Preliminary Analysis of Serious-to-Fatal Injury in Rear Impact Crashes in the United States.

WM Tatem, HC Gabler

Abstract One of the most common crash modes on US roadways are rear end collisions. Despite this large number of crash occurrences, rear impact crashes are generally viewed as a benign crash mode primarily involving only property damage or at most minor injuries. However, in 2015, there were nearly 1,000 fatalities in rear struck passenger cars and light trucks; 757 (63%) of these fatalities occurred in model year 2000 or later vehicles. The question becomes, if rear impacts are indeed a benign crash mode, what is leading to these fatalities? This study investigates the factors associated with serious-to-fatal rear impact crashes. Compartmental collapse appears to be a major risk factor in rear impact crashes, particularly for occupants seated in the rear seats. The vast majority of fatal crashes appear to involve compartmental collapse, which is present in 4.4% of all rear impact crashes, although other injury mechanisms such as direct head contact to rigid interior vehicle structures and thoracic loading from the seat tend to be responsible for serious but survivable occupant injuries.

Keywords head impact, motor vehicle crash, occupant compartment collapse, rear crash, thoracic loading

I. INTRODUCTION

One of the most common crash modes on US roadways are rear end collisions. The National Highway Traffic Safety Administration (NHTSA) has reported that approximately 2.1 million rear end crashes occurred in the US in 2015 [1]. Despite this large number of crash occurrences, rear impact crashes are generally viewed as a benign crash mode with property damage only and at most minor injuries. However, in 2015, there were nearly 1,000 fatalities in rear struck passenger vehicles, and 757 (63%) of these fatalities occurred in model year 2000 or greater cars and light trucks. Rear struck crashes account for approximately 5% of fatalities in passenger vehicles overall. The question becomes, if rear impacts are indeed a benign crash mode, what is leading to these fatalities?

Currently, the only US regulatory test evaluating the rear impact crash mode is the NHTSA Federal Motor Vehicle Safety Standard (FMVSS) No. 301, Fuel System Integrity test. This test is intended to check for fuel spills, which may result from fuel tank deformation during a rear end collision and lead potentially to post-crash fires. Prior to model year (MY) 2007, the FMVSS No. 301 test consisted of a 1814 kg (4000 lbs) movable rigid impactor which struck the rear of the subject vehicle at 48 km/h (30 mph). The impact involved full engagement of the rear of the subject vehicle. In December 2003, NHTSA amended FMVSS No. 301 to increase the severity of the test. Phase-in of the higher-severity FMVSS rear crash test occurred from MY 2007 to MY 2009. The upgraded FMVSS No. 301 rear crash test requires striking the rear of the subject vehicle at 80 km/h (50 mph) with a 1,368 kg (3,015 lbs.) moving deformable barrier at a 70% overlap with the subject vehicle. While this has been a realistic means of testing for fuel tank performance, it does not however measure or place limits on occupant loads.

The objective of this study is to investigate the characteristics of serious-to-fatal rear impact crashes and to identify the underlying crash features that may lead to serious or fatal injury for occupants seated in rear-impacted vehicles.

II. METHODS

The data sources for this study were the National Automotive Sampling System (NASS)/General Estimates

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System (GES), the NASS/Crashworthiness Data System (CDS), and the Fatality Analysis Reporting System (FARS). Table I describes the sample selection, approximate number of cases per year, and use for each database in the current study. CDS crashes were collected by trained field investigators, whereas GES and FARS cases were aggregated by NHTSA from police accident reports. The in-depth investigations in CDS include a collection of medical records for injured occupants as well as estimates of delta-V. Therefore, CDS was used to characterise serious injury crashes in this study.

TABLE I
Description of Nationally Representative Crash Databases

Characteristic	GES	CDS	FARS
Inclusion Criteria	All police reported crashes	Tow-away crashes	Census of Fatal Crashes
Number of Cases Per Year (Approximate)	50,000	4,000	30,000
Study Use	All Crashes	Serious Injury Crashes	Fatal Crashes

The GES and CDS databases are probability samples of US crashes. The sample designers assign a weighting factor to each crash that corresponds to the number of similar collisions that occurred during the sample period. To make the estimates presented in this study nationally representative, the weights were used in all analyses for GES and CDS unless otherwise noted.

