DETAILED ANALYSIS OF TARGET CRASHES FOR PRE-CRASH SENSING APPLICATIONS

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ABSTRACT

Target pre-crash scenarios, crash modes, and occupant injury mechanisms are statistically described for crash imminent braking (CIB) and advanced restraint system (ARS) applications based on pre-crash sensing. Vehicle-object and vehicle-vehicle crashes are distinguished between single-impact and multiple-impact crashes. This analysis focuses on light vehicles of model year 1998 or higher that suffered frontal damage from the first most harmful event. An in-depth examination of candidate crash cases from target crashes was conducted to understand crash mechanisms and circumstances as well as occupant injury scenarios. Consideration was given to pre-crash conditions for CIB applications and to injury source for ARS applications. Results will be used in subsequent research to assess candidate CIB and ARS technologies, develop system functional requirements, devise test procedures, and estimate safety benefits.

INTRODUCTION

Pre-crash sensing applications encompass active safety measures aimed at reducing injuries once the crash is deemed unavoidable. These applications detect a crash earlier than accelerometer-based approaches with anticipatory sensors, communicate this information to the vehicle and its occupant protection systems, and take appropriate actions to reduce the crash severity or alleviate the severity of crash injury [1]. Crash avoidance systems are now appearing on new vehicle models in the United States (US). These systems offer the opportunity to improve vehicle crashworthiness by providing environmental awareness data so that automatic braking and crashworthiness protection systems can be activated when a crash becomes imminent and before the vehicles contact each other. Today's airbag and seatbelt systems will be more effective if advanced occupant sensors are added to pre-crash sensors, creating occupant protections with advanced restraints that adapt to whoever happens to be sitting in the vehicle and to the demands of a variety of crash scenarios.

This paper describes crash scenarios based on an in-depth examination of applicable crash cases for full-authority last-second crash imminent braking (CIB) and advanced restraint systems (ARS). The CIB system is designed to reduce impact severity by dissipating energy from the crash. ARS are intended to improve the coupling of occupants to the vehicle, reducing firing times of airbags, among others. This crash analysis supports two joint research efforts on CIB and ARS between the US Department of Transportation and the Crash Avoidance Metrics Partnership comprised of three automakers and major suppliers [2, 3]. These two research efforts have common objectives:

- Develop and validate minimum performance requirements and objective test procedures for CIB and ARS that appear to provide an opportunity to reduce the societal harm resulting from light-vehicle crashes in the US.
- Identify and fabricate the most promising CIB and ARS prototypes, and complete objective testing to evaluate their performance.
- Obtain preliminary estimates of potential safety benefits of these prototype systems.

Development and integration of internal and external sensors, advanced braking systems, and restraints systems focus on the time period when a crash becomes unavoidable. Priority of these research efforts is given to the development and evaluation of autonomous vehicle systems, crash types causing the most societal harm, and systems considered technically feasible for near-term deployment (3-5 years from project completion).

This paper presents results of the crash analysis conducted in support of the cooperative CIB and ARS projects. Target crashes were identified and prioritized for CIB and ARS applications using the National Automotive Sampling System's Crashworthiness Data System (CDS) and General Estimates System (GES), Fatality Analysis Reporting System (FARS), and data from event data recorders [4]. Most common and harmful pre-crash scenarios were correlated with impact crash modes to produce target crashes to be addressed within these two projects. From these crashes, candidate crash cases were selected for in-depth examination to understand crash mechanisms and circumstances as well as occupant injury scenarios. This research step

determined applicable crashes and served to filter out crash cases that are not amenable to CIB or ARS applications. The crash scenarios for the applicable collision cases provide the crash context that can be used for the development of pre-crash sensor specifications, minimum performance requirements, and objective test methods. This paper summarizes the results from the in-depth examination of applicable crash cases.

Next, this paper describes the crash analysis approach and highlights the results of the prioritized target crash scenarios. After that, results from the analysis of the CIB applicable crash cases are presented. This is followed by results from the in-depth examination of ARS applicable crash cases. This paper concludes with a summary of key results.

CRASH ANALYSIS APPROACH

A two-stage crash analysis approach was adopted to identify target crash scenarios and statistically describe applicable crash cases that could be amenable to CIB and ARS applications. As illustrated in Figure 1, the first stage consists of a top-down analysis that involved data queries of national crash databases to identify and prioritize crash scenarios for further examination in the second stage named the bottom-up analysis. These analyses targeted light vehicles of model year 1998 or higher (MY98$^+$) that sustained frontal damage from the first harmful event. The model year served as the surrogate for modern restraint systems including three-point lap and shoulder belts, presence of pretensioners, load limiters, the advent of the second generation, de-powered airbags, and more advanced seatbelt and airbag technology. The first harmful event was considered to accommodate the development of functional requirements for forward-looking pre-crash sensors that would enable the CIB application and augment advanced restraints. The ARS analysis focused on understanding the injury suffered by the driver and the front seat passenger of 13 years of age or older (FSP13$^+$). The age restriction placed upon the front seat occupant is consistent with the position in the US that child passengers should ride in the rear seating positions until they are 12 years. The CIB analysis considered all persons in crashes that involved at least one target vehicle.

