PRE-CRASH SCENARIOS FOR DETERMINING TARGET POPULATIONS OF ACTIVE SAFETY SYSTEMS

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ABSTRACT

The of active safety systems is to prevent or mitigate collisions. A critical component in the design of active safety systems is to identify the target population for a proposed system. The target population for an active safety system is that set of crashes that a proposed system could prevent or mitigate. Target crashes have scenarios in which the sensors and algorithms would likely activate. For example, the rear-end crash scenario, where the front of one vehicle contacts another vehicle traveling in the same direction and in the same lane as the striking vehicle, is one scenario in which Forward Collision Warning (FCW) would be most effective in mitigating or preventing. This paper presents novel pre-crash scenarios based upon coded variables from NHTSA's nationally representative crash databases. Using three databases the scenarios developed in this study can be used to quantify the number of police reported crashes, seriously injured occupants, and fatalities that are applicable to proposed systems. In this paper, we use the pre-crash scenarios to identify the target populations for FCW, Lane Departure Warning (LDW), and Vehicle-to-Vehicle (V2V) or Vehicle-to-Infrastructure (V2I) systems. This study found that these three systems could potentially mitigate or prevent 59% of both seriously injured occupants and fatalities.

INTRODUCTION

The target population for an active safety system is that set of crashes that a proposed system could prevent or mitigate. These crashes have scenarios in which the sensors and algorithms would likely activate. For example, the rear-end crash scenario, where the front of one vehicle contacts another vehicle traveling in the same direction and in the same lane as the striking vehicle, is one scenario in which a Forward Collision Avoidance System (FCAS) would activate. Many of FCAS systems utilize forward-facing sensors, e.g. radar. Because the vehicle is in view of the sensors prior to the crash, rear-end collision are likely to be detected. In other forward crash scenarios, such as intersection or turning crashes, a struck vehicle may come in view of the sensors too late to activate. This is especially true for the warning component, which needs longer times to be maximally effective.

Another important aspect of the target population is the societal cost which a proposed active safety system could potentially mitigate. These societal costs of crashes can be measured by the costs associated with injured occupants including the costs of medical treatment, lost wages, and long-term disability. Because active safety systems have tremendous equipment and development costs for automakers, the systems that can potentially mitigate the most injuries should be prioritized based on cost reduction. Therefore, systems that can potentially mitigate the most injuries should be prioritized.

An important tool in identifying target populations for countermeasures is examining the crash population in terms of crash scenarios. Crash scenarios group similar crashes in real-world crash databases using the variables coded for each case. Previous researchers have developed crash scenarios for nationally representative crash databases, such as those by Eigen and Najm [1]. The approach in Eigen and Najm was to use variables that described the pre-crash phase of the collision to group scenarios. We will adapt these scenarios for the current study and

use them to examine the target population of forward collision avoidance systems as an example.

The objective of this study is to develop crash scenarios for use in identifying the target population for active safety systems.

METHODOLOGY

Data Sources

Three data sources were used for this study: the National Automotive Sampling System (NASS) General Estimates System (GES), the NASS Crashworthiness Data System (CDS), and the Fatality Analysis Reporting Systems (FARS). GES is a representative sample of all police reported crashes in the U.S. CDS is a representative sample of crashes which involve passenger vehicles towed from the scene due to damage. FARS is a census of all traffic related fatalities in the U.S. All three databases are funded and maintained by the National Highway Traffic Safety Administration (NHTSA) and are released to the public on an annual basis.

Each data base represents a different population of crashes. The GES sample is an estimate of all crash exposure in the U.S. There are approximately 50,000 crashes per year that make up the GES sample. The CDS database is similar, but is restricted to tow-away crashes only. Unlike GES that collects data from police accident reports only, CDS has trained crash investigation teams that gather in-depth information on each crash. The CDS investigators photograph and diagram the crash scene, prepare scene diagrams, measure vehicle damage, conduct interviews with occupants involved, and collect injury information from medical sources. FARS is similar to GES in that most of the data is gathered from police accident reports. GES and CDS are probability samples of police reported crashes that are weighted to represent all crashes. FARS is meant to be a census of all fatal traffic crashes.

