The Crash Injury Risk to Rear Seated Passenger Vehicle Occupants

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Academic Abstract

Historically, rear seat occupants have been at a lower risk of serious injury and fatality in motor vehicle crashes than their front seat counterparts. However, many passive safety advancements that have occurred over the past few decades such as advanced airbag and seatbelt technology primarily benefit occupants of the front seat. Indeed, safety for front seat occupants has improved drastically in the 21st century, but has it improved so much that the front seat is now safer than the rear? Today, rear-seated occupants account for 10% of all passenger vehicle fatalities. In this era focused on achieving zero traffic deaths, the safety of rear-seated occupants must be further addressed.

This dissertation analyzed U.S. national crash data to quantify the risk of injury and fatality to rear-seated passenger vehicle occupants while accounting for the influence of associated crash, vehicle, and occupant characteristics such as crash severity, vehicle model year, and occupant age/sex. In rear impacts, the risk of moderate-to-fatal injury was greater for rear-seated occupants than their front-seated counterparts. In high-severity rear impact crashes, catastrophic occupant compartment collapse can occur and carries with it a great fatality risk. In frontal impacts, there is evidence that the rear versus front seat relative risk of fatality has been increasing in vehicle model years 2007 and newer. Rear-seated occupants often sustained serious thoracic, abdomen, and/or head injuries that are generally related to seatbelt use. Seatbelt pretensioners and load limiters – commonplace technology in the front seating positions – aim to mitigate these types of injuries but are rarely provided as standard safety equipment in the rear seats of vehicles today. Finally, in side impacts, injury and fatality risks to rear- and front-seated occupants are more similar than in the other crash modes studied, though disparities in protection remain, especially in near-side vehicle-to-vehicle crashes. Finally, this work projects great injury reduction benefits if a rear seat belt reminder system were to be widely implemented in the U.S. vehicle fleet.

This dissertation presents a comprehensive investigation of the factors that contribute to rear-seated occupant injury and/or fatality through retrospective studies on rear, front, and side impacts. The overall goal of this dissertation is to better quantify the current risk of injury to rear-seated occupants under a variety of crash conditions, compare this to the current risk to front-seated occupants, and, when possible, identify how exactly injuries are occurring and ways in which they may be prevented in the future. The findings can benefit automakers who seek to improve the effectiveness of rear seat safety systems as well as regulatory agencies seeking to improve was vehicle tests targeting rear seat passenger vehicle safety.

The Crash Injury Risk to Rear Seated Passenger Vehicle Occupants

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General Audience Abstract

Historically, if a passenger vehicle such as a sedan or SUV is in a crash, occupants who are rear-seated were less likely to be hurt than someone who was front-seated. In other words, rear-seated occupants have been at a lower risk of injury than front-seated occupants. Indeed, safety for front seat occupants has improved drastically in the 21st century due to advancements in airbag and seatbelt technologies, among others, but has it improved so much that the front seat is now safer than the rear? Today, of all vehicle occupants who are killed in crashes on U.S. roadways, 10% are rear-seated. During this time when conversations surrounding vehicle safety are focused on achieving zero traffic deaths, the safety of rear-seated occupants must be further studied.

This dissertation looked at national databases of all police-reported crashes that occur each year in the United States. The risk of injury to rear-seated passenger vehicle occupants was quantified and compared to that of front-seated occupants. Factors that may increase or decrease this risk of injury and fatality such as crash type, vehicle type, and occupant demographics were further explored and reported. In vehicles that were rear-ended, the risk of injury was greater for rear-seated occupants than their front-seated counterparts. When a vehicle crashes into something front-first (the most common type of impact in a vehicle crash), evidence is presented that the risk of fatality is greater in the rear seats than the front seats in model year 2007 and newer vehicles which generally are equipped with the most recent airbag and seatbelt technology. When a vehicle is hit on either of its sides, the risk of injury is closer between rear- and front-seated occupants than it was in the rear-end or frontal crashes previously studied. That said, differences in occupant protection were still observed between the rear and front seats, especially when the occupants studied were seated on the closest side of impact, or the near-side, and the vehicle was struck by another vehicle rather than sliding into an object such as a pole. Finally, this work projects great injury reduction benefits if a rear seat belt reminder system were to be widely implemented in the U.S. vehicle fleet.

This dissertation presents a comprehensive investigation of the factors that contribute to rear-seated occupant injury and/or fatality through retrospective studies on rear, front, and side impacts. The overall goal of this dissertation is to better quantify the current risk of injury to rear-seated occupants under a variety of crash conditions, compare this to the current risk to front-seated occupants, and, when possible, identify how exactly injuries are occurring and ways in which they may be prevented in the future. The findings can benefit automakers who seek to improve the effectiveness of rear seat safety systems as well as regulatory agencies seeking to improve was vehicle tests targeting rear seat passenger vehicle safety.

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1. INTRODUCTION

MOTIVATION

Historically, rear seat occupants have been at a lower risk of serious injury and fatality in motor vehicle crashes than their front seat counterparts [1-4]. However, over the past couple of decades, automotive safety has taken great strides forward with passive safety technologies such as advanced multi-stage frontal airbags, seatbelt pretensioners and load limiters, and small overlap crash protection. The imminent rise of active safety systems in the vehicle fleet, such as forward collision avoidance systems (FCAS), will also likely change the type and incidence of crashes that are seen on U.S. roadways in the future [5-8].

A common thread amongst most of the passive safety systems mentioned is that they primarily benefit occupants of the front seat. Indeed, safety for front seat occupants has improved drastically in the 21st century, but has it improved so much that the front seat is now safer than the rear? At least since the introduction of advanced airbags and seatbelt pretensioners and load limiters, a few studies have suggested that yes – the front seat is safer than the rear seat for specific occupants (children universally appear to remain safer when rear-seated) [9-11]. Likely due to the introduction of frontal airbags, the literature shows a decrease in head injuries among front seat occupants, but this trend is not seen in the rear seats [10]. Other common injuries seen in the rear seats are to the thorax and/or abdomen. These types of injuries are more common in rear seats than the front, perhaps due to the lack of load limiting seatbelt technology being implemented in those seating positions [9, 10, 12-14].

Many studies looking at rear seat occupant safety either consider only a single crash mode or consider the crash mode as a covariate in any injury risk calculations. This dissertation will explore each crash mode separately, as each mode implicates unique injury mechanisms and potential countermeasures. Further, this dissertation presents not only absolute injury risks but also considers how injury risks and influenced by a number of potential crash-level, vehicle-level, and occupant-level factors, which are at times overlooked in current literature.

Rear Seat Occupancy Rates in the U.S. Passenger Vehicle Fleet: Implications of Rideshare and Highly Automated Vehicles (HAVs)

Current vehicle regulation and available safety systems are biased towards the front seat [15]. The rationale for this front seat emphasis is that whereas there is always a driver and often a front seat passenger, far fewer passenger vehicle occupants travel in the rear seats than the front seats. Only about 13% of person-trips contain at least one rear-seated occupant [16]. When paired with annual vehicle trip statistics, this equates to 34.5 billion trips and almost 400 billion vehicle miles traveled annual with at least one rear-seated occupant [17]. Even though this rear seat occupant exposure is of course smaller than that of front seat occupants, it is still a very large at-risk population.

Recently, rideshare services such as Uber and Lyft have become prominent in the transportation industry. Passengers of these services often have a desire to sit in the rear seat as this has become somewhat of a social norm. Rideshare users have somewhat of a predisposition to sit in the rear seat, as this is customary when riding as a passenger in a traditional taxi. In addition to rideshare, there has been much discussion in the vehicle industry surrounding the rise of Highly Automated Vehicles (HAVs), usually used in reference to ‘high automation’ Level 4 and ‘fully automated’ Level 5 vehicles per the SAE definitions [18]. There is much speculation about HAVs and how they might change both occupant behavior and injury outcomes. One hypothesis is that the percentage of rear seat passengers will increase in part due to the fact that the ‘driver’s seating position,’ a front seat position, will almost certainly no longer need to be occupied. Additionally, these HAVs will likely be first tested and introduced as ride-share and taxi services with companies such as Uber and Lyft, amongst others [19, 20], where passengers seem to be showing preference for the rear seats.

Literature is slowly beginning to emerge on this topic of occupant’s seating position preferences in HAVs. Given hypothetical traveling scenarios in an HAV, online survey participants in the first study on this topic were most likely to indicate a preference to sit in the conventional driver’s seating position in every scenario [21]. Real-world data collection on occupants seating position choices in HAVs is a worthy research objective that should be prioritized, as it will be an important step towards understanding how occupancy rates in each seating position may change.

LITERATURE REVIEW

Injury in Rear Impacts

In rear impacts, injury risks, mechanisms, and thresholds are not well-defined at higher impact speeds. This is becoming increasingly problematic because, in order to specify acceptable occupant injury outcomes in crash tests, there need to be well defined thresholds at which injury is likely to occur. Most studies which have investigated rear crash injury outcomes in correlation to real-world crash severity focus almost exclusively on low speed impacts [22, 23], which are common, but generally yield none to only minor injury consequences, such as whiplash. Real-world crash severity is defined by a vehicle's change in velocity, or delta-V, that is often determined from the crashed vehicle's event data recorder (EDR) [24, 25]. A European study examining the German In-Depth Accident Study (GIDAS) found that rear impacts did not result in high rates of severe, or AIS3+, injuries [26]. However, many study occupants suffered minor, or AIS1, injuries, such as whiplash. When AIS3+ injuries were present, they were most often to the head and thorax, primarily including concussion and rib fracture(s). Moderate injuries to the extremities were also seen, though rare. Observed injury severities on the AIS scale were not correlated with crash delta-v in this study. While research efforts such as this offer preliminary glimpses into rear impact injury epidemiology, more detailed research is needed on injury characteristics, mechanisms, and thresholds. Having a better understanding of how and at what velocities more serious injuries occur in the rear impact mode will inform the development of mitigating safety systems to prevent these types of injuries from occurring in the future.

A few studies have looked at rear impacts in an effort to draw conclusions about rear-struck occupant injury and fatality risks. Having a well-defined set of risk factors for occupants in rear impacts will help shed light on injury mechanisms in this crash mode. So far, higher risks for severe injury and fatality in rear-struck occupants have been associated with factors such as seating position, seatbelt use, ejection, occupant compartment intrusion, and improper seatback support, among others.

<u>Seating Position</u>

In comparison to drivers and right-front passengers, the fatality risk and serious injury rate for rear occupants are greatest in rear impacts [12]. Compared to other crash modes, rear seat occupants have the highest injury risks in crashes in which the primary direction of force (PDOF) was directed toward their seating position [1, 27]. This involves direct rear impacts (6 o'clock) for all rear occupants and oblique rear impacts (specifically 4-5 o'clock for 2nd row right passengers and 7-8 o'clock for 2nd row left passengers). A study from the 1990s – before it was widely recommended to seat children in the rear and airbags were mandatory – found that children in rear seats were at a significant disadvantage in rear impact crashes, having a 61% higher risk of fatal injury than children in front seats [28]. Recent studies of real-world crash databases such as the National Automotive Sampling System (NASS) / Crashworthiness Data System (CDS) and the Fatality Analysis Reporting System (FARS) show that, after controlling for occupant age and gender, the relative risk of death for restrained rear row occupants is significantly higher than that of front seat occupants in rear impact crashes [29].

Seatbelt Use

Findings are somewhat mixed regarding whether seatbelts have a protective effect in rear impacts. According to early rear impact sled test results, a three-point belt system has no significant effect on dummy response [30]. However, computational models from the same study revealed that the seatbelt played a greater role when varying the friction between the occupant and seat-back, representative of varying seat covering materials. At high delta-v and low seatback friction, the occupant response tends to ramp up along the seat back, but seatbelt use limits this motion, presumably decreasing injury risk [30, 31]. More recent results of studies focusing on real-world crash data from NASS-CDS, NASS-General Estimates System (GES), and FARS have suggested that seatbelt use lowers the risk for severe injury in rear crashes [12, 32, 33]. That being said, numerous observational studies have reported that seat belt use in rear seating positions is consistently lower than in the front seats [34]. This may be due in part to the lack of mandatory rear seat belt reminders and the lack of enforcement for seat belt laws in the rear seats [35]. Of course, if a seat belt is not being worn, any protective effects it may have had are diminished.

