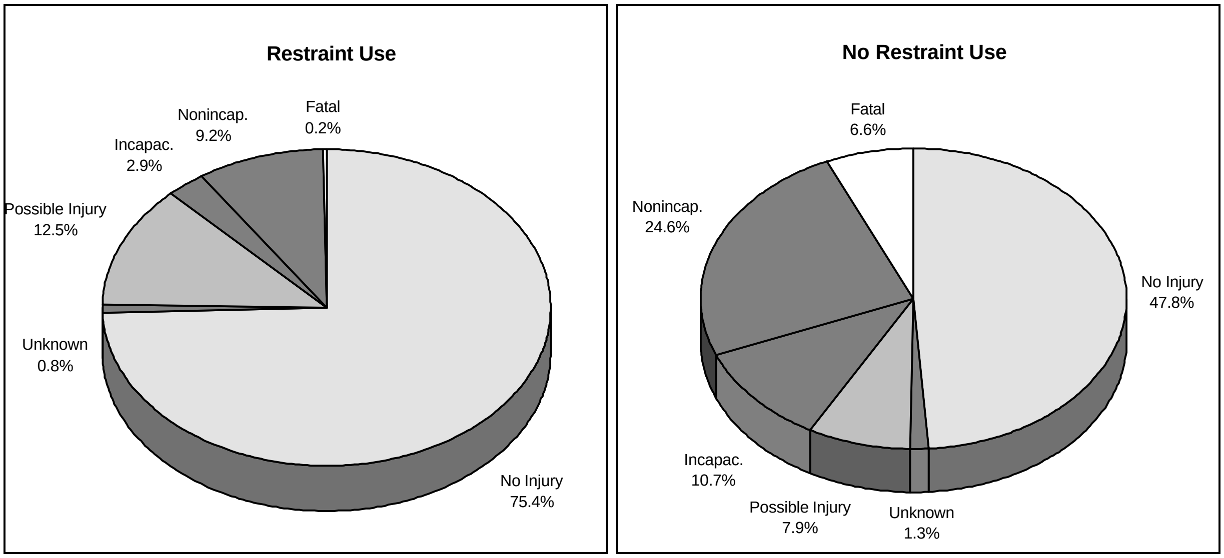


Figure 2-D3. Injury Severity by Restraint Protection for Occupants of Vehicles Involved in Interstate Barrier Crashes

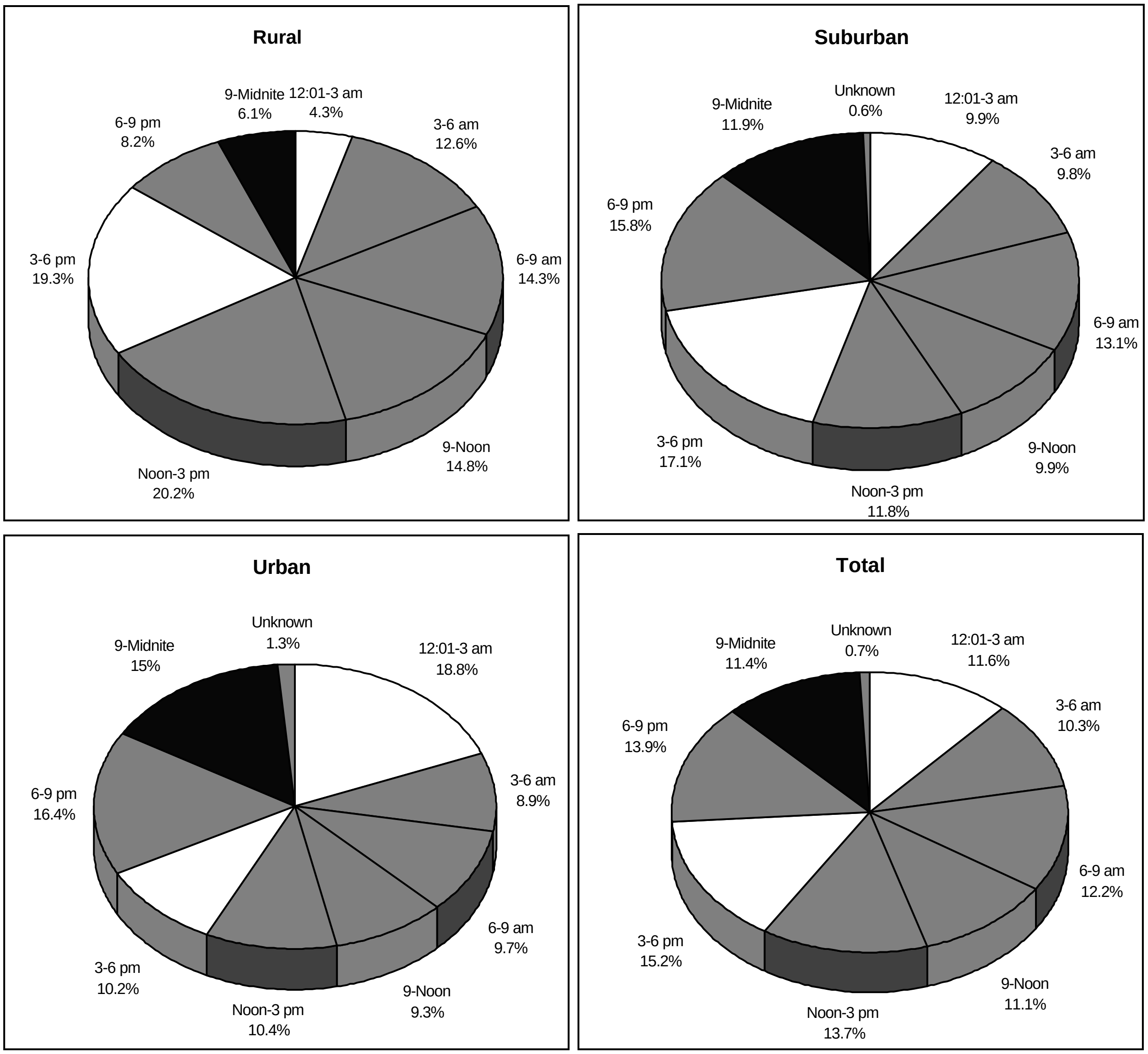


Figure 2-D4. Time of Day by Location for Interstate Barrier Crashes

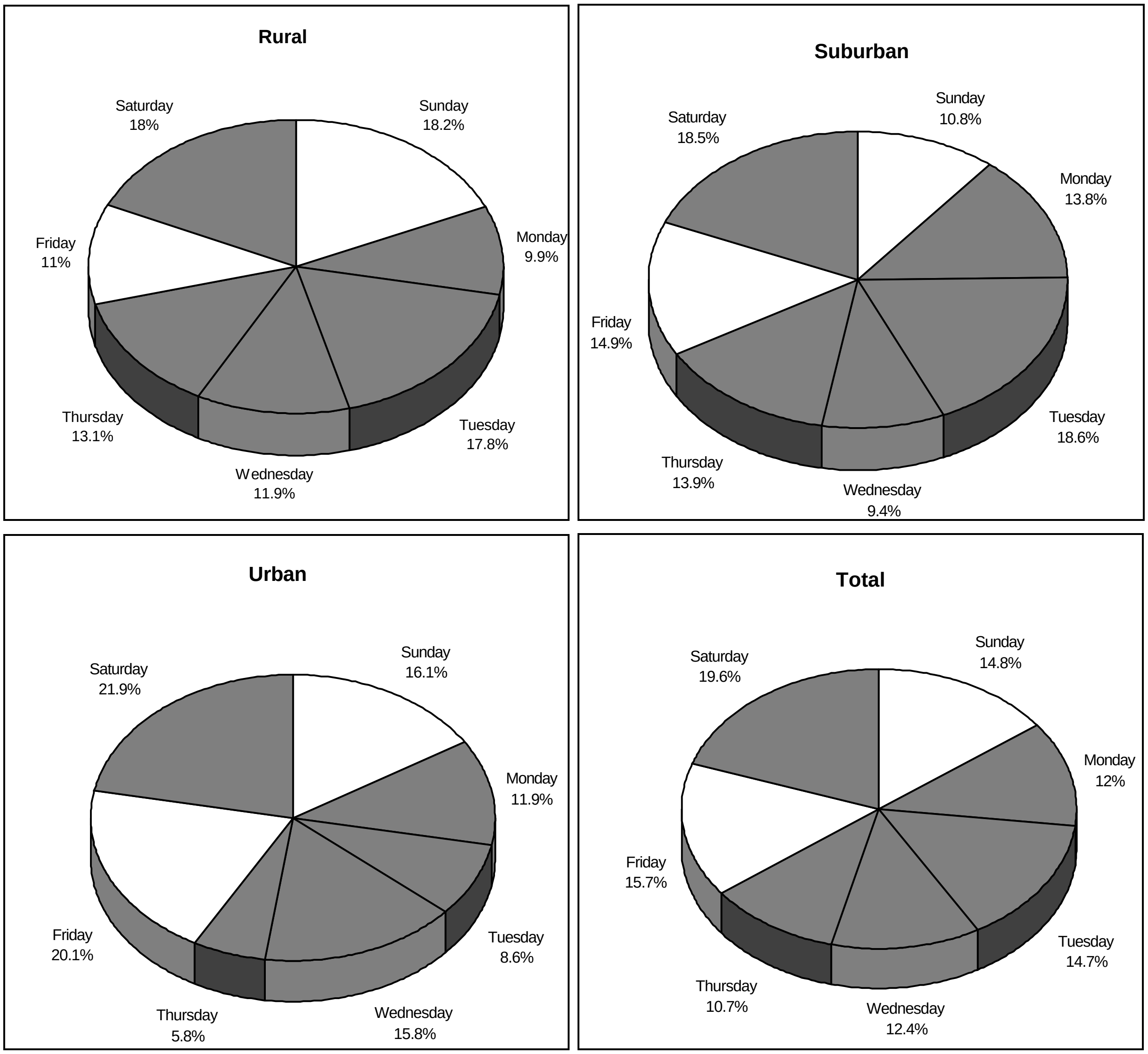


Figure 2-D5. Time of Day by Location for Interstate Barrier Crashes

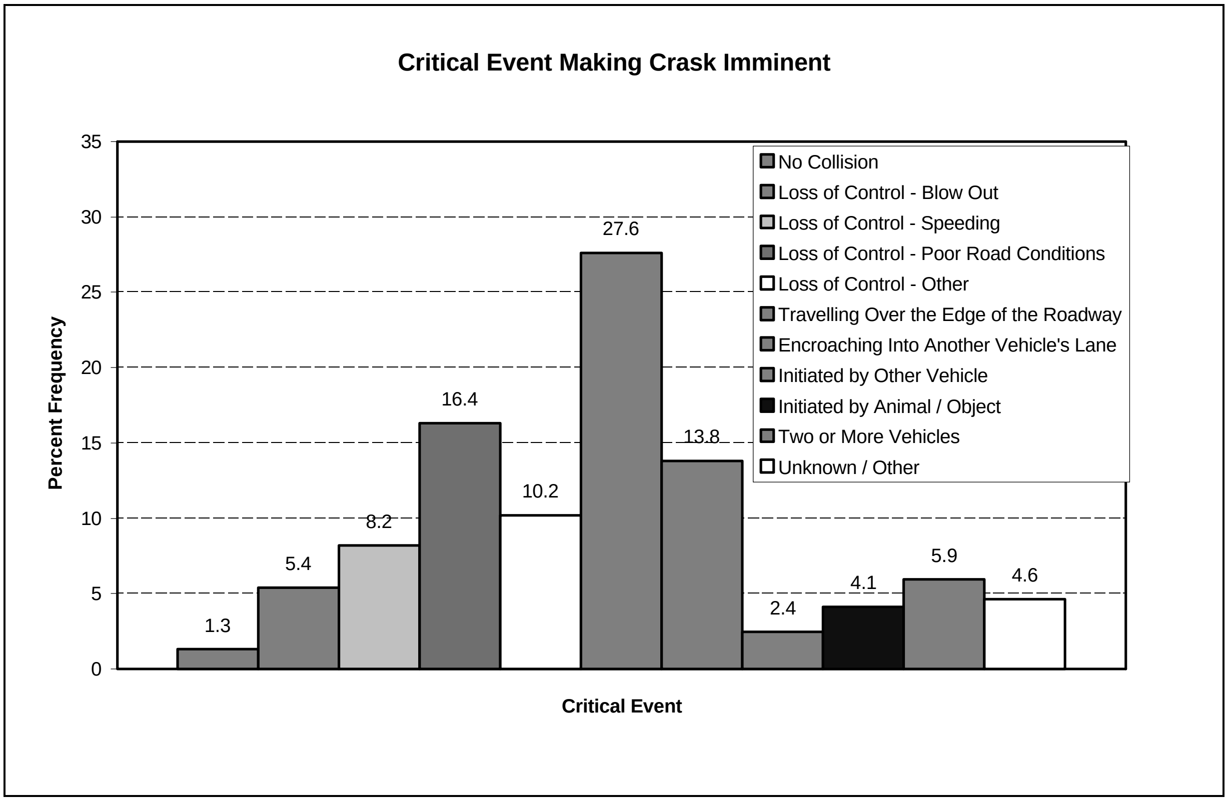


Figure 2-D6. Critical Event Making Crash Imminent for Interstate Barrier Crashes

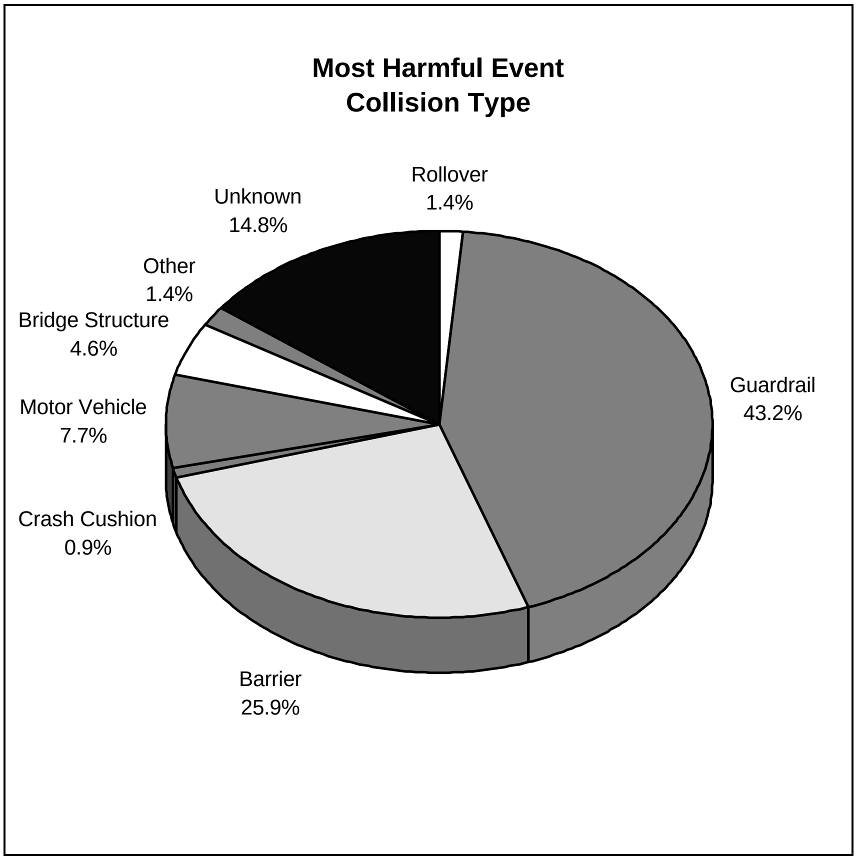


Figure 2-D7. Most Harmful Event for Interstate Barrier Crashes

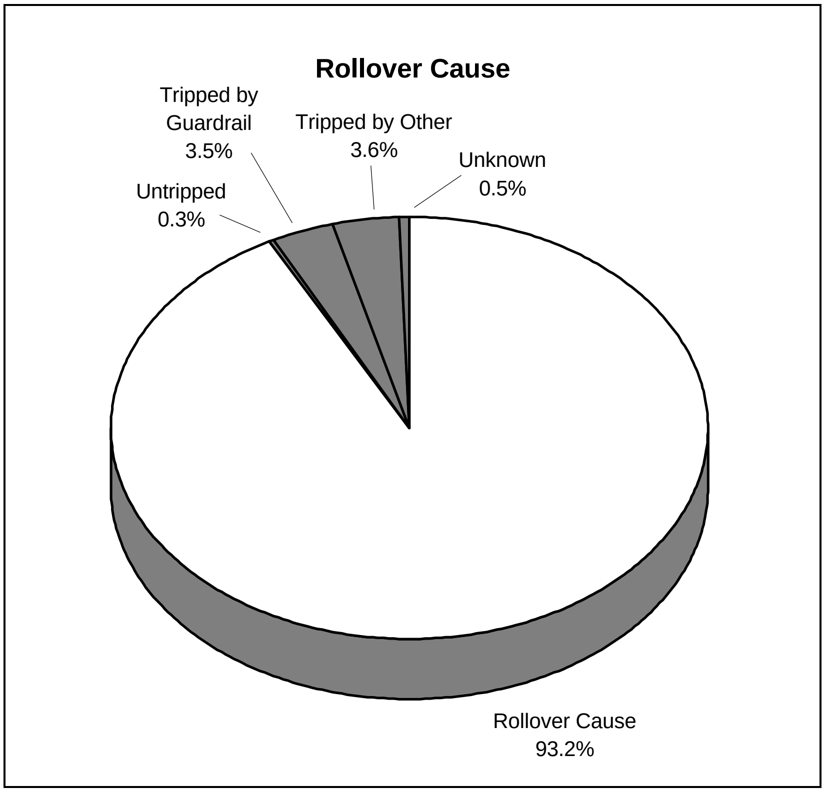


Figure 2-D8. Rollover Causes for Interstate Barrier Crashes

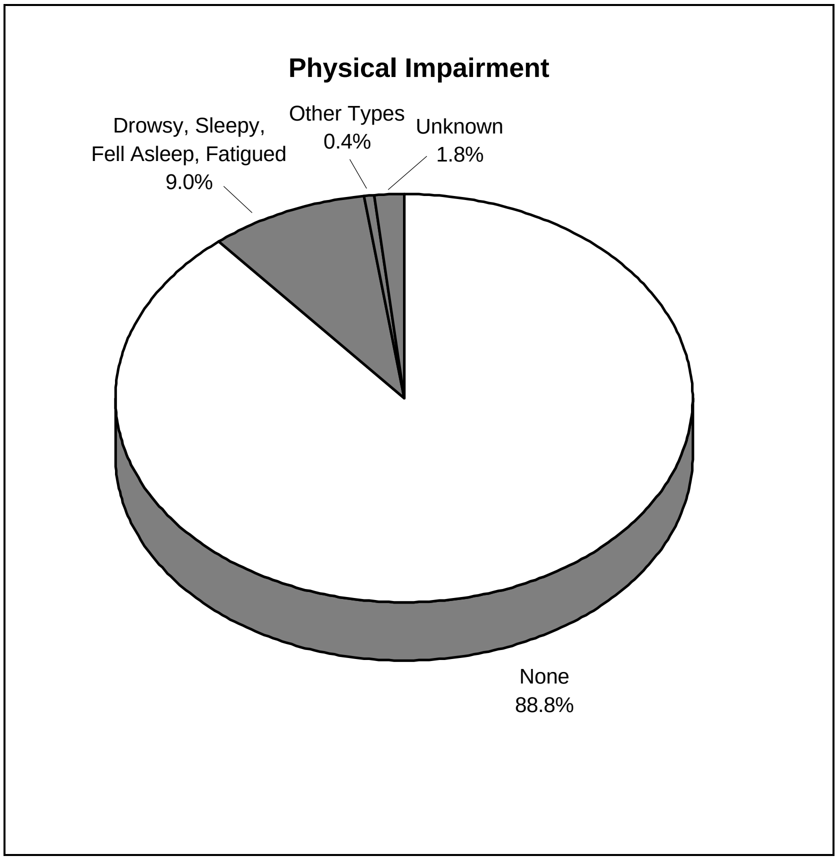


Figure 2-D9. Impairments of Drivers Involved in Interstate Barrier Crashes

4.0 STATISTICS FOR BARRIER CRASHES (CDS)

Table 2-D8. Type of Damage Distribution for Barrier Crashes

Damage Distribution	Narrow Corner	Narrow Area	Sideswipe	Wide Area	Unknown	Total
Frequency	4445	547	1488	7588	10687	24755
Percent (%)	17.9	2.2	6.0	30.7	43.2	100

Table 2-D9. General Area of Damage for Barrier Crashes

Deformation Location	Rear	Front	Left	Right	Unknown	Total
Frequency	494	12474	272	827	10688	24755
Percent (%)	2.0	50.4	1.1	3.3	43.2	100

Table 2-D10. Accident Type for Barrier Crashes

Accident Type	Drive Off Road - R.S. Departure	Control/Traction Loss - R.S. Departure	Drive Off Road - L.S. Departure	Control/Traction Loss - L.S. Departure	Other	Total
Frequency	784	715	100	3996	1475	7070
Percent (%)	11.1	10.1	1.4	56.6	20.9	100.0

Table 2-D11. Restraint Protection by Maximum Injury in Vehicle for Barrier Crashes

Injury	Unrestrained	Restrained	Row Total
None	583 5.76 16.2	2156 21.3 33.1	2739 27.1
Minor	1894 18.7 52.6	4160 41.1 63.8	7054 69.7
Moderate	46 0.5 1.3	113 1.1 1.7	159 1.6
Serious	1014 10.0 28.2	82 0.8 1.3	1096 10.8
Critical		6 0.1 0.1	6 0.1
Maximum	7 0.1 0.2		7 0.1
Unknown	57 0.6 1.6		57 0.6
Column Total	3601 35.6	6517 64.4	10118 100.0

Table 2-D12. Deformation Extent (Highest) for Barrier Crashes

Deformation Extent	1	2	3	6	7	9	Total
Frequency	2636	3806	493	5	23	108	7071
Percent (%)	18.6	26.9	3.5	0.0	0.2	0.8	100.0

Table 2-D13. Restraint Protection by Maximum Treatment in Vehicle for Barrier Crashes

Treatment	Unrestrained	Restrained	Row Total
None	1769 17.5 49.1	3343 33.0 51.3	5112 50.5
Fatal	85 0.8 2.4	6 0.1 0.1	91 0.9
Hospitalized	975 9.6 27.1	243 2.4 3.7	1218 12.0
Treated and Released	773 7.6 21.5	1384 13.7 21.2	2157 21.3
Treated Later		1541 15.2 23.6	1541 15.2
Column Total	3601 35.6	6517 64.4	10118 100.0

Table 2-D14. Maximum Injury by Object Contacted for Barrier Crashes

Injury	Concrete Barrier	Impact Attenuator	Other	Row Total
None	1362 19.3 29.2		323 4.6 14.0	1685 23.8
Minor	3061 43.3 65.6	39 0.6 40.2	1025 14.5 44.4	4125 58.3
Moderate	121 1.7 2.6		113 1.6 4.9	234 3.3
Serious	111 1.6 2.4		849 11.8 36.8	960 13.6
Critical	6 0.1 0.1			6 0.1
Maximum	4 0.1 0.1			4 0.1
Unknown		58 0.8 59.8		57 0.8
Column Total	4664 65.9	97 1.4	2310 32.7	7071 100.0

Table 2-D15. Maximum Treatment in Vehicle by Object Contacted for Barrier Crashes

Treatment	Concrete Barrier	Impact Attenuator	Other	Row Total
None	2549 57.1 30.0		323 14.0 4.6	2872 40.6
Fatal	10 0.2 0.1		42 1.8 0.6	52 0.7
Hospitalized	104 2.2 1.5	97 1.4 100.0	920 39.8 13.0	1121 15.9
Treated and Released	1480 31.7 20.9		776 33.6 11.0	2265 32.0
Treated Later	522 11.2 7.4		249 10.8 3.5	771 10.9
Column Total	4664 65.9	97 1.4	2310 32.7	7071 100.0

APPENDIX E

1.0 DATA FILES AND FILTERS TO DEFINE INTERSTATE DEPARTURE CRASHES

Interstate roadway departure crashes are characterized by data from the 1992 GES data files. The analysis is limited to single vehicle run-off-road crashes on interstate highways where the first harmful event occurs off the roadway and the precrash situation is characterized by a right or left roadside departure or a forward impact (excluding pedestrians or animals). The GES variable restrictions are:

INT_HWY = 1	(crash occurred on an interstate highway)
VEH_INVL = 1	(single vehicle collision)
REL_RWY = 2,3,4	(on shoulder or parking lane, off roadway/shoulder/parking lane, on median)
ACC_TYPE = 1-12,14-16	(right or left roadside departure or forward impact excluding pedestrians/animals)
BODY_TYP < 90	(excludes off road vehicles, snowmobiles, farm equipment, etc.)

All tabulations represent GES weighted estimates.

CDS data are used to provide a more accurate assessment of occupant injury resulting from run-off-road crashes. Vehicle damage is not assessed since the extent information is not straightforward for the variety of crush configurations that may occur with vehicles involved in this crash type. As a result, the algorithms used to calculate ΔV information do not apply to this crash type.

Data from the CDS files are restricted to roadways where the posted or statutory speed limit is greater than 50 mph, since interstate highway information is not available in the CDS data set. As with the GES data file, the precrash situation is characterized by a right or left roadside departure or a forward impact (excluding pedestrians or animals). The CDS variable restrictions are:

SPLIMIT > 50	(crash occurred on highway with posted or statutory speed limit greater than 50 mph)
VEHFORMS = 1	(# general vehicles forms submitted = 1)
ACC_TYPE = 1-12,14-16	(right or left roadside departure or forward impact excluding pedestrians/animals)

All CDS frequencies represent weighted estimates.