Because these three data sources are all maintained by NHTSA, some of the key variables are similar. Of interest when defining pre-crash scenarios are those coded variables that pertain to the pre-crash period of the event. In the last several years of data collection, i.e. 2010 and 2011, the pre-crash variables in GES and FARS have been standardized so that they match the CDS definitions [2]. The standardization of these pre-crash variables across all three databases allows for the comparison of these data sources. Such a comparison prior to year 2010 would have not been possible. For this study, the last 5 years of NASS/CDS (2007 to 2011) were used. For GES and FARS years 2010 and 2011 were used. Previous years of FARS and GES either do not have pre-crash variables or they were drastically changed for the 2010 standardization and could not be used for this study. In order to be included in the CDS database, at least one passenger vehicle must have been towed from the scene due to damage. To facilitate comparisons between data sources, cases from FARS and GES were restricted to those involving at least one passenger vehicle. The variable definitions for passenger vehicles, including cars, light utility, light vans, and light trucks, are included in the appendix.

The data are provided by NHTSA to the public via download (ftp://ftp.nhtsa.dot.gov/). Files are sometimes modified from their original release, to correct mistakes in the data. GES 2010 files were dated October 11, 2011 and 2011 files were dated December 9, 2012. CDS 2007 files were dated August 15, 2008, 2008 files were dated December 1, 2011, 2009 files were dated September 20, 2010, 2010 files were dated September 11, 2011, and 2011 files were dated December 18, 2012. FARS 2010 files were dated July 31, 2012 and 2011 files were dated August 14, 2012.

Crash Scenarios

Figure 1 shows photographs taken as part of a fatal rear-end collision involving a 2010 Ford Fusion (right of Figure 1) which struck a 2007 Subaru Impreza (left), which was stopped in traffic. This case is an example of a crash that would be applicable to FCAS. The driver of the Impreza, a 37-year-old male, was fatally injured (brain stem transection) while a 3-year-old female in a child seat in the middle position of the back seat only suffered moderate injuries (a foot fracture and lung contusion). The driver of the Fusion was a 49-year-old male who had a 0.0 blood alcohol concentration as measured by a police administered test. The driver of the striking vehicle was seriously injured with

bilateral rib fractures that required a 9-day hospitalization.

Figure 1. Photograph from NASS/CDS Investigation of a Fatal Rear-end Collision (Case 2010-82-137).

In the three NHTSA databases, the critical pre-crash event, pre-crash movement, and accident type variables provide information about the configuration and driver maneuvers in each crash. Figure 2 shows the approach developed for this study to classify collisions using database variables. Example values for each variable are provided below for the striking vehicle of the rear-end shown above. The critical pre-crash event is the event that made the crash imminent as determined by the investigator. The databases in our study had 92 critical event categories. The accident type variable describes the configuration of the crash for the first harmful event and has approximately 100 values. Finally, the pre-crash maneuver describes the vehicle's activity prior to the crash, such as decelerating in lane, passing, or going straight. Together these three variables were used to assign every vehicle in each database a pre-crash scenario. All crashes in the database were assigned a single crash scenario. Each crash was assigned a scenario based upon the crash scenarios of the two vehicles involved in the first harmful event in the crash. If there was only one vehicle involved in the crash, this vehicle was used to determine the scenario.

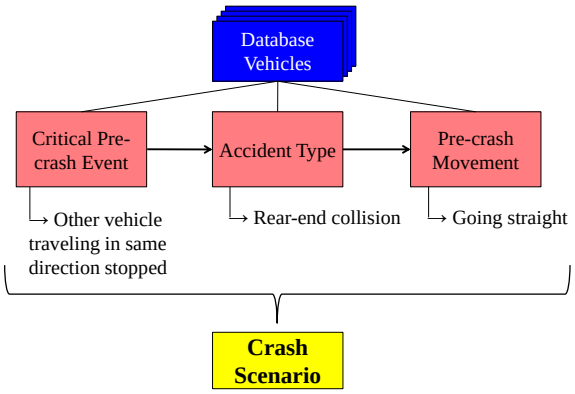

Figure 2. Approach for Determining Pre-Crash Scenario from NASS/CDS Variables.