For the GES and FARS databases, years 2010 to 2015 were aggregated. For the CDS database, years 2000-2015 – the last 16 years of data available – were aggregated. Presented results are proportions of the entire samples unless otherwise noted.

The GES and FARS cases for our analysis were selected to meet the following criteria:

- Struck vehicle was either a car or a light truck, van, or sport utility vehicle (LTV) of model year 2000 or greater.
- First harmful event was a rear impact. A rear impact was defined in this study as an event involving crash damage to the back plane of the vehicle.

The CDS cases that met the following criteria were selected for the analysis:

- Struck vehicle was either a car or LTV of model year 2000 or later.
- Most harmful event was a rear impact.
- Struck vehicles only experienced a single event.
- Cases with unknown seating position were excluded.
- Cases in which injury outcomes were unknown were excluded.
- Crashes with zero sampling weights or sampling weights over 5000 were excluded.

These criteria were chosen to include only the latest safety technologies. In the following analysis, model year 2000-2008 passenger vehicles were compared to model year 2009 and later vehicles in an effort to distinguish effects that FMVSS 301 may have had on vehicle safety performance in the rear impact crash mode.

Our analysis classified injury severity by the maximum Abbreviated Injury Scale (AIS) level injury sustained by an occupant. Moderate-to-fatal injury crashes were extracted from CDS. Our hypothesis was that factors which led to fatal injury might also have been present in lower injury severity crashes in which the occupants survived the impact. CDS describes the severity of these injuries based on the AIS [2]. AIS rank injuries on a scale of 1-6 based on the threat to the life of the occupant; AIS1 is a minor injury and AIS6 is an injury of maximal severity which is currently untreatable. A moderate-to-fatal injury crash was defined as an event in which at least one involved occupant suffered a maximum AIS (MAIS) score of 2 or greater. Fatally injured occupants were included in the MAIS2+F category regardless of maximum AIS level.

III. RESULTS

The composition of the GES and FARS datasets are presented in TABLE II. The data were used to examine occupant deaths (FARS) in relation to total exposure (GES) in rear crashes. Data in TABLE II shows that, between the years of 2010 to 2015, there were approximately 12.5 million crashes involving a rear struck vehicle. In

2,912 of these crashes, at least one rear struck vehicle occupant was fatally injured.

TABLE II
Compilation of GES and FARS Rear Crash Data

Rear Crash Data	All Crashes (GES 2010-2015)		Fatal Crashes (FARS 2010-2015)
	Unweighted	Weighted	Frequency
Number of Rear Struck Vehicles	90,276	12,572,654	2,912
Number of Rear Struck Occupants	131,477	17,989,838	5,892
Number of Rear Struck Fatalities	127	2,398	3,353

As shown in Fig. 1, the absolute number of rear impact crashes has been increasing. Fig. 2 shows the same trend for fatalities in rear struck passenger vehicles. In fact, rear impact fatalities in model year 2009 and greater vehicles, those specifically designed for, and required to meet, the upgraded FMVSS 301, are increasing as well. As shown in Fig. 3, MY 2000-2008 vehicles are over-represented in fatality outcome with 63% of rear struck vehicle and occupant exposure but 77% of rear struck fatalities. This evidence suggests that advances in MY 2009+ vehicles to meet FMVSS 301 have yielded some rear impact occupant protection improvement. To understand why rear impact fatalities persist, injury mechanisms in rear struck vehicle occupants must be further studied.