2.0 STATISTICS FOR INTERSTATE DEPARTURE CRASHES (GES)

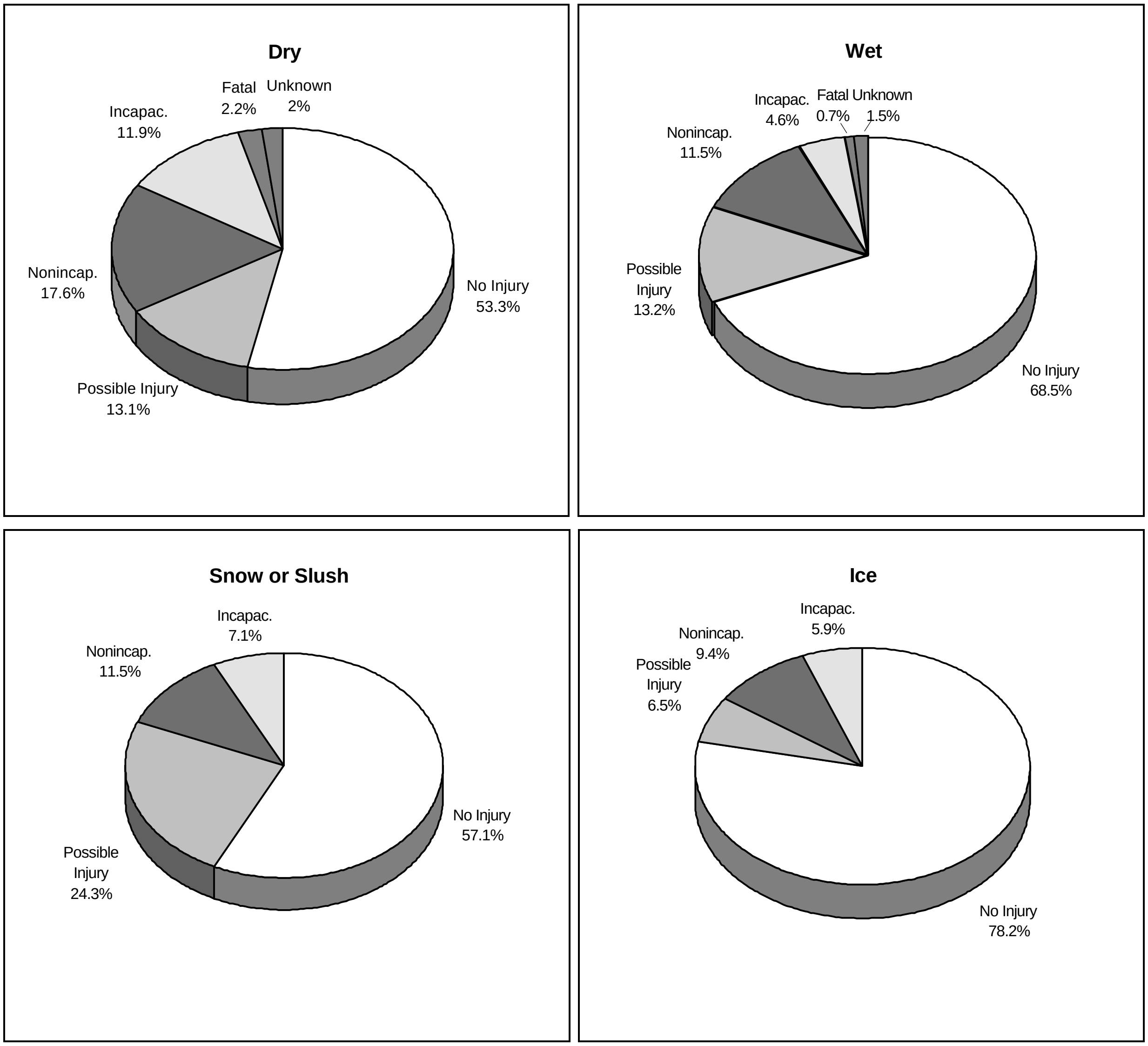


Figure 2-E1. Occupant Injury Severity by Surface Condition for Interstate Departure Crashes

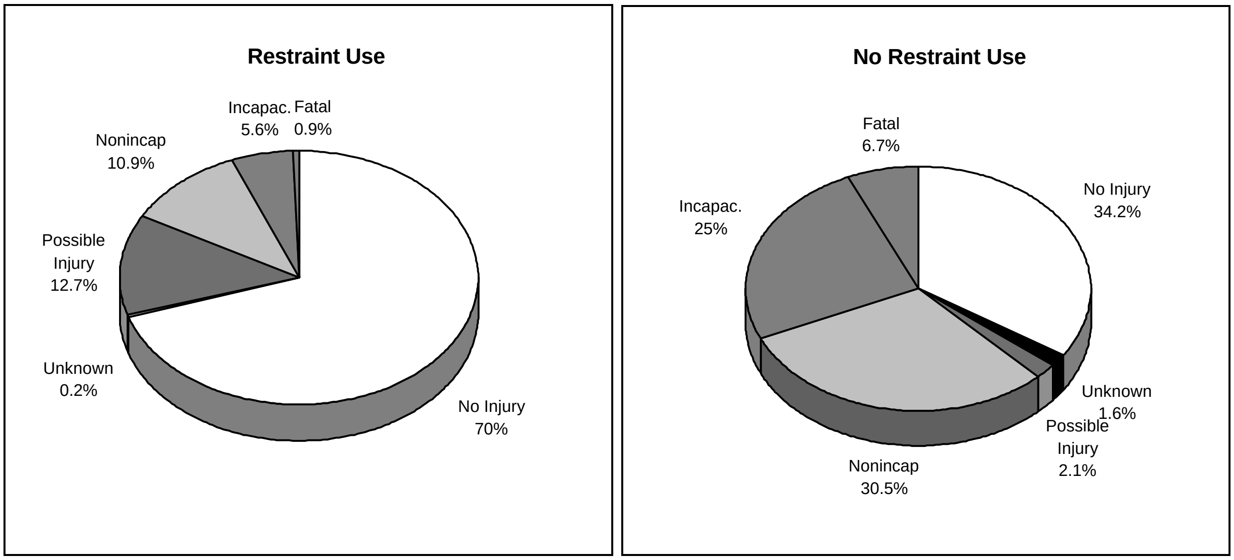


Figure 2-E2. Occupant Injury Severity by Restraint Use for Interstate Departure Crashes

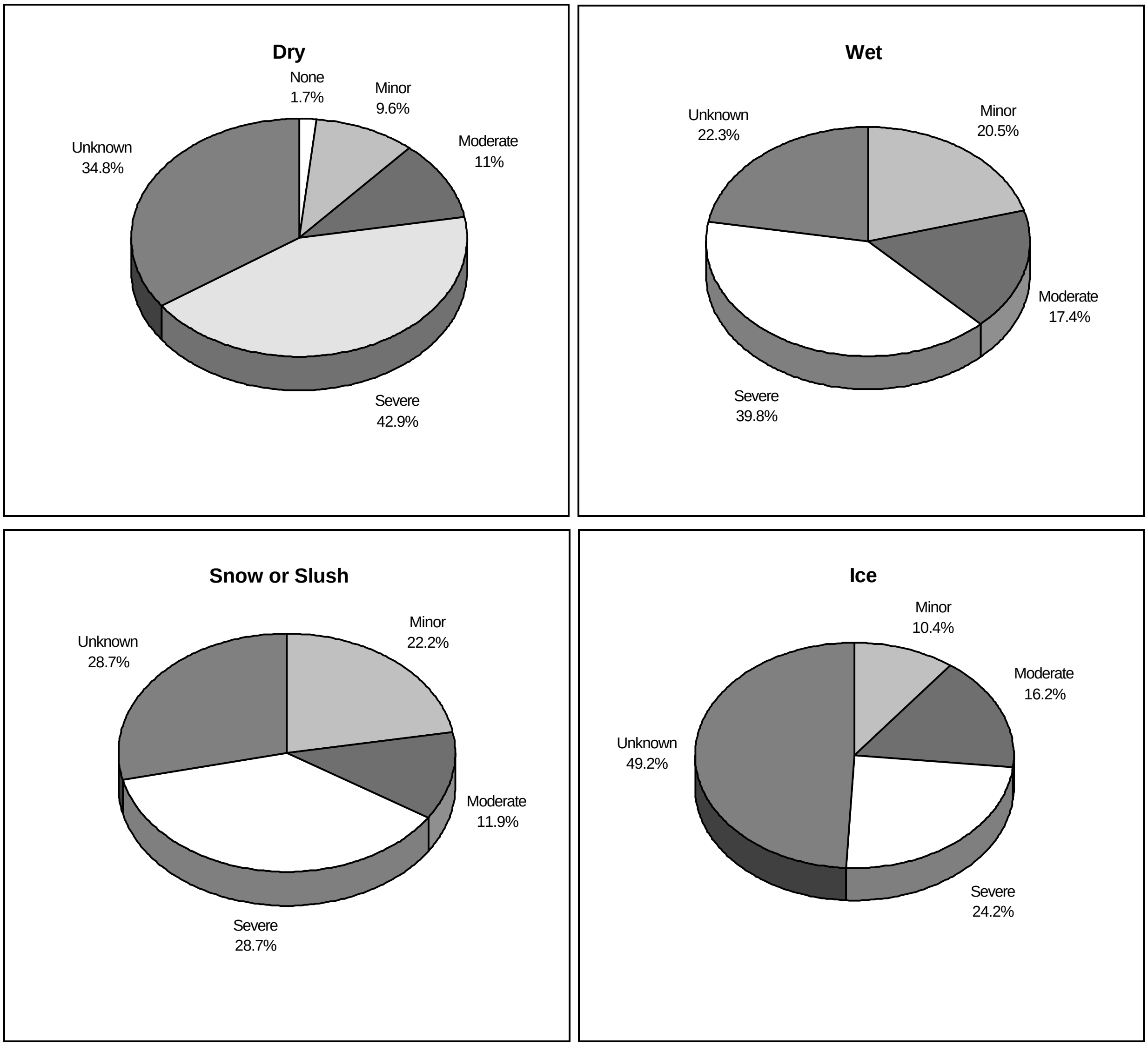


Figure 2-E3. Vehicle Damage by Surface Condition for Interstate Departure Crashes

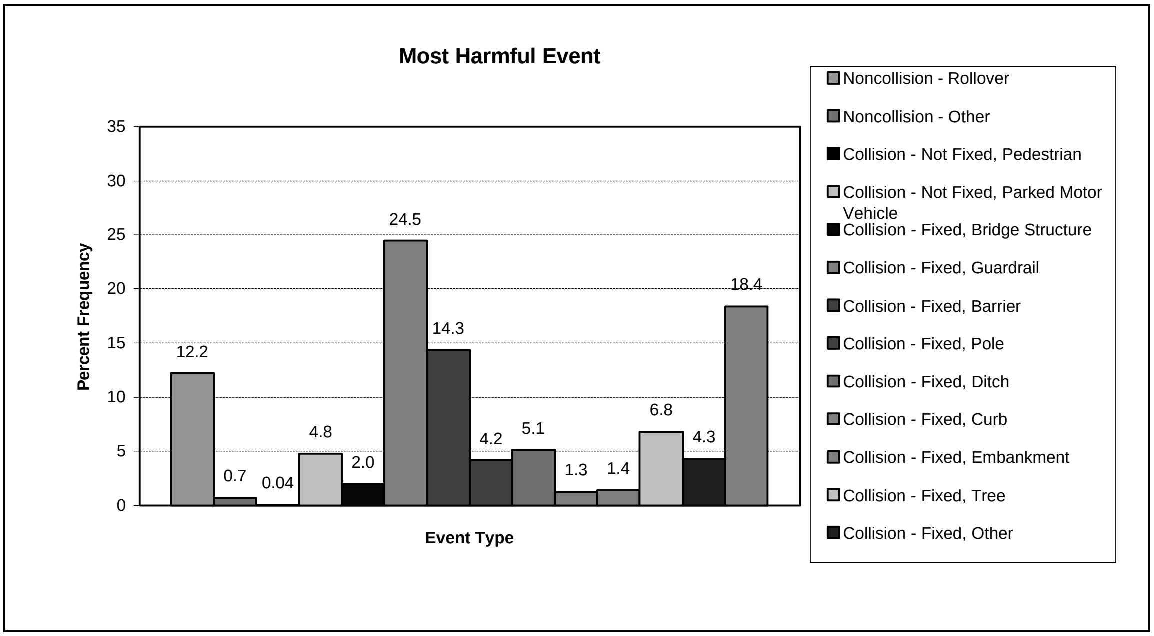


Figure 2-E4. Most Harmful Event for Vehicles Involved in Interstate Departure Crashes

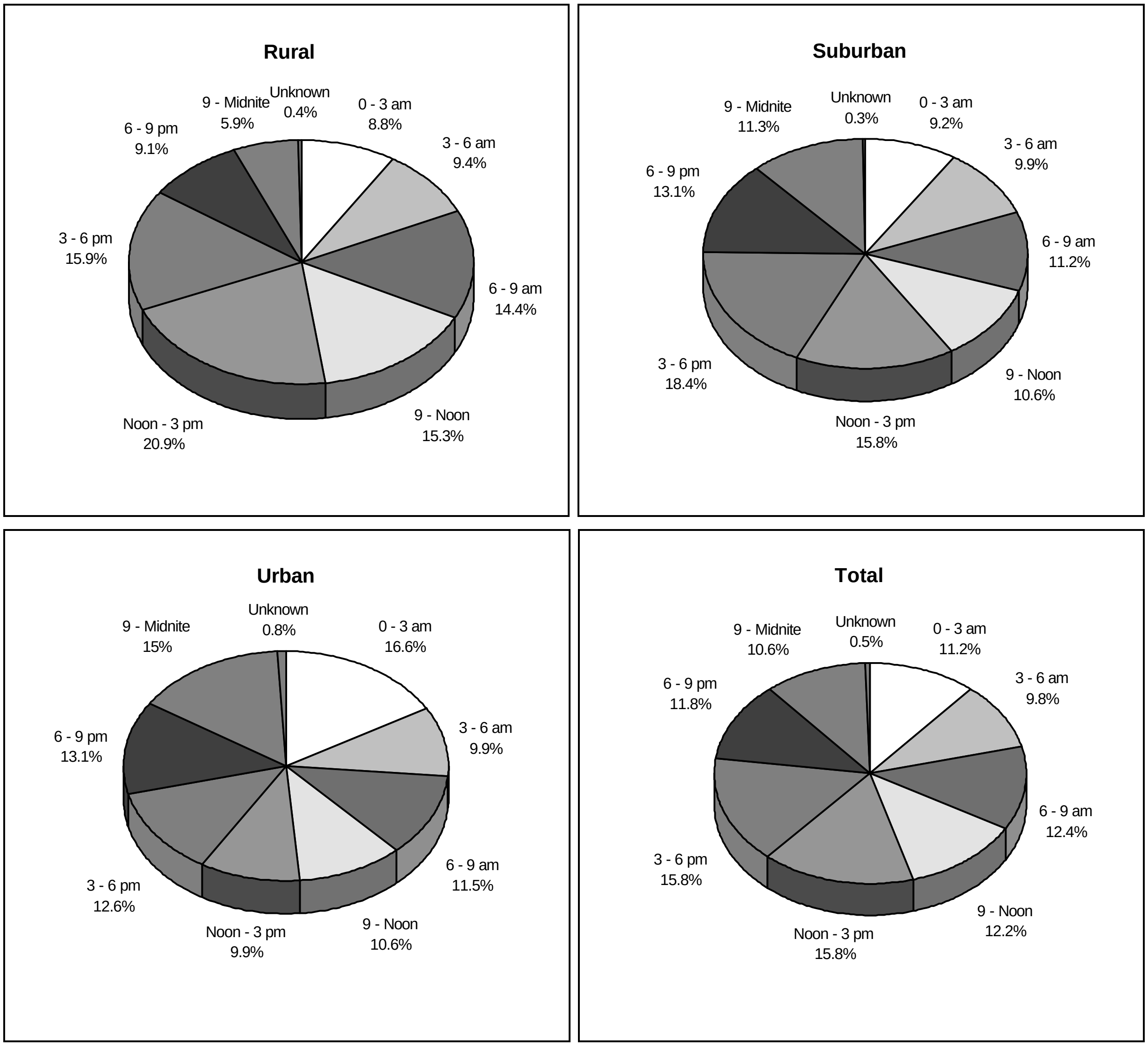


Figure 2-E5. Time of Day for Interstate Departure Crashes

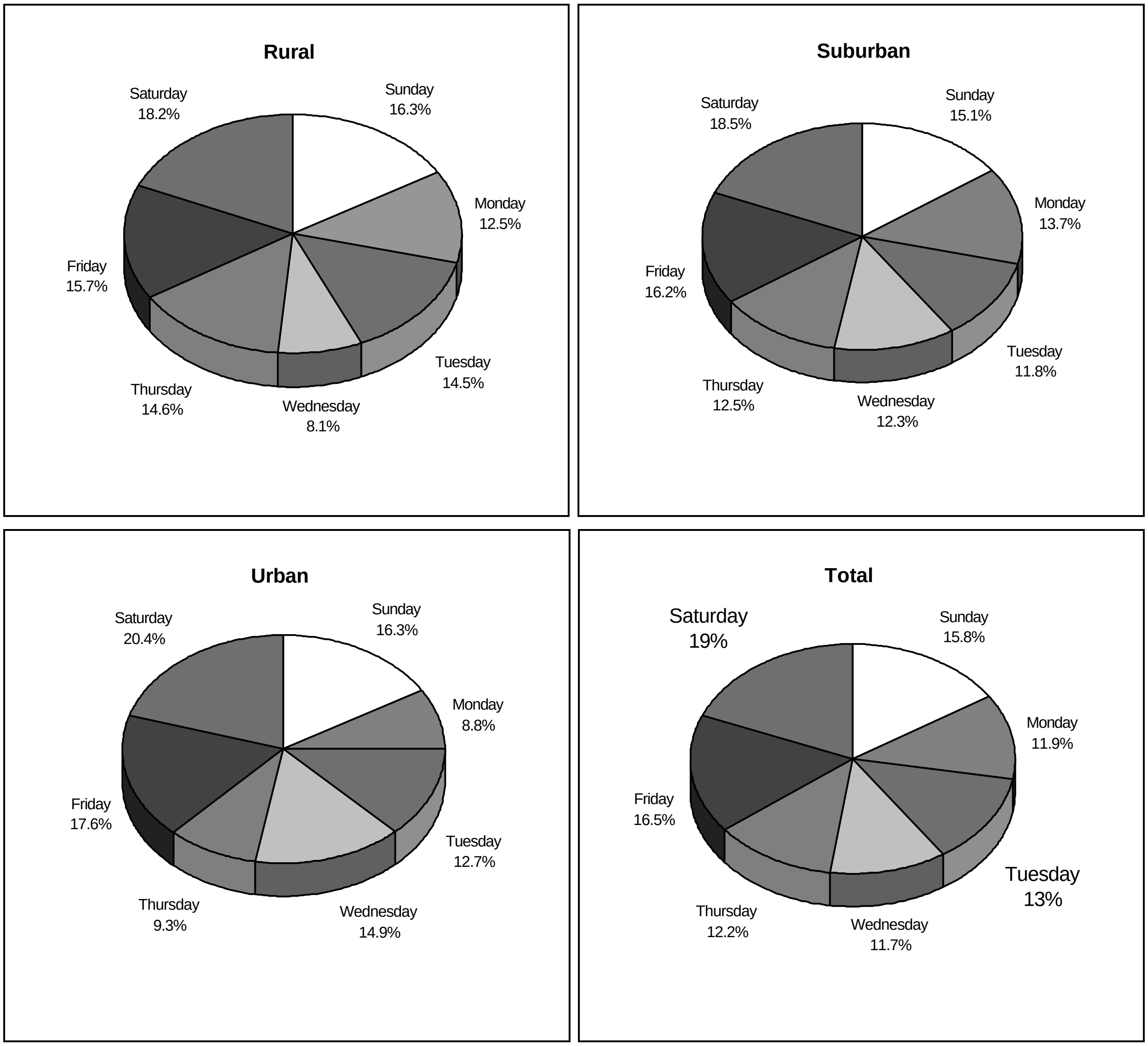


Figure 2-E6. Day of Week for Interstate Departure Crashes

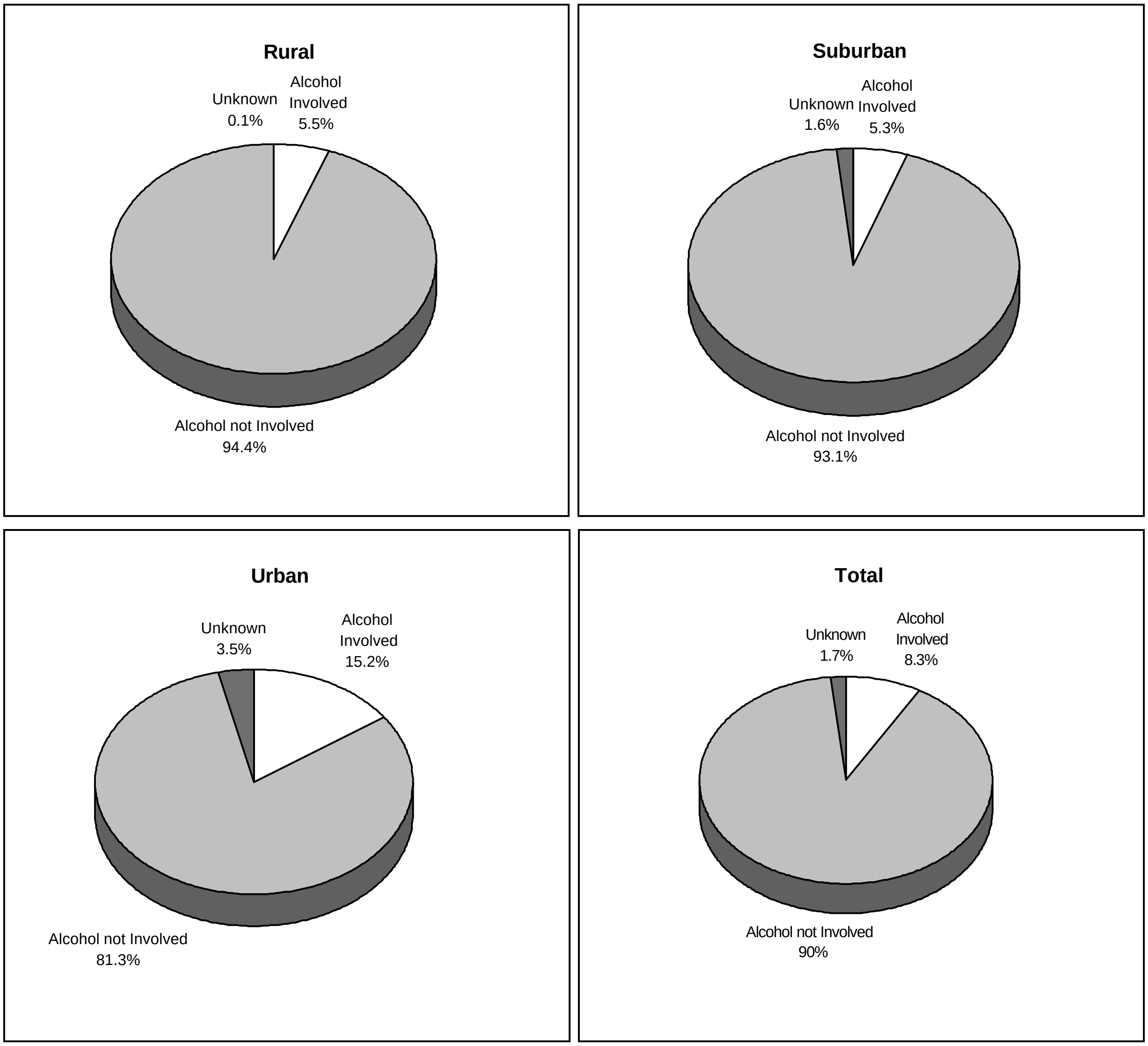


Figure 2-E7. Police Reported Alcohol Involvement for Interstate Departure Crashes

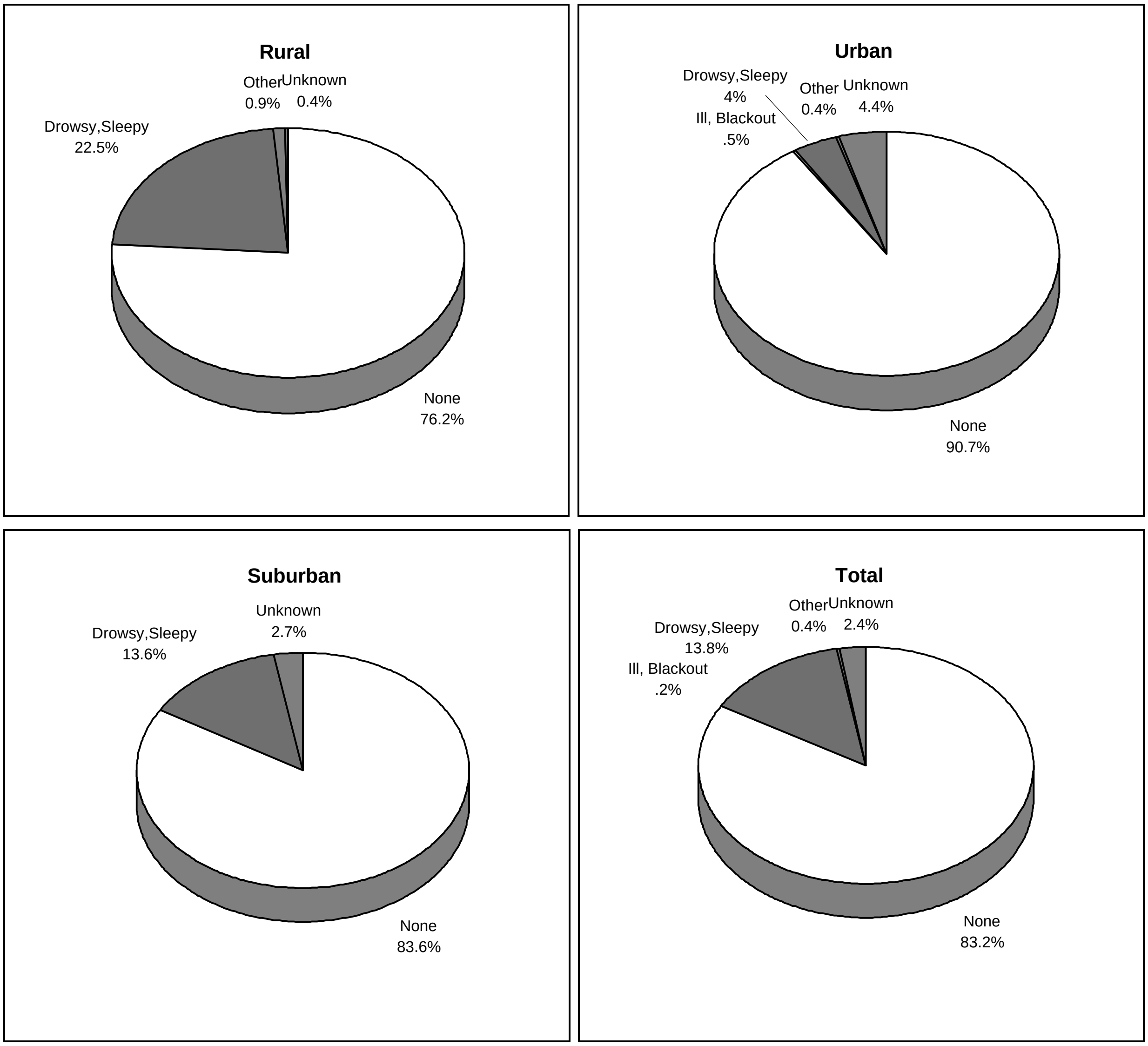


Figure 2-E8. Driver Impairment by Location for Interstate Departure Crashes

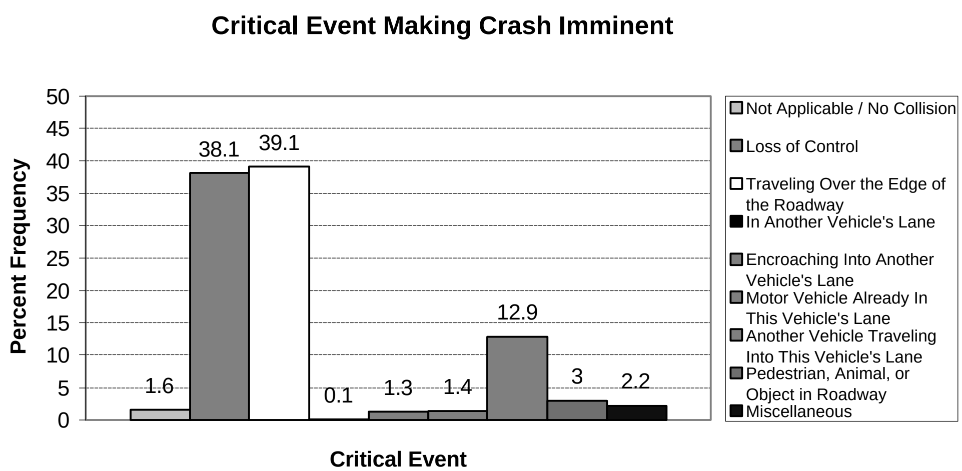


Figure 2-E9. Critical Event that Made Interstate Departure Imminent

3.0 STATISTICS FOR DEPARTURE CRASHES (CDS)

Table 2-E1. Highest Injury Level for Vehicle Occupants

Injury Level	Frequency	Percent
Not Injured	23,315	24.0
Minor	44,386	45.7
Moderate	15,104	15.5
Serious	8,019	8.3
Severe	981	1.0
Critical	537	0.6
Untreatable	188	0.2
Unknown Severity	3,920	4.0
Unknown if Injured	689	0.7
Total	97,139	100.0

Table 2-E2. Most Intensive Level of Medical Treatment for Vehicle Occupants

Treatment	Frequency	Percent
No Treatment	31,651	32.6
Fatal	2,407	2.5
Fatal - Ruled Disease	259	0.3
Hospitalized	17,066	17.6
Transported and Released	36,917	38.0
Treatment at Scene	280	0.3
Treatment Later	3,390	3.5
Treatment - Other	1,383	1.4
Unknown	3,785	3.9
Total	97,139	100.0

Table 2-E3. Occupant Injury Severity by Restraint Use

Injury Level	Unrestrained	Restrained	Unknown	Total
Not Injured	4,560 (13.8)	38,600 (37.7)	4,222 (43.2)	47,382 (32.6)
Minor	15,030 (45.6)	42,905 (41.9)	3,326 (34.0)	61,261 (42.2)
Moderate	5,550 (16.8)	12,744 (12.4)	699 (7.2)	18,992 (13.1)
Serious	4,551 (13.8)	3,705 (3.6)	545 (5.6)	8,801 (6.1)
Severe	942 (2.9)	190 (0.2)	150 (1.5)	1,282 (0.9)
Critical	267 (0.8)	279 (0.3)	19 (0.2)	564 (0.4)
Untreatable	132 (0.4)	52 (0.1)	4 (0.0)	188 (0.1)
Unknown Severity	1,895 (5.7)	3,891 (3.8)	121 (1.2)	5,906 (4.1)
Unknown if Injured	54 (0.2)	135 (0.1)	689 (7.0)	877 (0.6)
Total	32,979 (22.7)	102,501 (70.6)	9,775 (6.7)	145,254 (100.0)

(Numbers in parentheses are column percents, except for totals which are row percents.)