In many cases the critical pre-crash event and accident type variables indicate very similar information, such as in the example rear-end crash above. The accident type variable must correspond to the first impact in a crash whereas the critical pre-crash event describes what made the first pre-crash event unavoidable. In some scenarios this can lead to meaningful differences with regard to if an active safety system would activate. Consider NASS/CDS case 2011-41-116 whose scene diagram is shown in the left of Figure 3. Vehicle 1, a 2001 Mercedes Benz E-class departed its lane and struck vehicle 2, which was stopped. The pre-crash critical event for the striking vehicle was "this vehicle traveling over the left lane line" and the accident type was a rear-end collision. The pre-crash maneuver of the striking vehicle was going straight, not changing lanes or avoiding another critical event. For the study of active safety systems, this crash would most likely be mitigated by a Lane Departure Warning (LDW) system that could have warned the driver he was exiting his lane. Compare this rear-end crash with the one involving the Fusion and Impreza, shown in the right of Figure 3. FCAS could more likely be applicable to this crash because the struck vehicle would have been in view of the front-facing sensors in time to either deliver a warning or take action. In

our approach to assign pre-crash scenarios, pre-crash critical event was prioritized over accident type because it described the portion of the pre-crash phase where active safety systems would activate more completely.

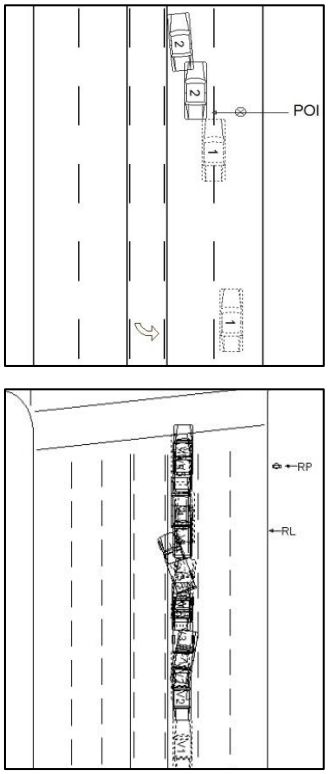

Figure 3. Scene Diagram Prepared by Investigator for NASS/CDS Cases 2011-41-116 (Top) and 2010-82-137 (Bottom).

Figure 4 shows the single vehicle crash scenarios: single vehicle crashes with fixed objects on the roadside, control loss, caused by an animal in the road, caused by a pedestrian or cyclist in the road, object in the road, and other. Similarly, scenarios for multiple vehicle collision are shown in Figure 5. For target population analysis, many of these crashes can be broken down further into subgroups based on pre-crash maneuver (e.g. turning, going straight) or object struck.

Measure of Injury and Harm

In addition to examining the frequency of crashes, the number of injuries is also an important measure of the target population. NASS/CDS codes individual injuries using the Abbreviated Injury Scale (AIS). The AIS is a one to six score that measures the threat to life an injury poses [3]. A score of one corresponds to a minor injury and a score of six corresponds to an unsurvivable injury. NASS/CDS includes AIS codes for each injury suffered by occupants. AIS scores are derived from medical records and coded by a trained AIS coding specialist. Other crash databases, such as GES, often use less exact injury scales, e.g. the KABCO scale, that are designed to be assigned by non-medical staff, e.g. police officers filling out police accident reports. These less exact injury measures assign either no injury, possible injury, moderate injury, incapacitating injury, or fatal injury to each occupant. This assessment is often made at the crash scene, is not based on medical records, and is less reliable [4].