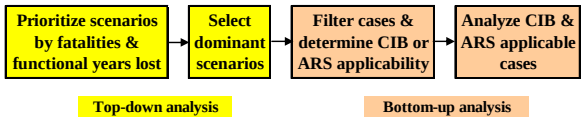

Figure 1. Crash Analysis Approach

The analysis distinguished crashes between vehicle-object and vehicle-vehicle crash types by the type of obstacle struck during the first harmful event based on whether or not the obstacle was a vehicle in transport. As seen in Figure 2, vehicle-object crashes are characterized by a vehicle in transport contacting a "not vehicle in transport" obstacle. Obstacle categories include tree, pole, ground, structure, person, vehicle, animal, not-fixed object, non-collision, and unknown. Attention is paid to whether the target vehicle is involved in a single- or multi-impact crash. In single-vehicle crashes, the target vehicle does not hit a vehicle in transport. However, in a multi-impact crash, it is important to identify the object type that was contacted during the first harmful event. In vehicle-vehicle or multi-vehicle crashes, the target vehicle contacts a vehicle in transport. In a multi-impact crash, it is possible for the target vehicle to strike an object first before hitting another vehicle in transport. Thus, the analysis separates multi-vehicle crashes based on the first harmful event into vehicle-object and vehicle-vehicle crashes as shown in Figure 2.

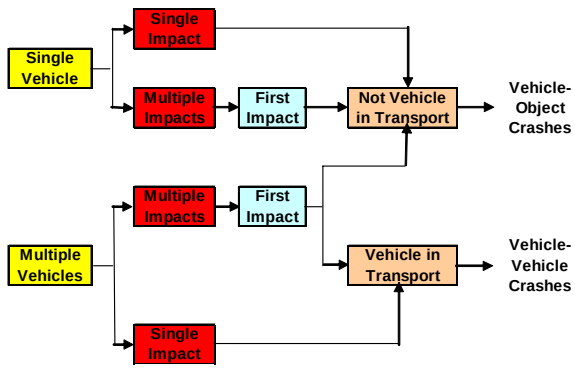

Figure 2. Breakdown of Target Crash Types

The top-down analysis correlated pre-crash scenarios to the manner of collision such as pole in vehicle-object crashes and front-back in vehicle-vehicle crashes. These correlations of crash scenarios were then prioritized and ranked by severity. The number of fatalities from FARS and the number of functional years lost (FYL) derived from CDS and GES injury data were selected to quantify crash severity. The FYL measure sums the years of life lost to fatal injury and the years of functional capacity lost to nonfatal injury using the Maximum Abbreviated Injury Scale (MAIS) [5]. The ARS analysis only counted MAIS levels 3 through 6 by the driver and FSP13$^+$ in target vehicles, while the CIB analysis incorporated all persons involved in the crash with MAIS levels 2 through 6. Results of the top-down analysis are summarized in the next section and are described in Reference [4].

The bottom-up analysis encompassed detailed examinations of individual filtered cases to determine the applicability of CIB and to understand why and how the target occupants were at least seriously injured for ARS application. The top-down analysis identified lists of case numbers from the CDS for the dominant crash scenarios. Researchers then reviewed these CDS cases and assessed their usefulness for the bottom-up analysis. This paper discusses the bottom-up analysis and presents the results for CIB and ARS in the following sections.

TARGET CRASH SCENARIOS

The top-down analysis identified and prioritized target crash scenarios for CIB and ARS applications based on injury statistics from the 1997-2006 CDS databases. Ranking of scenarios was established using the FYL measure that integrated the MAIS levels 3-6 of the driver and FSP 13^+ in target vehicles for ARS and the MAIS levels 2-6 of all persons involved in the crash for CIB.

Road departure was the dominant pre-crash scenario in vehicle-object crashes for CIB and ARS. In this scenario, the vehicle is typically going straight and then departs the edge of the road due to driver inattention, drowsiness, or under the influence or alcohol impairment. The vehicle may also be negotiating a curve, turning left or right at a junction, changing lanes or passing, or entering or leaving a parking position. Road departure with different struck obstacle combinations had the same order of severity for CIB and ARS, as shown below in a descending order:

1. Road departure – ground
2. Road departure – pole
3. Road departure – structure
4. Road departure – tree

Table 1 lists the ranking of vehicle-vehicle crash scenarios for CIB and ARS. There are five dominant pre-crash scenarios:

- Opposite direction (OD): vehicle is typically going straight, drifts at a non-junction, and then encroaches into another vehicle traveling in the opposite direction. Vehicle may also be negotiating a curve or passing.
- Rear-end (RE): vehicle is typically going straight and then closes in on a lead vehicle that may be stopped, decelerating, accelerating, or moving at slower constant speed. Vehicle may also be starting in traffic, changing lanes, passing, or turning and then closes in on a lead vehicle.
- Left turn across path/opposite direction (LTAP/OD): vehicle is turning left at a junction and then cuts across the path of another vehicle traveling from the opposite direction.
- Straight crossing paths (SCP): vehicle is going straight through a junction and then intersects the path of another straight crossing vehicle from lateral direction. Vehicle may also stop and proceed against crossing traffic or both vehicles first stopping and then proceeding on straight crossing paths.
- Turning: these scenarios refer to any crossing-paths turning maneuvers other than the LTAP/OD scenario.

Table 1. Vehicle-Vehicle Crash Scenario Ranking

Crash Scenario	CIB	ARS
Opposite-Direction - Front-Front	1	1
Rear-End - Front-Back	2	2
LTAP/OD - Front-Front	3	3
SCP - Front-Left Side	4	5
Turning - Front-Left Side	5	4
SCP - Front-Right Side	6	6

ANALYSIS OF CIB CRASH CASES

The filtering scheme is first outlined to select crash cases from target crashes for further examination. Applicable CIB cases from vehicle-object and vehicle-vehicle crashes are later described separately. This description includes CDS statistics on the breakdown of target vehicles by vehicle type (i.e., passenger car or light truck or van), attempted avoidance maneuver by the target vehicle, environmental conditions, and Delta V (ΔV).