APPENDIX F

1.0 DATA FILES AND FILTERS TO DEFINE OBJECT/ANIMAL IN ROADWAY CRASHES

Object/animal related crashes on interstates are characterized using the 1992 GES data files. The analysis is limited to interstate highway crashes that occur on the roadway, where the orientation of the vehicle involved in the collision is listed as “not collision with motor vehicle in transport”. The first harmful event is recorded as “collision with object not fixed” or “collision with fixed object”. The precrash situation is characterized as a single driver, forward impact with a stationary object or pedestrian/animal accident type. The GES variable restrictions are:

INT_HWY = 1	(crash occurred on an interstate highway)
MAN_COL = 0	(manner of collision is not with a motor vehicle in transport)
REL_RWY = 1	(crash occurred on roadway)
EVENT1 = 21-29	(first harmful event is collision with a fixed or non-fixed object in the roadway)
ACC_TYPE = 12,13	(accident type is single driver, forward impact with object or pedestrian/animal)
BODY_TYP < 90	(excludes off road vehicles, snowmobiles, farm equipment, etc.)

All tabulations represent GES weighted estimates.

CDS data are used to provide a more accurate assessment of occupant injury and vehicle damage resulting from object /animal in roadway crashes. Vehicle damage is estimated by restricting the general area of damage to the front of the vehicle and to wide areas of total damage distribution so that the extent information is not misrepresented (see discussion of extent of residual crush in rear-end crash section). The algorithms used to calculate ΔV information do not apply to this crash type.

Data from the CDS files are restricted to roadways where the posted or statutory speed limit is greater than 50 mph, since interstate highway information is not available in the CDS data set. The manner of collision is classified as “not collision with motor vehicle in transport”; the precrash situation is a single driver involved in a forward impact with an object or pedestrian/animal; and the vehicle type is restricted to passenger cars only so that occupant injuries are compared for similar vehicles. The CDS variable restrictions are:

SPLIMIT > 50	(crash occurred on highway with posted or statutory speed limit greater than 50 mph)
MAN_COL = 0	(manner of collision is not with a motor vehicle in transport)
ACC_TYPE = 12,13	(accident type is single driver, forward impact with object or pedestrian/animal)
BODY_TYP < 10	(passenger cars only)

For vehicle damage data (extent of residual crush) only:

GAD1 = ‘F’	(general area of damage is front)
TDD1 = ‘W’	(total damage distribution is wide)

All CDS frequencies represent weighted estimates.

2.0 STATISTICS FOR OBJECT/ANIMAL IN ROADWAY CRASHES (GES)

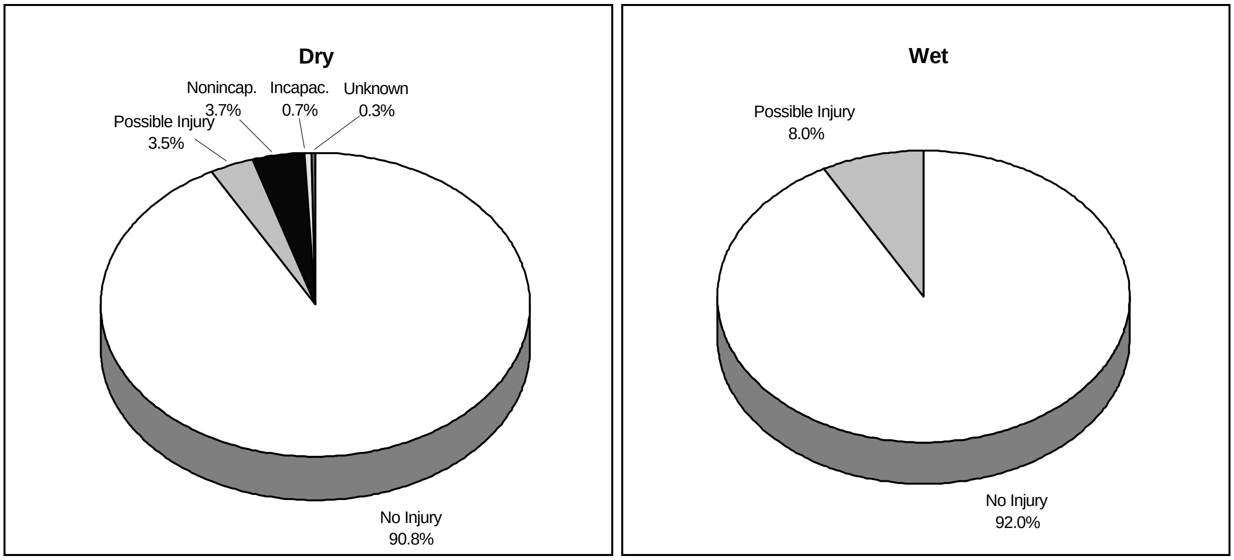


Figure 2-F1. Injury Severity by Surface Condition for Object/Animal in Roadway Crashes

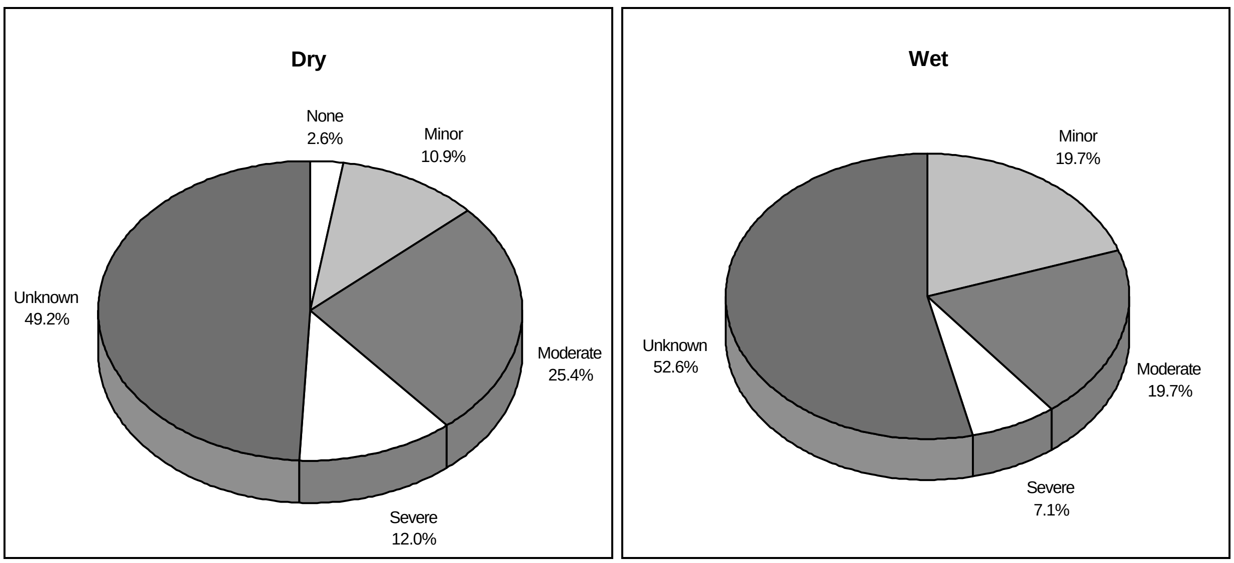


Figure 2-F2. Vehicle Damage by Surface Condition for Object/Animal in Roadway Crashes

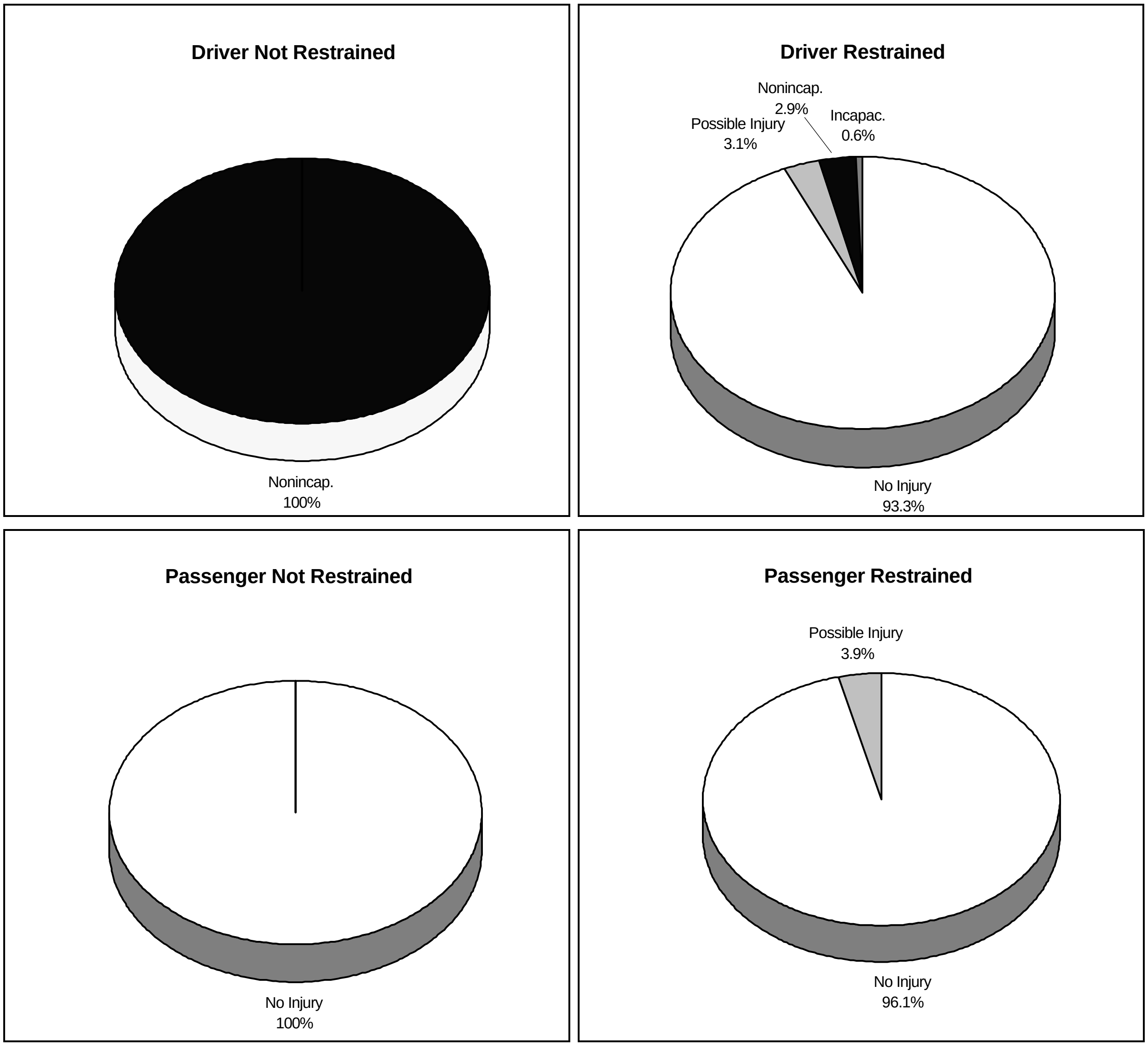


Figure 2-F3. Injury Severity by Restraint Use for Object/Animal in Roadway Crashes