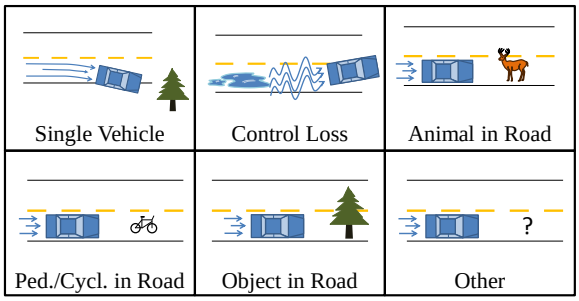

Figure 4. Single Vehicle Crash Scenario Categories.

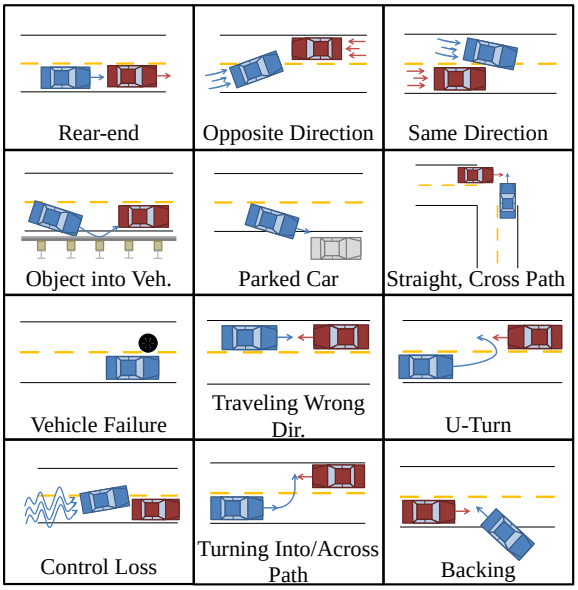

Figure 5. Multi-Vehicle Crash Scenario Categories.

In this study a serious injury to a body region was considered as those with AIS level 3 and above (AIS3+). Occupants were considered seriously to

fatally injured if the maximum of their body region AIS (MAIS) was of level 3 or greater (MAIS3+) or if the occupant was fatally injured. The AIS is a threat to life scale. Another measure, known as Harm, attempts to place a socioeconomic cost on injuries sustained from a crash. The Harm metric is based on medical costs, lost wages, and long term disability from an injury and is often measured with a monetary value. Each body region (e.g. head, chest, lower extremity) is assigned a representative cost for each AIS level of injury. Next, the costs of all injuries to an occupant are summed to find the Harm cost of a crash. In this study we used Harm values presented by Fildes *et al.* [5]-[7].

Target Populations for Active Safety Systems

The target population for an active safety system is the set of collisions that would be most likely mitigated by a system. To demonstrate the utility of the scenarios developed for this study, we will examine the target populations for several systems becoming available or being developed: Forward Collision Warning (FCW), Lane Departure Warning (LDW), and Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) systems. FCW and LDW warn drivers of impending frontal collisions and inadvertent lane departures, respectively. FCW and LDW are available as optional or standard equipment many on production vehicles. V2V and V2I are communication systems where vehicle safety data, e.g. position, speed, and heading, are shared between vehicles and infrastructure. This information can be used in safety applications similar to FCW and LDW. One advantage of V2V and V2I is that they are not restricted by line of sight of the sensors. FCW use radar and/or cameras to sense other vehicles and LDW systems often use cameras to track lane lines. The systems will fail if the objects being tracked are occluded, such as in intersection situations.

Table 1 summarizes the applicable crash scenarios for each of these systems. Rear-end collisions, where the driver was not maneuvering before the crash, are the most applicable scenario for FCW. The vehicles in front of the equipped vehicle must be tracked well before the crash in order to deliver an effective warning early enough. This is the case in rear-end collisions but might not be true for crash scenarios such as opposite direction crashes. LDW is applicable to road departure, opposite direction, and same direction crashes when the driver of the departing vehicle is lane keeping, i.e. going straight, prior to the departure. V2V and V2I systems could mitigate intersection and turning crashes. Drivers could be warned if they are about to enter an intersection at the same time as another vehicle as well as advise drivers when it is safe to turn across opposing lanes of traffic. V2V could also be used to accomplish the same goals as FCW. Rear-end crashes were not included in the V2V/V2I target population so that the systems' target populations are mutually exclusive.