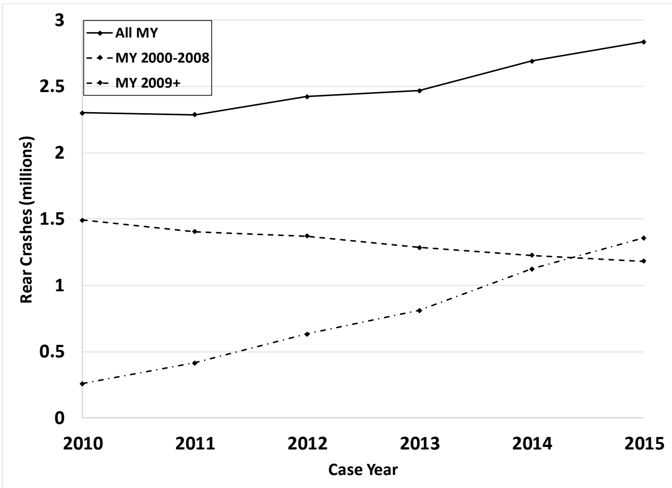

Fig. 1. Absolute number of rear impact crashes in all model years, model year 2000-2008, and model year 2009+ passenger cars and LTVs (GES 2010-2015).

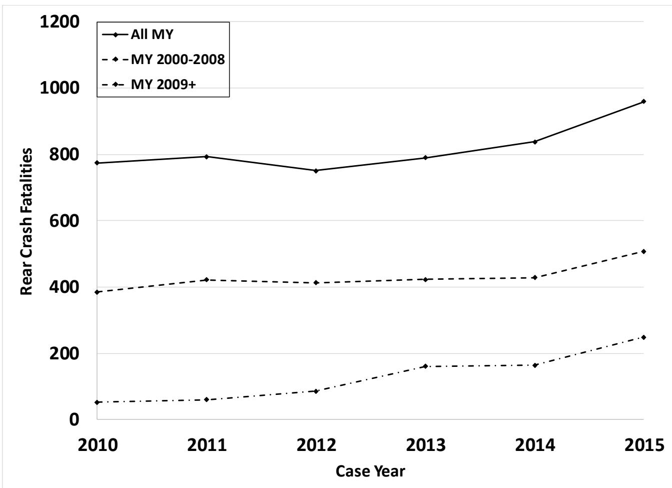

Fig. 2. Absolute number of fatalities in rear struck vehicles in all model years, model year 2000-2008, and model year 2009+ passenger cars and LTVs (FARS 2010-2015).

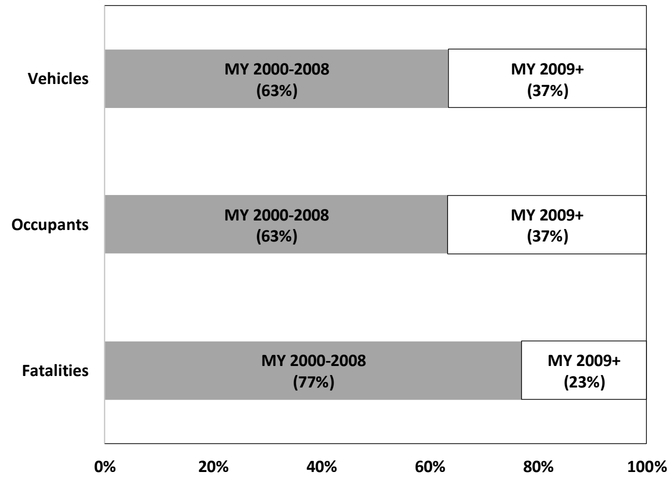

Fig. 3. Proportion of all rear struck vehicles, occupants, and fatalities in model year 2000-2008 and model year 2009+ passenger cars and LTVs (GES and FARS 2010-2015).