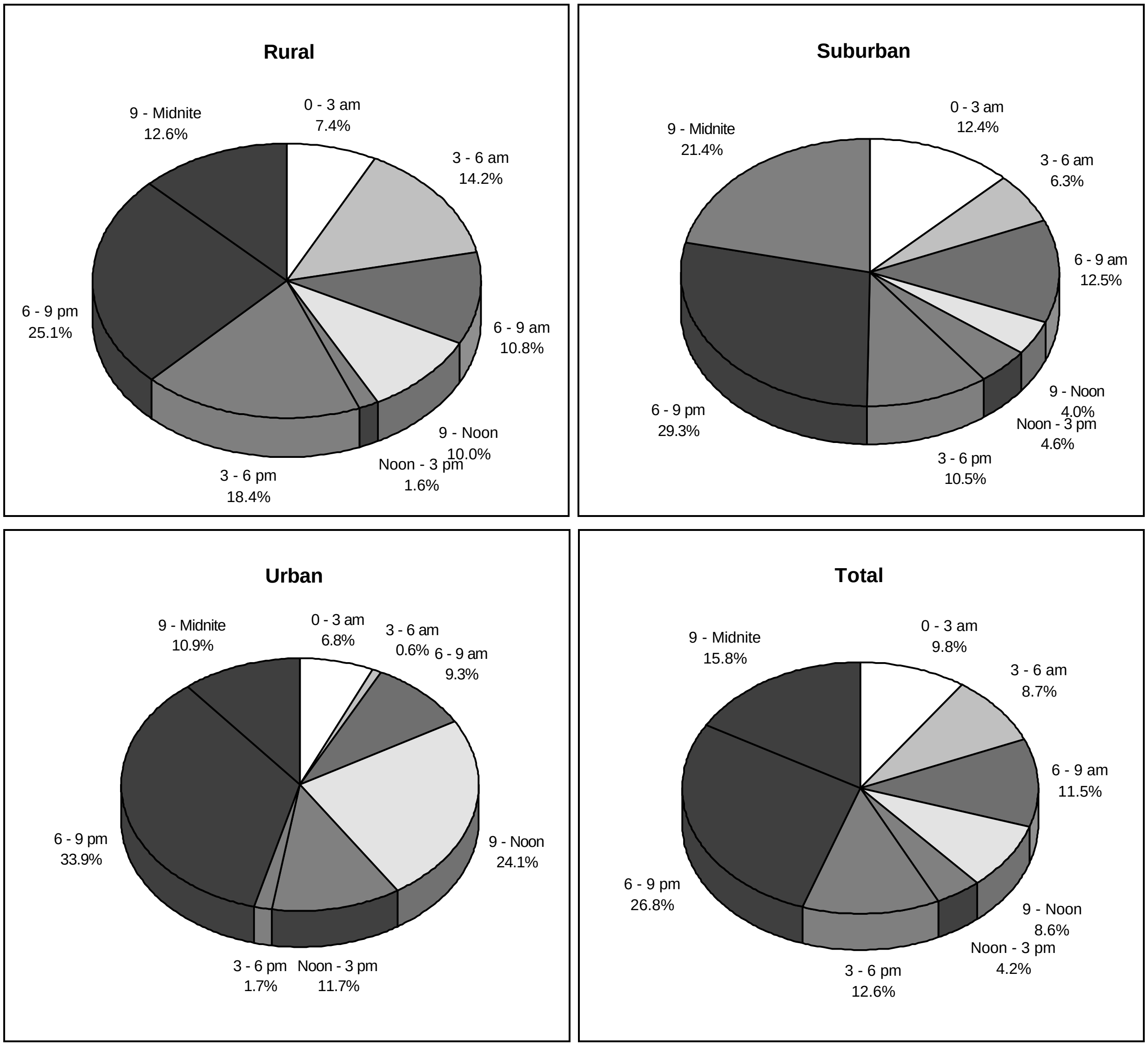


Figure 2-F4. Time of Day for Object/Animal in Roadway Crashes

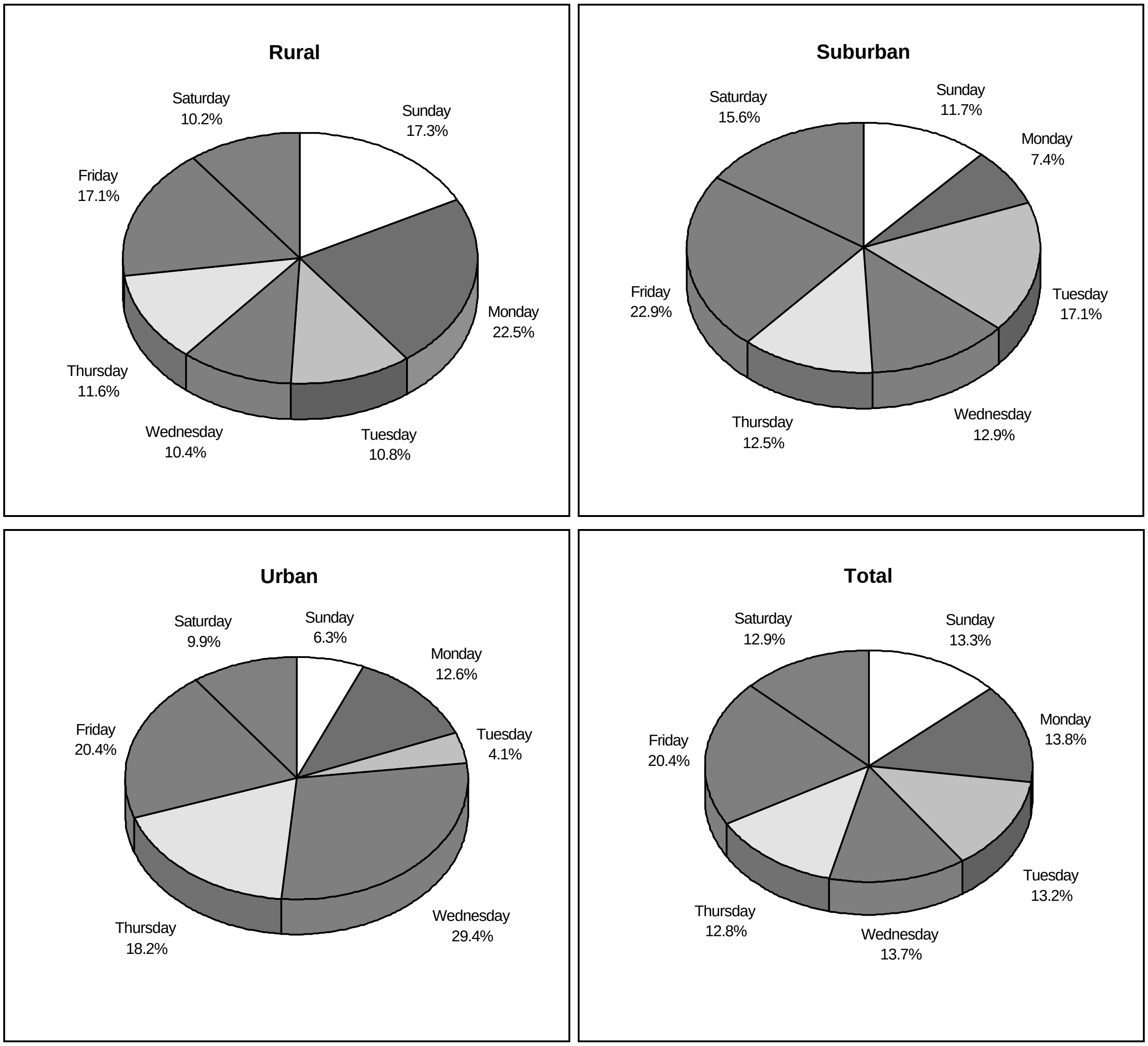


Figure 2-F5. Day of Week for Object/Animal in Roadway Crashes

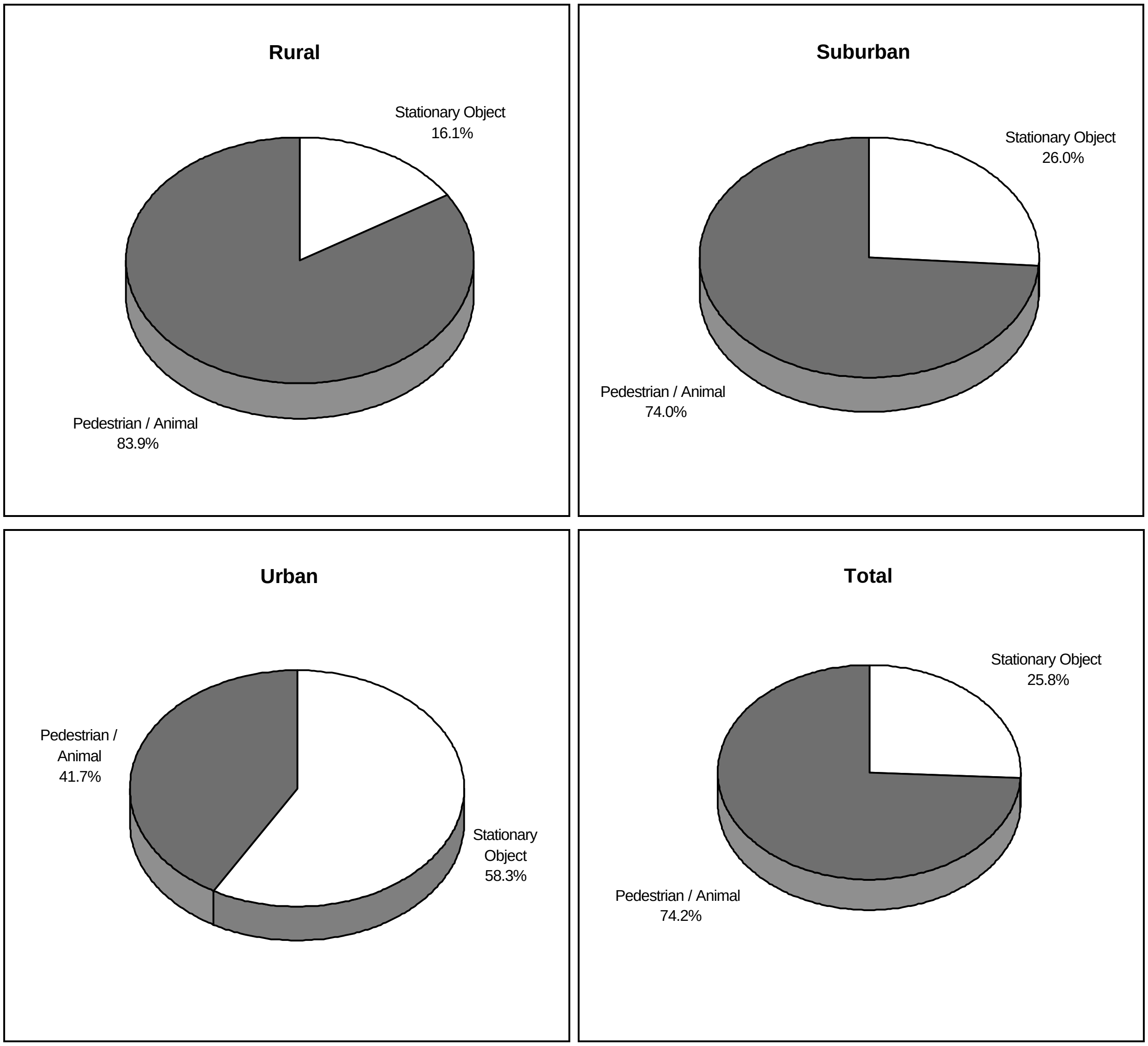


Figure 2-F6. Precrash Situation for Object/Animal in Roadway Crashes

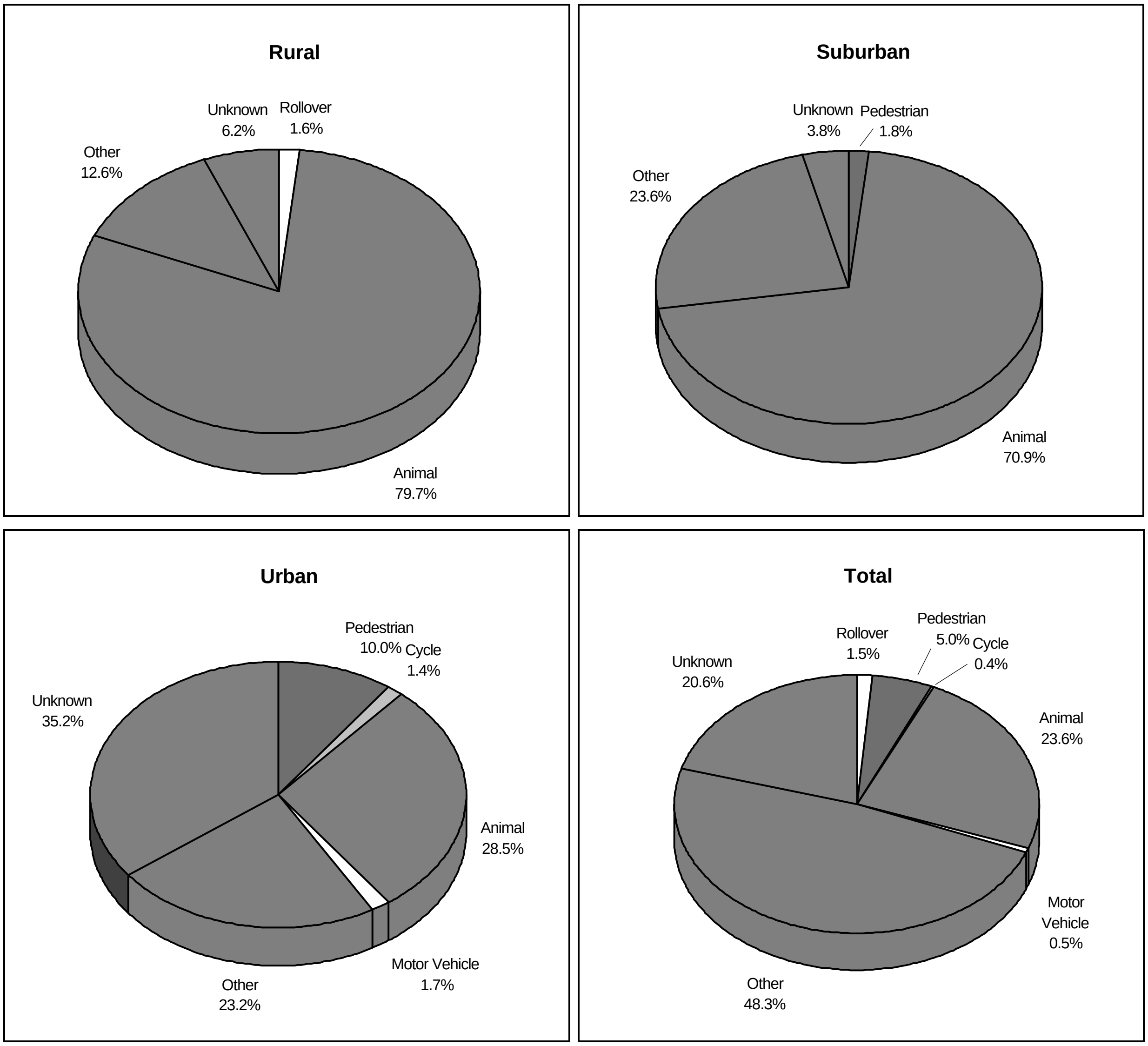


Figure 2-F7. Most Harmful Event for Object/Animal in Roadway Crashes

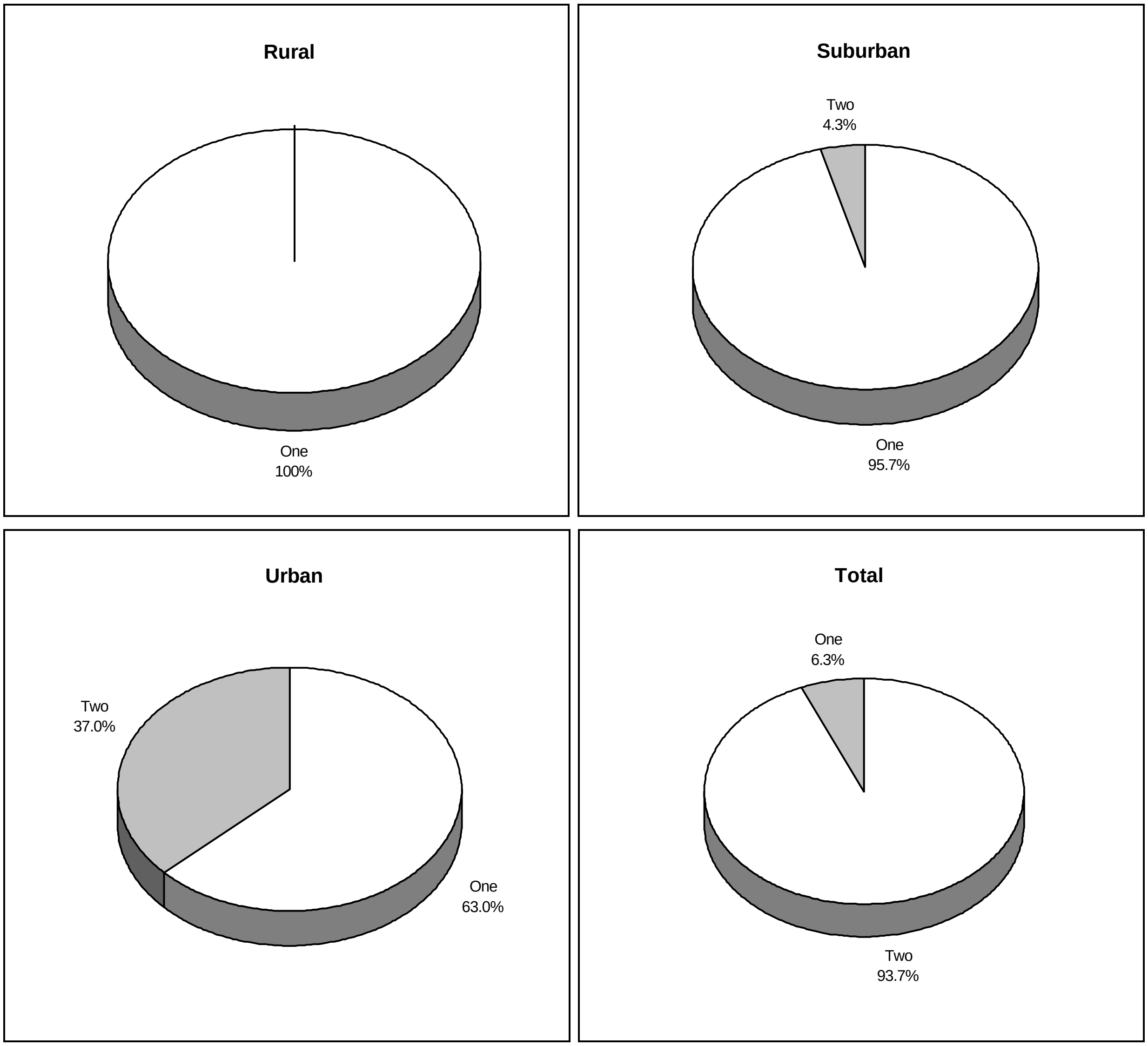


Figure 2-F8. Number of Vehicles Involved by Location for Object/Animal in Roadway Crashes

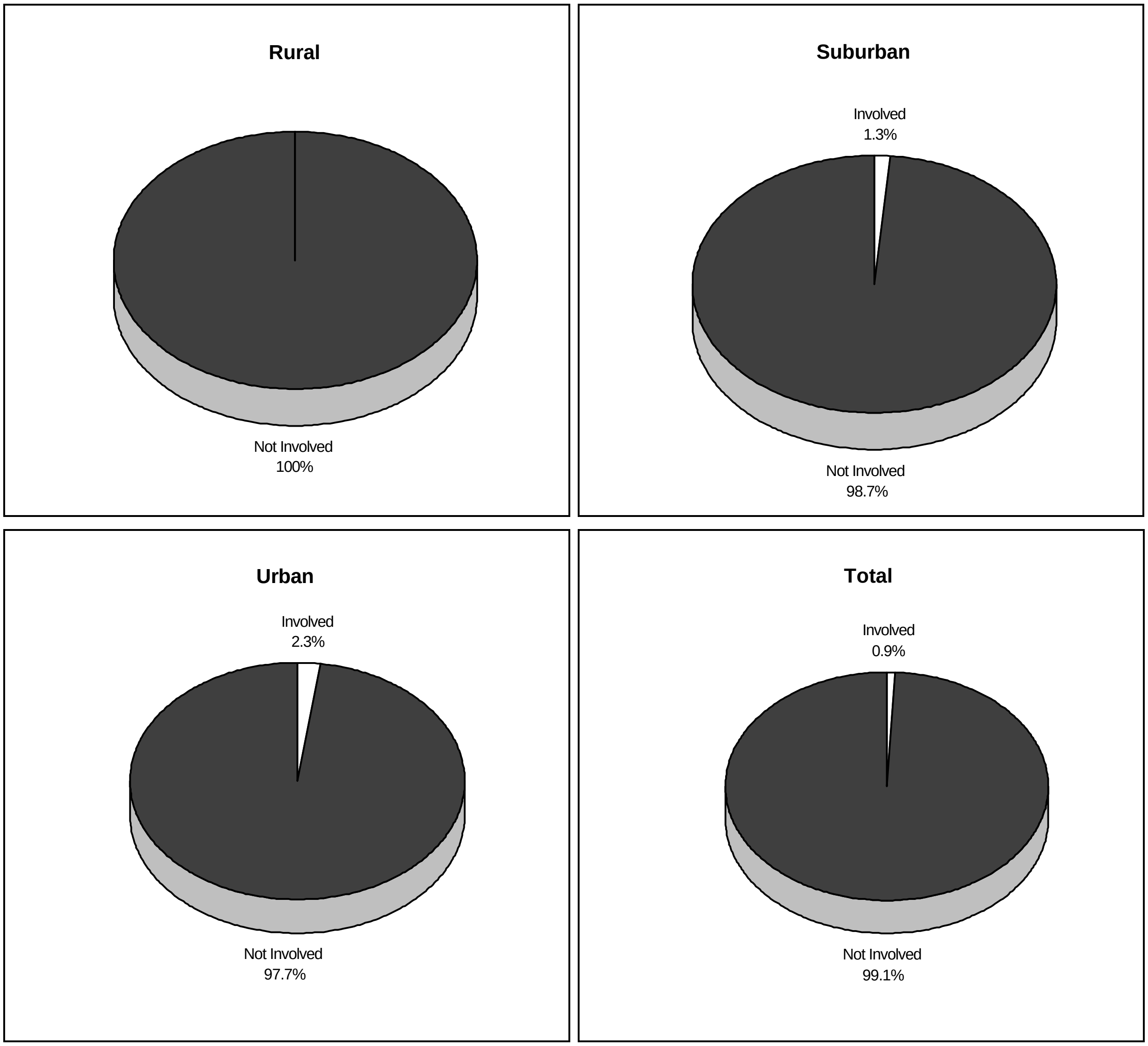


Figure 2-F9. Police Reported Alcohol Involvement for Object/Animal in Roadway Crashes

3.0 STATISTICS FOR OBJECT/ANIMAL IN ROADWAY CRASHES (CDS)

Table 2-F1. Highest Injury Level for Vehicle Occupants Involved in Object/Animal in Roadway Crashes

Injury Level	Frequency	Percent
Not Injured	8,080	67.7
Minor	3,515	29.4
Moderate	208	1.7
Unknown Severity	136	1.1
Total	11,938	100.0

Table 2-F2. Most Intensive Level of Medical Treatment for Vehicle Occupants Involved in Object/Animal in Roadway Crashes

Treatment	Frequency	Percent
No Treatment	7,994	67.0
Hospitalized	208	1.7
Transported and Released	3,601	30.2
Unknown	136	1.1
Total	11,938	100.0

Table 2-F3. Occupant Injury Severity by Restraint Use for Vehicles Involved in Object/Animal in Roadway Crashes

Injury Level	Unrestrained	Restrained	Unknown	Total
Not Injured	1,569 (76.0)	9,475 (72.6)	837 (97.1)	11,881 (74.4)
Minor	288 (14.0)	3,227 (24.7)		3,515 (22.0)
Moderate	208 (10.1)	208 (1.6)		415 (2.6)
Unknown Severity		136 (1.0)		136 (0.9)
Unknown			25 (2.9)	25 (0.2)
Total	2,065 (12.9)	13,045 (81.7)	862 (5.4)	15,972 (100.0)

(Numbers in parentheses are column percents, except for totals which are row percents.)

Table 2-F4. Extent of Vehicle Residual Crush for Vehicles Involved in Object/Animal in Roadway Crashes

Extent Zone	Frequency	Percent
1	7,184	77.3
3	2,110	22.7
Total	9,294	100.0

APPENDIX G

1.0 DATA FILES AND FILTERS TO DEFINE LANE CHANGE/MERGE CRASHES

Data from the 1992 GES data files provide general information about the characteristics of interstate lane change/merge crashes. The analysis is limited to angle or sideswipe collisions on interstate highways where at least two vehicles are involved and each vehicle must be striking, struck or both. The vehicle movement prior to the critical event is changing lanes or merging. The GES variable restrictions are:

INT_HWY = 1	(crash occurred on an interstate highway)
MAN_COL = 4,5	(manner of collision is angle or sideswipe)
P_CRASH1 = 16,17	(vehicle is changing lanes or merging)
VEH_INVL > 1	(at least 2 vehicles involved)
VEH_ROLE > 1	(vehicles involved are striking, struck or both)
BODY_TYP < 90	(excludes off road vehicles, snowmobiles, farm equipment, etc.)

All tabulations represent GES weighted estimates.

CDS data are used to provide a more accurate assessment of occupant injury resulting from lane change/merge crashes. Vehicle damage is not assessed since the extent information is not straightforward for the variety of crush configurations that may occur with vehicles involved in this crash type. As a result, the algorithms used to calculate ΔV information do not apply to this crash type.

Data from the CDS files are restricted to roadways where the posted or statutory speed limit is greater than 50 mph, since interstate highway information is not available in the CDS data set. A variable that specifies whether the vehicle is changing lanes or merging is not available in CDS, instead the precrash situation is restricted to a sideswipe/angle collision with another vehicle traveling on the same trafficway, in the same direction or a collision with another vehicle turning into the path a vehicle traveling in the same direction. The CDS variable restrictions are:

SPLIMIT > 50	(crash occurred on highway with posted or statutory speed limit greater than 50 mph)
ACC_TYPE = 44-49	(accident type: sideswipe/angle same trafficway, same direction)

All CDS frequencies represent weighted estimates.

2.0 STATISTICS FOR LANE CHANGE/MERGE CRASHES (GES)

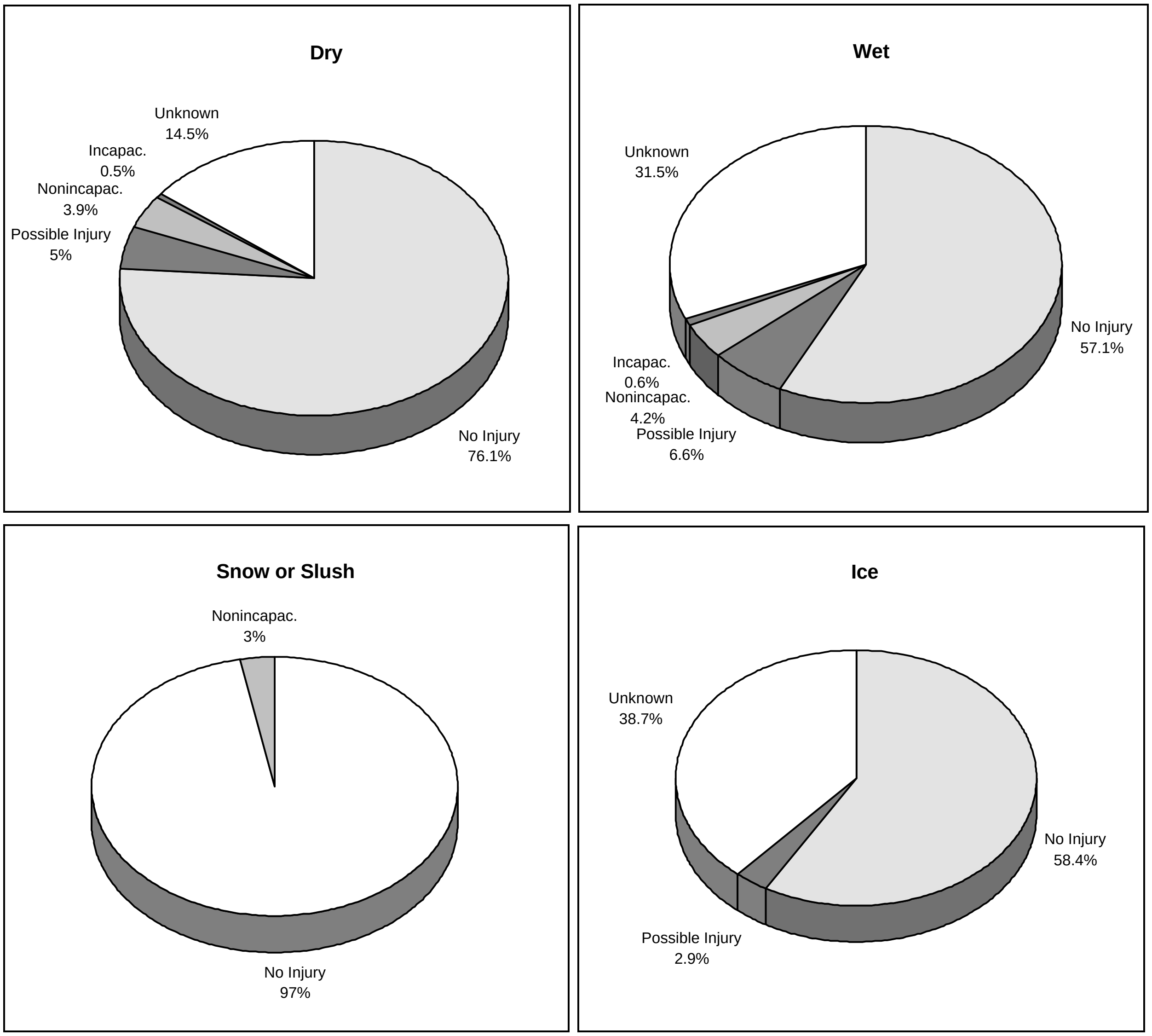


Figure 2-G1. Occupant Injury Severity by Surface Location for Vehicles Involved in Interstate Lane Change/Merge Crashes

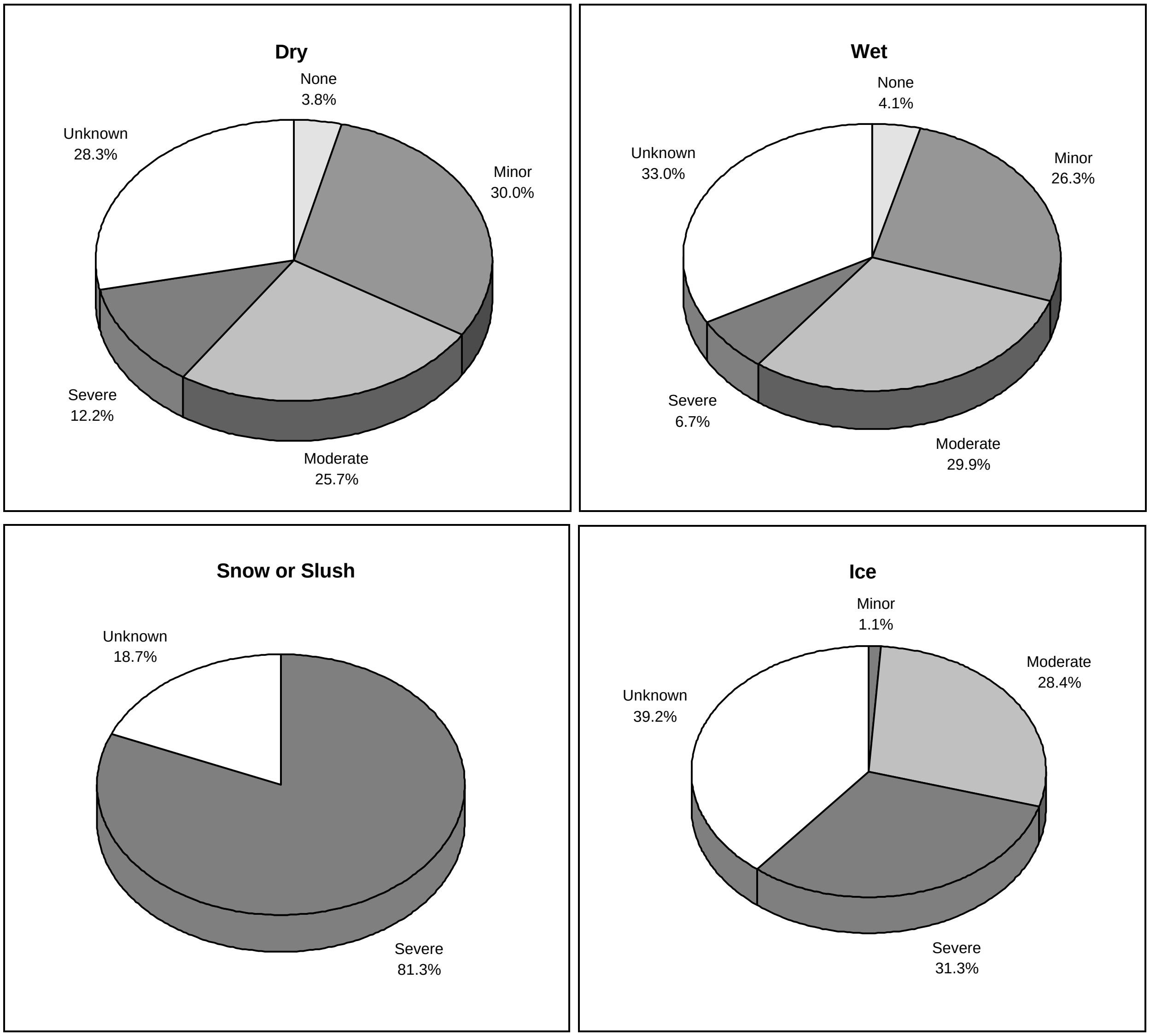


Figure 2-G2. Vehicle Damage Severity by Surface Location for Interstate Lane Change/Merge Crashes

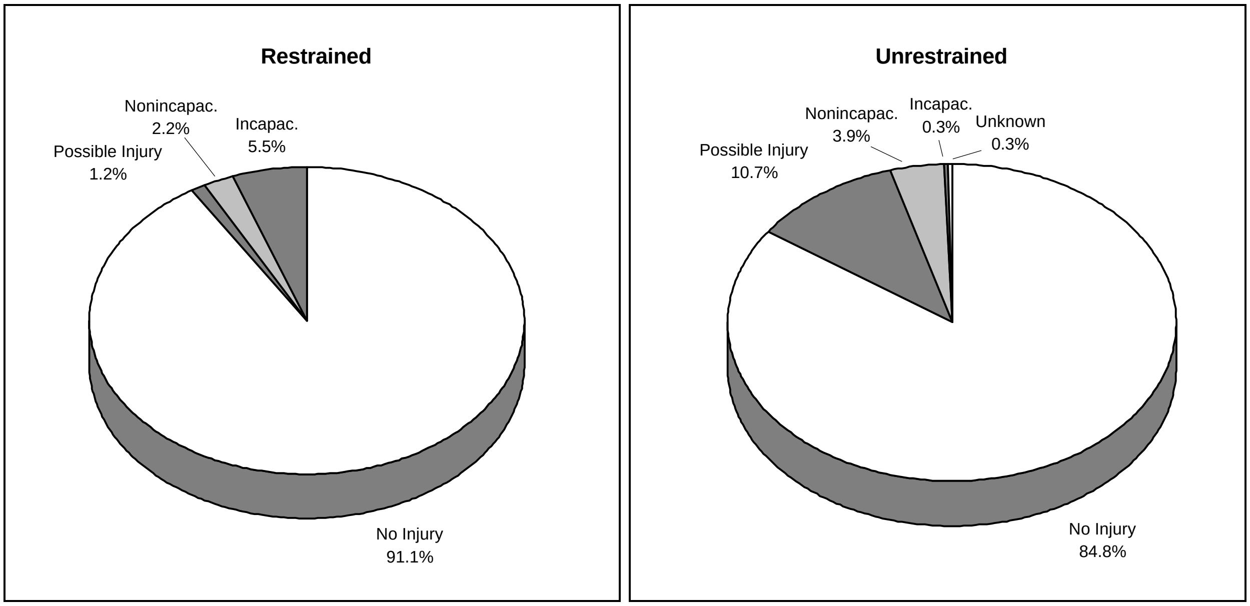


Figure 2-G3. Occupant Injury Severity by Restraint Use for Vehicles Involved in Interstate Lane Change/Merge Crashes