Selection of CIB Applicable Cases

The following five filters were applied to identify the final set of target vehicle cases that might be amenable to CIB applications:

1. Include crash cases where at least one occupant in any vehicle suffered an injury level of $MAIS2^+$.
2. Exclude crash cases in which the target vehicle attempted any braking maneuver. It is assumed that brake assist, a different countermeasure than CIB, would apply if brakes were applied in the target vehicle.
3. Exclude crash cases in which the target vehicle lost control as a result of an evasive maneuver. Stability control systems help in this situation.
4. Include crash cases in which the target vehicle had at least one of the following information:

longitudinal ΔV or estimated highest ΔV values from the CDS [6], or ΔV available from event data recorders [7].

5. Exclude crash cases in which the target vehicle experienced longitudinal ΔV over 45 mph (72 Km/h).

After the five filters were applied, remaining cases were individually analyzed to determine their applicability to CIB. Tables 2 and 3 provide the results of this filtering process for vehicle-object and vehicle-vehicle crashes, respectively. Out of 1,903 target vehicle cases from vehicle-object crashes, only 99 cases were determined to be amenable to CIB. Using the corresponding CDS weights for these cases, CIB addresses only 2% of the target vehicles. For vehicle-vehicle crashes, CIB addresses 871 target vehicle cases out of a total of 8,807 cases. Using weighted values, CIB could help only 4.3% of all target vehicles involved in vehicle-vehicle crashes. In total, intervention opportunity for CIB exists in about 4% of all target vehicles based on the total weighted counts in Tables 2 and 3.

Table 2. Applicable CIB Vehicle-Object Cases

Obstacle	Raw Count			Weighted Count		
	Initial	CIB	Ratio	Initial	CIB	Ratio
Pole	532	39	7.3%	203,582	7,928	3.9%
Tree	395	31	7.8%	95,033	3,231	3.4%
Ground	364	0	0.0%	197,139	0	0.0%
Structure	612	29	4.7%	183,902	2,363	1.3%
Total	1,903	99	5.2%	679,656	13,522	2.0%

Table 3. Applicable CIB Vehicle-Vehicle Cases

Crash Scenario	Raw Count			Weighted Count		
	Initial	CIB	Ratio	Initial	CIB Cases	Ratio
OD - FF	1,072	218	20.3%	222,638	58,904	26.5%
RE - FB	2,427	62	2.6%	1,637,691	16,343	1.0%
LTAP/OD - FF/FRS	2,414	293	12.1%	964,399	61,829	6.4%
SCP - FLS/FRS	2,005	218	10.9%	801,240	26,331	3.3%
Turning - FLS	889	80	9.0%	458,589	12,286	2.7%
Total	8,807	871	9.9%	4,084,557	175,693	4.3%

FF: Front-Front, FB: Front-Back, FLS: Front-Left Side
FRS: Front-Right Side

Description of CIB Vehicle-Object Cases

Statistical description of CIB vehicle-object cases is provided using CDS weighted values. About 63% of the target vehicles were light trucks or vans. Figure 3 shows statistics of attempted avoidance maneuver by the target vehicle in CIB-applicable vehicle-object crashes, excluding braking. Steering was noted for 22.4% of the target vehicles. Table 4 presents statistics on environmental conditions including atmospheric, lighting, and roadway surface conditions. In vehicle-object crashes, 96% of target vehicles were driving under clear weather, 91% were traversing dry road surfaces, and 56% were traveling in non-daylight conditions. Figure 4 plots the cumulative percentage of target vehicles by total ΔV. Almost two thirds of the vehicles (65%) suffered ΔV under 40 Km/h. Moreover, 95% of the vehicles experienced total ΔV under 55 Km/h. It should be noted that vehicles with longitudinal ΔV over 72 Km/h were excluded from this analysis.

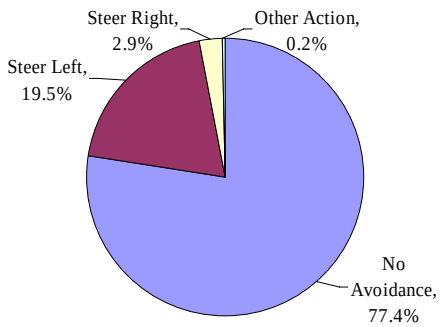

Figure 3. Avoidance Maneuver in CIB Vehicle-Object Crashes

Table 4. Environmental Conditions in CIB Vehicle-Object Crashes

		Weight	%
Atmospheric Condition	Clear	12,975	96.0%
	Adverse	547	4.0%
	Total	13,522	100.0%
Lighting Condition	Daylight	5,972	44.2%
	Dark	4,922	36.4%
	Dark/Lighted	2,466	18.2%
	Dawn	133	1.0%
	Dusk	27	0.2%
	Total	13,522	100.0%
Roadway Surface Condition	Dry	12,356	91.4%
	Slippery	1,165	8.6%
	Total	13,522	100.0%