Ejection

Ejection significantly increases the risk of severe injury for rear-struck light vehicle occupants [36]. Ejections from the rear seat are rare. For unbelted rear-struck occupants, the risk for complete ejection is approximately 3%, and for belted occupants it is a mere 0.003%. Vehicle yaw motion after the primary impact is often the catalyst for rear-struck occupant ejection when it does occur.

Occupant Compartment Intrusion

Studies focusing on adult, front-seat occupants of passenger cars, have shown that intrusion plays a substantial role in determining injury risk [32, 37]. Another study specifically examining second row children found that 68% of serious-to-fatal injuries sustained in rear impacts were associated with intrusion of at least 30 cm (12 in) into the occupant seating area [38]. Another study on children involved in crashes encompassing all directions of impact (i.e. frontal, side, and rear) found that the odds of at least one abbreviated injury scale (AIS) 2+ or AIS3+ injury increased on average by 2.9% or 4.0%, respectively, for each additional centimeter of intrusion to the occupant seating area when adjusting for age, restraint use, seating row, and direction of impact [39].

Seatback Support

The National Highway Traffic Safety Administration (NHTSA) opened a rulemaking docket in the early 1990s seeking comment on the design of automobile seats and their performance in rear impacts. This prompted a wave of research on optimal seatback stiffness and strength to minimize occupant injury in rear-impact crashes. However, nearly thirty years later, the debate on appropriate seatback stiffness has yet to be resolved, with numerous conflicting research findings [40].

The first argument is that there is no statistically significant relationship between seatback stiffness or strength and the risk of serious/fatal injury in rear-impact crashes. One study coming to this conclusion was based on real-world, police-reported crash data from a selection of states [41]. Seatback stiffness and strength data was collected independently by the lab through dynamic testing for 29 unique seatback designs used in 40 total vehicle models, though these values for stiffness and strength were never published. Another study indicated that several metrics of seatback behavior, such as quasi-static ultimate force, are poor predictors of anthropometric test device (ATD) neck loading, though for severe rear crashes there does seem to be an “optimum” range of seatback stiffness which is in the mid-range of commercially available seatback stiffnesses [42].

Almost all research on the topic would agree that there is an optimal seatback stiffness where seatbacks yield in a controlled manner if rapidly loaded, such as by an occupant in a rear-impact [43]. These research efforts are largely founded on the hypothesis that there is a relationship between seatback stiffness or strength and the risk of serious/fatal injury in rear-impact crashes. The consensus is that yielding seats result in better injury outcomes than stiff seats. Legislative history of seatback design standards also dictates that yielding seats have historically been considered a better approach than rigid seats [44]. Results of ATD head and chest accelerations from Federal Motor Vehicle Safety Standard (FMVSS) 301-type rear impact tests indicate low risks of injury to the head, neck, and chest in yielding seats over multiple test configurations, such as full engagement and offset tests [45]. However, all tests were run with either Hybrid II or III dummies, which were not designed for rear impact tests and are not biofidelic in this mode. Further, because these risk findings were not compared to ATD responses in stiff seats for the same suite of rear-impact tests, no conclusions can be drawn on any potential differences. That being said, a similar study with matched yielding and stiff seats and matching occupant size and weight found that ATD responses from rear impact tests showed that yielding seats provide a higher degree of safety for small to large adult occupants in rear crashes [46].

Real-world crash studies have also found that yielding seats offer improved occupant protection during rear-impact collisions. A number of studies using FARS and NASS-CDS found that, for a specific OEM’s yielding seat design, the odds for fatality were lower in rear-impacted vehicles equipped with the yielding seats [47-49]. An older study of NASS-CDS data similarly showed that yielding seats offer improved protection to occupants in rear impacts over stiffer seats [50]. When using societal harm as a metric for safety benefit, deformation associated with seatback yield was also shown to be beneficial, though it is difficult to conclusively tell if the studied seatback deformation was a direct result of the crash event or if the deformation occurred post-crash, such as by EMS personnel or damage incurred during vehicle towing and storage [31].

Another study found that severe injury risk for front-seat rear-struck occupants was lower with a reclined seatback in crashes when the delta-v exceeded 48 km/h (30 mph) [32]. Specifically, the risk of severe injury was 3.8-times greater when the seatback was non-rotated, or not reclined. At lower impact speeds of 32-48 km/h (20-30 mph), non-rotated seats similarly yielded higher rates of injury, though the disparity with rotated seats was not as pronounced. So while this study did not specifically look at yielding versus rigid seats, it did show that being rear-impacted in a more reclined position, a position similar to what would be produced by a yielding seat, may have contributed to a lower severe injury risk for front-seated occupants in rear impacts.

Throughout the body of work on seatback strength, many studies have suggested that seatback design should not be the only factor considered when studying injury in rear-impacts, but other crash factors, such as impact offset, delta-v, or striking vehicle over- or under-ride, may play an important role as well. A study on traumatic thorax injuries resulting from rear impacts found that, when these other factors are present, an occupant's head, neck, and/or upper body may displace off the side or top of the seatback, becoming unsupported, even when an occupant is lap-shoulder belted [51]. This motion prompts extension of the spine around the seatback frame often resulting in fracture-dislocation of the spine, potentially with spinal cord injury resulting in paraplegia. This phenomenon has been seen both in real-world crashes and in ATD responses [51, 52]. While this does suggest that occupants may be at risk for serious injury when the strength of the seat exceeds the extension tolerance of the spine and their head, neck, and/or upper body become unsupported, seatback strength may not be the only solution to explore. A more prudent solution may be to consider ways in which an occupant may be kept in a proper seating position throughout the rear-impact crash event so that the risk for spinal extension in minimized rather than reevaluate current seatback strengths.

Unfortunately, NHTSA terminated the rulemaking proceedings for seating systems in 2004 without publishing any conclusive findings and simply stating that additional research and data analyses would be needed before taking further action. Research has continued in this area, but comprehensive rear impact protection standards have yet to be formulated.

Injury in Frontal Impacts

The performance of rear seat occupant restraint systems in frontal impacts has not been studied as widely as front seat occupant restraints. In the few studies based on real-world crash data such as NASS that have probed into rear seat restraint performance, it has generally been found that for adult occupants, especially those over 50-55 years, the publicly perceived ‘protective effect’ of the rear seat decreases with increasing occupant age [4, 9, 10, 13]. For restrained, rear seated adults, the most commonly injured body region tends to be the thorax and the source of injury is the seatbelt itself [12]. This is indication that the seatbelt technology currently being implemented in front seats, such as load limiters, may not have been carried into the rear seating restraint systems.

The argument has become that the advances in front seat safety systems have been so great, that they now significantly outpace those safety systems provided in the rear seats, making the front seat substantially safer for adult occupants in newer vehicles. Indeed, a few studies have found that the relative effectiveness of rear versus front seat restraint systems for adults is diminished in newer model year vehicles compared to older models [10, 11, 13, 53]. Bilston et al. adopted a matched-cohort approach on NASS-CDS data from years 1993-2007 [11]. They evaluated the relative risk (RR) of AIS3+ injury in restrained front and rear seat occupants and found that the RR was significantly influenced by occupant age and vehicle model year. The study concluded that for children aged 9-15, the rear seat carried a lower risk of injury. However, for adults aged 16-50 years, in ‘newer’ vehicles (model year 1997-2007), the rear seat carried a higher risk of injury (RR = 1.98, CI = 1.90-2.06). Finally, for older adults over the age of 50, the rear seat carried a higher risk of injury. Together, these results suggest that, for vehicle occupants over the age of 15, the front seat is safer than the rear seat. This study did not however report on RRs across each crash mode, so no conclusions were made pertaining specifically to a frontal impact direction.

Durbin et al. also used NASS-CDS data in combination with FARS data from years 2007-2012 to determine the risk of AIS3+ injury and fatality for restrained rear row occupants [29]. The analysis used traditional logistic regression modeling and was limited to model year 2000 and newer vehicles. In calculating the RR of injury and fatality for rear versus front seats, front seat occupants were limited to passengers only (i.e. the front right seating position). The argument for this methodology was that the front passenger position environment is more directly comparable to the rear seat environment due to the lack of a steering wheel/column. When not discerning by crash mode, the RR of death was lower for restrained children up to 8 years old in the rear compared with passengers in the right front seat but was higher for 9-12 year old children. There was no difference in the RR of death in the rear versus front seat for adult occupants aged 13-54. While not statistically significant, there appeared to be a trend for an increased RR of death for older adults aged 55 and over in the rear versus passengers in the right front seat (RR = 1.41, CI = 0.94-2.13). In newer vehicles (model year 2007 and newer), after controlling for occupant age and gender, the RR of death for restrained rear row occupants was significantly higher than that of front seat occupants. However, when investigating RR by impact direction, there was no significant difference in the RR of fatal injury for rear versus front seats in frontal crashes (RR = 0.96, CI = 0.75-1.23).

Mitchell et al. used the same matched-cohort analysis methods as Bilston et al. but on a different dataset [54]. This study looked at crashes involving injured rear versus front seat car passengers identified in linked police reports, hospitalization records, and emergency department records in New South Wales, Australia from years 2001-2011. Odds ratios (OR) were estimated using logistic mixed models. The study found that rear seat occupants are sustaining injuries of a higher severity compared to front seat occupants traveling in the same vehicle (OR = 1.10, CI = 1.01-1.21). This study did not report on the overall difference in injury ORs of the rear versus front seat across crash modes, so no conclusions were presented solely on a frontal impact crash direction.

Injury in Side Impacts

The injury risk for rear occupants in side crashes has been discussed in past literature, largely with an emphasis on the risk to children, as they are the most common age demographic seated in the rear. For occupants of all ages in side impacts, previous literature makes clear that those occupants seated on the near-side of impact are at highest risk of serious injury [55], usually to the head and/or torso. These injuries often result from impacts with the intruding side structure [56-59]. However, in more recent years, side airbags appear to benefit occupants in side crashes, though the focus of many research efforts on this topic have been specifically on front seat occupants [60, 61]. When focusing exclusively on rear seated adults, the fatality risk was highest in side and rear crashes, and the risk for serious injury was also highest in side crashes [12].

Today, the side impact crash mode is one of the only crash modes that is regulated in both the front and rear seats. Consequently, side impact countermeasures such as side airbags have greatly penetrated the vehicle fleet. Since many of these past studies were published prior to the implementation of the FMVSS 214 pole test, it is worth revisiting how injury risks in this crash mode have changed and how they differ between seating positions.

LIMITATIONS OF PREVIOUS STUDIES

Many of the aforementioned studies examined only a limited set of crash and occupant factors in their analyses of injury risk, which could stand to be supplemented for the most robust results possible. Further, many studies suggest that the difference in injury risk between the front and rear seats will likely be increasingly exaggerated in more recent model year vehicles. The issue of relative rear seat safety has not been thoroughly investigated within the last decade, so the ‘most recent’ model year vehicles are not adequately represented in current literature. Finally, while many studies present injury risks and relative risks, injury mechanisms to rear-seated occupants are not always clear and warrant further investigation.

RESEARCH OBJECTIVES

The aim of this dissertation is to address the current injury risk to rear seated occupants in passenger vehicles across multiple crash modes. As rear-end crashes are the most common crash mode on U.S. roadways today, this impact configuration will be emphasized. Furthermore, this dissertation will identify crash factors influential to rear seat occupant injury risk and explore how the injury risk to rear seated occupants compares to that of front seat occupants. Finally, this dissertation will project how the increasing presence and effectiveness of forward collision avoidance systems (FCAS) may further influence rear-end crash and injury outcome. To address these topics, the following research objectives will be met:

1. Characterize the population of rear seat occupants involved in passenger vehicle crashes in the United States vehicle fleet.

2. Investigate the characteristics of serious-to-fatal rear crashes, and identify the underlying crash features that may lead to serious or fatal injury for occupants seated in rear-impacted vehicles.
3. Determine the injury risk to rear seated occupants in frontal impacts, and quantify the difference in injury risk for rear versus front seated occupants.
4. Evaluate the injury risk to rear seated occupants in side impacts, both vehicle-to-vehicle and vehicle-to-object, and compare the difference in injury risk for rear versus front seated occupants in both near- and far-side impact configurations.
5. Forecast the number of rear-seated occupant injuries that would be prevented if a rear seat belt reminder system were to be deployed throughout the future U.S. vehicle fleet.

The overall goal of this dissertation will be to provide a better understanding of the current state of rear seat occupant safety, especially how it relates to that of front seat occupants. This knowledge can benefit automakers who seek to improve the overall effectiveness of crash countermeasures that serve rear seat occupants, as well as regulatory agencies who may seek to improve tests targeted at bolstering rear seat occupant safety.