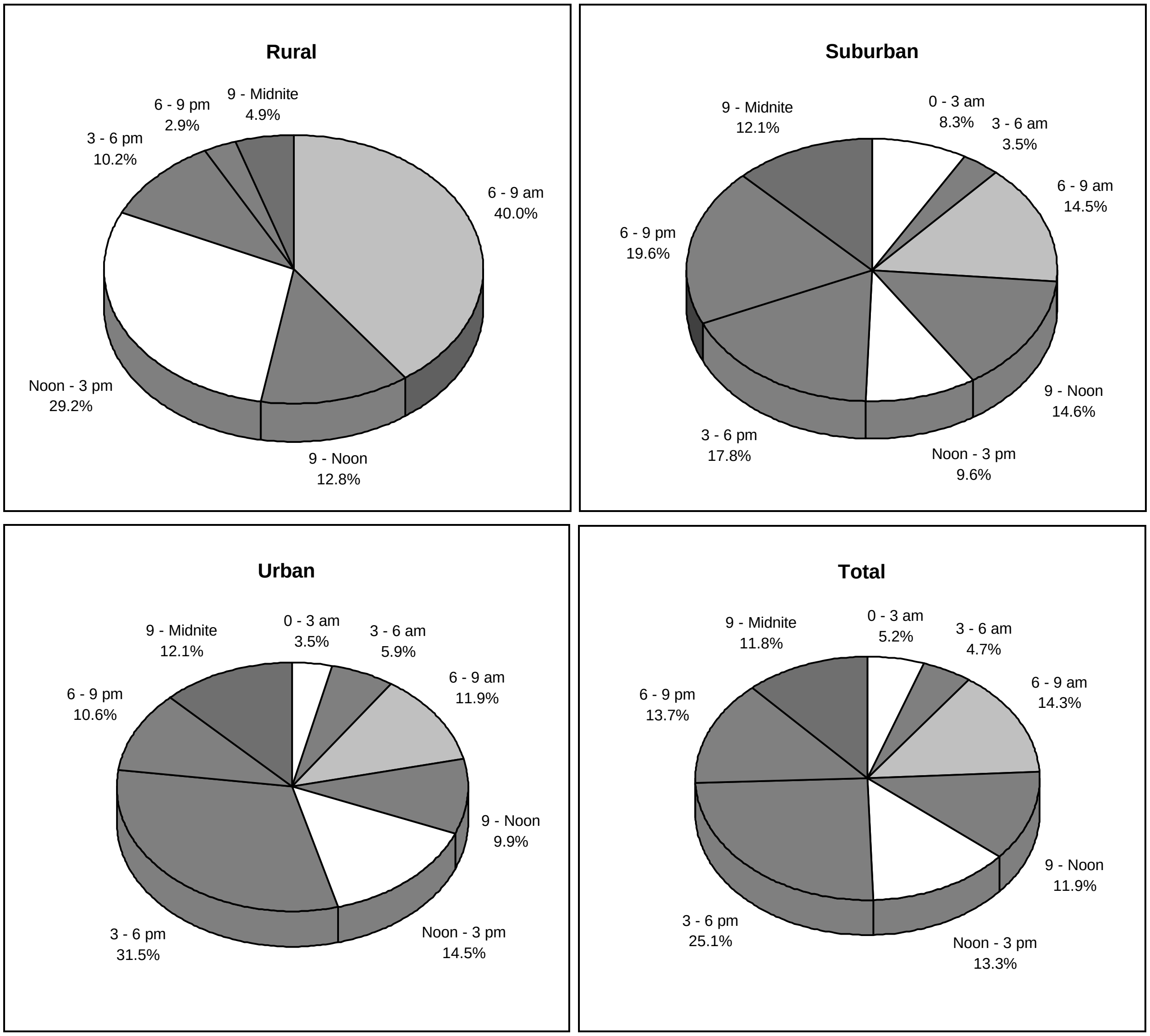


Figure 2-G4. Time of Day for Interstate Lane Change/Merge Crashes

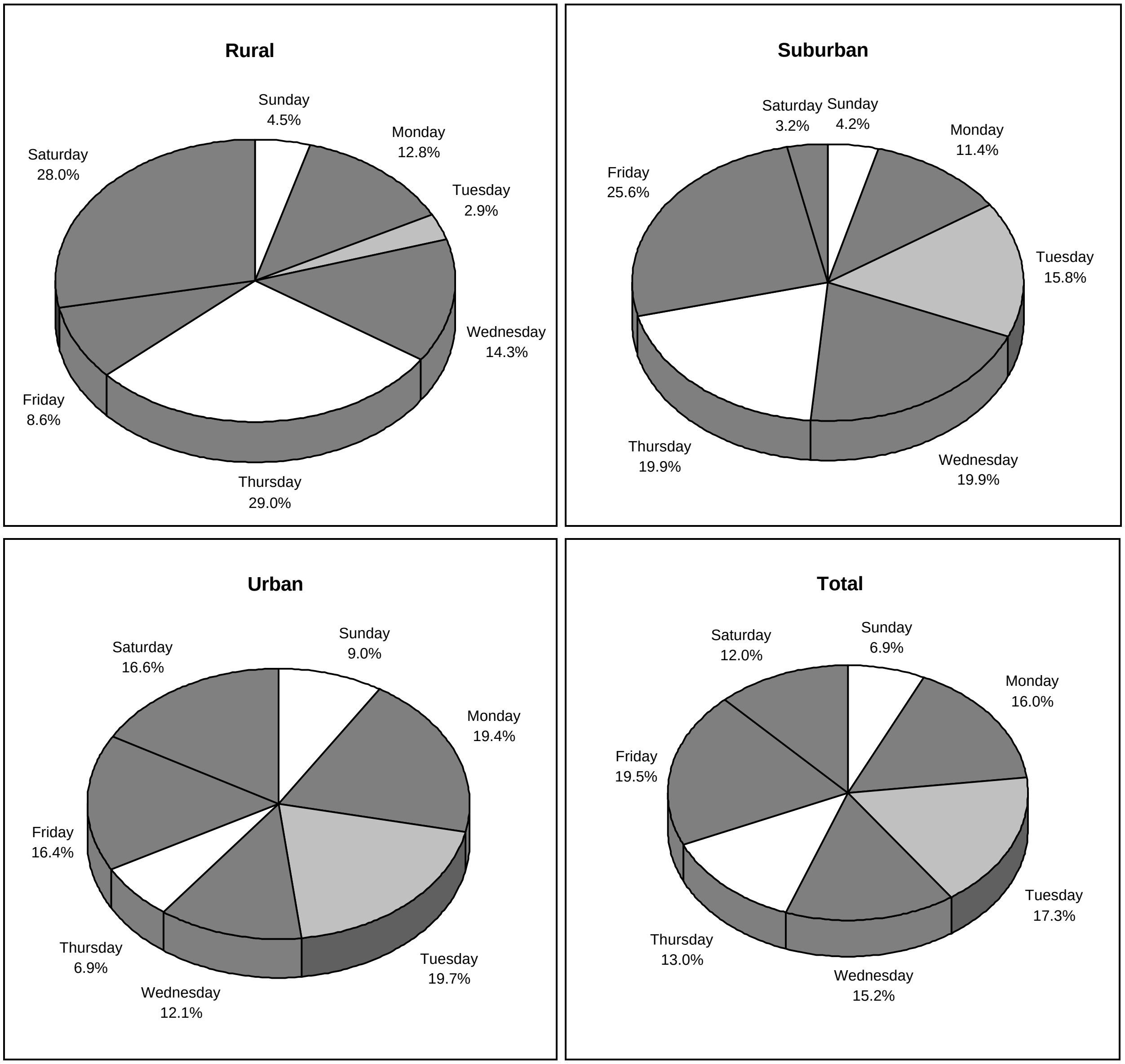


Figure 2-G5. Day of Week for Interstate Lane Change/Merge Crashes

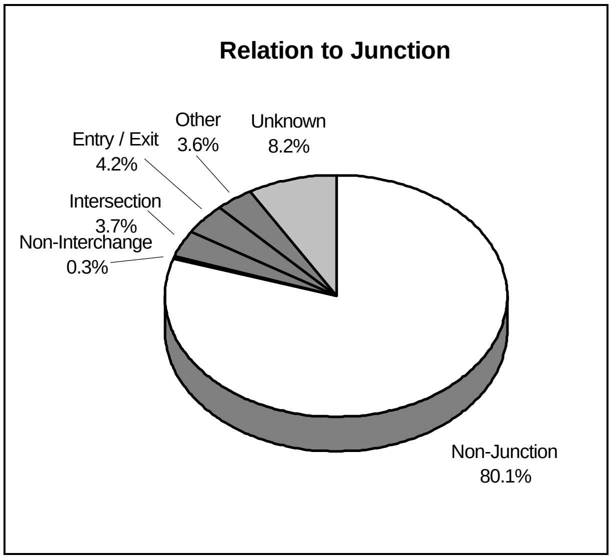


Figure 2-G6. Relation to Junction for Interstate Lane Change/Merge Crashes

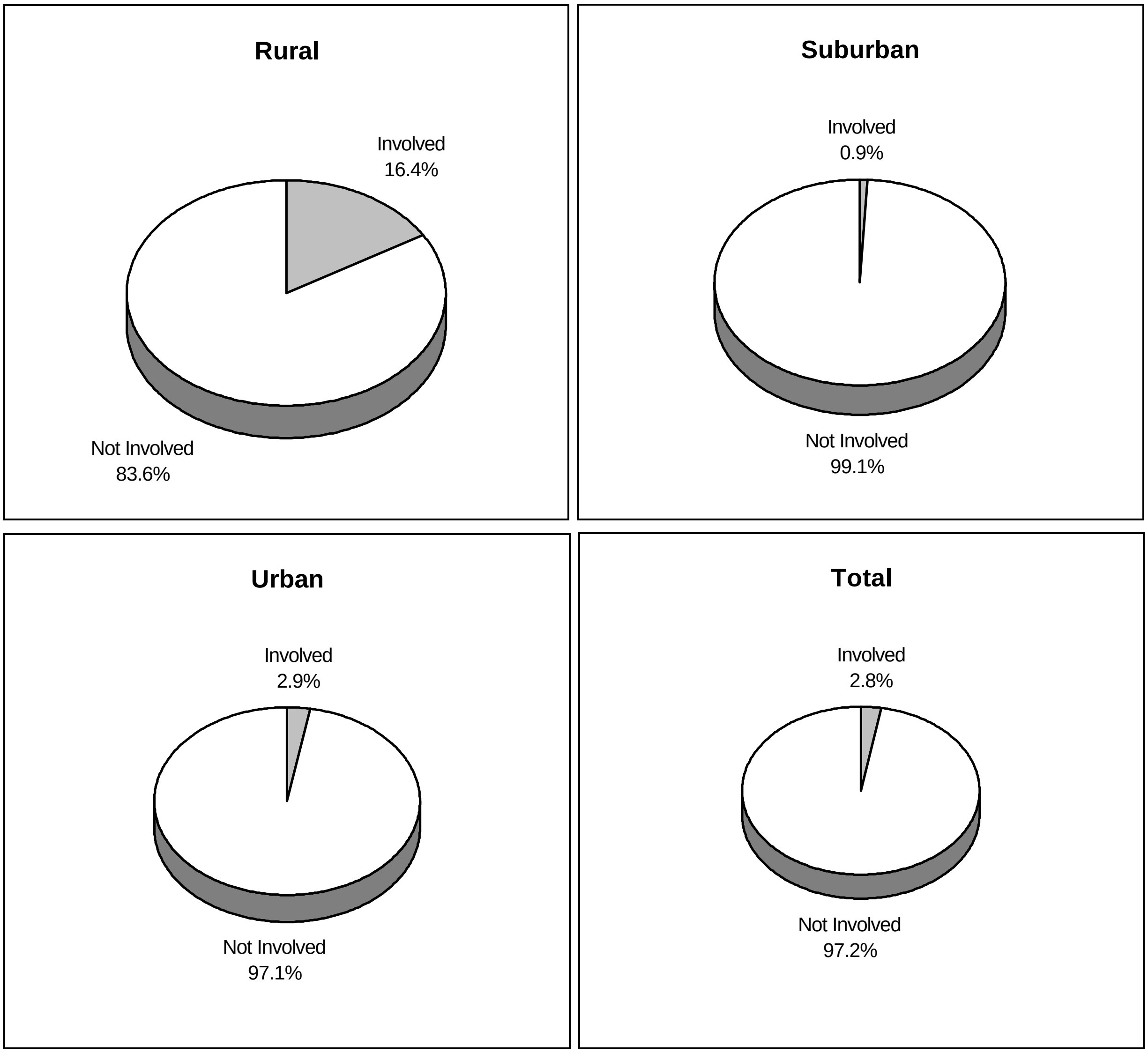


Figure 2-G7. Police Reported Alcohol Involvement by Location for Interstate Lane Change/Merge Crashes

3.0 STATISTICS FOR LANE CHANGE/MERGE CRASHES (CDS)

Table 2-G1. Highest Injury Level for Occupants of Vehicles Involved in Interstate Lane Change/Merge Crashes

Injury Level	Frequency	Percent
Not Injured	460	5.3
Minor	4,135	47.3
Moderate	3,152	36.1
Serious	510	5.8
Severe	15	0.2
Critical	46	0.5
Unknown Severity	417	4.8
Total	8,735	100.0

Table 2-G2. Most Intensive Level of Medical Treatment for Occupants of Vehicles Involved in Interstate Lane Change/Merge Crashes

Treatment	Frequency	Percent
No Treatment	2,456	28.1
Fatal	100	1.1
Hospitalized	818	9.4
Transported and Released	5,199	59.5
Treatment at Scene	8	0.1
Unknown	154	1.8
Total	8,735	100.0

Table 2-G3. Injury Severity by Restraint Use for Occupants of Vehicles Involved in Interstate Lane Change/Merge Crashes

Injury Level	Unrestrained	Restrained	Unknown	Total
Not Injured	49 (3.3)	697 (9.8)	8 (0.4)	755 (6.9)
Minor	1,167 (77.7)	4,295 (60.2)	4 (0.2)	5,466 (49.9)
Moderate	124 (8.2)	1,903 (26.7)	1,203 (52.2)	3,230 (29.5)
Serious	12 (0.8)	122 (1.7)	376 (16.3)	510 (4.7)
Severe	4 (0.2)	11 (0.2)	4 (0.2)	19 (0.2)
Critical	46 (3.1)			46 (0.4)
Unknown Severity	101 (6.7)	108 (1.5)	712 (30.8)	921 (8.4)
Total	1503 (13.7)	7,137 (65.2)	2,307 (21.1)	10,946 (100.0)

(Numbers in parentheses are column percents, except for totals which are row percents.)

APPENDIX H

1.0 DATA FILES AND FILTERS TO DEFINE INTERSTATE IMPAIRED DRIVER CRASHES

Types of Driver Impairments (GES)
Variable restrictions:
INT_HWY = 1 (interstate highway crash)
PER_TYPE = 1 (driver)

Characteristics of Interstate Crashes Involving Alcohol/Drug Violations (GES)
Variable restrictions:
INT_HWY = 1 (interstate highway crash)
PER_TYPE = 1 (driver)
VIOLATN = 1 or 3 (driver charged with alcohol/drug or alcohol/drug and speeding violation)

Fatal Interstate Crashes with Alcohol/Drug Violations (FARS)
Variable restrictions:
ROUTE SIGNING = 1 (crash occurred on an interstate highway)
VIOLATIONS CHARGED = 1 OR 3 (violations charged for alcohol or drugs, alcohol or drugs speeding)
PERSON TYPE = 1 (driver)

Characteristics of Interstate Crashes Involving Drowsy Drivers (GES)
Variable restrictions:
INT_HWY = 1 (crash occurred on an interstate highway)
PER_TYPE = 1 (driver)
IMPAIRMT = 1 (drowsy physical impairment)

Fatal Interstate Crashes with Drowsy Impaired Drivers (FARS)
Variable restrictions:
ROUTE SIGNING = 1 (crash occurred on an interstate highway)
RELATED FACTORS
DRIVER LEVEL = 1 (driver impairment is drowsy)
PERSON TYPE = 1 (driver)

Characteristics of Interstate Crashes Involving Older Drivers (GES)
Variable restrictions:
INT_HWY = 1 (crash occurred on an interstate highway)
PER_TYPE = 1 (driver)

2.0 STATISTICS FOR ALCOHOL/DRUG RELATED CRASHES (GES)

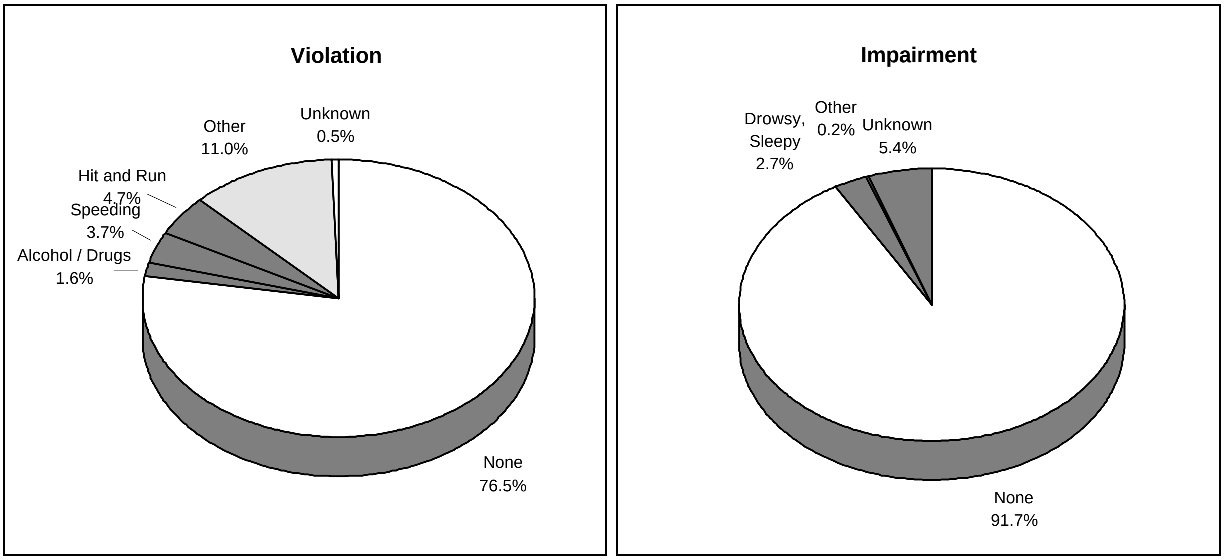


Figure 2-H1. Violations and Impairments for Drivers of Vehicles Involved in Interstate Crashes

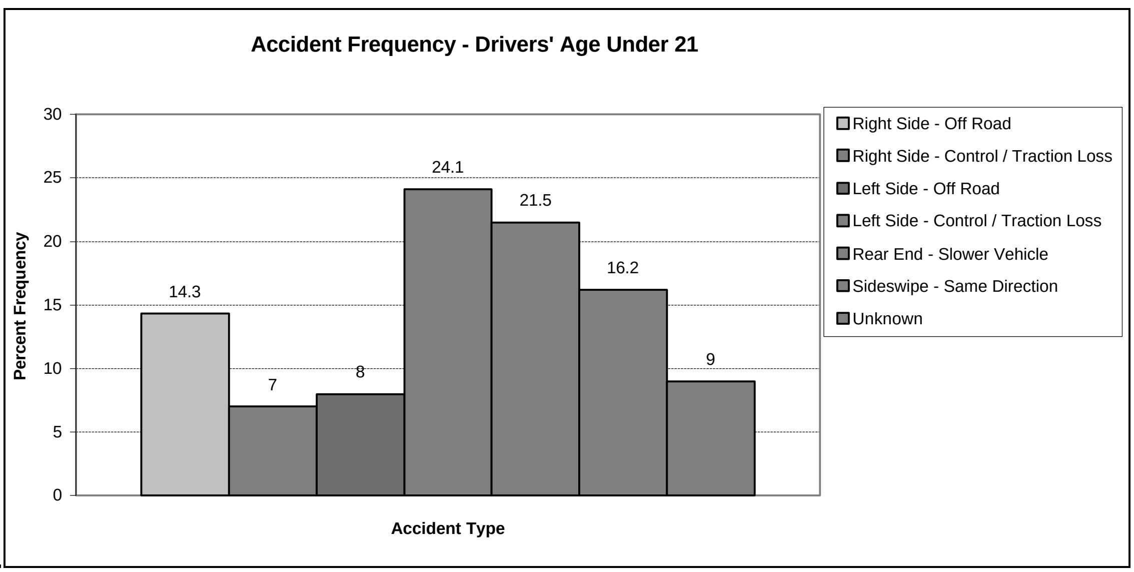


Figure 2-H2a. Accident Type by Age Group for Drivers of Vehicles Involved in Interstate Alcohol/Drug Related Crashes

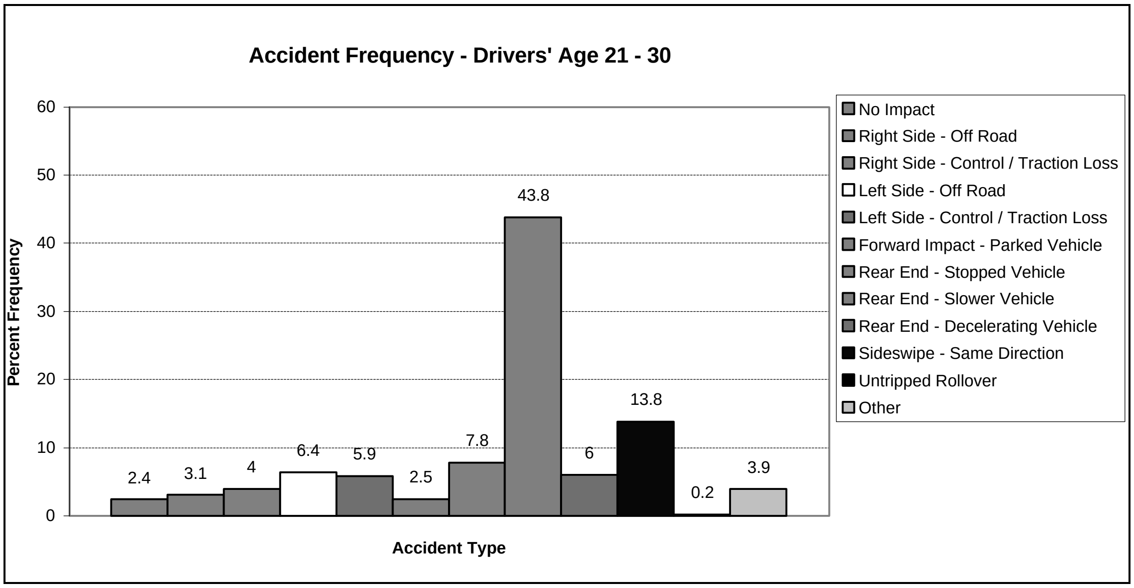


Figure 2-H2b. Accident Type by Age Group for Drivers of Vehicles Involved in Interstate Alcohol/Drug Related Crashes

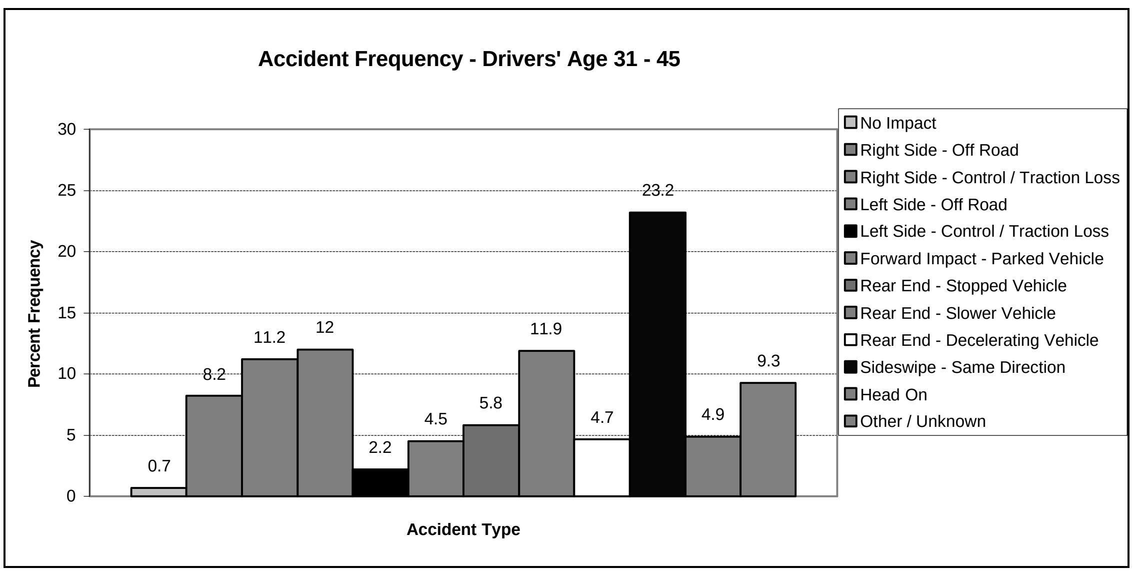


Figure 2-H2c. Accident Type by Age Group for Drivers of Vehicles Involved in Interstate Alcohol/Drug Related Crashes

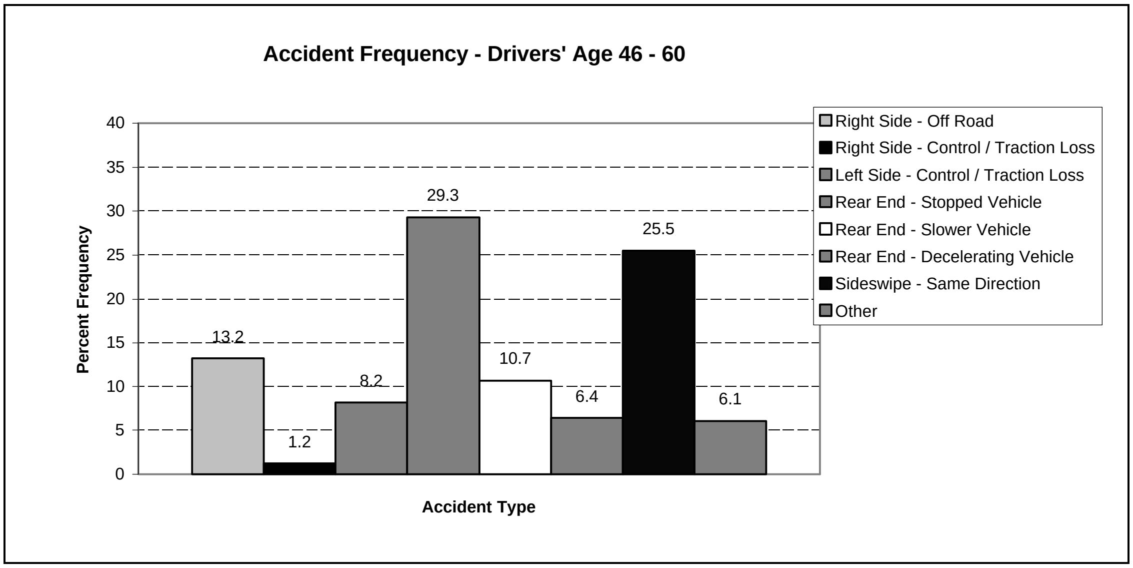


Figure 2-H2d. Accident Type by Age Group for Drivers of Vehicles Involved in Interstate Alcohol/Drug Related Crashes

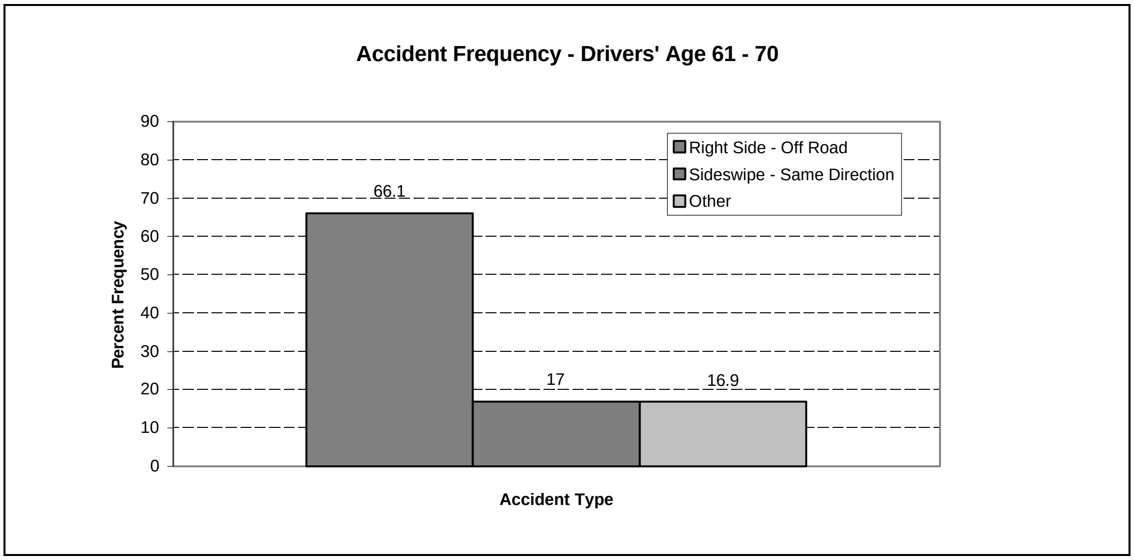


Figure 2-H2e. Accident Type by Age Group for Drivers of Vehicles Involved in Interstate Alcohol/Drug Related Crashes

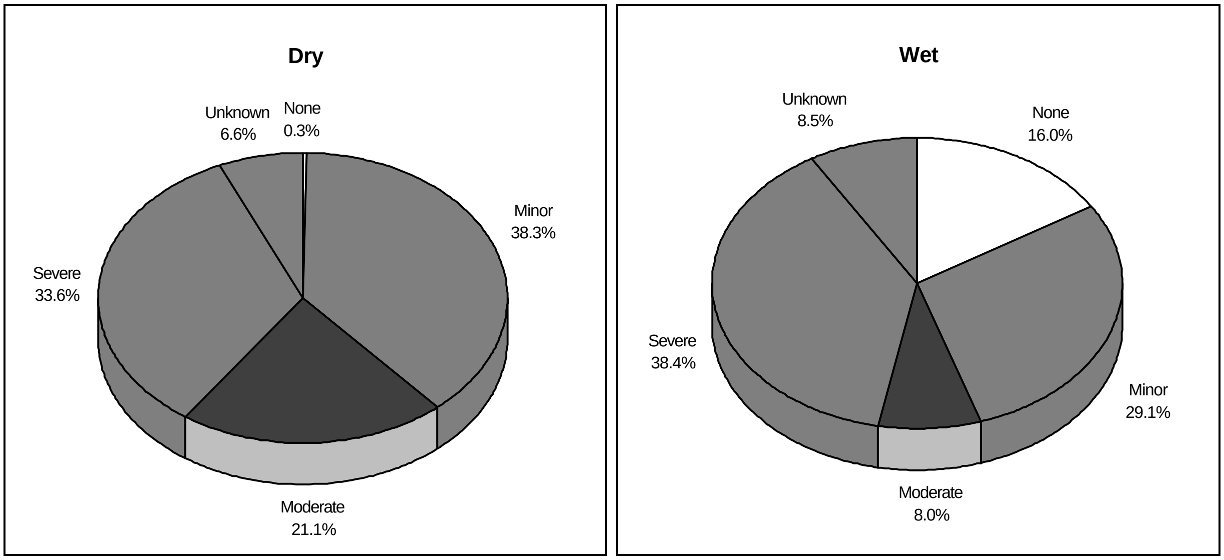


Figure 2-H3. Maximum Injury Severity in Vehicle by Roadway Surface Condition for Occupants of Vehicles Involved in Alcohol/Drug Related Interstate Crashes

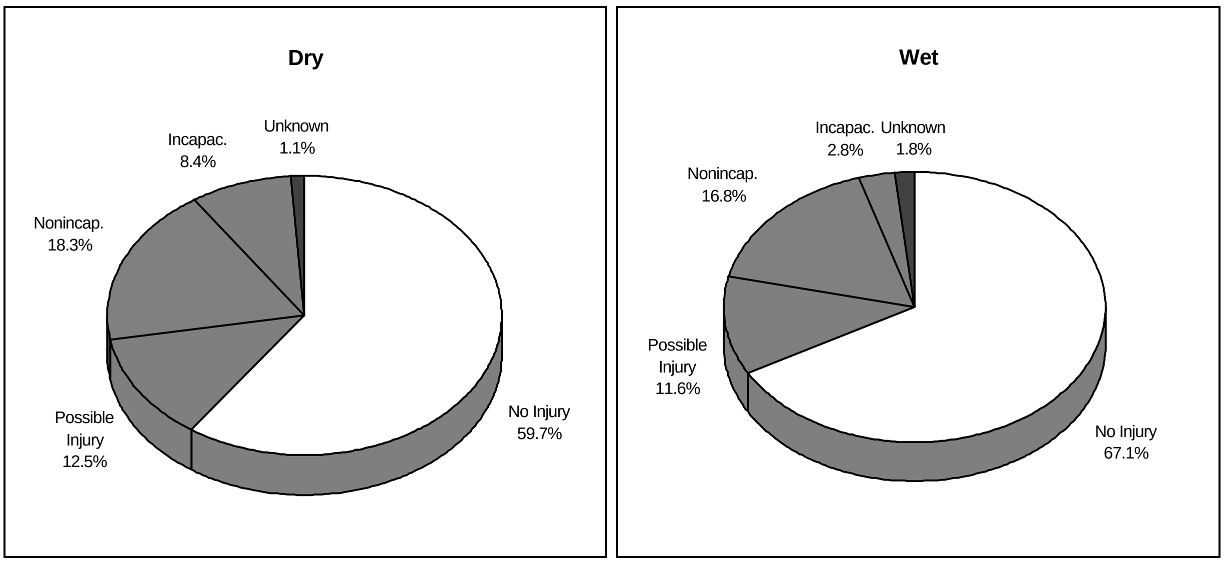
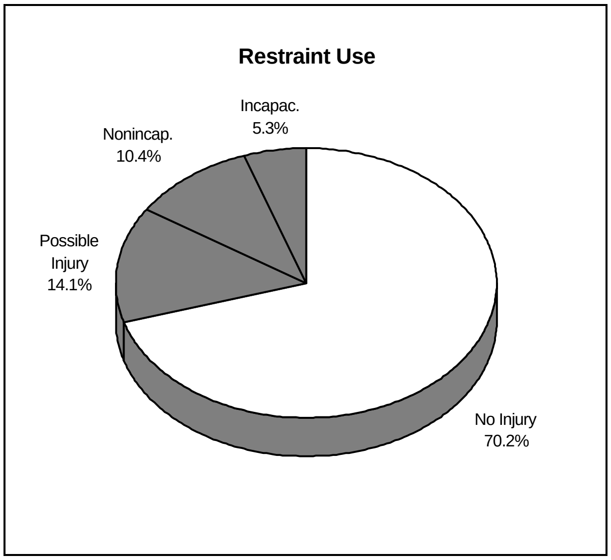