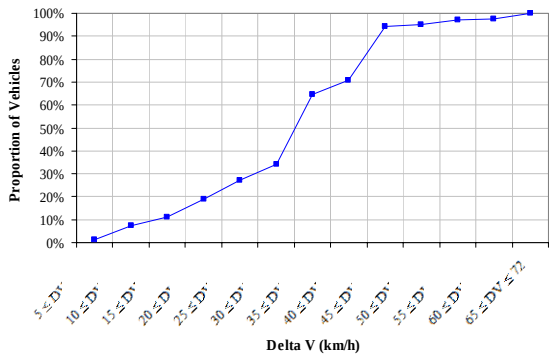

Figure 4. Cumulative Distribution of Vehicles by Total ΔV in CIB Vehicle-Object Crashes

Description of CIB Vehicle-Vehicle Cases

About 53% of the target vehicles involved in vehicle-vehicle crashes were light trucks or vans. Table 5 shows statistics of attempted avoidance maneuver by the target vehicle in CIB-applicable vehicle-vehicle crash scenarios, excluding braking. Steering was noted for 17.4% of the target vehicles. Rear-end crash scenario had the highest steering percentage (56%) among other vehicle-vehicle crash scenarios. On the other hand, opposite direction crash scenario had the least steering maneuvers (11%) by target vehicles. Table 6 provides CDS statistics on environmental conditions including atmospheric, lighting, and roadway surface conditions. In vehicle-vehicle crashes, 94% of target vehicles were driving under clear weather, 92% were traversing dry road surfaces, and 58% were traveling in daylight. Figure 5 plots the cumulative percentage of target vehicles by total ΔV in vehicle-vehicle crash scenarios. Almost two thirds of the target vehicles (66%) suffered ΔV under 25 Km/h. Moreover, 95% of the vehicles experienced total ΔV under 45 Km/h. It should be noted that vehicles with longitudinal ΔV over 72 Km/h were excluded from this analysis. Table 7 presents statistics on the relative direction of vehicles when they crashed. This information is relevant to the development of performance requirements for the field-of-view of pre-crash sensors.

Table 5. Avoidance Maneuver Statistics in CIB Vehicle-Vehicle Crash Scenarios

Attempted Avoidance Maneuver	OD	RE	LTAP/ OD	SCP	Turning	All
No Avoidance	89%	44%	87%	85%	64%	82%
Steering Left	4%	0.3%	1%	9%	24%	5%
Steering Right	7%	56%	11%	5%	9%	13%
Accelerating & Steer Left	0.1%		0.2%	0.03%	1%	0.2%
Accelerating			1%	0.1%		0.4%
Other Action	1%		0.1%		2%	0.3%
Total	100%	100%	100%	100%	100%	100%

Table 6. Statistics of Environmental Conditions in CIB Vehicle-Vehicle Crash Scenarios

		OD	RE	LTAP/ OD	SCP	Turning	All
Weather Condition	Clear	91%	99%	93%	96%	96%	94%
	Adverse	9%	1%	7%	4%	4%	6%
	Total	100%	100%	100%	100%	100%	100%
Lighting Condition	Dark	5%	10%	14%	5%	3%	8%
	Dark/Lighted	68%	12%	17%	14%	6%	32%
	Dawn	0%	3%	1%	1%	0%	1%
	Daylight	26%	73%	67%	80%	91%	58%
	Dusk	1%	3%	1%	0%	0%	1%
	Total	100%	100%	100%	100%	100%	100%
Roadway Surface Condition	Dry	91%	99%	91%	93%	89%	92%
	Slippery	9%	1%	9%	7%	11%	8%
	Total	100%	100%	100%	100%	100%	100%

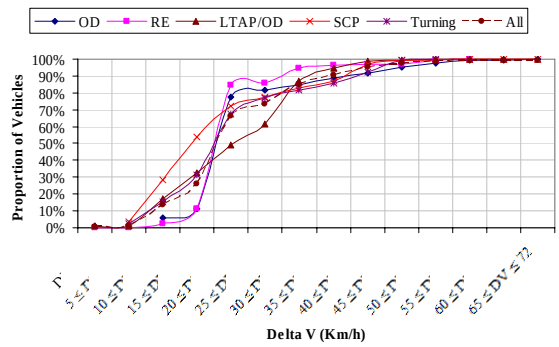

Figure 5. Cumulative Distribution of Vehicles by Total ΔV in CIB Vehicle-Vehicle Crash Scenarios

Table 7. Relative Direction Statistics in CIB Vehicle-Vehicle Crash Scenarios

Relative Clock	OD	RE	LTAP/ OD	SCP	Turning	All
1	2%		18%			7%
10	0.2%		5%	0.1%		2%
10-11	5%		24%			10%
11	4%		4%	0.1%		3%
11-12	75%		6%			28%
1-2	0.2%		16%		13%	7%
12, head on	4%					1%
12-1	8%		14%			8%
2			2%	0.4%	5%	1%
9-10	1%					0.2%
2-3	0.2%		1%	3%	61%	5%
3, angle		0.1%		43%	4%	7%
3-4				11%	13%	3%
4					0.1%	0.01%
4-5					0.4%	0.03%
5					2%	0.1%
5-6		92%			2%	9%
6-7		8%				1%
7-8						0%
8			0.1%			0.04%
8-9			1%	5%		1%
9,angle			1%	36%		6%
9-10			8%	2%		3%
Total	100%	100%	100%	100%	100%	100%

Figure 6 illustrates the configurations of the relative direction for head-on/angle and rear-end/angle collisions. In rear-end pre-crash scenarios, the front of the target vehicle struck the back of the other vehicle within ±30 degrees in 100% of the cases, relative clock between 5 and 7 as indicated in Table 7. In opposite direction pre-crash scenarios, the front of the target vehicle struck the front of the other vehicle within ±30 degrees in 94% of the cases, relative clock between 1 and 11. In straight crossing path pre-crash scenarios, the front of the target vehicle struck the side of the other vehicle at 90 degrees in 79% of the cases, relative clock at 3 or 9. In LTAP/OD pre-crash scenarios, the relative angle of collision between the target vehicle and the other vehicle was between 30 and 60 degrees in 69% of the cases, relative clock between 1 and 2 and between 10 and 11. In all CIB vehicle-vehicle crash scenarios, 56% and 76% of the target vehicles experienced a relative angle of collision respectively within ±30 and ±60 degrees.