2. DATA SOURCES

The overall approach of this thesis is to use real world crash data to characterize the injury outcomes of rear seated occupants in passenger vehicles. Specifically, the research utilizes a set of U.S. nationally-representative crash databases. This chapter provides an overview of those data sources referenced in this thesis.

THE NATIONAL AUTOMOTIVE SAMPLING SYSTEM (NASS)

The National Automotive Sampling System (NASS) was a crash data collection program conducted by the National Highway Traffic Safety Administration (NHTSA). NASS is a nationally representative system which estimates both crash occurrence and injury outcomes from a clustered, stratified, and weighted sample of police accident reports (PARs). The weight assigned to each NASS case represents the number of police-reported crashes that occurred in the U.S. that year that are similar to the selected case [62]. For many decades, NASS has been the basis for both crash safety research and U.S. national traffic safety policy and regulation. NASS is made up of two separate databases – the General Estimates System and the Crashworthiness Data System.

NASS General Estimates System (NASS-GES)

Data in NASS-GES are available from years 1988 to 2015 and come from a sample of all police-reported crashes [63, 64]. These crashes involve all vehicle types and range in severity from fatal to property damage only crashes. The only additional criteria for case selection is that the crash must have involved at least one vehicle traveling on a public traffic way. Cases were collected from Primary Sampling Units (PSUs), of which there are 60 in different geographic regions. These regions were chosen to provide a representative sample of national geography. Each year, approximately 50,000 PARs were sampled from the PSUs and coded into NASS-GES. However, other than data recoded in the selected PARs, no additional information is collected regarding each crash. The result is a database containing a wide variety of crash cases but with limited detail on accident, vehicle, and occupant characteristics. Due to its diverse sample, the NASS-GES data are ideally used for assessing the national exposure to traffic crashes and for studies for which in-depth data is unavailable, e.g., for vulnerable road users [65, 66].

In 2016, NHTSA replaced NASS-GES with the Crash Report Sampling System (CRSS). Among other changes, CRSS uses a different set of PSUs to better reflect the geographic population distribution changes that have occurred since the creation of GES. Because GES and CRSS use different sampling locations, the data from these two systems cannot readily be combined. Because to date very little CRSS data is available, this thesis will use GES rather than CRSS.

NASS Crashworthiness Data System (NASS-CDS)

Data in NASS-CDS are available from years 1979 to 2015 and come from a sample of police-reported crashes involving passenger vehicles (cars, light trucks, and vans) in which at least one involved vehicle was towed from the crash scene [64]. The selection scheme oversamples crashes with more serious outcomes and late model year vehicles. However, despite not being a random sample of PARs, the case weighting ultimately yields a nationally representative sample. The PARs collected were obtained from 24 of the 60 PSUs used by NASS-GES. Each year, approximately 4,000 PARs are sampled, investigated, and coded into NASS-CDS. In contrast to GES, CDS contains much more detailed information on accident, vehicle, and occupant characteristics. Highly trained field crash investigators collected data from crash sites, the physical vehicles involved, interviews with involved crash occupants, and medical records of any injured occupants. Due to its more detailed data, especially on occupant injury outcomes, the NASS-CDS data are ideal for assessing the crash performance and both active and passive vehicle safety systems of passenger vehicles [67-70].

NHTSA is also in the process of retiring NASS-CDS, instead building the Crash Investigation Sampling System (CISS). In the future, CISS will similarly collect detailed crash data on a representative sample of crashes involving at least one passenger vehicle which was towed from the scene. Pilot CISS data for case year 2016 is currently available.

<u>Event Data Recorders (EDRs)</u>

NASS-CDS investigators collect Event Data Recorder (EDR) data when possible. EDRs are similar to the “black boxes” in airplanes. Although not required by the FMVSS, most new passenger vehicles are equipped with EDR modules which, in the event of a crash, record precrash data (e.g. brake and accelerator input, vehicle speed), change in velocity (delta-V), and restraint information (e.g. seatbelt use and airbag deployment status), among others [71].

Since model year 2012, cars and light trucks equipped with EDRs must meet the minimum requirements prescribed in 49 CFR Part 563 [72]. Because EDRs directly measure vehicle impact speed and delta-V, these devices can provide substantially more accurate records of crash severity than can traditional crash reconstruction techniques. In crash tests using highly instrumented vehicles, the delta-V recorded by EDRs have been shown to be within 6-7% of the delta-V measured by laboratory grade accelerometers [73-75].

Abbreviated Injury Scale (AIS)

In NASS-CDS, injury severity was coded using the Abbreviated Injury Scale (AIS) [76]. The AIS is a scoring system for ranking injury severity according to its relative threat to life. The AIS classifies individual injures by body region on a six point ordinal scale as shown in Table 1.

Table 1. AIS Injury Severity Ranking

AIS Code	Severity
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6	Maximal (currently untreatable)

An example of an AIS1 injury would be a shallow bruise or laceration, whereas an AIS6 injury – which are typically fatal – would be an aortic rupture. NASS/CDS codes an AIS score for each injury experienced by an occupant.

When occupants have multiple AIS scores, it is useful to have some single metric to classify each occupant's overall injury severity. One common approach is to record the overall injury severity experienced by an occupant with the maximum AIS value incurred in the crash [77]. This is the approach used in this thesis. In the following thesis, the acronym MAIS 'X' +F, indicates MAIS 'X' injury or greater, including fatality because of crash injuries. Most studies will look at either moderate-to-fatal (MAIS2+F) or serious-to-fatal (MAIS3+F) injuries.

Another method of handling multiple injuries is the Injury Severity Score (ISS) [78]. The ISS is calculated by summing the squares of the three greatest AIS scores in three different body regions, i.e. the head/neck, face, thorax, abdomen/pelvic contents, extremities/pelvic girdle, and external, as shown in Equation 1. AIS scores of 6 are excluded from this calculation. In some research studies, this is another useful metric to classify and compare occupant injury severities.

$$ISS = \sum_{i=1}^{3} [max(AIS)^2]_{Body\ Region\ i} \quad \text{Equation 1}$$

In all subsequent analyses of this dissertation, fatally injured occupants are included in the ‘injured’ occupant population. However, the identification of fatally injured occupants cannot be done by looking at AIS/MAIS alone. In order to accurately identify fatally injured occupants in CDS, the NASS/CDS variable TREATMNT code for treatment and mortality can be used. In subsequent analyses, all occupants who are coded as having fatal mortality are included in the injured occupant population regardless of their MAIS. This excludes those few fatalities that are identified as being due to disease rather than the crash. An example of this would be an elderly occupant who died as the result of suffering multiple AIS 2 severity injuries. This occupant would be included in a count of MAIS3+F injuries despite having received no higher than an AIS 2 injury.

FATALITY ANALYSIS REPORTING SYSTEM (FARS)

FARS is a national census of motor vehicle crashes yielding fatality and contains data from years 1975 to 2017 [79]. A traffic crash fatality is considered to be any death that occurs within 30 days of a crash and is attributable to an injury sustained during the crash. Like GES, FARS data consists of the information provided in the PAR with a few additional details, though not as comprehensive as CDS. The resulting database is of course ideal for studying crashes with fatal outcomes, though the lack of detail makes identification of injury mechanisms difficult. However, having absolute fatality counts from FARS is invaluable to automotive injury research and greatly supplements the data collected by NASS, as GES and CDS have been known to underestimate fatal injury outcomes.

3. CHARACTERISTICS OF CRASH-INVOLVED REAR SEATED OCCUPANTS IN THE U.S.

BACKGROUND

This dissertation will examine rear seat occupants and their injury outcomes in a variety of crash modes. When considering a specific occupant population in passenger vehicle crashes, such as those who were rear seated, it is important to first understand what is ‘typical’ of that group across all crash types. Especially when comparisons were made, such as between rear and front seated occupants, it is vital to know if these differences exist when collectively considering all passenger vehicle crashes or if disparities were unique to a particular crash mode. This overarching view of the rear seat occupant population in the U.S. vehicle fleet will inform hypothesis and assumptions made in subsequent chapters of this work.

OBJECTIVE

This chapter seeks to determine the characteristics which may influence the risk of injury and/or fatality in crashes involving rear-seated occupants in the United States and how these characteristics may differ from the front seat occupant population. To achieve this objective, the study will identify the crash conditions, types of vehicles, and occupants which were typical of crashes of all severity, serious-to-fatal injury severity, and fatal injury severity. These characteristics will be evaluated in the context of all rear-seated occupants as well as all front-seated occupants so that comparisons may be made between the two occupant populations. This approach will allow for an understanding of characteristics unique to serious injury and fatality outcomes crashes, as compared to characteristics of all crashes, as well as characteristics that may be significantly different between the rear- and front-seated occupant populations.

METHODOLOGY

This study was based upon real world crashes extracted from NASS-GES case years 2011-2015, NASS-CDS case years 2006-2015, and FARS case years 2011-2015. In order to be included in the dataset, occupants from these databases were required to be traveling in a passenger vehicle of model year 2000 or newer and have a front or rear (second through fifth row) seating position. For this study, all occupants with a known row position were included for analysis. The final dataset of occupants was divided into those who were front and rear seated. All crashes and vehicles containing occupants selected based on these criteria were included for crash- and vehicle-level analysis. However, these characteristics were based on the number of crashes or vehicles as opposed to the number of occupants involved. Hence, crashes that involved multiple occupants were only included once in the analysis of crash and vehicle characteristics.

These selected data were used to complete analyses of the similarities and differences between crash, vehicle, and occupant characteristics across a range of injury levels. Comparisons were also made between the rear- and front-seated occupant populations. All GES cases were used to represent occupant crash exposure, or occupants involved in crashes at all injury levels, from those who were uninjured to fatally injured. CDS cases were selected to represent seriously injured occupants, which was defined as an occupant who sustained any serious-to-fatal injury on the AIS (MAIS3+F). Each year, the number of seriously injured occupants sampled in CDS was relatively low. To achieve a reasonable sample size for subsequent statistical analyses, the case year inclusion criteria for CDS was expanded in comparison to GES and FARS. Finally, FARS case occupants were only included for analysis if they were among the fatally injured. In all analyses, occupants were excluded if the variable of interest was missing or otherwise unknown.

Certain demographics of interest, such as occupant height and weight, were not available in GES and only available for select occupants in FARS. Therefore, CDS was used exclusively to define the 'exposed,' 'seriously injured,' and 'fatal' occupant populations for these analyses. All occupants in CDS were included to define 'exposed' occupants regardless of MAIS. Seriously injured occupants remain those sustaining a MAIS3+F injury, and fatal occupants were identified by their mortality.

Finally, the severity of the injuries sustained by all rear-seated study occupants were further quantified for select characteristics of interest by using the AIS injury data in CDS. Estimates of absolute rear-seat MAIS3+F injury risk with corresponding 95% confidence intervals were calculated. Here, the risk of serious injury was defined as

$$Risk\ of\ MAIS3F\ Injury = \frac{\#\ MAIS3F\ Injured\ Occupants}{\#\ of\ Occupants\ Exposed\ to\ Crashes} \qquad \text{Equation 2}$$

where both the number of MAIS3+F injured and all exposed occupant counts came from weighted totals of CDS cases.

RESULTS AND DISCUSSION

Dataset Composition

The number of occupants in this study dataset are presented in Table 2. In all crashes from GES (exposed) during the 2011-2015 time period of study, 12.0% of all vehicle occupants were rear seated. Looking at GES and FARS data from the past decade in Figure 1 reveals that the percentage of rear seated occupants, both those crash-exposed and those fatally injured, has been relatively stable over time. Based on GES exposure and FARS fatality counts from 2011-2015, of the rear seated occupants in this study only 0.11% were fatally injured. By comparison, 0.14% of their front seat counterparts were fatally injured. The estimated 31,424 (469 observed) rear seated occupants selected as seriously injured (MAIS3+F) for subsequent analyses accounted for 8.7% of all occupants with serious-to-fatal injuries in CDS over the last decade. Among rear seated occupants in this dataset, the absolute risk of serious-to-fatal injury was 0.5%, which was slightly lower than the 0.7% risk of injury for front seat occupants.

Table 2. Occupants in selected study cases, observed count (estimated count).