Figure 2-H4. Vehicle Damage by Roadway Surface Condition for Occupants of Vehicles Involved in Alcohol/Drug Related Interstate Crashes



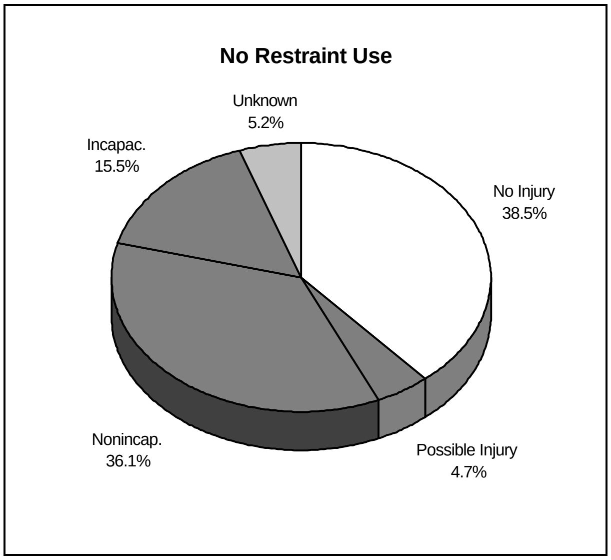


Figure 2-H5. Driver Injury Severity by Vehicle Restraint Protection for Alcohol/Drug Related Interstate Crashes

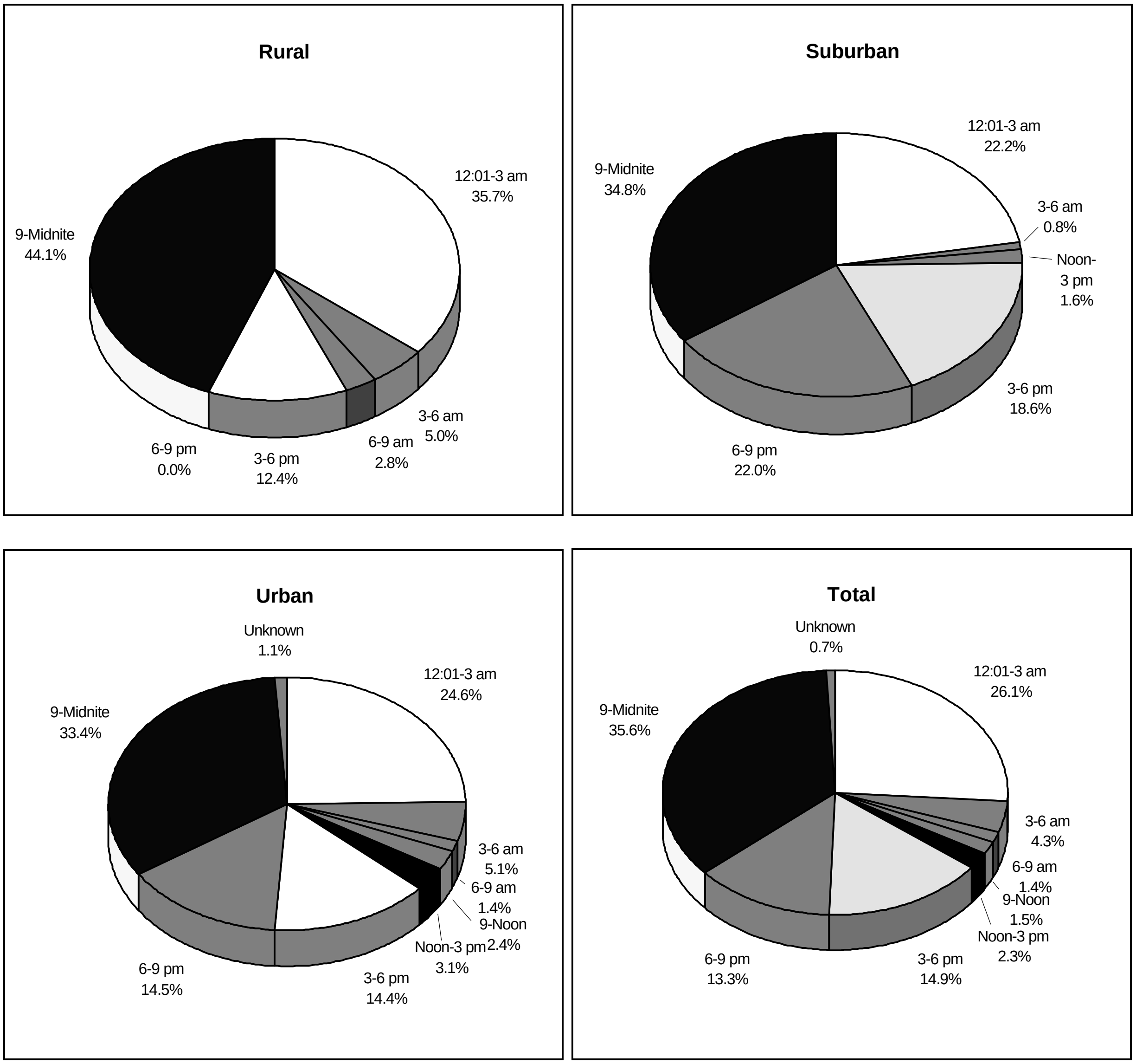


Figure 2-H6. Time of Day by Location for Alcohol/Drug Related Interstate Crashes

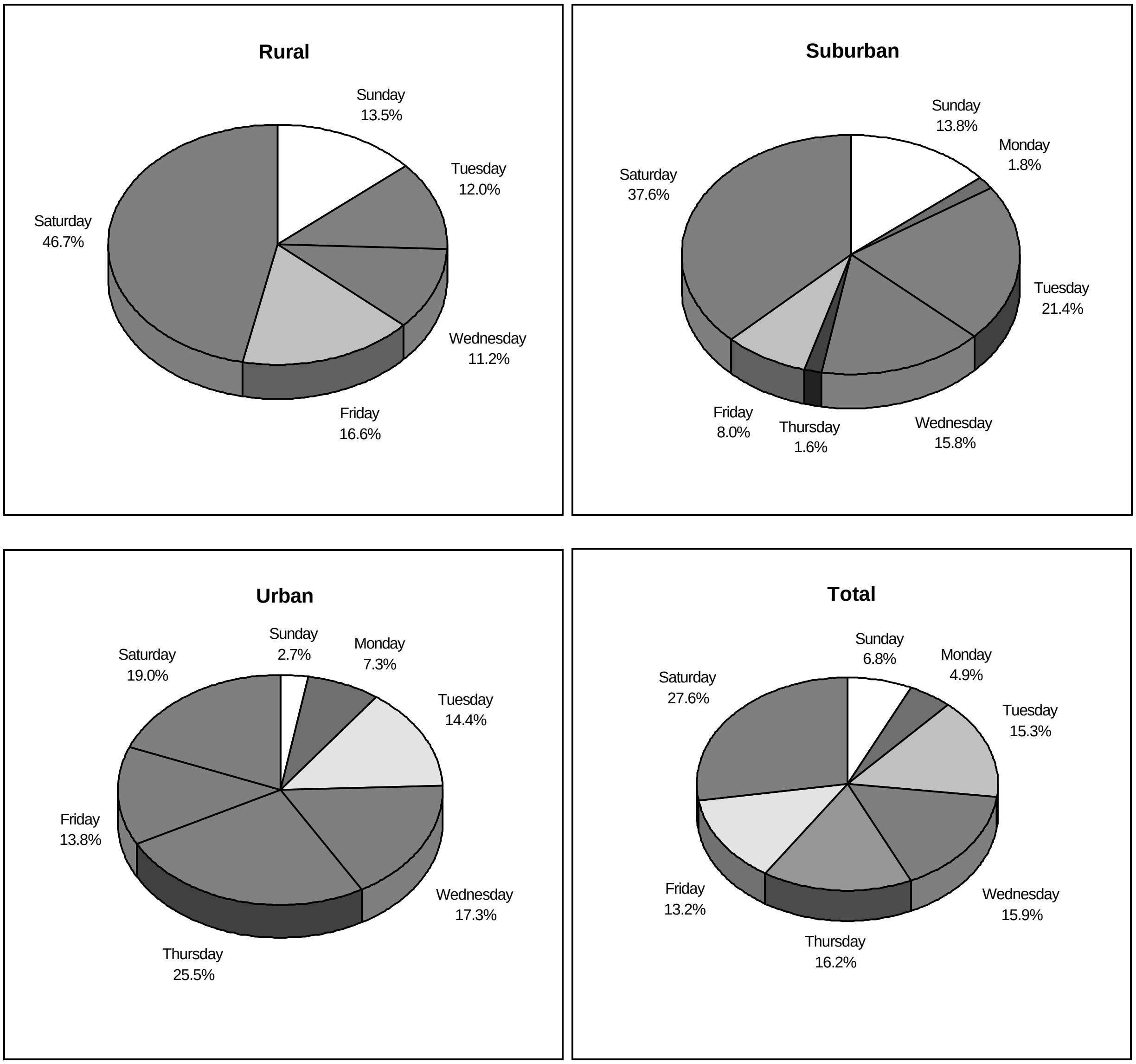


Figure 2-H7. Weekday by Location for Alcohol/Drug Related Interstate Crashes

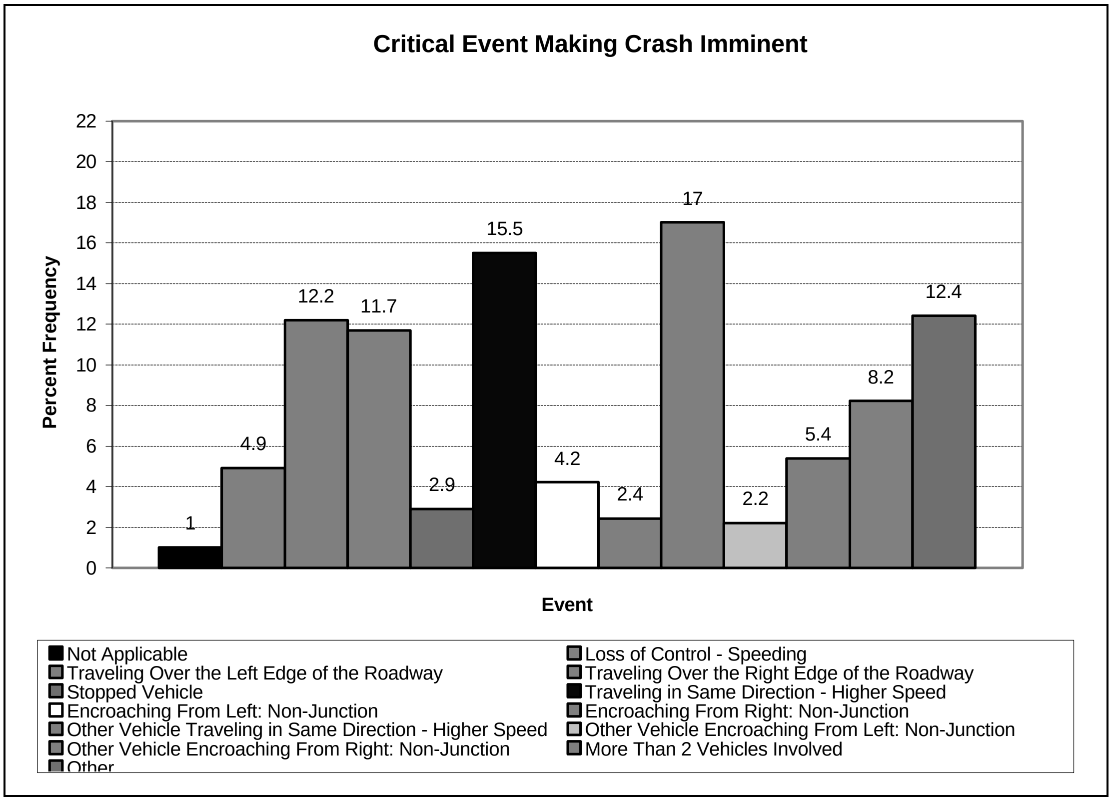


Figure 2-H8. Critical Event Making Crash Imminent by Vehicle Role for Alcohol/Drug Related Interstate Crashes

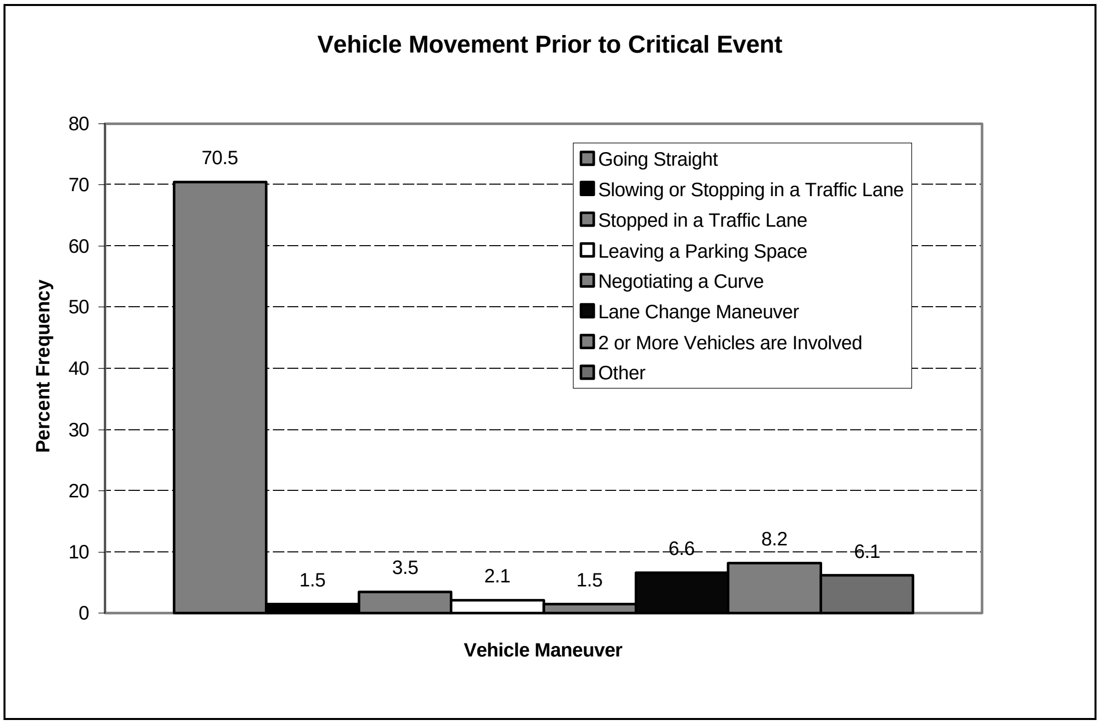


Figure 2-H9. Movement Prior to Critical Event by Vehicle Role for Alcohol/Drug Related Interstate Crashes

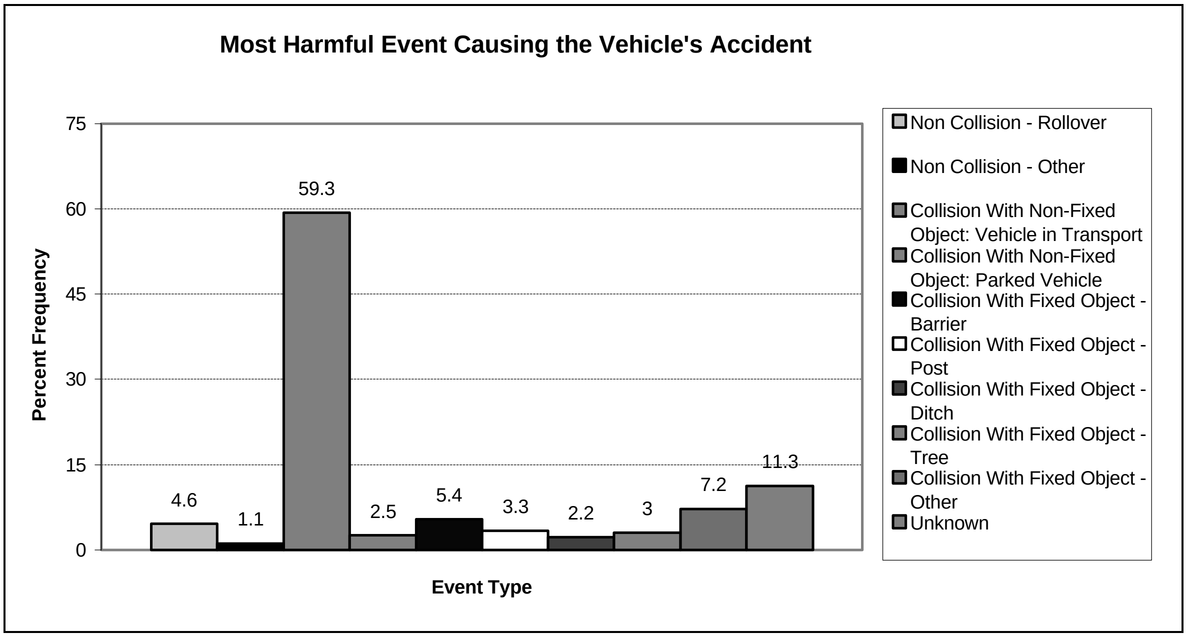


Figure 2-H10. Most Harmful Event by Vehicle Role for Alcohol/Drug Related Interstate Crashes

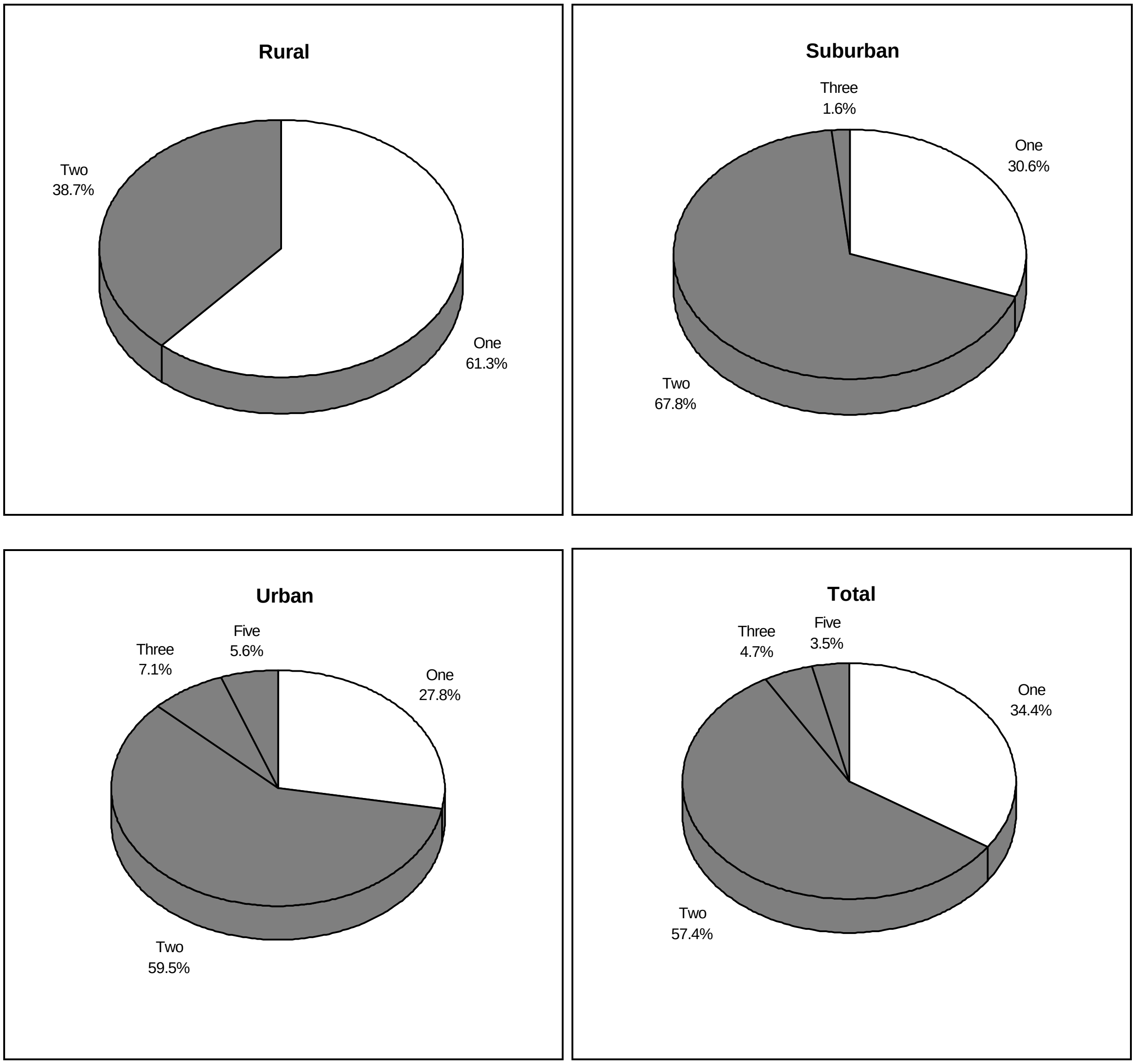


Figure 2-H11. Number Vehicles Involved by Location for Alcohol/Drug Related Interstate Crashes

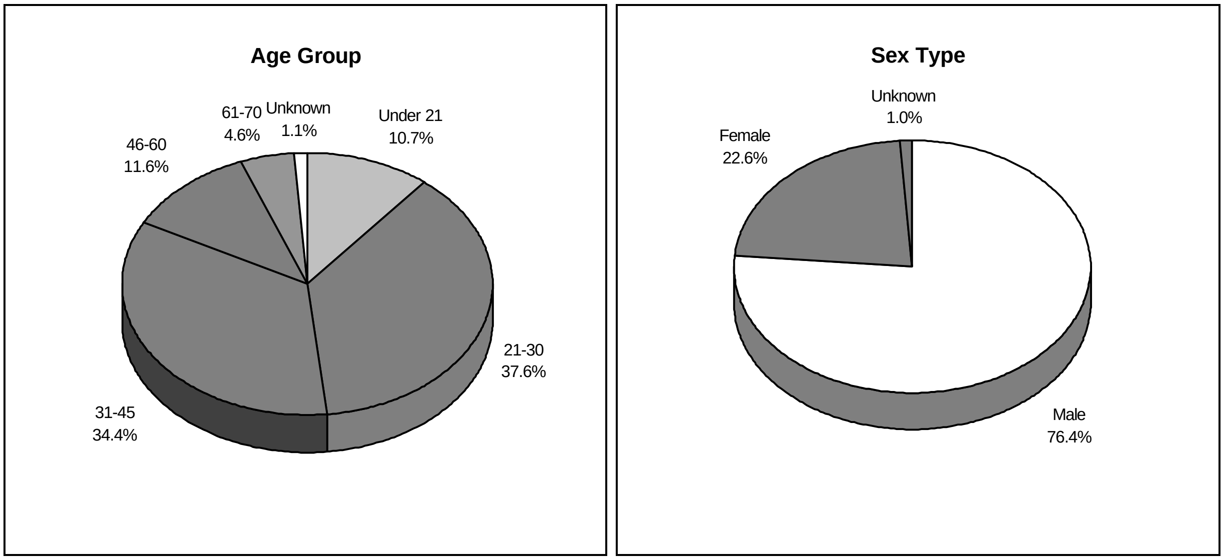


Figure 2-H12. Age Group and Sex of Drivers Involved in Alcohol/Drug Related Interstate Crashes

3.0 STATISTICS FOR ALCOHOL/DRUG RELATED CRASHES (FARS)

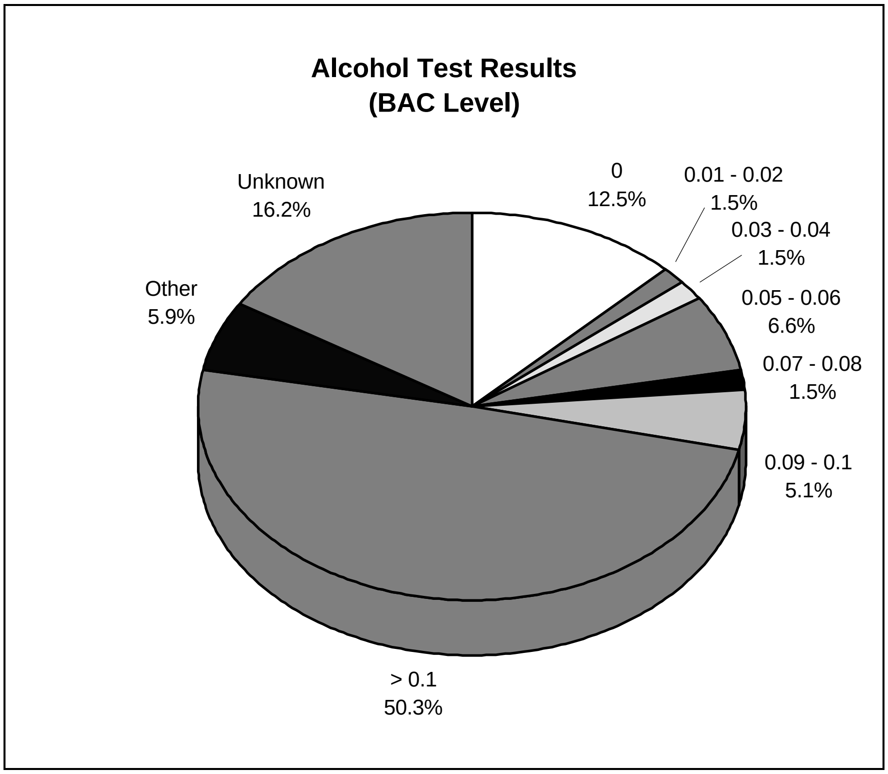


Figure 2-H13. Alcohol Test Results for Alcohol/Drug Related Fatal Interstate Crashes