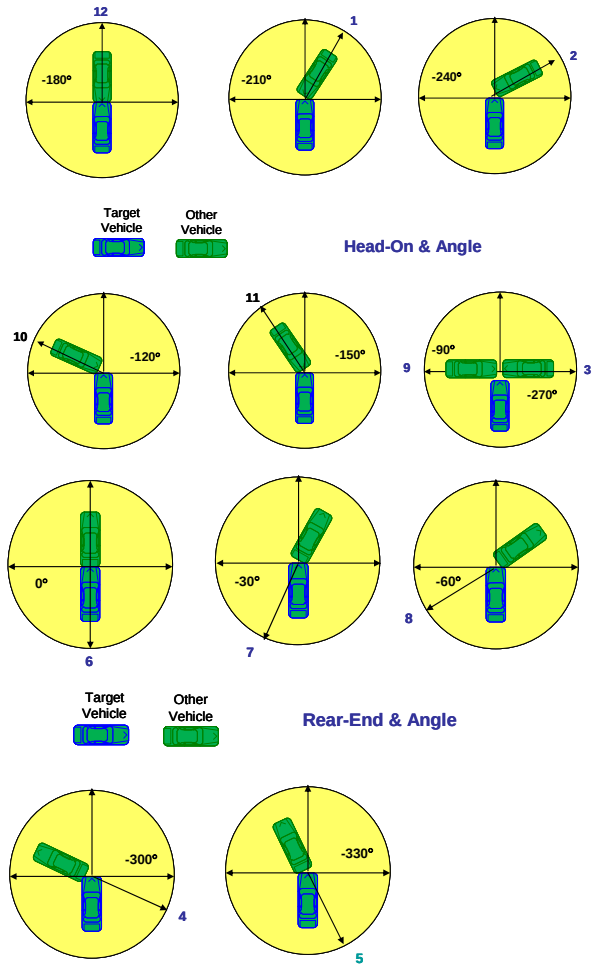

Figure 6. Configurations of Relative Directions

ANALYSIS OF ARS CRASH CASES

Results are presented from a detailed examination of individual crash cases deemed as priority for intervention opportunities by ARS with pre-crash sensing capability. This analysis included target vehicles in which the driver or FSP13^{+} suffered an injury level of MAIS3^{+}. All relevant cases belonging to the following five crash scenarios were selected from the 1997-2006 CDS databases for further examination:

- Opposite direction pre-crash scenarios with different impact modes
- Rear-end pre-crash scenarios with front-to-back impact mode
- LTAP/OD pre-crash scenarios with different impact modes
- Road departure pre-crash scenarios
- Control loss pre-crash scenarios

The selection and review of candidate cases are first delineated. This will be followed by a statistical description of the target occupants in terms of their breakdown by crash scenario, number of impact events, ΔV, and vehicle damage location and offset. In addition, statistics are provided about the distribution of injured body regions by crash scenario and injury source.

Selection and Review of Occupant Cases

All relevant cases from the CDS were divided and assigned to different reviewers. Cases lacking clarity or missing information were subjected to a group review or discarded. Reviewers were asked to consider coded, photographic, graphic, and supplementary unedited data sources, resident on the NASS CDS case access viewer [8]. Instructions were given to reviewers prior to accessing this viewer to encourage uniformity in consideration and synthesis of analysis. As a result, some cases were excluded from the analysis due to insufficient data, incorrect crash modes, and unique modes not applicable to this study such as A-pillar contact with predominant side impact damage. Also excluded were cases that had losses in passenger compartment integrity. This constraint was placed on the analysis owing to the technologies contemplated and their potential countermeasures.

During the review, consideration was given to the role of active and passive restraint systems resident in the target vehicle. The applicability of newer generation restraint systems was assessed in terms of their potential capability to mitigate or avoid injuries produced in the various crash types. In each vehicle case, the driver and $FSP13^+$ with $AIS3^+$ injuries were examined separately. This examination focused on injured occupants who were restrained using a lap and shoulder belt and their airbag was deployed. All $AIS3^+$ injuries were included; however, many lower extremity cases exist in which the present restraint or an advanced restraint would have been superfluous based upon the specific crash parameters. Consideration, however, was given to the potential presence of knee airbags and their role in injury mitigation or prevention. Each body region was analyzed separately if a driver or $FSP13^+$ had $AIS3^+$ injuries to more than one body region. If a single body region sustained multiple $AIS3^+$ injuries, the analysis then focused on the most severe injury.

Injury information was based on vehicle inspection and injury assessment records. Vehicle inspection involved an examination of the vehicle and evidence of relevant occupant contact. This was tempered by a review of medical records and vehicle contact assessment. The case reviewer consulted the various photographs taken in support of the crash investigation, scene diagram, and the unedited text version of crash events. Table 8 lists the number of relevant vehicle and occupant files reviewed and disaggregates them by reviewer disposition. Counts of vehicles and occupants were weighted to reflect national CDS representation. These dispositions were assessed relevant to the injuries sustained and the applicability of a restraint system. It should be noted that the majority of relevant occupants was submitted to the automotive partners as candidate members of advanced restraints systems. Overall, 71% of the weighted number of vehicles and occupants (63% of counts) were accepted for further examination. The following analyses were conducted on target occupants who were accepted by case reviewers as candidates for ARS applications.