Typically, fatally injured occupants are more likely to be unrestrained and ejected than other vehicle occupants. Additionally, fuel tank integrity may be lost in rear impact crashes, possibly resulting in vehicle fire, which often has severe injury consequences. However, findings shown in Fig. 4 and Fig. 5 show that none of these factors overwhelmingly contributed to rear impact fatalities in either older or newer vehicles. A majority, 67-82%, of fatal rear struck vehicle occupants were belted at the time of the crash, and less than 10-11% were ejected or involved in a vehicle fire. However, a notable 72% of fatally injured occupants were seated in cars as opposed to LTVs (28%). Another early clue to fatality mechanisms is shown in Fig. 6 and Fig. 7. Rear seat passengers (24% of fatalities) were over-represented in fatalities when compared with GES exposure (13% of all rear struck occupants) in both older and newer vehicles. Previous studies have also indicated that, in comparison to drivers and front passengers, rear occupant fatality risk and serious injury rate was greatest in rear impacts [3].

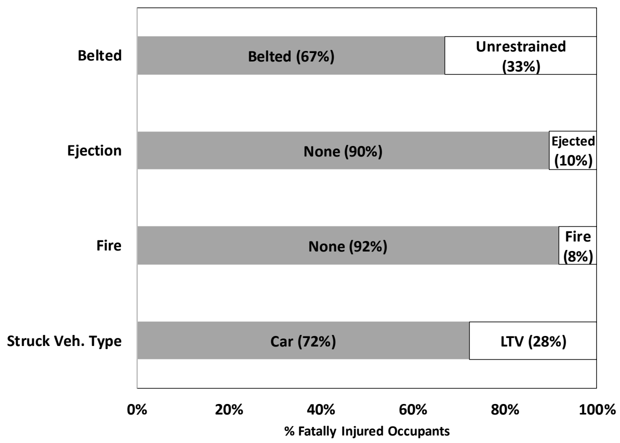

Fig. 4. Incidence of seatbelt use, ejection, fire, and struck vehicle type in model year 2000-2008 passenger vehicles for fatally injured rear struck occupants (FARS 2010-2015).

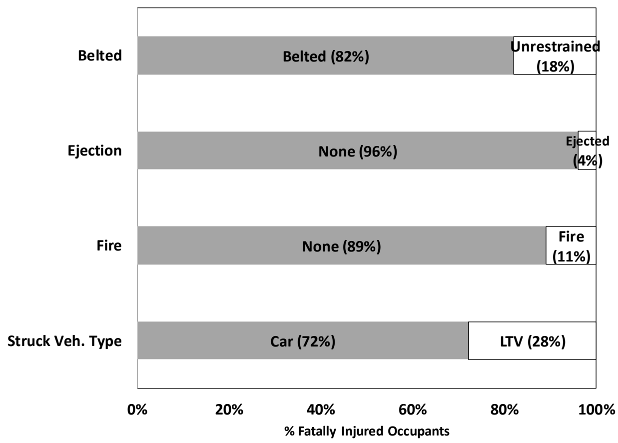

Fig. 5. Incidence of seatbelt use, ejection, fire, and struck vehicle type in model year 2009+ passenger vehicles for fatally injured rear struck occupants (FARS 2010-2015).

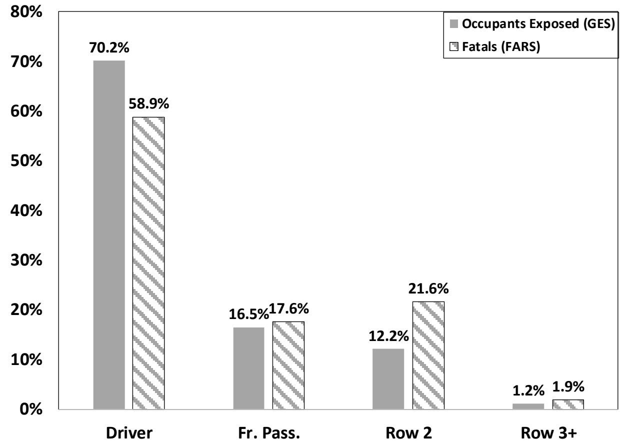

Fig. 6. Rear struck vehicle occupant exposure and fatality distribution by occupant seat position in model year 2000-2008 passenger vehicles (GES and FARS 2010-2015).