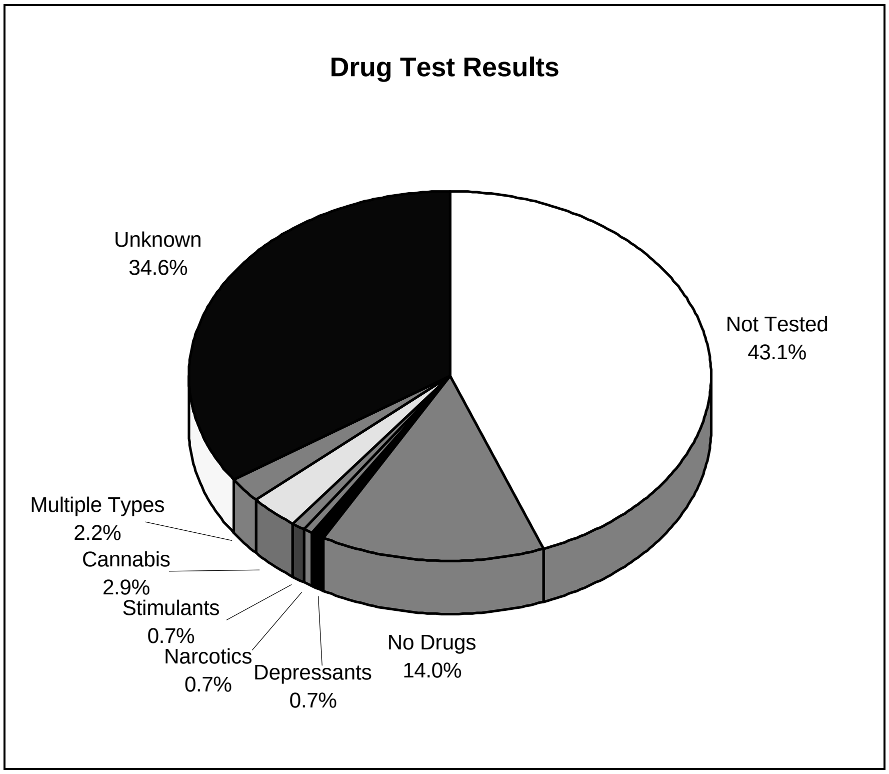


Figure 2-H14. Drug Test Results for Alcohol/Drug Related Fatal Interstate Crashes

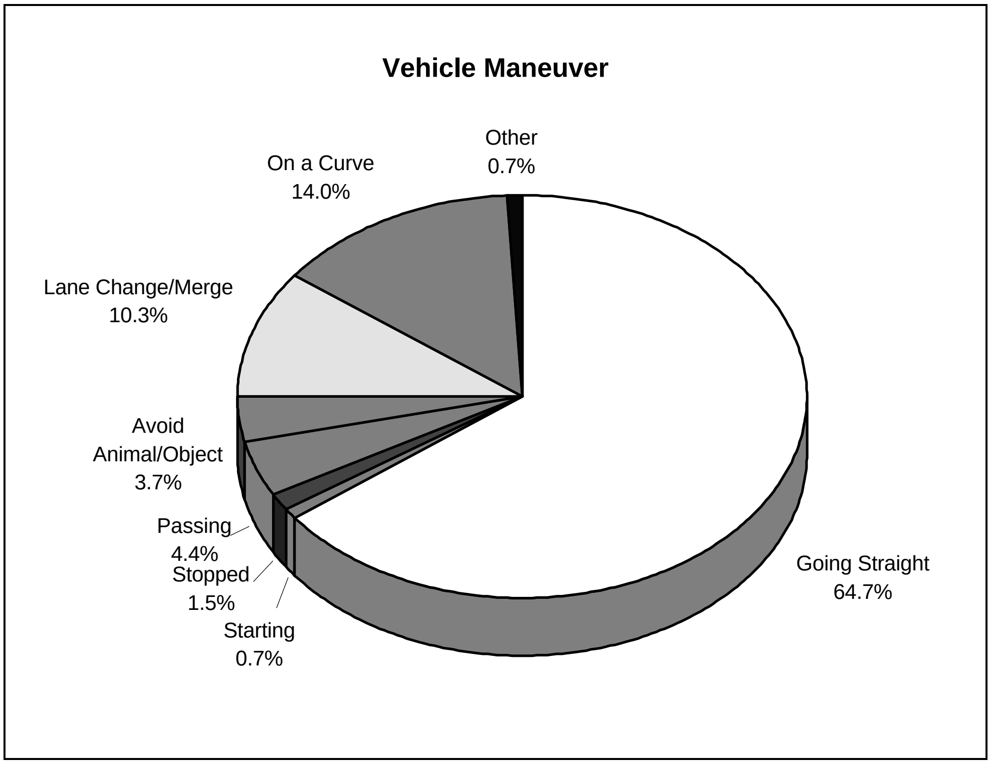


Figure 2-H15. Vehicle Maneuver for Alcohol/Drug Related Fatal Interstate Crashes

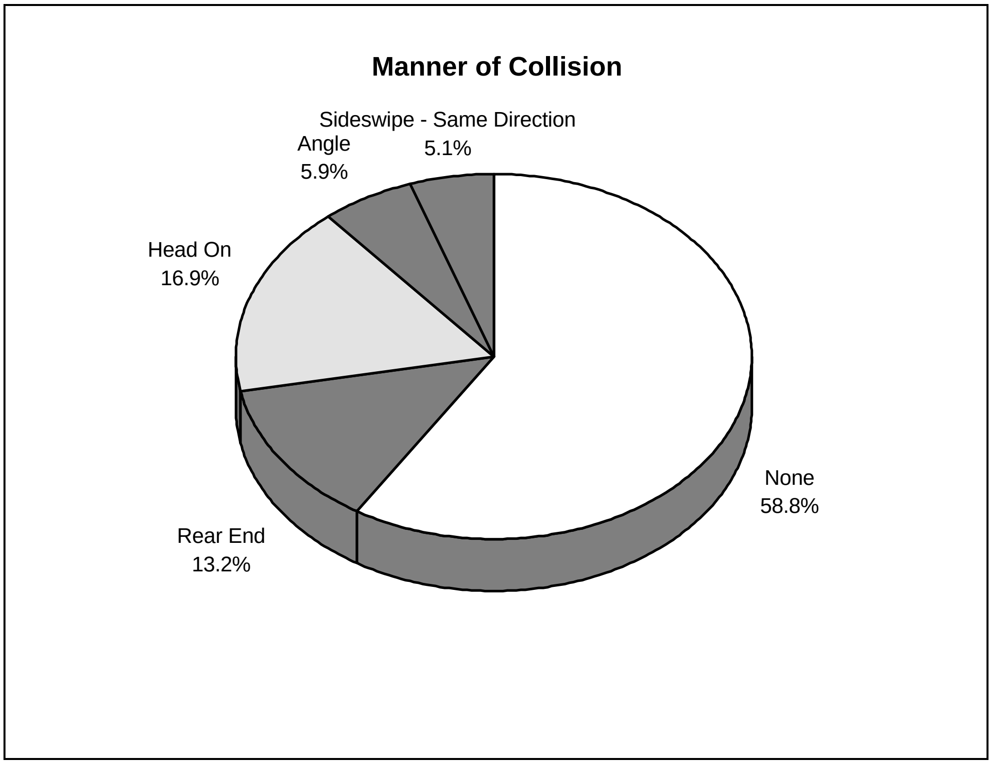


Figure 2-H16. Manner of Collision for Alcohol/Drug Related Fatal Interstate Crashes

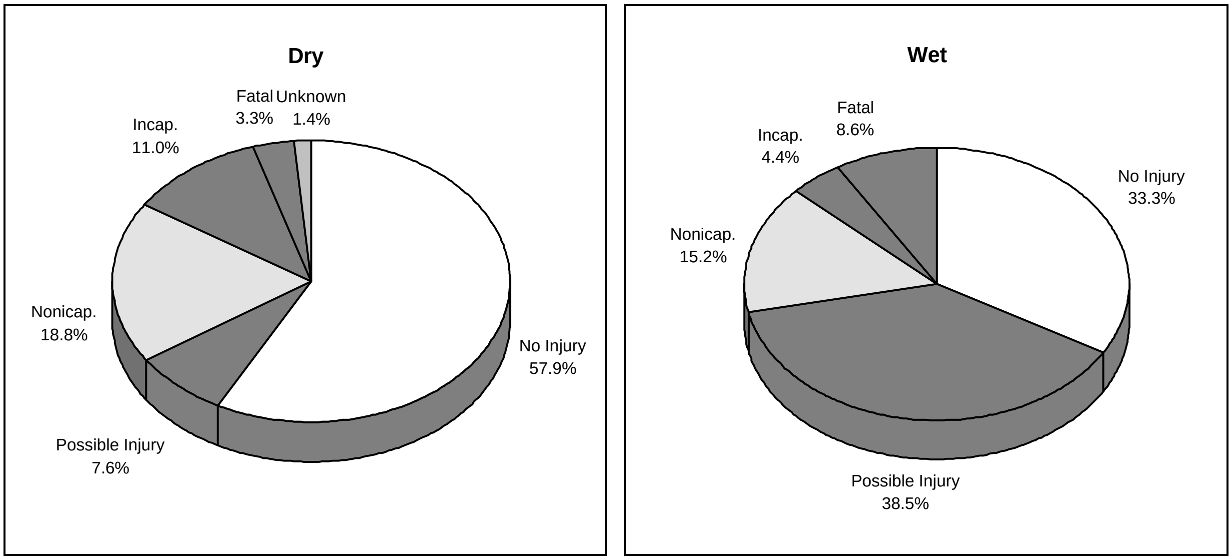


Figure 2-H17. Maximum Injury Severity in Vehicle by Roadway Surface Condition for Drowsy Driver Related Interstate Crashes

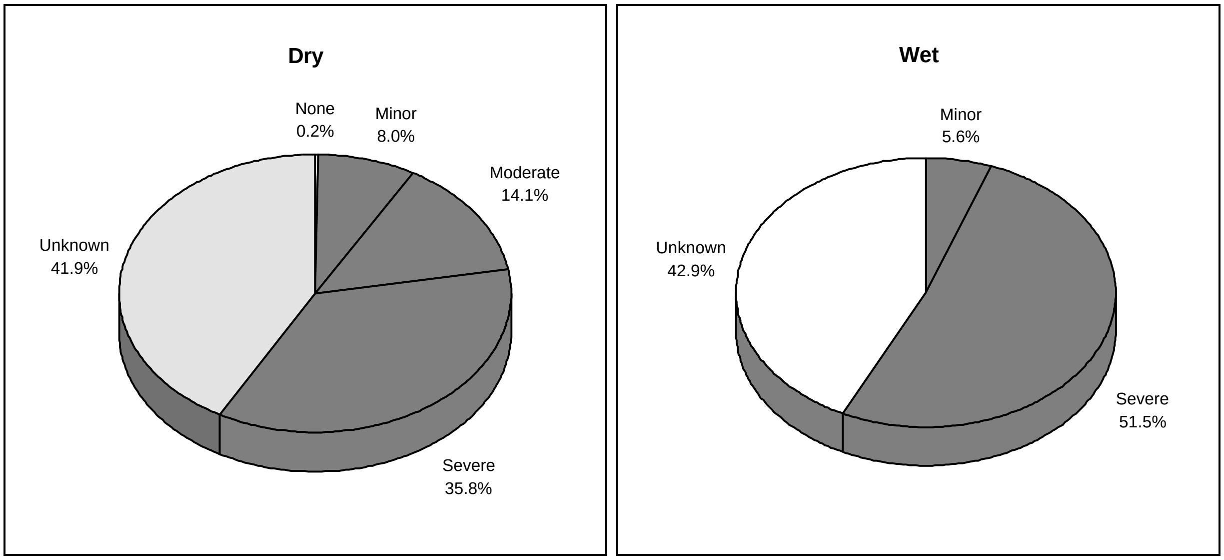


Figure 2-H18. Vehicle Damage by Roadway Surface Condition for Drowsy Driver Related Interstate Crashes

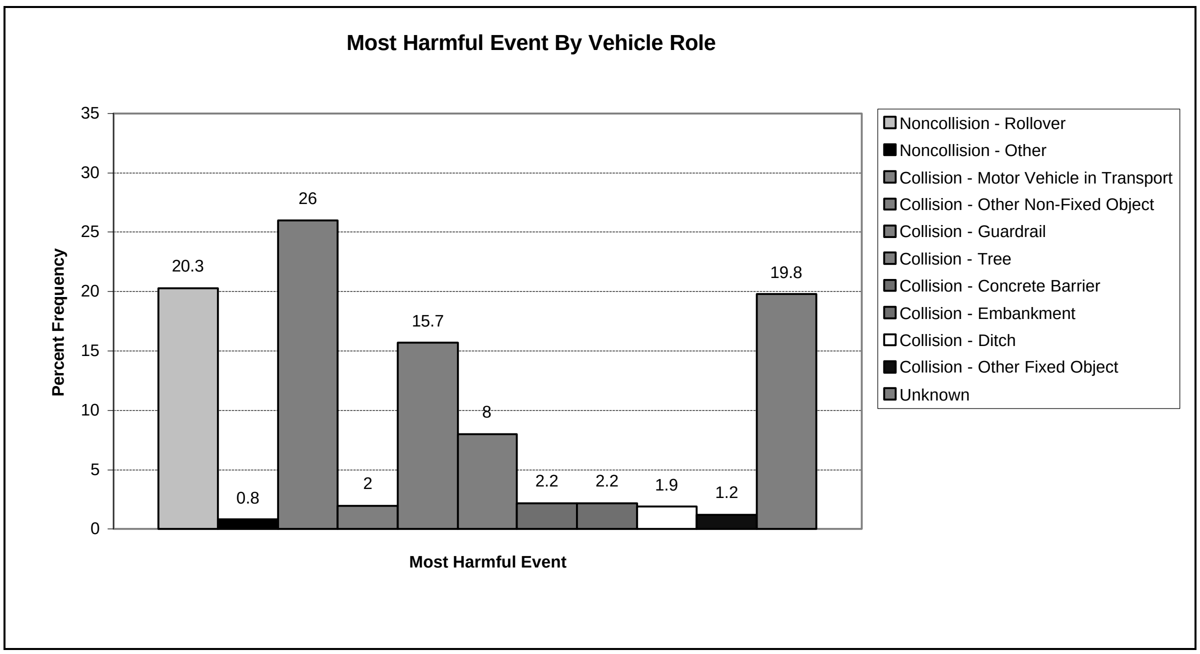


Figure 2-H19. Most Harmful Event for Drowsy Driver Related Interstate Crashes

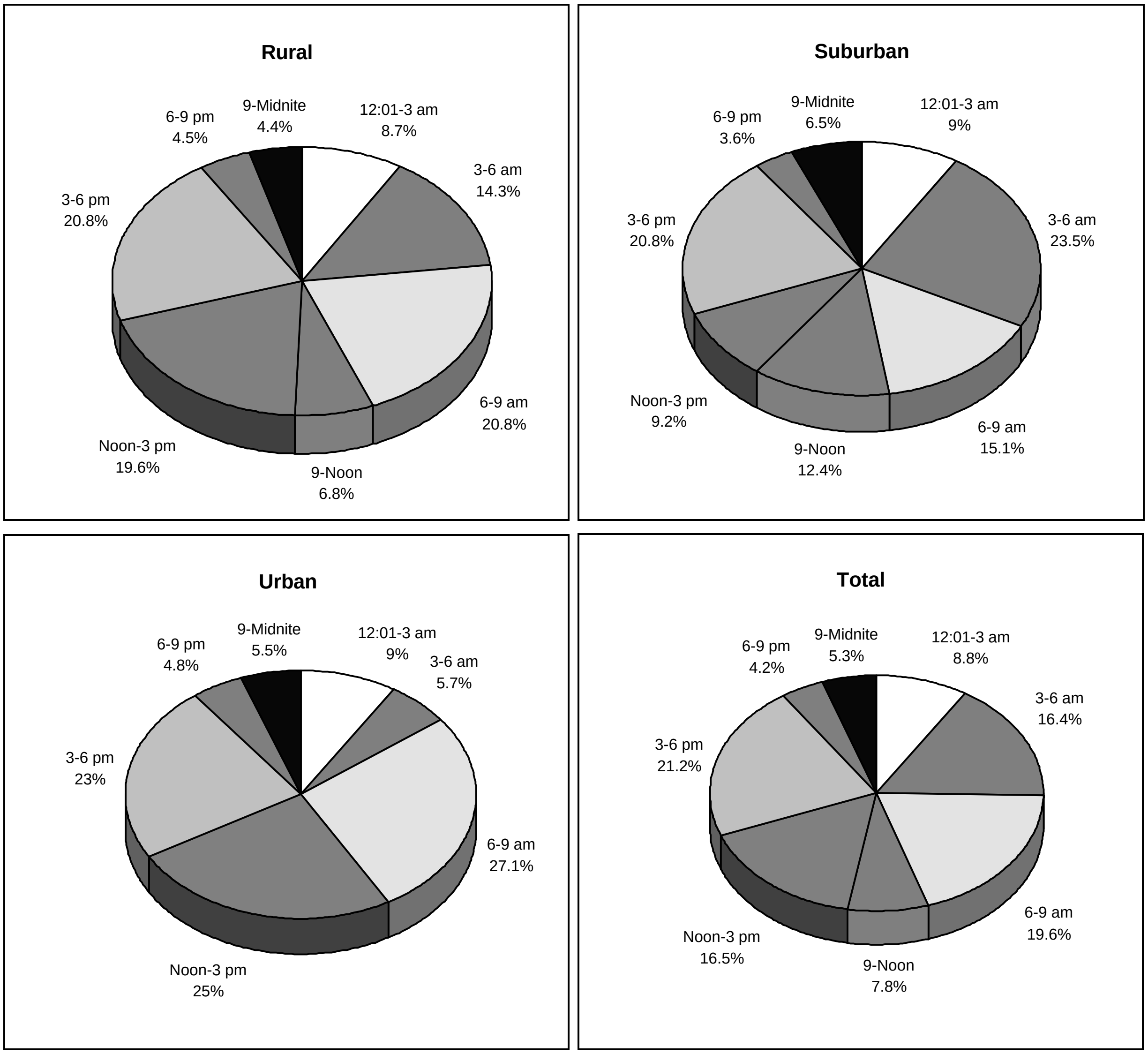


Figure 2-H20. Time by Location for Drowsy Driver Related Interstate Crashes

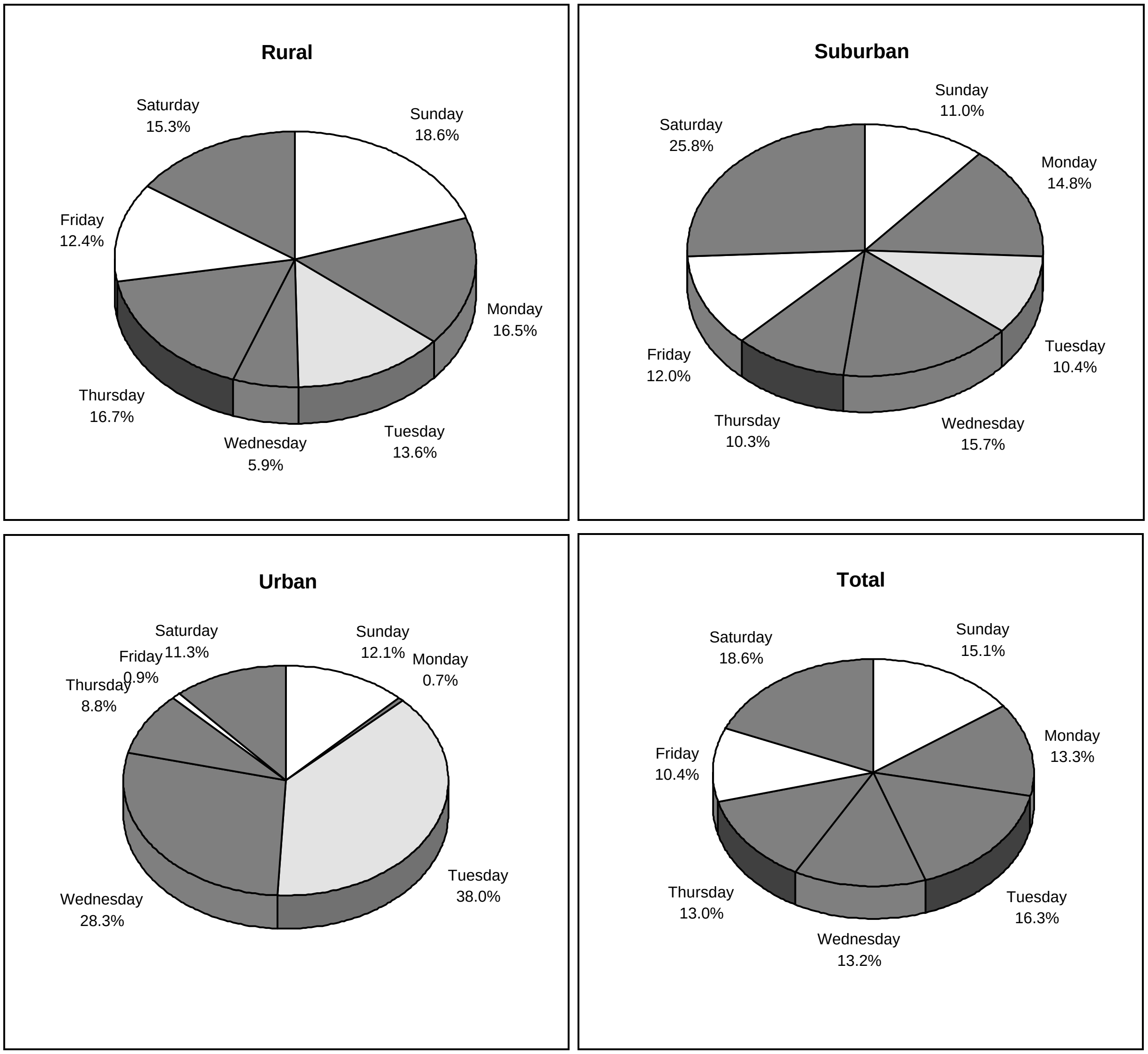


Figure 2-H21. Weekday by Location for Drowsy Driver Related Interstate Crashes

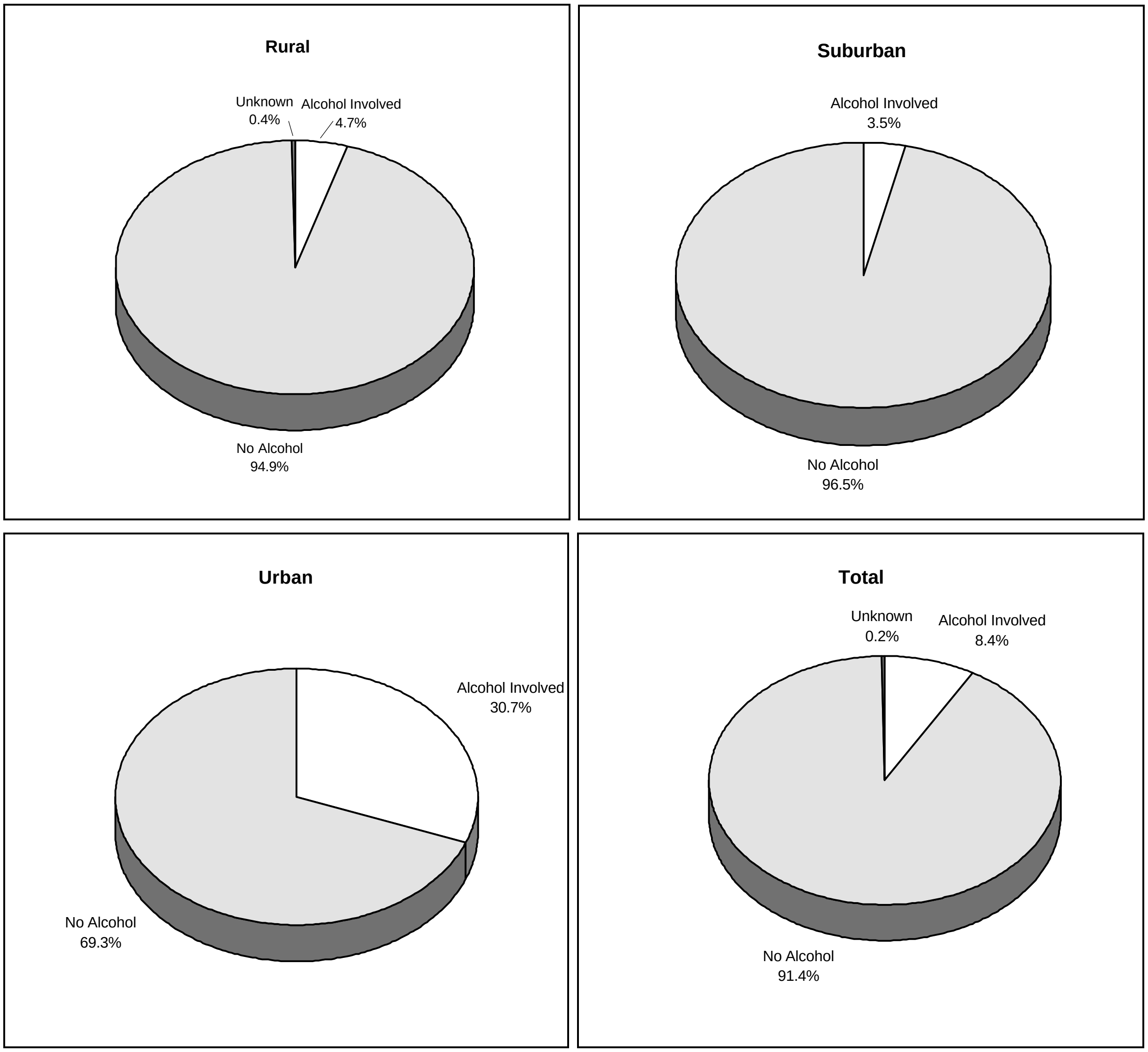


Figure 2-H22. Alcohol Use by Location for Drowsy Driver Related Interstate Crashes