Table 1.
Applicable Crash Scenarios for Three Active Safety Systems

System	Crash Scenarios
Forward Collision Warning (FCW)	• Rear-end, no maneuvers
Lane Departure Warning (LDW)	• Road departures, lane keeping • Opposite direction, lane keeping • Same direction, lane keeping
V2V/V2I	• Straight crossing paths (SCP) • Left turn across path, Opposite Direction (LTAP/OD) • Left turn across path, Perpendicular • Turn into path, Same Direction

RESULTS

Crash Scenarios

Table 2 shows the number of crashes from GES, CDS, and FARS. GES and CDS are weighted samples of crashes. Each crash in the database is assigned a weight that describes the number of similar collisions that occurred nationally during the sample time. On average, there were 5.2 million police reported crashes, 2.1 million tow-away crashes, and 28,373 fatal crashes per year involving at least one passenger vehicle. The total number of involved occupants, both in motor vehicles and non-

motorists, was tabulated from all GES crashes. There are approximately 37.6 million persons exposed to traffic related crashes involving at least one passenger vehicle per year. The number of seriously injured occupants (MAIS3+) was tabulated from CDS and totals approximately 70,129 persons per year. Finally, there was an average of 30,960 fatalities annually, tabulated from FARS. NASS/CDS focuses on crashes that involve injury that occurs to passengers in motor vehicle crashes. Because at least one passenger vehicle must have been towed from the scene due to damage in NASS/CDS cases, there are very few crashes that involve non-motorists, i.e. pedestrians and cyclists. To aid comparison with CDS, GES and FARS were restricted to crashes involving at least one passenger vehicle. This restriction accounted for 96% of GES crashes and 94% of FARS crashes.

Table 2.
Number of Crashes and Persons involving at least one Passenger Vehicle from GES 2010-2011, CDS 2007-2011, and FARS 2010-2011

	Total		Annual Average	
Category	**n**	**Frequency**	**n**	**Frequency**
GES Crashes	97,975	10,404,563	48,988	5,202,281
CDS Crashes	24,464	10,267,849	4,893	2,053,570
FARS Crashes	56,745	56,745	28,373	28,373
Total Occupants (GES)	652,854	75,239,504	326,427	37,619,752
MAIS3+ Occupants (CDS)	4,733	350,645	947	70,129
Fatalities (FARS)	61,919	61,919	30,960	30,960

Figure 6 shows the number of occupants (GES), seriously injured (MAIS3+) occupants (CDS), and fatalities (FARS) for single and multiple vehicle crashes. Only 20% of occupants were involved in single vehicle crashes, yet 46% of seriously injured occupants and 56% fatalities were in single vehicle crashes. Of fatal single vehicle crashes, however, almost 1 in 5 were vehicles striking pedestrians or cyclists, almost all of which were fatalities involving occupants not in a motor vehicle. Of all fatalities, 45% were single vehicle crashes excluding pedestrian and cyclist crashes, almost equaling the proportion of seriously injured occupants involved in single vehicle crashes. Approximately 43% of Harm was in single vehicle crashes, which agrees with the number of seriously injured drivers (not shown in graph).