Table 8. Number of Relevant Vehicles and Occupants by Reviewer Disposition

Reviewer Disposition	Vehicles		Occupants	
	Weighted	Count	Weighted	Count
Accepted	32,134	389	33,006	407
Rejected	12,739	226	13,434	239
Questionable	145	1	145	1
Total	45,018	616	46,585	647

Breakdown of Occupants by Crash Scenario and Number of Events

Figure 7 shows a breakdown of the weighted number of accepted occupant cases by the five crash scenarios. About 61% of the occupants were traveling in vehicles that were involved in single-vehicle crashes: road departure and control loss. Of these occupants involved in single-vehicle crashes, 72% of the occupants were in a single impact or a multi-impact crash in which the first event was the most harmful. In contrast, 93% of the occupants who were involved in multi-vehicle crashes were traveling in vehicles sustaining a single impact or a most harmful first event in a multi-impact crash. In general, only 20% of target occupants were involved in multi-impact crashes where the most harmful event resulted from secondary impacts.

Figure 8 shows the breakdown of target occupant cases by the crash scenario and event category. The following results can be observed:

- Opposite direction crashes had the highest rate of occupants in single events (59% of all occupants in opposite direction crashes).
- Rear-end crashes had the highest rate of occupants in multi-impact, most harmful first events (53% of all occupants in rear-end crashes).

- Road departure crashes had the highest rate of occupants in multi-impact, most harmful secondary events (30% of all occupants in road departure crashes).

In multi-impact crashes in which the most harmful event happened in secondary events, about 87% of the target occupants were in vehicles experiencing frontal damage in the most severe event. Damage to the undercarriage was reported as the most severe event for 6% of the occupants. The remaining 7% of the occupants were evenly split between right and left damage areas of the vehicles in the most severe event. Overall, 98% of the target occupants were in vehicles suffering frontal damage in the most harmful event in single- and multi-impact crashes. Thus, the remainder of this section presents occupant results independent of the number of impact events.

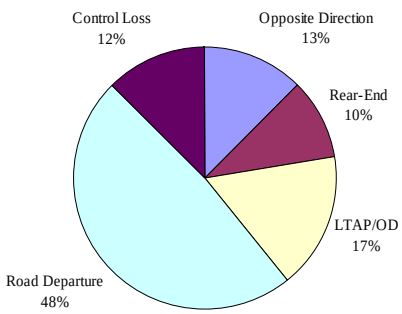

Figure 7. Breakdown of Occupants by Crash Scenario

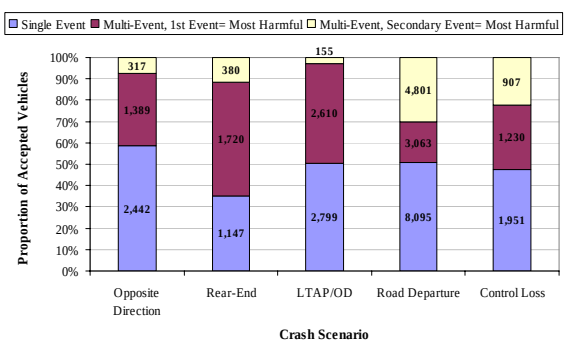

Figure 8. Breakdown of Occupants by Crash Scenario and Event

Breakdown of Occupants by Delta V, Damage Location, and Offset

Figure 9 shows the cumulative distribution of occupants by ΔV, representing a proportional redistribution of vehicles with only calculated ΔV values. Not included were 24% of the occupants in vehicles that had other or unknown information coded in the CDS. About 96% of the occupants were in vehicles that experienced ΔV below 70 Km/h. Moreover, 49% of the occupants were in vehicles having ΔV values below 30 Km/h.

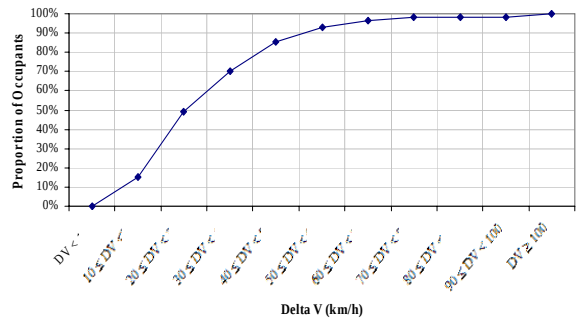

Figure 9. Cumulative Distribution of Occupants by Delta V

Breakdown of the number of occupants by vehicle damage location and offset percentage in Figure 10 shows:

- 50% of the occupants were in vehicles sustaining left frontal damage with offset percentage of 50% or less.
- 23% of the occupants were in vehicles suffering center frontal damage with offset percentage greater than 50%.
- 17% of the occupants were in vehicles experiencing right frontal damage with offset percentage of 50% or less.