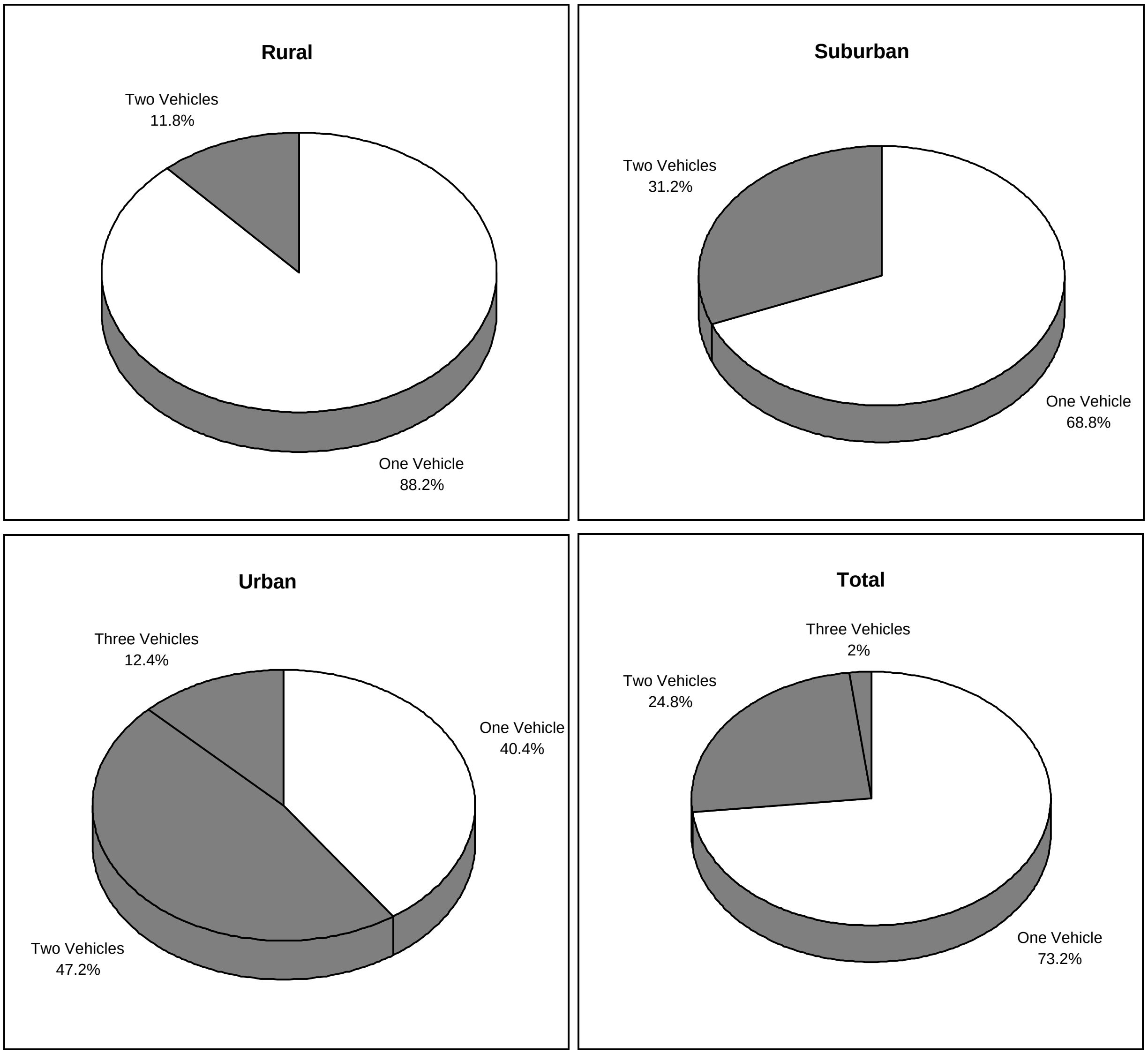
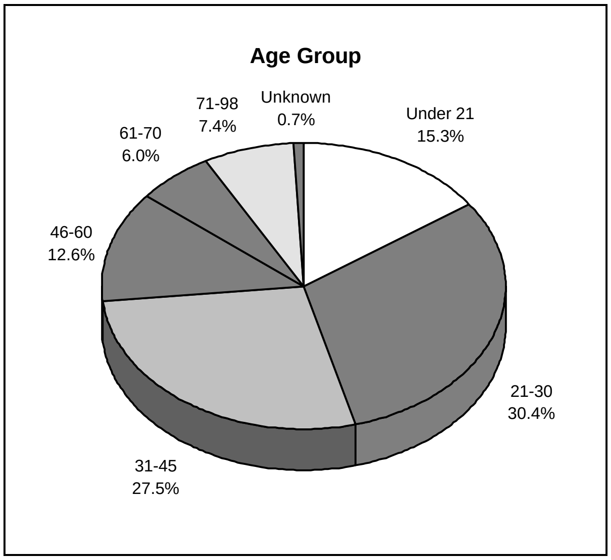


Figure 2-H23. Number of Vehicles Involved by Location for Drowsy Driver Related Interstate Crashes



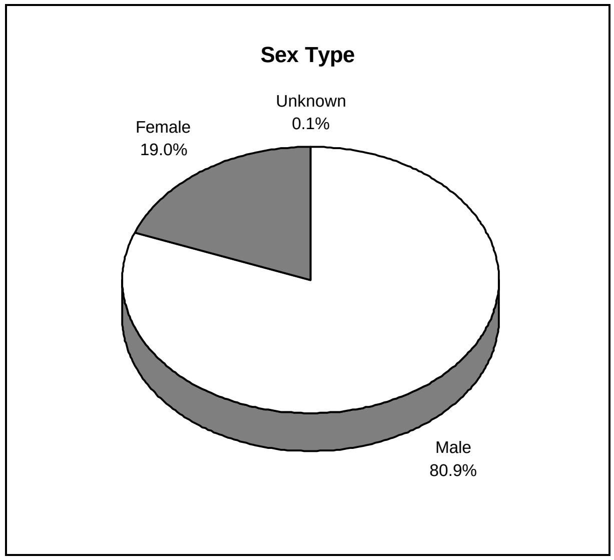


Figure 2-H24. Age and Sex of Drowsy Impaired Driver for Interstate Crashes

Table 2-H1. Accident Type by Age Group for Drowsy Driver Fatal Interstate Crashes

Accident Type	Age Group					
	< 21	21 - 30	31 - 45	46 - 60	61 - 70	> 70
Single Driver						
Right Roadside Departure						
Drive Off Road	18.6	29.3	20.1	37.6	61.1	20.4
Control/Traction Loss	19.2	9.9	9.4	12.2	12.1	37.3
Left Roadside Departure						
Drive Off Road	13.8	17.6	23.7	6.8	0.0	0.0
Control/Traction Loss	19.7	7.9	7.3	0.0	0.0	18.4
Forward Impact	8.5	1.9	0.1	0.5	0.0	0.0
Same Trafficway, Same Direction						
Rear-End	4.3	16.9	20.7	17.9	20.8	0.0
Sideswipe Angle	15.9	9.7	8.5	24.6	0.0	0.0
Same Trafficway, Opposite Direction						
Head-On	0.0	0.0	0.2	0.5	0.0	0.0
Sideswipe Angle	0.0	0.4	0.0	0.0	0.0	0.0
Miscellaneous						
Backing, etc.						
Untripped Rollover	0.0	3.6	1.4	0.0	0.0	24.0
Other/Unknown	0.0	2.7	8.5	0.0	6.0	0.0
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Table 2-H2. Alcohol Test Results for Drowsy Driver Fatal Interstate Crashes

BAC	Frequency	Percent
0	**182**	**40.8%**
0.01 - 0.02	**6**	**1.3%**
0.03 - 0.04	**5**	**1.1%**
0.05 - 0.06	**7**	**1.6%**
0.07 - 0.08	**7**	**1.6%**
0.09 - 0.1	**7**	**1.6%**
> 0.1	**31**	**7.0%**
None Give	**164**	**36.8%**
Results Unknown	**12**	**2.7%**
Unknown	**25**	**5.6%**
Total	**446**	**100.0%**

Table 2-H3. Drug Test Results for Drowsy Driver Fatal Interstate Crashes

Result	Frequency	Percent
Not Tested	**257**	**57.6%**
No Drugs Reported	**78**	**17.5%**
Depressants	**1**	**0.2%**
Stimulants	**5**	**1.1%**
Cannabis	**3**	**0.7%**
Multiple Drugs	**3**	**0.7%**
Unknown	**99**	**22.2%**
Total	**446**	**100.0%**

Table 2-H4. Vehicle Maneuver for Drowsy Driver Fatal Interstate Crashes

Maneuver	Frequency	Percent
Going Straight	**375**	**84.1%**
Stopped in Traffic Lane	**4**	**0.9%**
Passing	**5**	**1.1%**
Avoiding Animal / Object	**6**	**1.3%**
Lane Change / Merge	**4**	**0.9%**
Negotiating a Curve	**51**	**11.4%**
Unknown	**1**	**0.2%**
Total	**446**	**100.0%**

Table 2-H5. Manner of Collision for Drowsy Driver Fatal Interstate Crashes

Collision Type	Frequency	Percent
None	**391**	**87.7%**
Rear-End	**27**	**6.1%**
Head-On	**16**	**3.6%**
Angle	**7**	**1.6%**
Sideswipe - Same Direction	**4**	**0.9%**
Unknown	**1**	**0.2%**
Total	**446**	**100.0%**

Table 2-H6. First Harmful Event for Drowsy Driver Fatal Interstate Crashes

Event	Frequency	Percent
Overturn	**170**	**38.1%**
Other - Non-Collision	**1**	**0.2%**
Collision with Pedestrian	**4**	**0.9%**
Collision with Motor Vehicle in Transport	**40**	**9.0%**
Collision with Guardrail	**72**	**16.1%**
Collision with Tree	**22**	**4.9%**
Collision with Other	**137**	**30.7%**
Total	**446**	**100.0%**

APPENDIX I

1.0 DATA FILES AND FILTERS TO DEFINE MIXED VEHICLE CRASHES

Data from the 1992 GES data files provide general information about the characteristics of mixed vehicle crashes. The scope of the analysis is limited to two-vehicle crashes on interstates where one of the vehicles involved is a passenger car or light truck and the other vehicle is a medium or heavy truck. The GES data restrictions are:

INT_HWY = 1	(crash occurred on an interstate highway)
VEH_INVL = 2	(# vehicles involved is two)
(VEHNO=1, BODY_TYP=1 - 49 & VEHNO=2, BODY_TYP=60 -79) or (VEHNO=1, BODY_TYP=60 -79 & VEHNO=2, BODY_TYP=1-49)	(one vehicle type is automobile or light truck, & other vehicle type is medium or heavy truck*)

*This restriction required several filter and merge steps.
All tabulations represent GES weighted estimates.

2.0 STATISTICS FOR MIXED VEHICLE CRASHES

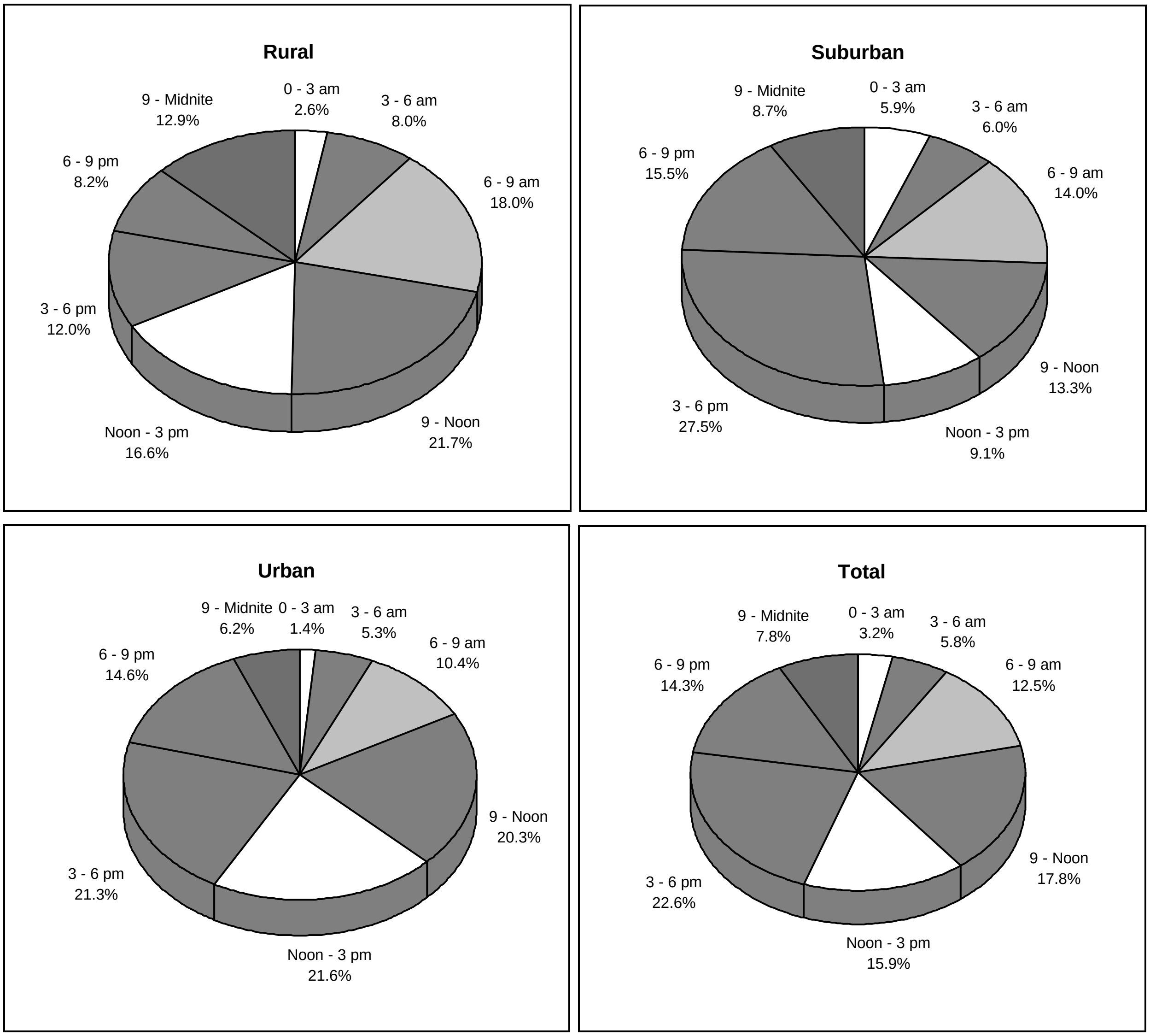


Figure 2-I1. Time of Day for Interstate Mixed Vehicle Crashes

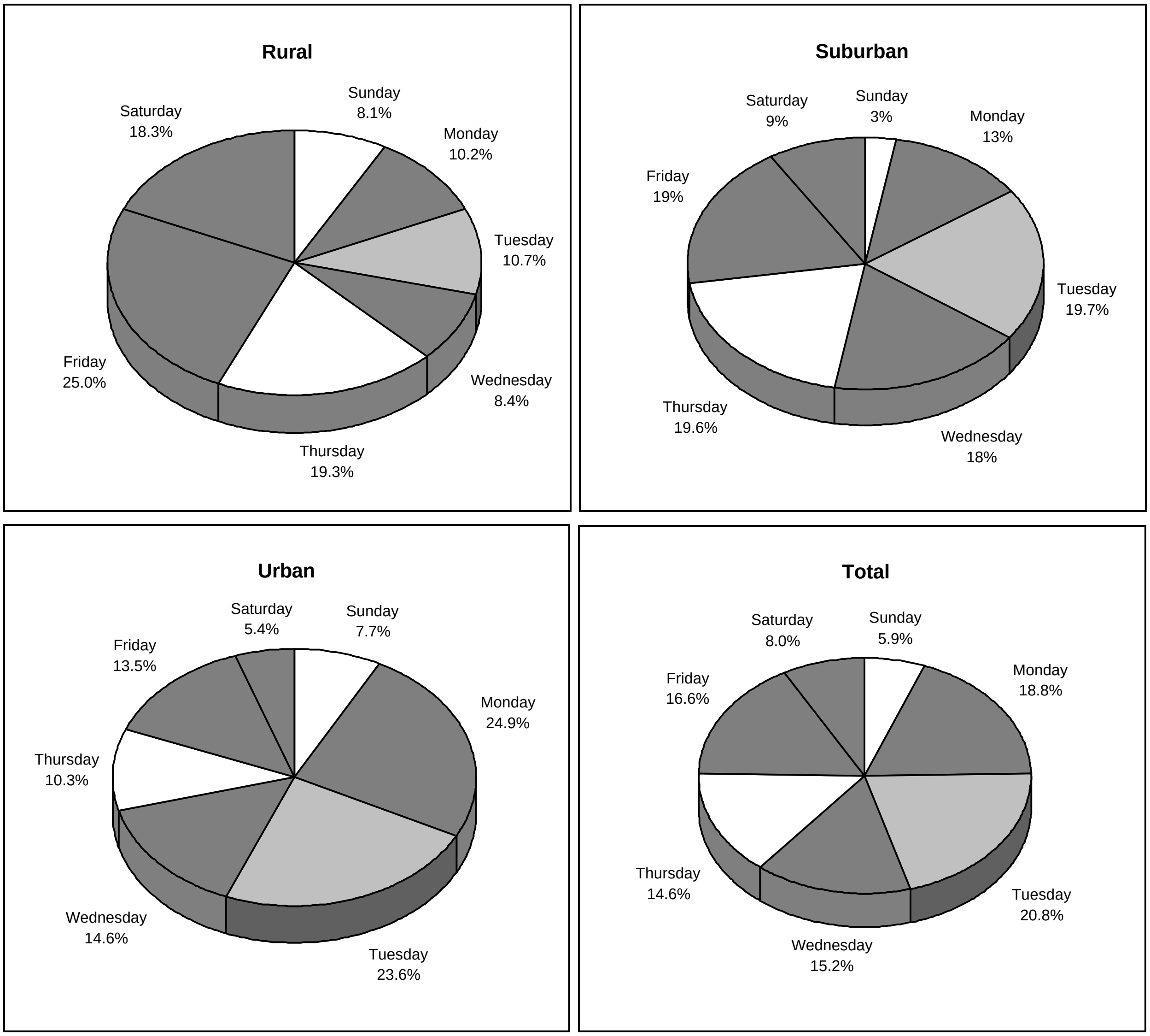


Figure 2-I2. Day of Week for Interstate Mixed Vehicle Crashes

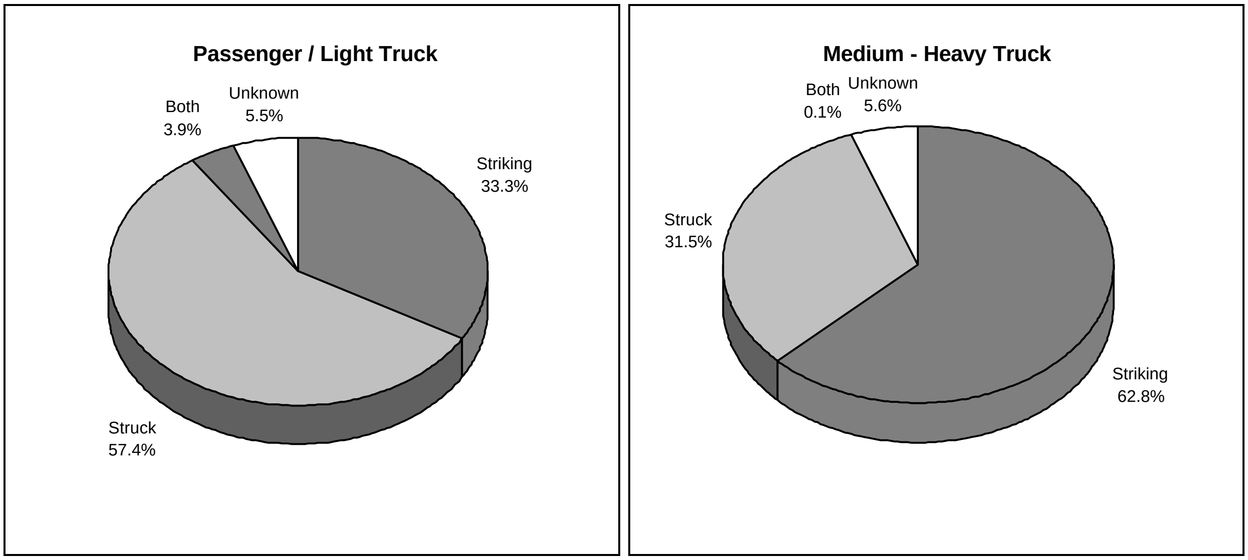


Figure 2-I3. Vehicle Role by Vehicle Type for Interstate Mixed Vehicle Crashes

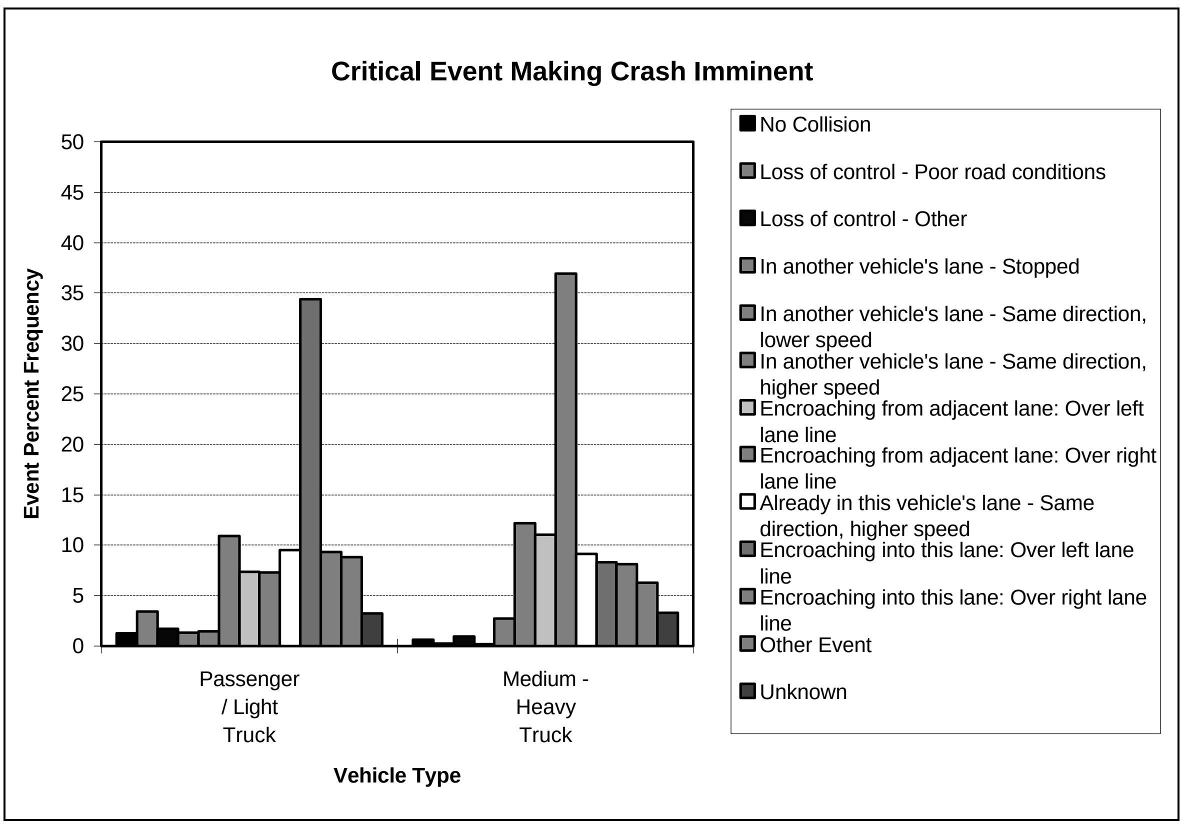


Figure 2-I4. Critical Event for Interstate Mixed Vehicle Crashes

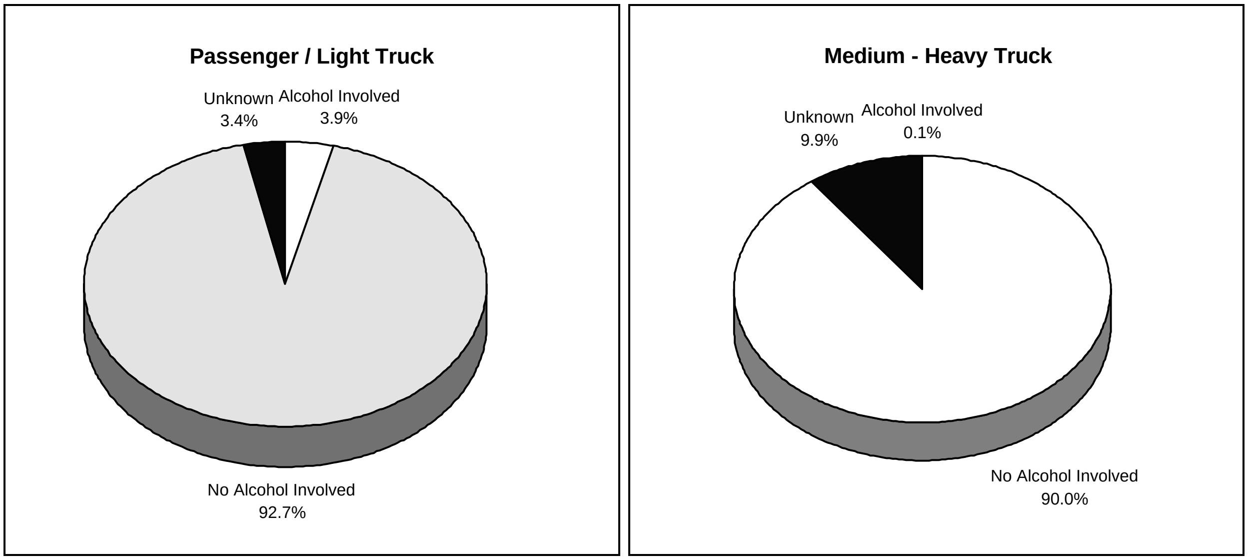


Figure 2-I5. Police Reported Alcohol Involvement for Interstate Mixed Vehicle Crashes

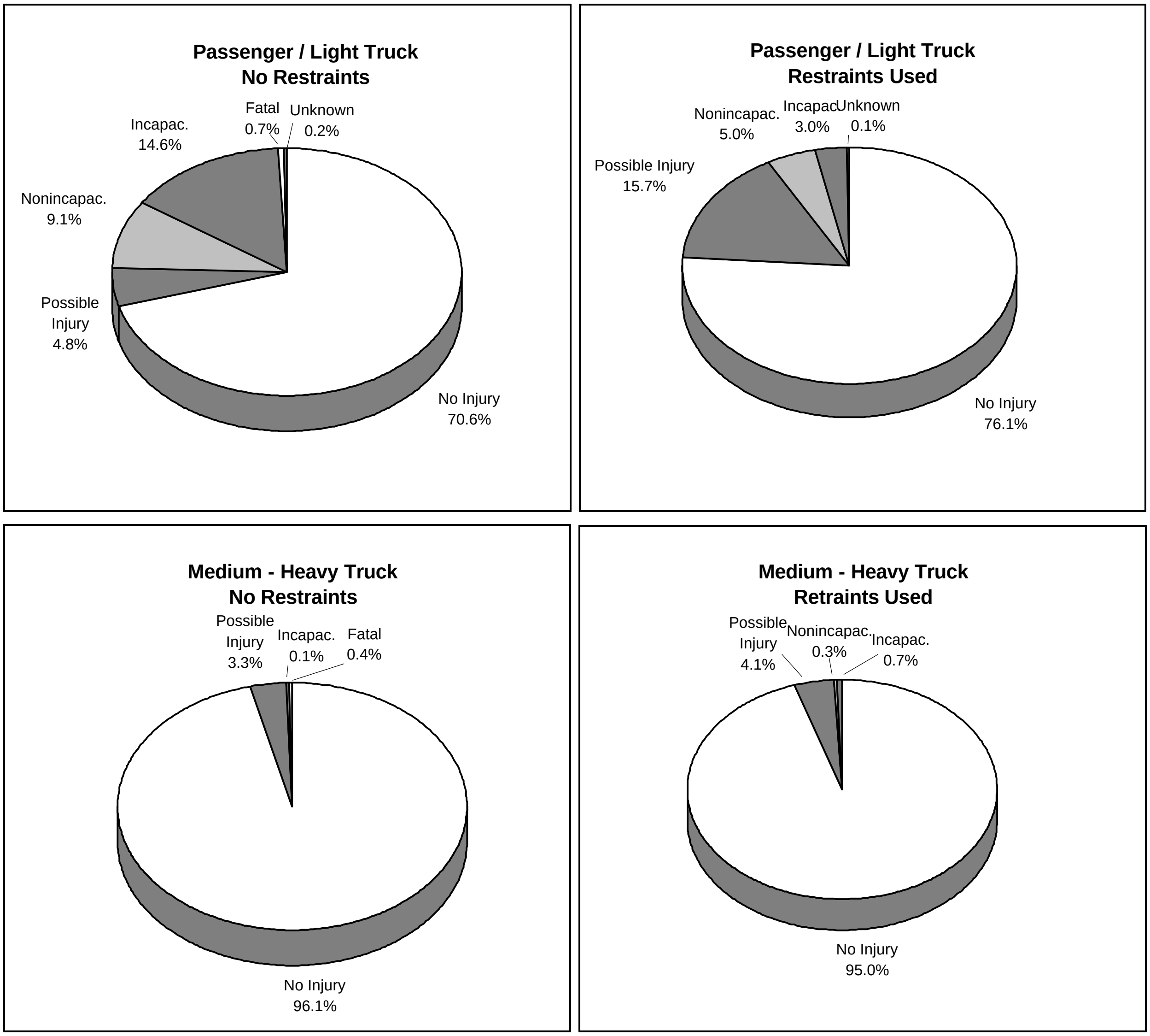


Figure 2-I6. Occupant Injury Severity by Restraint Use for Interstate Mixed Vehicle Crashes

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