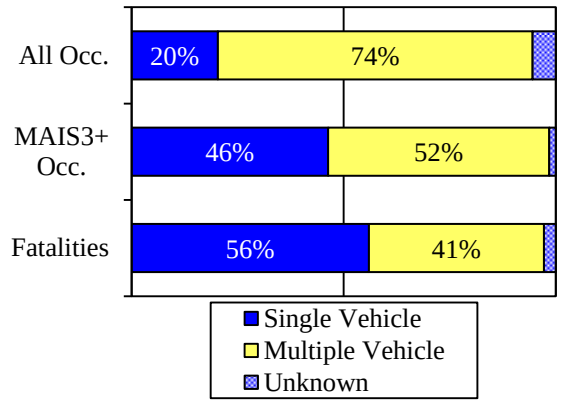

Figure 6. Number of Occupants, Seriously Injured (MAIS3+) Occupants, and Fatalities in Single and Multiple Vehicle Crashes involving at least one Passenger Vehicles.

The number of seriously injured occupants (MAIS3+) and fatalities vs. the total number of occupants for the most frequent crash scenarios is shown in Figure 7 and Figure 8. Points that fall above the diagonal line are overrepresented in injury or fatality frequency with respect to their exposure and *vice versa* for those points that fall below the diagonal line. Opposite direction, single vehicle control loss, and single vehicle crashes were the most overrepresented crash scenarios. Straight crossing path (SCP) and turning into/across path crashes were slightly overrepresented in injured drivers and fatalities. Rear-end collisions were the single most frequent crash mode (35% of occupants) but accounted for only 7.2% of MAIS33+ occupants and 6.8% of fatalities. The number of crashes and occupants for all pre-crash scenario are tabulated in the appendix.

Active Safety Applicable Crashes

Figure 9 summarizes the number of occupants, seriously injured occupants, and fatalities applicable to FCW, LDW, and V2V/V2I systems. FCW is

applicable to the most number of exposed occupants, but is applicable to a smaller proportion of injured occupants and fatalities compared to LDW and V2V/V2I. In total, these three systems could potentially mitigate 59% of both seriously injured occupants and fatalities. Annually the three systems could potentially mitigate 3,256,150 crashes, 41,625 seriously injured occupants, and 18,366 fatalities.

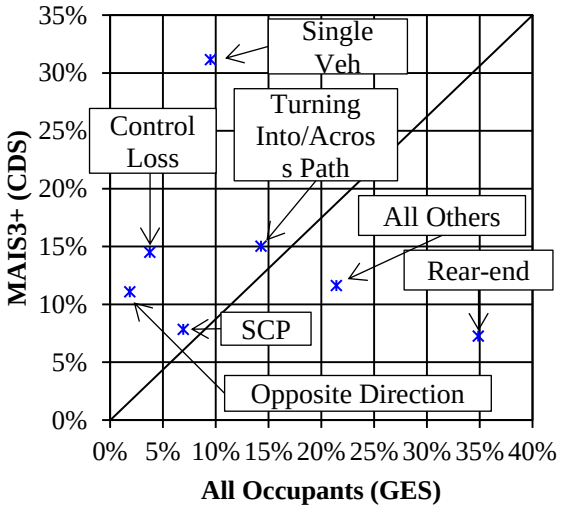

Figure 7. Number of Seriously Injured Occupants (MAIS3+) vs. Number of Occupants by Crash Scenario for Crashes involving at least one Passenger Vehicle.

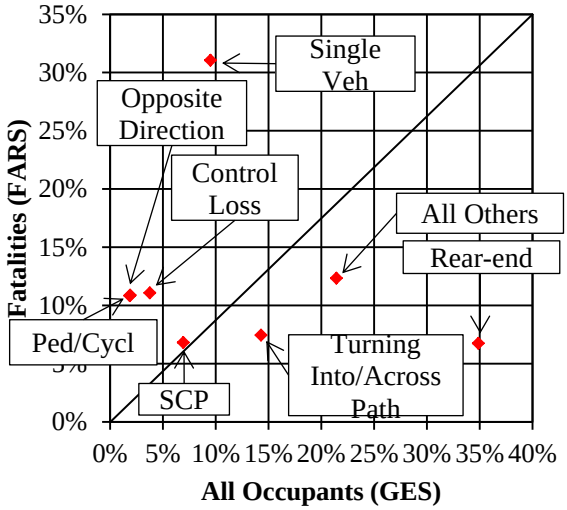

Figure 8. Number of Fatalities vs. Number of Occupants by Crash Scenario for Crashes involving at least one Passenger Vehicle.