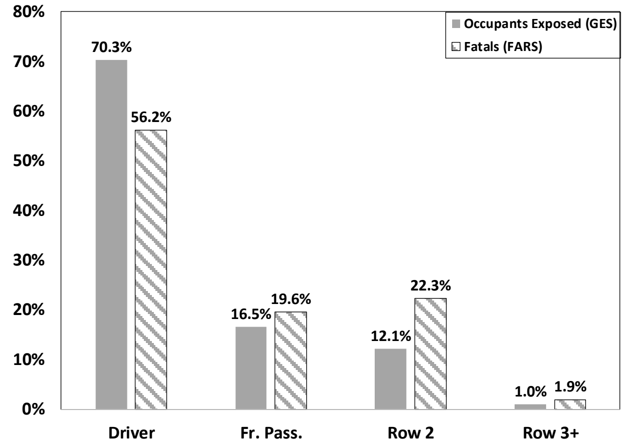

Fig. 7. Rear struck vehicle occupant exposure and fatality distribution by occupant seat position in model year 2009+ passenger vehicles (GES and FARS 2010-2015).

FARS includes no additional information detailing occupant injuries. To better understand these serious injuries, CDS was used to characterise injury patterns and their possible sources. As shown in TABLE III, the dataset of MAIS2+F crashes included 95 rear impact cases, which involved 108 rear struck occupants with associated injury data. This relatively small sample size is a limitation of this study and does not allow for meaningful tests of significance, though the trends presented will be useful in guiding and narrowing future research efforts.

As shown in Fig. 8, of the MAIS2+F injured occupants, 63% were in rear struck cars with the remaining 37% in LTVs. Most (82%) of MAIS2+F occupants were belted. Ejection was a rare occurrence, presenting itself in only 1% of the injury cases. Only 0.03% of cases involved a vehicle fire. As observed in FARS, Fig. 9 shows that rear seat passengers (22% of MAIS2+F injuries) were over-represented in injury outcome when compared with exposure (13% of all rear-struck occupants). Interestingly, right front passengers were also over-represented in injury outcome.

TABLE III

Compilation of CDS Rear Crash Data

Rear Crash Data	MAIS2+F Crashes (CDS 2000-2015)		MAIS3+F Crashes (CDS 2000-2015)	
	Unweighted	Weighted	Unweighted	Weighted
Number of Crashes	95	18,112	34	2,619
Number of Occupants	108	19,607	38	2,817
Number of Fatalities	11	499	11	499

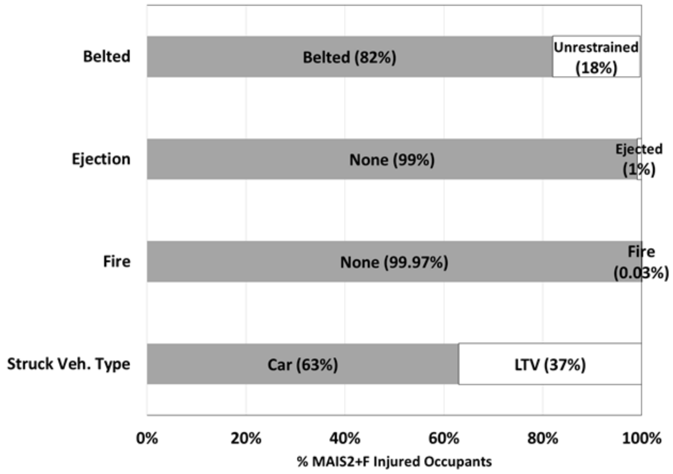

Fig. 8. Incidence of seatbelt use, ejection, fire, and struck vehicle type in tow-away MAIS2+F injured rear struck vehicle occupants (CDS 2000-2015).