	Rear	**Front**
Exposed	55,825 (6,214,486)	395,349 (46,613,681)
Seriously Injured	469 (31,424)	4,118 (329,214)
Fatally Injured	6,888 (NA)	64,930 (NA)

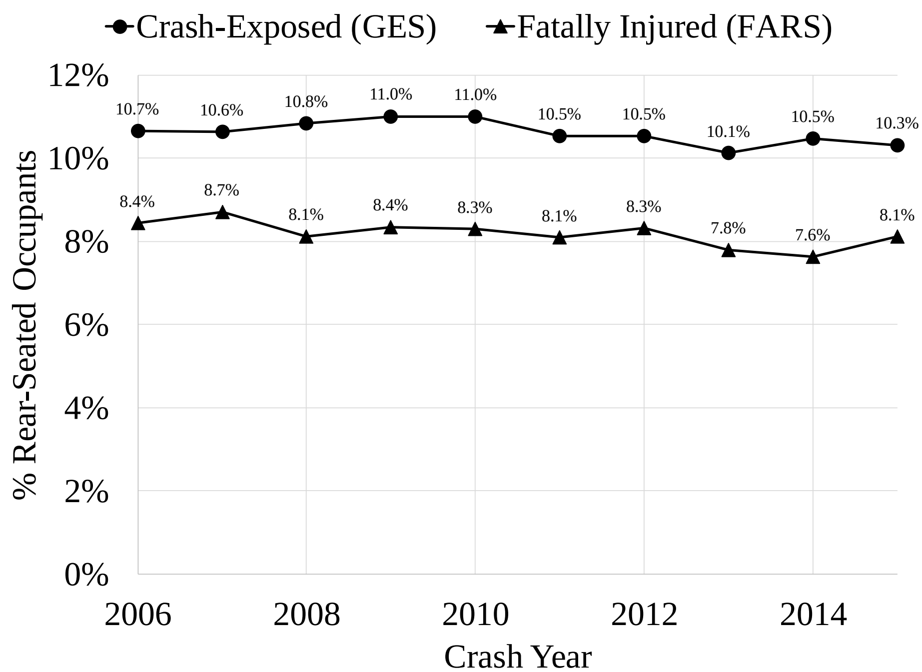


Figure 1. Distribution of occupants who are rear-seated and crash-exposed (from GES) and fatally injured (from FARS) by crash year.

Crash Types

The 'manner of collision' of a crash describes the orientation of the motor vehicles involved in the crash when the first harmful (damage and/or injury inducing event) occurs. As shown in Figure 2, the highest percentage of crashes involving rear-seated occupants were rear-end collisions (44.1%), though this crash mode only accounted for 9.4% of the seriously injured and 11.0% of the fatally injured rear seat occupant population. This shows that rear-seated occupants were under-represented in injury outcomes in rear-end crashes, which suggests this crash mode carries a decreased risk of injury compared to other crash types. Indeed, as shown in Table 3, rear-end collisions carry the lowest risk of MAIS3+F injury in the event of a crash to rear-seated occupants at 0.5%.

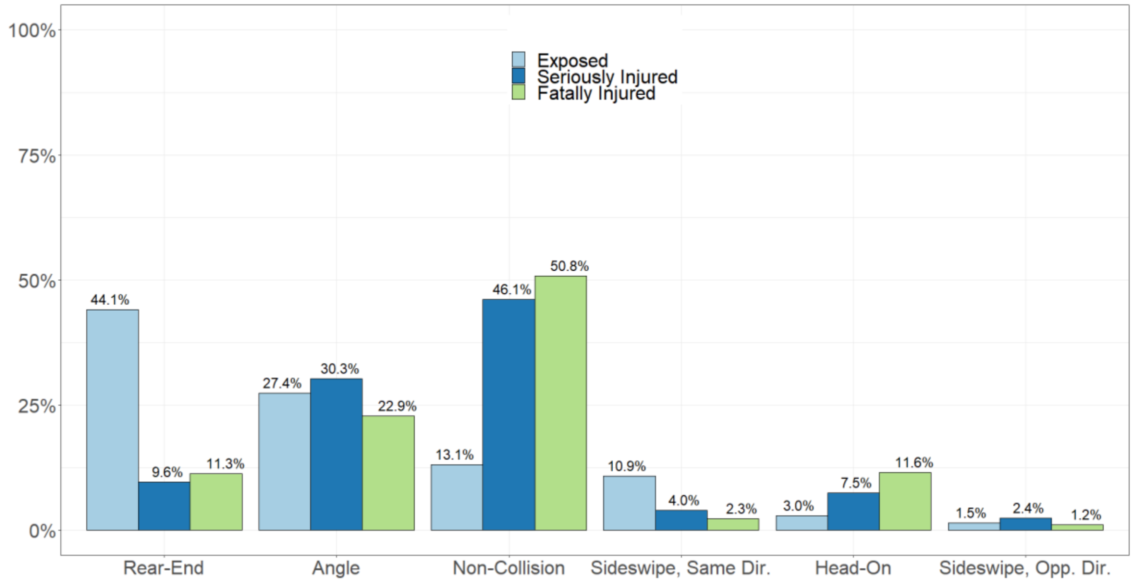


Figure 2. Manner of collision distribution of crashes involving rear-seated occupants.

Table 3. Absolute risk of MAIS3+F injury by manner of collision.

	Absolute Risk of MAIS3+F Injury (95% CI)	
Manner of Collision	**Rear**	**Front**
Rear-End	0.5% (0.0-1.0)	0.6% (0.4-0.9)
Angle	1.0% (0.3-1.6)	1.3% (0.9-1.7)
Non-Collision	2.8% (1.5-4.0)	3.3% (2.4-4.3)
Sideswipe, Same Dir.	1.5% (0.0-3.3)	1.0% (0.6-1.5)
Head-On	2.7% (0.0-5.6)	7.2% (3.6-10.9)
Sideswipe, Opp. Dir.	1.6% (0.5-2.7)	4.0% (2.6-5.5)

In contrast, non-collision, or single-vehicle, crashes accounted for the highest proportion of seriously and fatally injured rear seat occupants (46.1% and 50.8%, respectively) while making up a relatively small proportion of total crash exposure (13.1%). These types of crashes include single-vehicle events that tend to be high severity, such as crashes into fixed objects and rollovers, so it was not unreasonable that this crash mode may carry a higher risk of injury to rear-seated occupants than other modes. The other manner of collision where rear-seated occupants were over-represented in serious and fatal injury outcomes were head-on crashes.

The trends seen in the rear seat occupant population were consistent with what was observed in the front seat occupant population, whose manner of collision distribution is shown in Figure 3. When comparing the distributions of those occupants who were seriously and fatally injured between the rear and front seats, it can be seen that rear-seated occupants were more frequently injured in rear-end, angle, and same direction sideswipe crashes than their front seat counterparts.

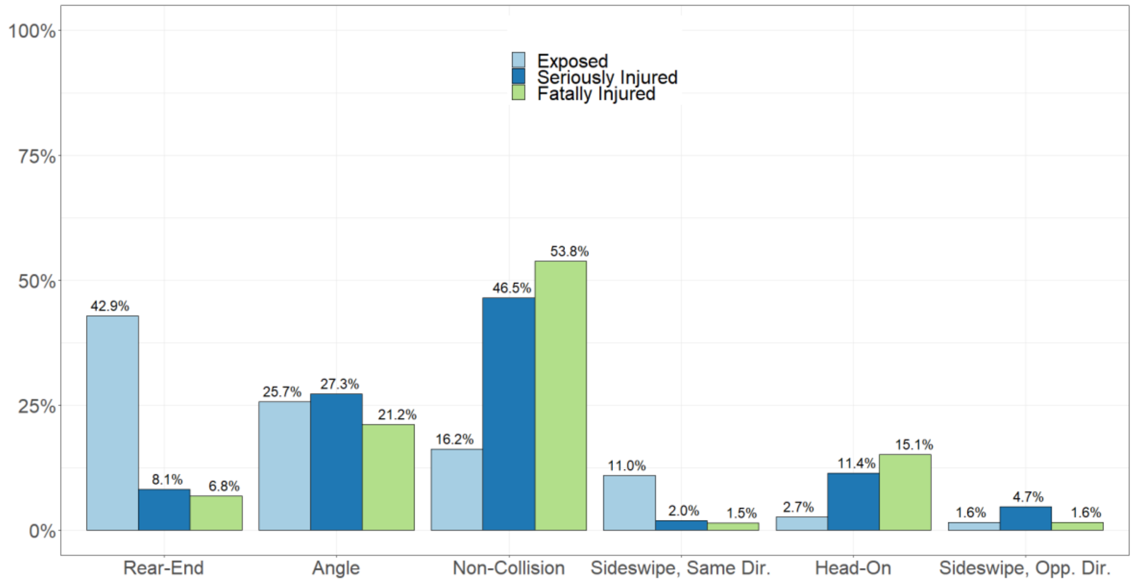


Figure 3. Manner of collision distribution of crashes involving front-seated occupants.

Vehicle Characteristics

The percentage of crash-involved vehicles containing rear-seated occupants by body type is shown in Figure 4. Cars include traditional automobiles, while the LTV category stands for ‘light trucks and vans,’ which includes SUVs, minivans, and pickup trucks. Crash-involved rear-seated occupants were equally likely to be seated in either a car or LTV (50.3% and 49.7%, respectively), although the serious injury incidence in the rear-seated occupant population was slightly lower in cars than LTVs (44.1% vs. 55.9%). The absolute risk of MAIS3+F injury to a rear-seated occupant, while higher on average in LTVs, was not statistically different than that in cars as shown in Table 4. However, fatally injured rear-seated occupants were more likely to be seated in a car at the time of the crash (55.7%).

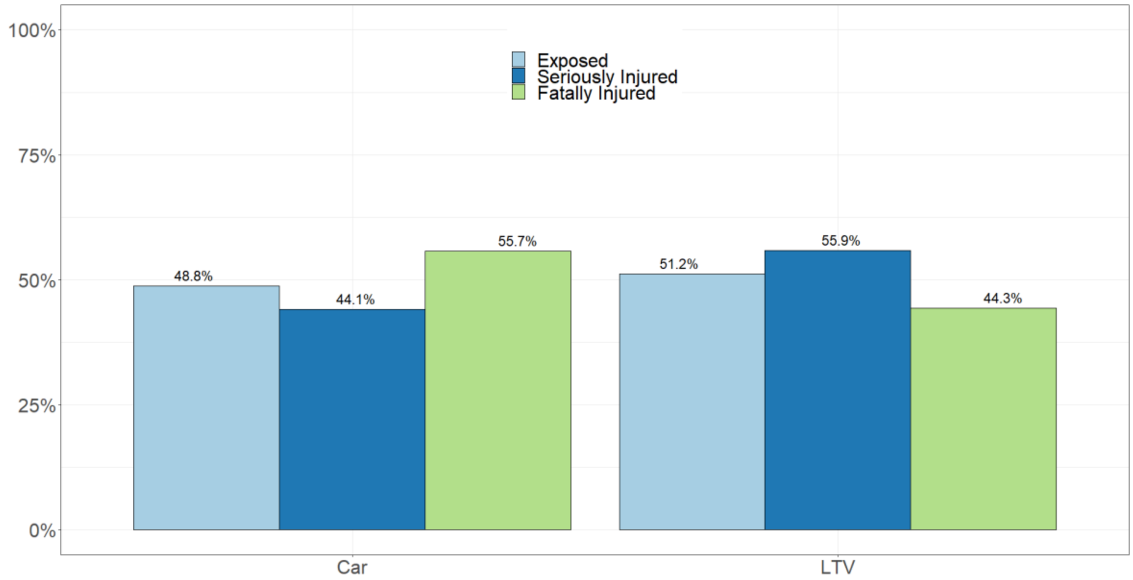


Figure 4. Body type distribution of passenger vehicles involved in crashes with rear-seated occupants.

Table 4. Absolute risk of MAIS3+F injury by vehicle body type.

	Absolute Risk of MAIS3+F Injury (95% CI)	
Vehicle Body Type	**Rear**	**Front**
Car	1.0% (0.6-1.4)	1.9% (1.4-2.3)
LTV	1.7% (0.9-2.4)	1.9% (1.2-2.5)

In contrast, crash-involved front-seated occupants were less likely to be traveling in an LTV (42.2%) as shown in Figure 5. This may be expected as LTVs were larger and tend to have room for more occupants than cars, so it follows that more rear-seated occupants may have been traveling in LTVs. Looking at the average number of occupants traveling in each vehicle type in the CDS dataset, as shown in Figure 6, confirms that SUVs and minivans have higher occupancy rates on average than passenger cars. The crash-exposed front-seated occupants who sustained serious injuries were further under-represented in LTVs (36.5%), though the risk of MAIS3+F injury was not statistically different for front-seated occupants between cars and LTVs.