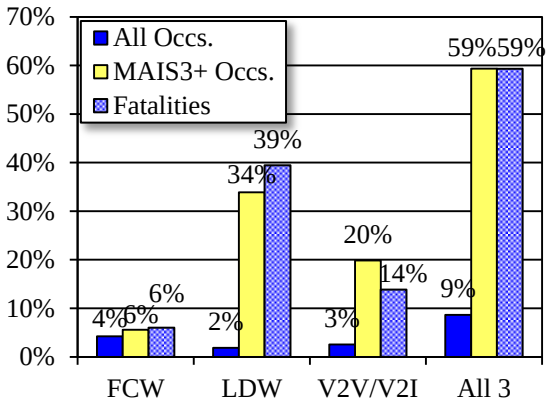

Figure 9. Proportions of Occupants, Seriously Injured Occupants (MAIS3+), and Fatalities Applicable to Active Safety Systems.

CONCLUSIONS

This paper presented novel pre-crash scenarios that describe the pre-crash scenarios in crashes from real-world crash databases. These scenarios can be applied to these databases to identify the target populations for active safety systems. We identified the target population for three emerging active safety systems: FCW, LDW, and V2V/V2I systems. FCW was applicable to the largest number of exposed occupants, but was not applicable to as many seriously injured occupants and fatalities as compared to LDW and V2V/V2I. In total, these three systems could potentially mitigate 59% of both seriously injured occupants and fatalities, representing 3.3 million crashes and 18,366 fatalities anually. These crash scenarios are unique to past efforts in that they are comparable between the three major NHTSA databases, GES, CDS, and FARS. This comparison is only possible for GES and FARS 2010 due to major changes in pre-crash variables that resulted from harmonization of pre-crash variables among these databases.

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APPENDIX

Table A2.
Body Style Codes for GES, CDS, and FARS

Group	Codes between	and	Excluding
Cars	1	13	
Light Utility Vehicle	14	19	
Light Van	20	29	
Light Truck	30	49	42
Bus	50	59	
Heavy Vehicle	60	79	65 and 73
Motor Home	42, 65, 73		
Motorcycle/Moped	80	89	
Other Vehicle (e.g. ATV, construction equipment, golf cart)	90	97	
Not Reported	98		
Unknown			

Table A2.
Number of Crashes per Pre-Crash Scenario Category

	Crashes			% Crashes		
Scenario	**GES**	**CDS**	**FARS**	**GES**	**CDS**	**FARS**
No Scenario	449,717	175,211	1,507	4.3%	1.7%	2.7%
Sing Veh - Departure	1,246,953	1,775,040	18,041	12.0%	17.3%	31.8%
Sing Veh - Control Loss	766,695	1,161,477	6,278	7.4%	11.3%	11.1%
Sing Veh - Animal in Road	566,055	198,867	667	5.4%	1.9%	1.2%
Sing Veh - Ped/Cyclist in Road	173,224	9,950	6,682	1.7%	0.1%	11.8%
Sing Veh - Object in Road	38,114	52,368	73	0.4%	0.5%	0.1%
Sing Veh - Other	168,383	60,468	980	1.6%	0.6%	1.7%
Mult Veh - Rear-end	3,386,482	2,536,117	3,779	32.5%	24.7%	6.7%
Mult Veh - Opp Dir, no turning	136,744	236,813	5,548	1.3%	2.3%	9.8%
Mult Veh - Same Dir, no turning	655,103	268,560	1,033	6.3%	2.6%	1.8%
Mult Veh - Control Loss	154,836	265,596	1,791	1.5%	2.6%	3.2%
Mult Veh - Object into Vehicle	6,753	26,967	272	0.1%	0.3%	0.5%
Mult Veh - Parked Car	425	207,750	12	0.0%	2.0%	0.0%
Mult Veh - Crossing Path, Both Straight	667,587	894,554	3,750	6.4%	8.7%	6.6%
Mult Veh - Turning Into/Across Path	1,540,901	2,126,451	4,343	14.8%	20.7%	7.7%
Mult Veh - Wrong Direction	11,520	29,396	809	0.1%	0.3%	1.4%
Mult Veh - U-turn	41,092	61,157	118	0.4%	0.6%	0.2%
Mult Veh - Backing	166,675	30,074	49	1.6%	0.3%	0.1%
Vehicle Failure	74,029	107,784	530	0.7%	1.0%	0.9%
Multiple/Conflicting Scenarios	147,690	39,232	394	1.4%	0.4%	0.7%
No Driver	5,585	4,018	89	0.1%	0.0%	0.2%
Total	**10,404,563**	**10,267,849**	**56,745**	**100.0%**	**100.0%**	**100.0%**