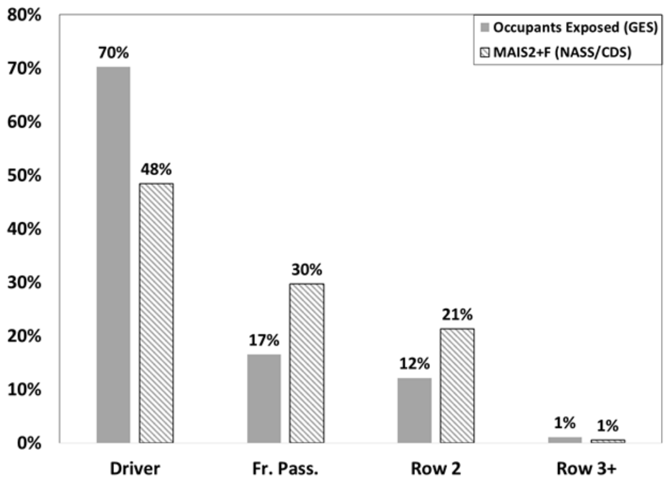

Fig. 9. Occupant exposure and MAIS2+F distribution in tow-away rear struck vehicles by occupant seat position (GES 2010-2015 and CDS 2000-2015).

To more fully understand injury mechanism in rear impact crashes, in-depth case reviews were conducted for the 38 rear stuck occupants in CDS 2000-2015 who had MAIS3+F injuries.

Fatal Injury Cases

Our dataset included 10 crashes with 11 fatalities. Eight (8) of these fatalities (73%) involved catastrophic compartmental collapse. An example of such a crash can be seen in Fig. 10. In this case, a 2006 Toyota Scion TC was rear impacted by a 2007 Mazda3. The second row, right seat passenger of the Scion died due to a blunt impact head injury caused by the C-pillar being driven into the back of his head. If the compartment had not collapsed, this crash would have been highly likely to be survivable: the driver and front right passenger experienced only AIS1 whiplash because of the crash. In our sample, rear occupants were always affected by the compartmental collapse. In some cases, compartmental collapse was also sufficiently severe to induce serious-to-fatal injury in the front seat occupants as well, a phenomenon that had been previously noted [4].

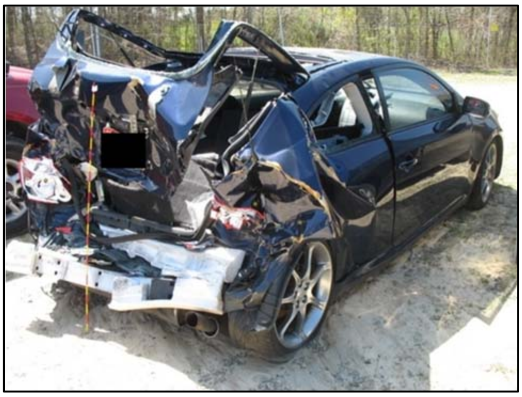

Fig. 10. Fatal rear crash in which compartmental collapse resulted in the right rear passenger sustaining a fatal head injury. The driver and right front passengers sustained only minor AIS1 injuries in this crash (CDS 2010-43-051).

One hypothesis is that these massive compartment collapses are a result of cars being overridden by LTVs. While this may be true in some cases, it is certainly not overwhelmingly so. Four (4) of the fatal cases involved an LTV striking a car (with no obvious override), three (3) were LTV to LTV, two (2) were car to car, and one (the double fatality) was a car being struck by a large tractor-trailer. This raw count distribution is shown in Fig. 11.

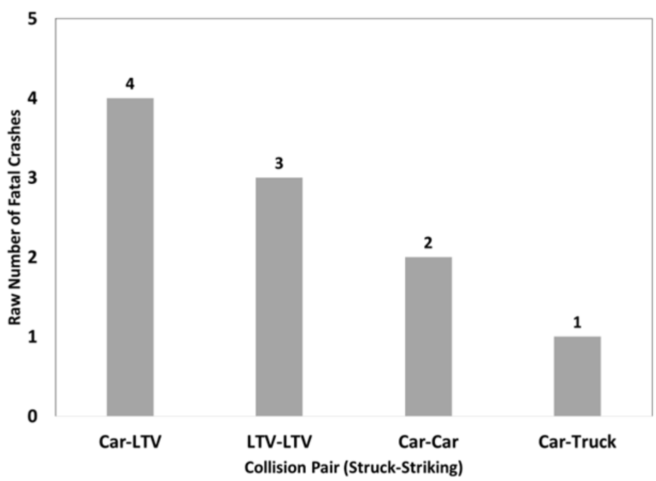

Fig. 11. Collision pair (struck-striking vehicle) distribution in fatal rear impact crashes (CDS 2000-2015).