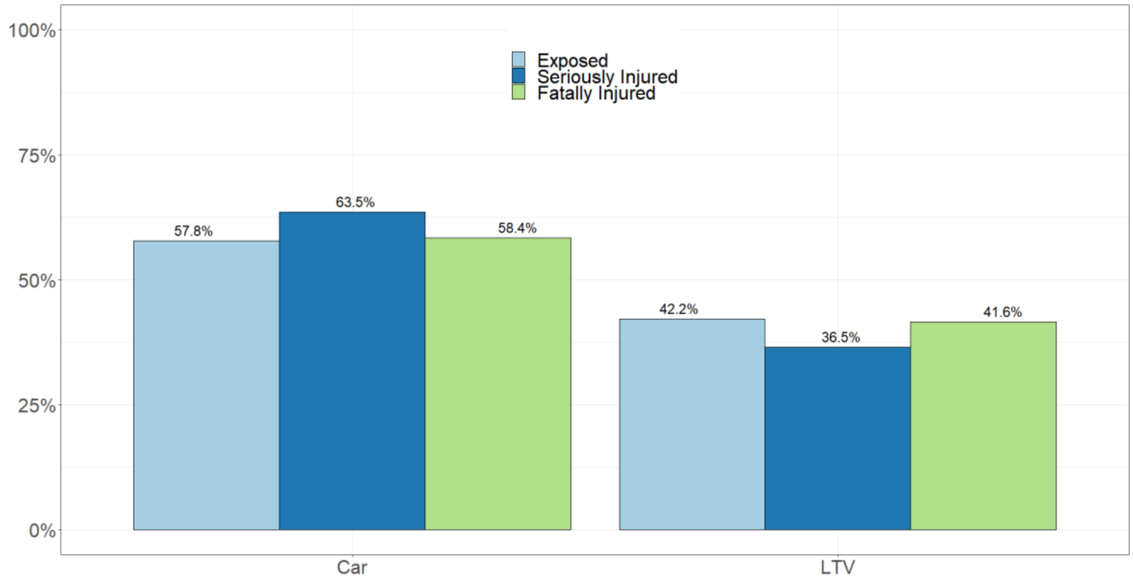


Figure 5. Body type distribution of passenger vehicles involved in crashes with front-seated occupants.

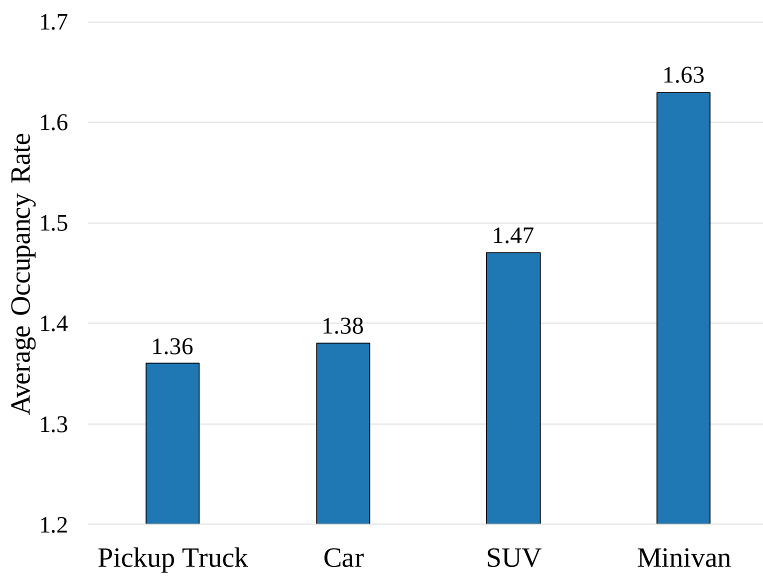


Figure 6. Average passenger vehicle occupancy rate by vehicle body type.

There was evidence that rear-seated occupants were traveling in passenger vehicles of comparable vehicle model years to the front seat occupant population. Figure 7 shows the cumulative distribution of vehicle model year for rear- and front-seated occupants, and Table 5 provides the mean and median vehicle model years for each occupant population of interest. The median vehicle model year for both rear- and front-seated occupants was 2007, and the average model year for front seated-occupants was 2006. The mean and median vehicle model years were older for both the rear and front seat occupant populations when considering serious and fatal injury outcomes, suggesting that occupants were more frequently injured in older vehicles, likely due to the lack of more current safety system advances.

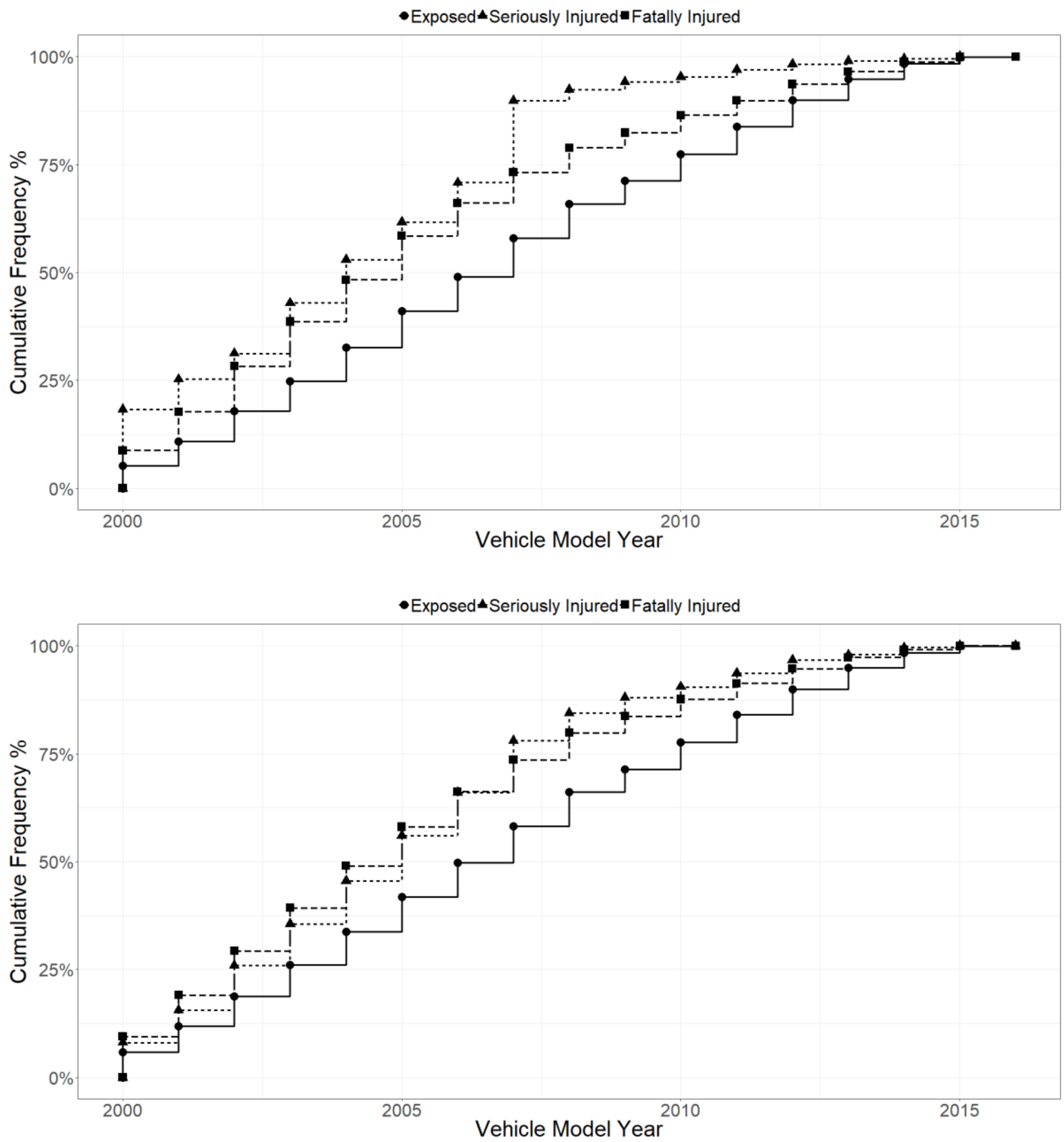
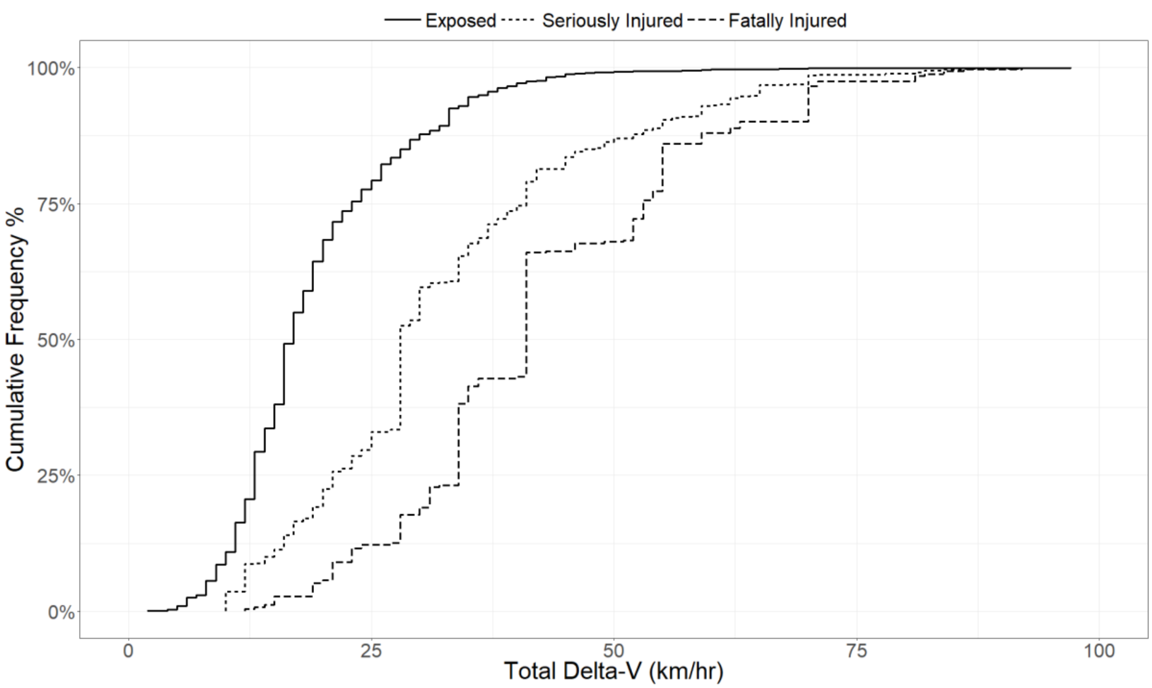


Figure 7. Cumulative distribution of vehicle model year for rear-seated (top) and front-seated (bottom) occupants.

Table 5. Mean and median vehicle model year for rear- and front-seated occupants.

	Mean Vehicle Model Year		Median Vehicle Model Year	
	Rear	**Front**	**Rear**	**Front**
Exposed	2007	2006	2007	2007
Seriously Injured	2004	2005	2004	2005
Fatally Injured	2005	2005	2005	2005

The crashed vehicle's delta-v, a measure of crash severity, was compared between crash-exposed rear- and front-seated occupants. A lower delta-v indicates a lower crash severity. Figure 8 shows the cumulative distribution of total delta-v in km/hr for rear- and front-seated occupants, and Table 6 provides the mean and median delta-v for each distribution. The trends in delta-v between rear- and front-seated occupants suggest that rear-seated occupants are exposed to crashes at slightly lower delta-v's than front-seated occupants (17 vs. 18 km/hr). Rear-seated occupants were also seriously and fatally injured at lower delta-v's than front-seated occupants.