Table A3.
Number of Occupants, MAIS3+ Occupants, Harm, and Fatalities

	Frequency				%			
Scenario	**Total Occ.**	**MAIS3+**	**Harm**	**Fatalities**	**GES**	**MAIS3+**	**Harm**	**Fatalities**
No Scenario	4,097,882	5,321	2,688	1,629	5.4%	1.5%	1.4%	2.6%
Sing Veh - Departure	7,150,105	109,263	58,885	19,234	9.5%	31.2%	29.8%	31.1%
Sing Veh - Control Loss	2,831,220	50,826	24,186	6,859	3.8%	14.5%	12.2%	11.1%
Sing Veh - Animal in Road	2,153,844	1,332	890	687	2.9%	0.4%	0.5%	1.1%
Sing Veh - Ped/Cyclist in Road	1,428,716	0	5	6,741	1.9%	0.0%	0.0%	10.9%
Sing Veh - Object in Road	80,534	0	56	80	0.1%	0.0%	0.0%	0.1%
Sing Veh - Other	1,643,124	1,034	1,104	1,048	2.2%	0.3%	0.6%	1.7%
Mult Veh - Rear-end	26,237,454	25,415	19,307	4,182	34.9%	7.2%	9.8%	6.8%
Mult Veh - Opp Dir, no turning	1,402,784	38,883	19,500	6,706	1.9%	11.1%	9.9%	10.8%
Mult Veh - Same Dir, no turning	6,941,534	6,243	3,395	1,158	9.2%	1.8%	1.7%	1.9%
Mult Veh - Control Loss	1,157,907	18,190	9,257	2,083	1.5%	5.2%	4.7%	3.4%
Mult Veh - Object into Vehicle	36,463	2,417	1,788	320	0.0%	0.7%	0.9%	0.5%
Mult Veh - Parked Car	1,041	2,444	1,241	16	0.0%	0.7%	0.6%	0.0%
Mult Veh - Crossing Path, Both Straight	5,212,537	27,460	17,292	4,220	6.9%	7.8%	8.8%	6.8%
Mult Veh - Turning Into/Across Path	10,754,450	52,693	32,254	4,610	14.3%	15.0%	16.3%	7.4%
Mult Veh - Wrong Direction	55,965	3,181	2,001	991	0.1%	0.9%	1.0%	1.6%
Mult Veh - U-turn	378,652	1,301	840	125	0.5%	0.4%	0.4%	0.2%
Mult Veh - Backing	1,228,872	177	156	53	1.6%	0.1%	0.1%	0.1%
Vehicle Failure	272,519	4,023	2,321	636	0.4%	1.1%	1.2%	1.0%
Multiple/Conflicting Scenarios	2,171,653	442	272	448	2.9%	0.1%	0.1%	0.7%
No Driver	2,245	0	1	93	0.0%	0.0%	0.0%	0.2%
Total	**83,344,310**	**350,470**	**197,305**	**65,252**	**100.0%**	**100.0%**	**100.0%**	**100.0%**