Knowing that three-fourths of fatal rear struck occupants were injured due to compartmental collapse begs the question – how often do rear struck vehicles collapse? Our study used vehicle crush and damage profiles recorded in CDS as a quantitative indicator of compartment collapse. CDS codes the damage extent for each struck vehicle using the collision deformation classification (CDC) [5], and damage extent is a good indicator of overall vehicle crush. An extent greater than or equal to 5 indicates vehicle damage at least up to the rearmost vehicle seat. Damage at this level was used in our study as the threshold for compartment collapse. Sideswipes were excluded from this calculation as they often yield damage extents greater than 5 but typically involve only superficial vehicle damage and little or no intrusion. Fig. 12 shows results by crash overlap configuration where full engagement corresponds to full vehicle frame interaction and moderate overlap correlates to partial vehicle frame interaction. Almost 7% of moderate overlap rear impact crashes resulted in struck vehicle compartment collapse. When considering rear impact crashes regardless of vehicle overlap, 4.4% of the rear struck vehicles suffered compartmental collapse. This finding is rooted in a relatively small sample size and will be explored further in future studies.

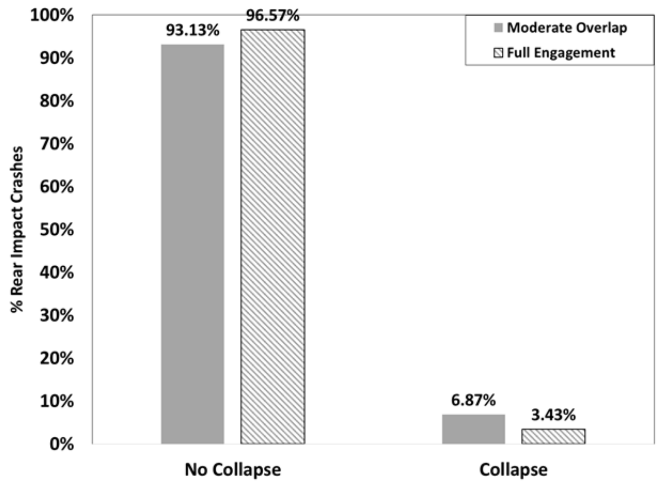

Fig. 12. Incidence of rear struck vehicle occupant compartment collapse by crash overlap configuration (CDS 2000-2015).

For fatal cases not involving compartmental collapse, one fatality was due to ejection, one was due to blunt head injury as a result of striking the B-pillar, and one was due to extreme inertial loading of the thorax. The age range of fatally injured occupants was wide, from seven to 86 years with an average of 48 years. This is older than the population of all rear-struck occupants where the average age of occupants was approximately 36 years old with a range from infancy to 93 years.

MAIS4-5 (Severe) Injury Cases

There were 10 cases involving severely injured occupants in this data set. Four (4) of these occupants sustained MAIS4-5 injuries due to the compartmental collapse observed in the fatal cases. However, at this severity, the most prevalent injury mechanism shifted from compartmental collapse to head contact with a rigid interior vehicle object, such as the B-pillar or interior vehicle roof. An example of such a case involved a 2004 Kia Optima which was rear-ended by a 2001 Mercedes Benz S Class while attempting to make a U-turn (CDS 2009-09-014). In this case, while there was rear seat compartment collapse, the front seat remained intact. The driver though sustained a severe head injury as a result of direct contact to the B-pillar when the driver was thrust backwards because of the rear impact.