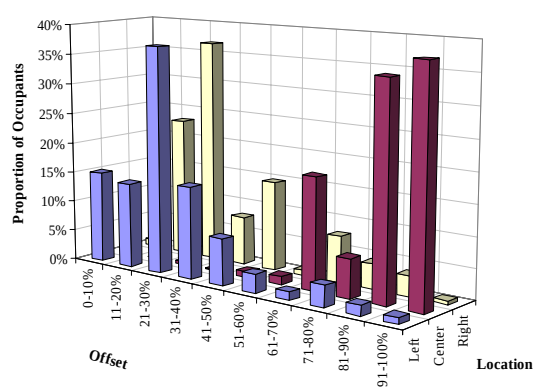

Figure 10. Distribution of Occupants by Vehicle Damage Location and Offset

Examination of Injuries

Figure 11 shows the distribution of 42,000 MAIS3^{+} injuries by injured body region. The highest

injured body region was the chest at 36% of all MAIS3$^+$ injuries. This was followed by the lower extremity. About 48% of MAIS3$^+$ injuries were associated with extremities. Figure 12 provides a distribution of MAIS3$^+$ injuries by crash scenario. Road departure resulted in most MAIS3$^+$ injuries at 49%. Overall, single-vehicle crashes and multi-vehicle crashes accounted respectively for 61% and 39% of all MAIS3$^+$ injuries to target occupants. Table 9 lists the weighted counts of MAIS3$^+$ injuries by injured body region and crash scenario.

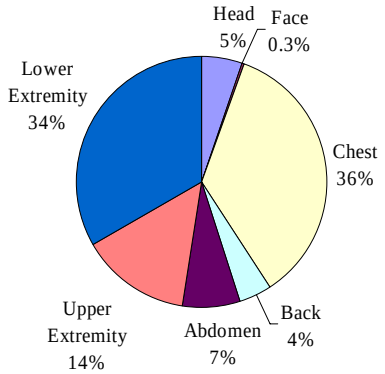

Figure 11. Distribution of MAIS3$^+$ injuries by Body Region

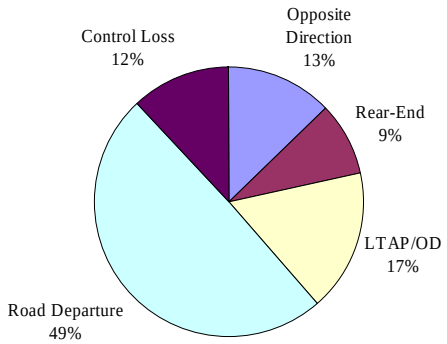

Figure 12. Distribution of MAIS3$^+$ injuries by Crash Scenario

Table 9. Breakdown of MAIS3$^+$ Injury Counts

Crash Scenario	Head	Face	Chest	Back	Abdomen	Upper Extremity	Lower Extremity	Total
Opposite Direction	178	18	1,538	125	702	535	2,301	5,398
Rear-End	191	0	297	204	42	804	2,205	3,743
LTAP/OD	526	4	1,961	108	272	1,944	2,312	7,127
Road Departure	1,088	60	8,558	776	1,838	2,358	6,243	20,921
Control Loss	278	58	2,463	605	245	344	1,064	5,057
Total	2,262	140	14,817	1,817	3,099	5,985	14,125	42,246

Analysis of Injury Sources

Figure 13 shows the distribution of MAIS3$^+$ injuries by the source of injury in the vehicle as identified by the case reviewer. Other non-specific sources of injury were reported as the highest rate at 23% of MAIS3$^+$ injuries. Instrument panel, seatbelt, and steering wheel were the three other sources of injury each at a rate over 10%, respectively at 18%, 16%, and 15% of MAIS3$^+$ injuries. Airbag and knee bolster followed respectively at 8% and 7% of MAIS3$^+$ injuries.

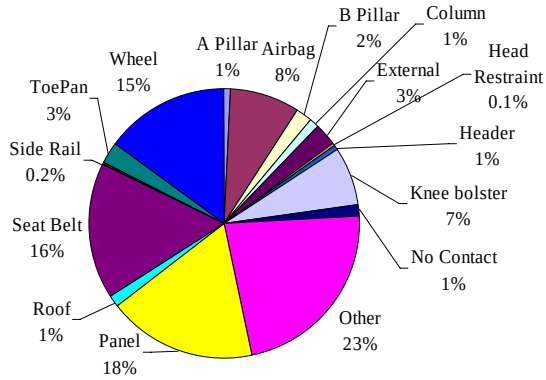

Figure 13. Distribution of MAIS3$^+$ Injuries by Source of Injury

Table 10 provides percentage values of MAIS3$^+$ injury source contribution rates to each body region. The highest rate to each body region is highlighted in yellow. The steering wheel had the highest contribution rate in chest, head, and upper extremity body regions. Injury to the abdomen was caused predominantly by the seatbelt at an extreme rate of 83%. It should be noted that target occupants were all belted. Instrument panel caused the highest rate of injury to the lower extremity at 40%.

Table 11 provides percentage values of MAIS3$^+$ injury source contribution rates in each crash scenario. The highest rate to each body region is highlighted in yellow and the second highest rate is highlighted in tan. Injury sources indicated by the reviewers as "other" were the most dominant in multi-vehicle crashes. Seatbelt was the second highest contributor to MAIS3$^+$ injury in opposite direction and rear-end crashes. On the other hand, knee bolster was the second highest injury source in LTAP/OD crashes. It is interesting that the instrument panel was the most dominant injury source in road departure crashes while the steering wheel was the most prevalent in control loss crashes. Control loss is usually associated with high speeds while road departure is associated with lower speeds and impaired drivers. Based upon these findings, it is possible that high

speed crashes cause drivers to strike steering wheel at a higher force.