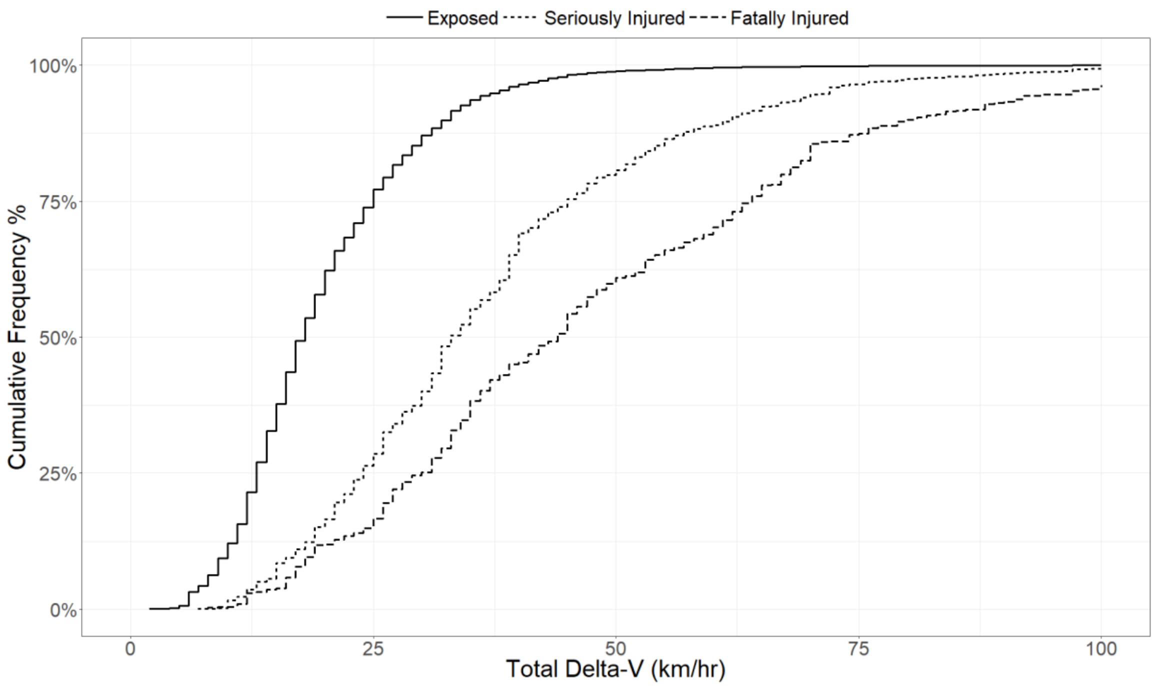


Figure 8. Cumulative distribution of total, or resultant, delta-v (km/hr) for rear-seated (top) and front-seated (bottom) occupants.

Table 6. Mean and median total, or resultant, delta-v (km/hr) for rear- and front-seated occupants.

	Mean Delta-V (km/hr)		Median Delta-V (km/hr)	
	Rear	**Front**	**Rear**	**Front**
Exposed	17	18	17	18
Seriously Injured	28	33	28	33
Fatally Injured	41	44	41	44

Occupant Demographics

While front-seated occupants can either be only a driver or front right seat passenger, rear-seated occupants can be seated at any of several seated locations. Each rear seating position can be categorized by both row, e.g. 2nd, 3rd, etc., and seat side, e.g. left, middle, or right. As shown in Figure 9, the overwhelming majority (93.8%) of crash-exposed rear-seated occupants were seated in the 2nd row of the passenger vehicle. This was partially because most passenger cars only have two seating rows.

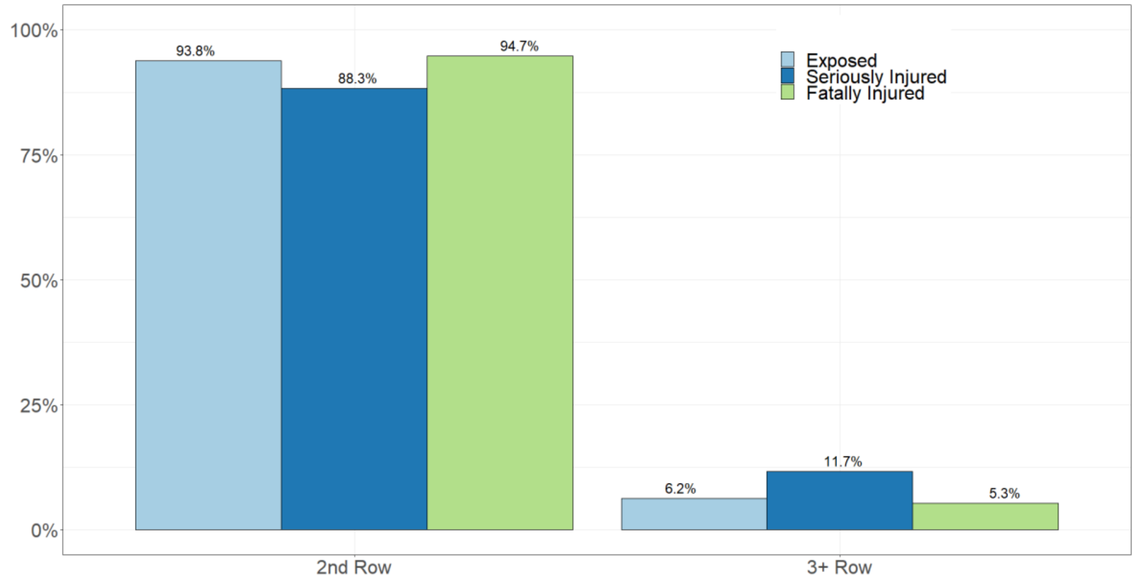


Figure 9. Rear row distribution of crash-involved rear-seated occupants.

As shown in Figure 10, most rear-seated occupants were seated in the right position (47.5%). Serious and fatal injury outcomes were relatively consistent with exposure trends. There was little to no difference in risk between the left, middle, and right rear row positions. The risks presented in Table 7 further verify that there was no significant difference in absolute injury risk between rear seat row or side.

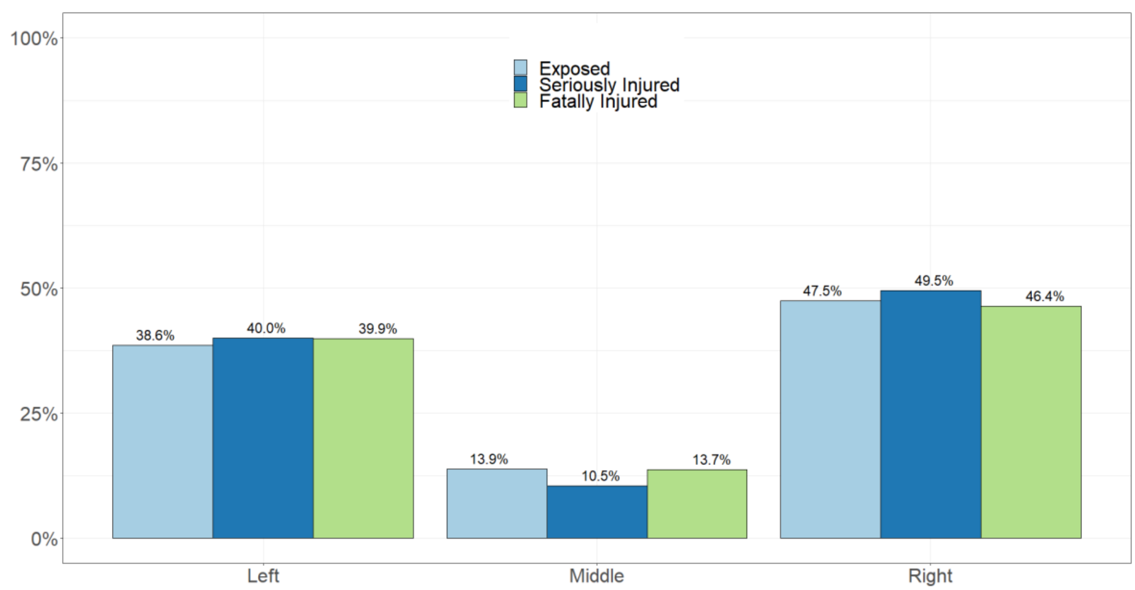


Figure 10. Rear seat side distribution of crash-involved rear-seated occupants.

Table 7. Absolute risk of MAIS3+F injury in the rear seats by seat row and vehicle side.

	Absolute Risk of MAIS3+F Injury (95% CI)
Seat Row	
2nd Row	1.2% (0.8-1.6)
3+ Row	2.8% (0.0-5.9)
Seat Side	
Left	1.3% (0.7-1.9)
Middle	1.0% (0.4-1.7)
Right	1.3% (0.8-1.8)

As shown in Figure 11, a majority (55.2%) of rear seated crash exposed occupants were children younger than 13 years of age. This was very different from front seat occupants, whose age distribution is shown in Figure 12, where a mere 1.5% were children. This was not surprising as NHTSA currently recommends that children under the age of 12 should always be seated in the back, especially if they use a CRS. While children were the most common seriously and fatally injured rear seat occupants, young adults aged 20-30 make up the largest proportion of seriously and fatally injured front seat occupants.

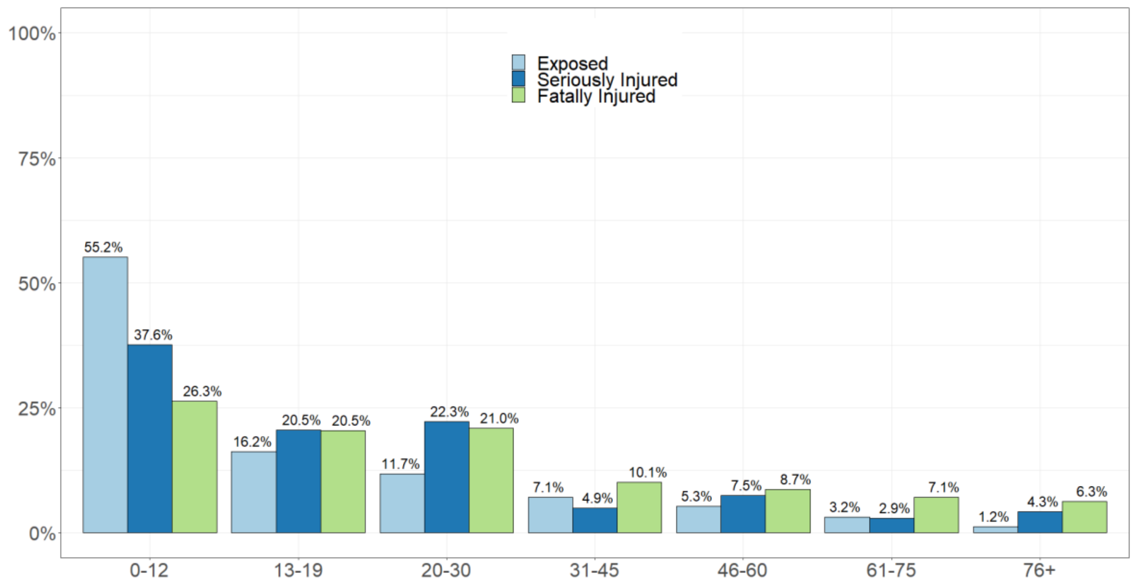


Figure 11. Age distribution of crash-involved rear seated occupants.