Within the non-collapse severe injury cases, five (5) cases were attributed to head contact to a rigid interior vehicle object, and one case was a cervical-spine fracture, which was attributed to the occupant’s contact to his head restraint system.

MAIS3 (Serious) Injury Cases

This data set included 17 serious injury cases, where, yet again, an interesting shift in apparent injury mechanism occurs. Many of the cases (six of 17) involved rib fractures. One example involved a 2002 Chevy Trailblazer which was rear-ended at a stoplight by a 2009 Toyota Corolla (CDS 2010-78-143). In this case, the front right passenger sustained three rib fractures while the passenger seated directly behind him and the driver sustained only minor bruises. The vehicle trunk collapsed, but there was no apparent intrusion into the occupant compartment. This suggests thoracic loading from the seat as the source of injury as opposed to direct contact with a hard surface. Historically, there has been much debate over appropriate seatback stiffness [6], and these case reviews suggest that current designs may not be appropriate in all crash modes and for all occupants. It is notable that most instances of rib fracture in our dataset (four of six) involved occupants over the age of 55, who may be more susceptible to injury and may not be able to withstand inertial loading as well as their younger counterparts.

Of the remaining 10 cases, injury locations were much more varied, encompassing serious upper and lower extremity fractures and cervical-spine fractures as well as head injuries comparable to those seen previously in severe injury cases. Only one MAIS3 injury could be attributed to compartmental collapse.

IV. DISCUSSION

This study has presented a preliminary analysis of crash characteristics associated with serious-to-fatal injuries in rear struck vehicles. The incidence of rear impact crashes and fatalities have been increasing, and although new vehicles designed to meet the upgraded FMVSS 301 have shown some rear impact protection improvements, they have not completely solved the problem of rear crash fatalities. There appear to be three mechanisms leading to serious-to-fatal injury in rear impact crashes: (1) catastrophic collapse of the occupant compartment, (2) impacts with hard vehicle interior components, e.g., the B-Pillar, and (3) thoracic loading from the seat, especially on older occupants.

All three injury mechanisms present themselves in each injury severity category, both fatal, severe, and serious. There appears to be a continuum of injury mechanisms. Compartment collapse was most often associated with fatal injuries, direct head contact produced predominantly severe injuries, and thoracic loading appears more related to serious injuries. This study is the first step in a research effort to explore the factors that lead to a higher injury risk in rear impact crashes. The next steps will be to expand this study to a more comprehensive analysis of rear structural response and seat performance to gain a deeper understanding of the injury mechanics in rear crashes, and to determine the priority for countermeasure development.

There are currently no US regulations to evaluate the potential for occupant injury in rear impacts. NHTSA FMVSS No. 301 is the only standard that requires new vehicles to be tested in a rear impact condition. However, the only risk factor evaluated in FMVSS No. 301 is the presence of post-crash fuel spills. The vehicles are not equipped with instrumented anthropometric test devices (ATDs) of any type. Given that so many individuals succumb to the injuries sustained in rear impact crashes annually, regulatory agencies should consider rear crash tests which evaluate occupant injury risk in a similar fashion to how other crash modes are evaluated. Our study has shown that rear crash fatalities persist even in vehicles certified to the upgraded FMVSS No. 301 regulation. If the US is to continue decreasing and eventually eliminating passenger vehicle fatalities, this crash mode must be addressed.

The findings presented in this study are limited by the small sample of fatal and serious injury rear impact crashes in CDS, and should be revisited when a larger CDS sample is available.

V. CONCLUSIONS

This study has investigated the factors associated with serious-to-fatal rear crashes. Despite the perception that rear crashes are benign, nearly 1,000 occupants were fatally injured in the US in 2015 when seated in a rear struck car or light truck. Compartmental collapse appears to be a major risk factor in rear impact crashes, particularly for occupants seated in the rear seats. The vast majority of fatal crashes appeared to involve compartmental collapse although other injury mechanisms such as direct head contact to rigid interior vehicle structures and thoracic loading from the seat should not be disregarded.

VI. REFERENCES

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