Table 10. Percentage of MAIS3$^+$ Body Region Injuries by Injury Source

Injury Source	Abdomen	Back	Chest	Face	Head	Lower Extremity	Upper Extremity
A Pillar				20%	8%		2%
Airbag		10%	19%		8%	3%	9%
B Pillar		7%			20%		1%
Column			4%				1%
External				**35%**	5%	2%	11%
Head Restraint					1%		
Header				10%	3%		3%
Knee bolster						19%	
No Contact		19%			3%		
Other	14%	**24%**	19%	19%	14%	28%	25%
Panel			1%		5%	**40%**	16%
Roof		22%			3%		
Seat Belt	**83%**	4%	28%		3%	1%	
Side Rail					3%		
ToePan						7%	
Wheel	3%	14%	**29%**	16%	**23%**	1%	**33%**
Total	100%	100%	100%	100%	100%	100%	100%

Table 11. Percentage of MAIS3$^+$ Injuries in Crash Scenarios by Injury Source

Injury Source	Opposite Direction	Rear-End	LTAP/OD	Road Departure	Control Loss
A Pillar	2%		2%		1%
Airbag	11%	10%	2%	12%	
B Pillar		1%	7%	1%	4%
Column	3%		1%		1%
External				3%	11%
Head Restraint					
Header	1%	5%			
Knee bolster	14%		**25%**		
No Contact	3%	9%			
Other	**34%**	**50%**	**27%**	13%	**23%**
Panel	3%	9%	10%	**30%**	11%
Roof				2%	2%
Seat Belt	**16%**	**12%**	11%	**20%**	14%
Side Rail			1%		
ToePan	5%	1%	6%	1%	3%
Wheel	6%	4%	9%	19%	**30%**
Total	100%	100%	100%	99%	100%

CONCLUSIONS

Based on results from general data queries that prioritized pre-crash scenario and impact mode combinations, individual CDS cases were selected for review for potential mitigation by CIB and ARS. Different filtering schemes were adopted to determine the applicability of CIB and ARS to selected cases. Descriptive statistics using weighted CDS data were provided to the CIB and ARS applicable case sets.

The CIB analysis identified 99 cases out of 1,903 target vehicle cases from vehicle-object crashes and 871 cases out of 8,807 target vehicle cases from vehicle-vehicle crashes to be amenable to CIB intervention. Brake assist or stability control was assumed to address some of the other cases. Using CDS weights for these cases, CIB addresses about 4% of all target vehicles. The analysis of CIB applicable vehicle cases revealed:

- About 63% of the target vehicles involved in vehicle-object crashes were light trucks or vans. By excluding braking from CIB applicable cases, steering was noted as the avoidance maneuver for 22% of the target vehicles. In vehicle-object crashes, 96% of target vehicles were driving under clear weather, 91% were traversing dry road surfaces, and 56% were traveling in non-daylight conditions. Almost two thirds of the vehicles suffered total ΔV under 40 Km/h. Moreover, 95% of the vehicles experienced total ΔV under 55 Km/h. Vehicles with longitudinal ΔV over 72 Km/h were excluded from the CIB applicable case set.
- About 53% of the target vehicles involved in vehicle-vehicle crashes were light trucks or vans. Excluding braking from CIB applicable cases, 17% of target vehicles attempted steering before the crash. In vehicle-vehicle crashes, 94% of target vehicles were driving under clear weather, 92% were traversing dry road surfaces, and 58% were traveling in daylight. Almost two thirds of the target vehicles (66%) suffered ΔV under 25 Km/h and 95% of the vehicles experienced total ΔV under 45 Km/h. In all CIB vehicle-vehicle crash scenarios, 56% and 76% of the target vehicles experienced a relative angle of collision respectively within ±30 and ±60 degrees.

The ARS analysis restricted target occupants to belted drivers and FSP13$^+$. Overall, 71% of the number of occupants were accepted for further examination. The raw number of CDS cases was 407 occupants. Results showed:

- 72% of occupants in single-vehicle crashes were in a single- or multi-impact crash in which the first event was the most harmful. In contrast, this rate was 93% in multi-vehicle crashes.
- 96% of occupants were in vehicles with ΔV below 70 Km/h.
- 50% and 17% of occupants were in vehicles sustaining left and right frontal damage, respectively, with offset percentage of 50% or less. The remaining 23% were in vehicles with center frontal damage at offset percentage greater than 50%.
- Single- and multi-vehicle crashes accounted respectively for 61% and 39% of all MAIS3$^+$ injuries to occupants.
- The body region most likely to be injured at MAIS3$^+$ was the chest, accounting for 36% of

all MAIS3$^+$ injuries. About 48% of MAIS3$^+$ injuries were associated with lower and upper extremities.

- Other non-specific sources of injury were reported as the highest rate at 23% of MAIS3$^+$ injuries. Instrument panel, seatbelt, and steering wheel followed respectively at 18%, 16%, and 15% of MAIS3$^+$ injuries. Airbag and knee bolster were noted at 8% and 7% of MAIS3$^+$ injuries.
- Steering wheel had the highest contribution rate to injury in chest, head, and upper extremity body regions. Injury to the abdomen was caused predominantly by the seat belt at an extreme rate of 83%. Instrument panel caused the highest rate of injury to the lower extremity at 40%.

Results from these crash analyses were used by the automotive partners and their suppliers to devise potential countermeasure concepts for CIB and ARS based on pre-crash sensing, and to develop preliminary functional requirements. Development of objective test procedures and estimation of safety benefits constitute next research steps.

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