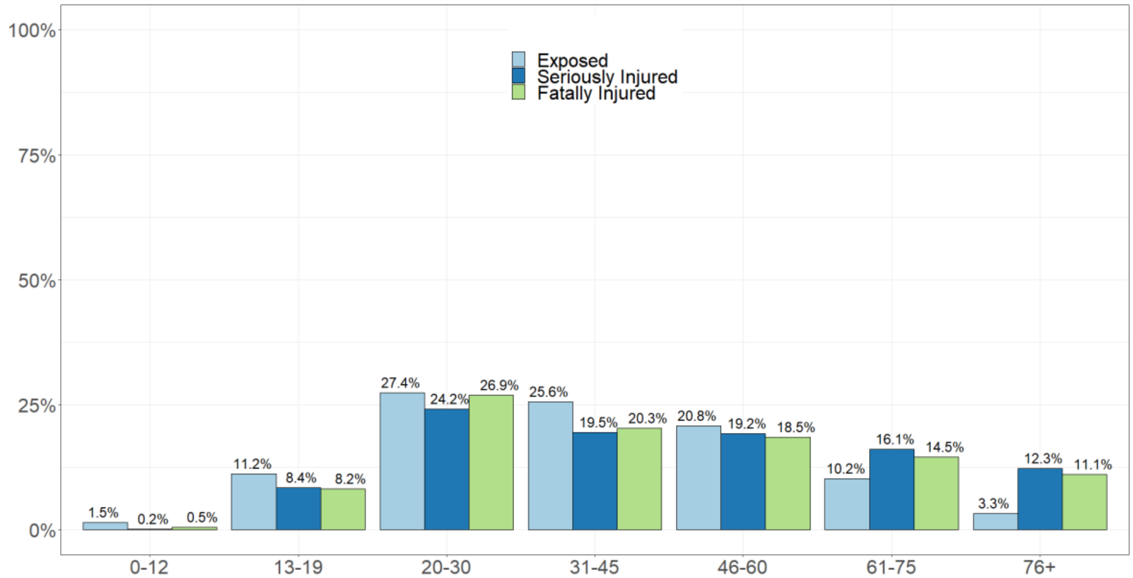


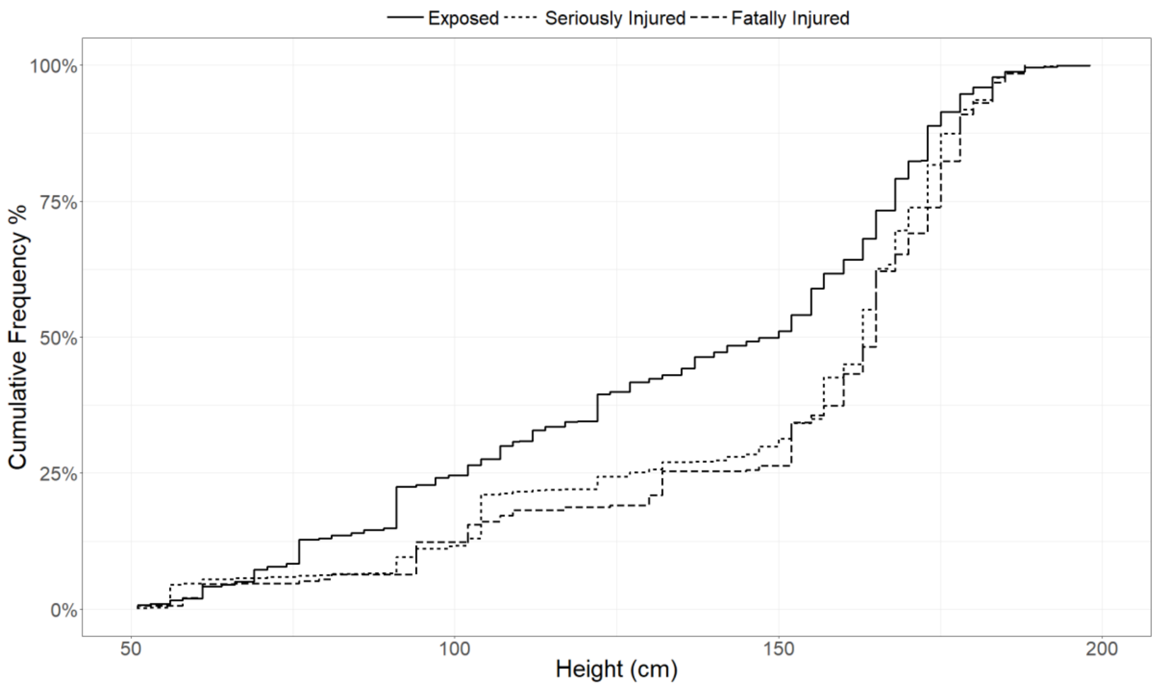
Figure 12. Age distribution of crash-involved front seated occupants.

Although adolescents account for most of the exposed rear seat occupant population, they make up a smaller proportion (37.6%) of the injured rear seat occupants populations, and a much smaller proportion (26.3%) of the fatally injured population. For all other older age groups, there were a higher percentage of rear seated occupants who were seriously and/or fatally injured than the percentage of people in the same age group exposed to a crash. This shows that these age groups are over-represented among injured and fatally injured rear row occupants, beginning as early as age 13. In contrast, when looking at the age distribution of front seat occupants, this over-representation of injury and fatality outcomes does not clearly begin until much later at occupant ages of 61 and over. The trend in both the rear- and front-seated occupant distributions that older occupants become increasingly over-represented in injury outcome was consistent with prior research showing that older occupants were at greater risk of injury and fatality compared to younger occupants [29, 80, 81]. This finding is further supported by the absolute injury risks presented in Table 8 where the risk tends to increase for both rear- and front-seated occupants with increasing occupant age.

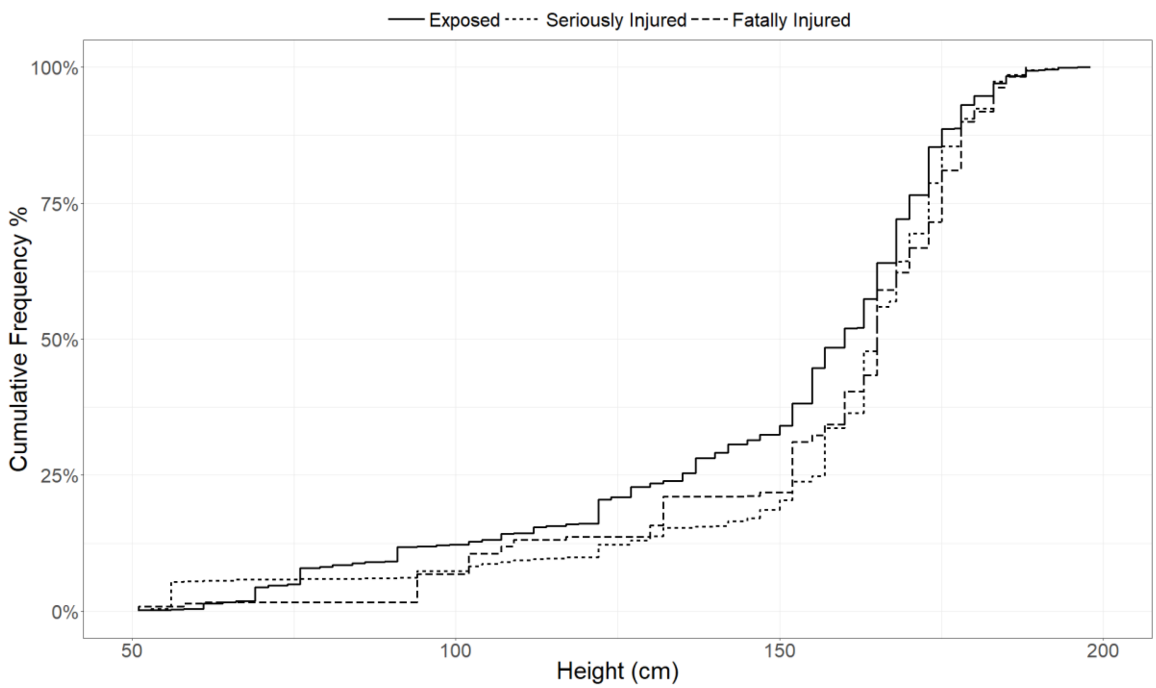
Table 8. Absolute risk of MAIS3+F injury by occupant age.

Occupant Age	Absolute Risk of MAIS3+F Injury (95% CI)	
	Rear	**Front**
0-12	0.9% (0.3-1.5)	0.3% (0.1-0.5)
13-19	1.3% (0.6-2.1)	1.4% (0.8-1.9)
20-30	2.5% (1.2-3.7)	1.4% (0.9-1.8)
31-45	1.4% (0.4-2.4)	1.6% (1.2-2.1)
46-60	3.4% (1.4-5.4)	2.0% (1.5-2.5)
61-75	2.9% (0.8-5.0)	3.4% (2.3-4.4)
76+	7.1% (0.8-13.4)	6.5% (4.0-9.1)

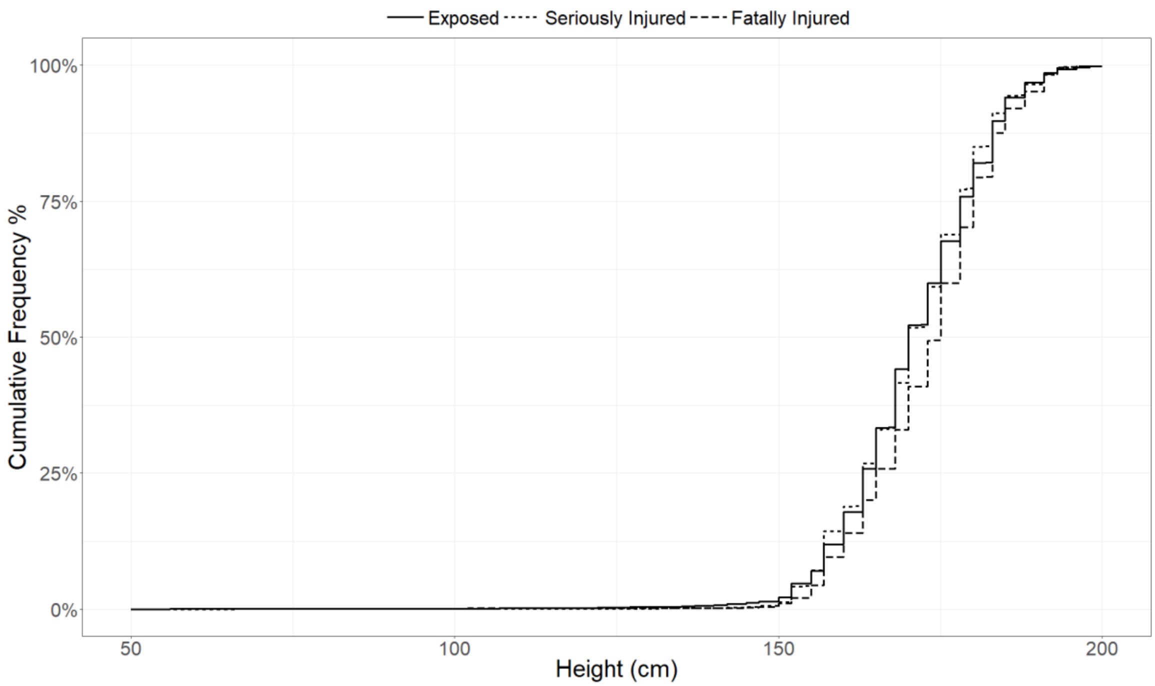
With such great differences in average age between the rear and front seat crash involved occupant populations, it was expected that occupant size may vary drastically as well. Figure 13 and shows the cumulative distribution of occupant height and weight, respectively, for all rear-seated occupants, rear-seated occupants who were not seated in a CRS, and all front-seated occupants. The mean height and weight of each occupant population is shown in Table 9 and Table 10, respectively. Overall, rear seat occupants were indeed smaller than their front seat counterparts in both height and weight. It was interesting to note that the average size in both height and weight of non-CRS restrained rear seat occupants was greater than the 5th percentile female Hybrid III ATD (59 inches tall and 108 lbs), which was the dummy most commonly used when evaluating rear seating positions in crash tests. Seeing that those injured were even larger than the exposed population further suggests that the challenge in rear seat occupant protection may not necessarily be small individuals. That being said, the average rear seat height and weight presented here were still smaller than the 50th percentile male Hybrid III (69 inches tall and 172 lbs).


Exposed
Seriously Injured
Fatally Injured
Cumulative Frequency %
100%
75%
50%
25%
0%
50
100
150
200
Height (cm)

(a)


Exposed
Seriously Injured
Fatally Injured
Cumulative Frequency %
100%
75%
50%
25%
0%
50
100
150
200
Height (cm)

(b)

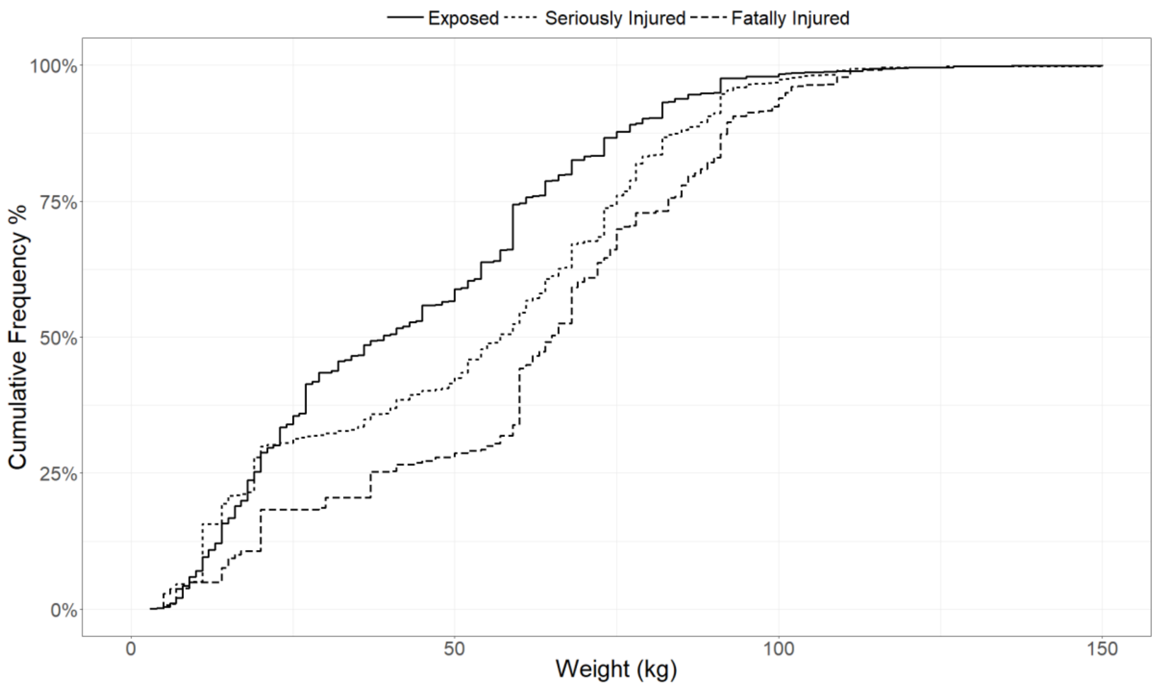


(c)

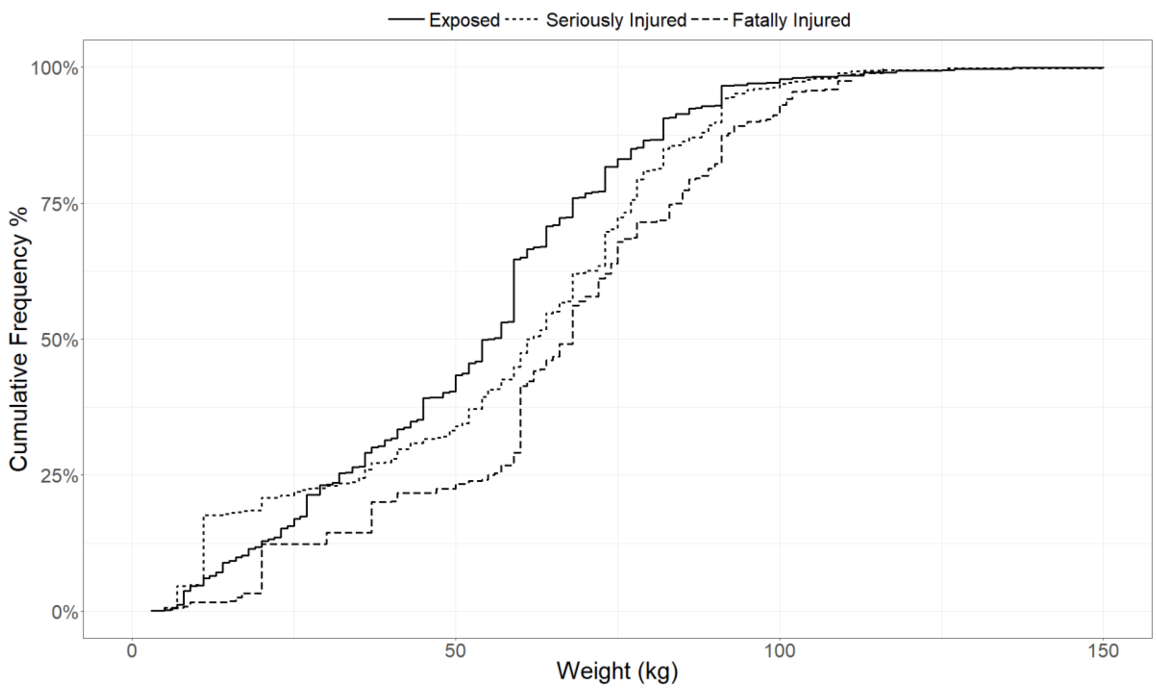
Figure 13. Cumulative distribution of occupant height (cm) for all rear-seated occupants (a, top), non-CRS-restrained rear-seated occupants (b, middle), and front-seated occupants (c, bottom).

Table 9. Mean reported height of crash-involved occupants.

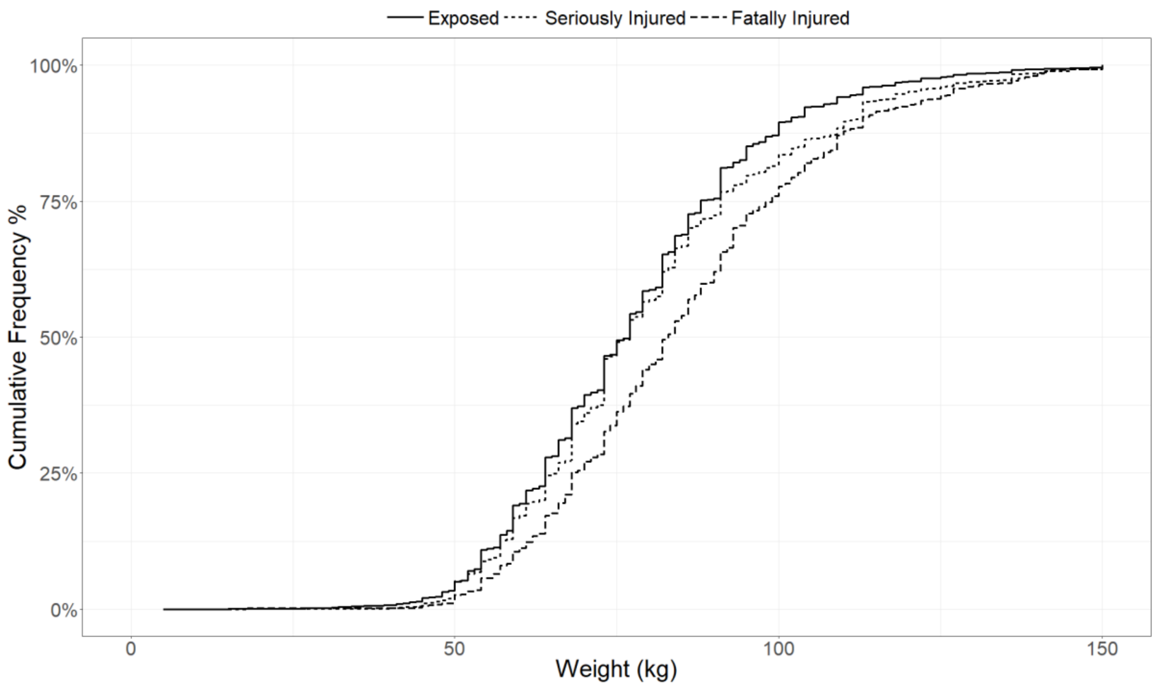
	Mean Height in cm (in)		
	Rear (All)	Rear (no CRS)	Front
Exposed	150 (59)	160 (63)	170 (67)
Seriously Injured	163 (64)	165 (65)	170 (67)
Fatally Injured	165 (65)	165 (65)	175 (69)


Exposed
Seriously Injured
Fatally Injured
Cumulative Frequency %
100%
75%
50%
25%
0%
0
50
100
150
Weight (kg)

(a)


Exposed
Seriously Injured
Fatally Injured
Cumulative Frequency %
100%
75%
50%
25%
0%
0
50
100
150
Weight (kg)

(b)



(c)

Figure 14. Cumulative distribution of occupant weight (kg) for for all rear-seated occupants (a, top), non-CRS-restrained rear-seated occupants (b, middle), and front-seated occupants (c, bottom).

Table 10. Mean reported weight of crash-involved occupants.

	Mean Weight in kg (lbs)		
	Rear	**Rear (no CRS)**	**Front**
Exposed	39 (86)	55 (121)	77 (170)
Seriously Injured	57 (126)	61 (134)	77 (170)
Fatally Injured	65 (143)	68 (150)	83 (183)

As shown in Figure 15, rear seated crash exposed occupants were only slightly more likely to be female (51.7%), and the distribution of injury and fatality outcomes were similar. As seen in Figure 16, front row crash exposed occupants were evenly split between males and females. In contrast to the rear seat occupant population, front seated men were far over-represented in fatality outcomes. However, the absolute risk of MAIS3+F injury for both rear- and front-seated occupants was consistent among the sexes, as evidenced by the risks presented in Table 11.

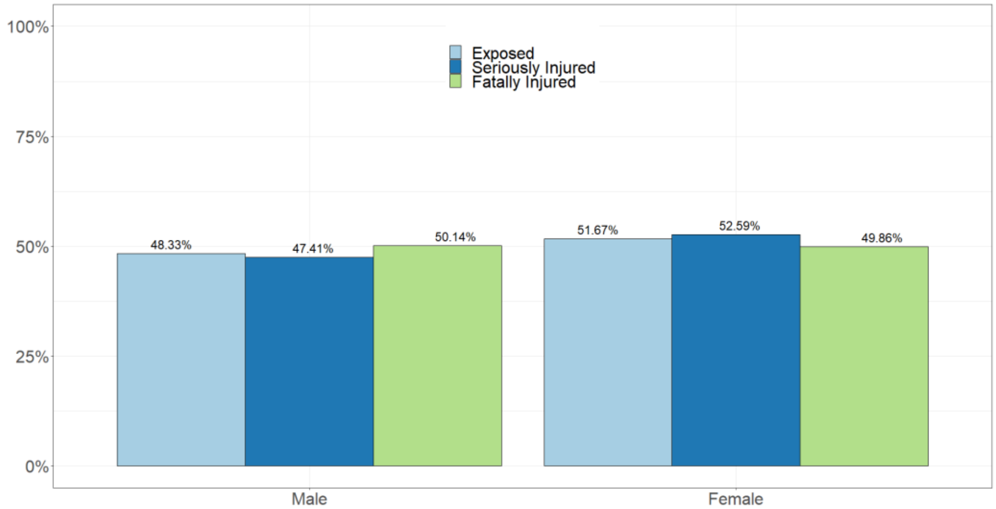


Figure 15. Sex distribution of crash-involved rear seated occupants.

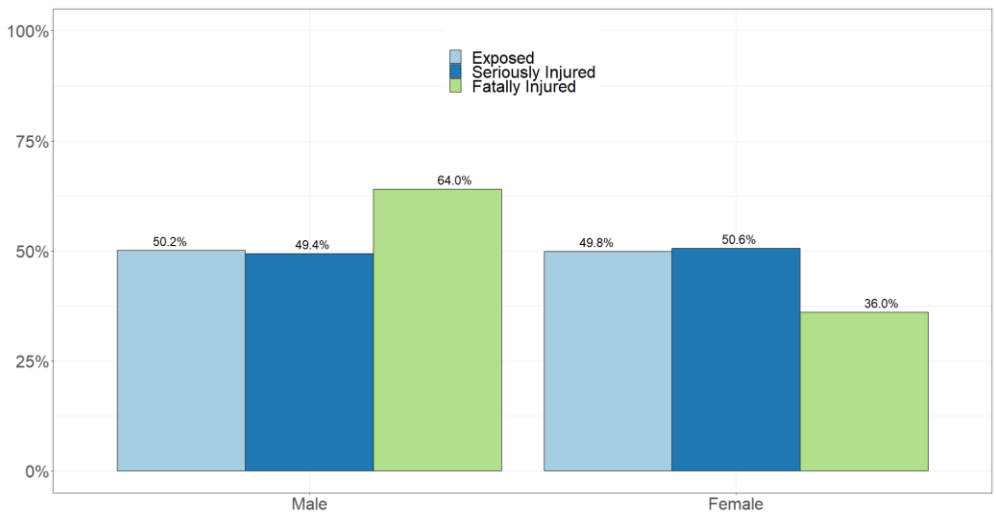


Figure 16. Sex distribution of crash-involved front seated occupants.

Table 11. Absolute risk of MAIS3+F injury by occupant sex.

	Absolute Risk of MAIS3+F Injury (95% CI)	
Occupant Sex	**Rear**	**Front**
Male	1.3% (0.8-1.9)	1.9% (1.3-2.4)
Female	1.3% (0.8-1.8)	1.8% (1.4-2.4)

The distribution of restraint usage is shown in Figure 17 and Figure 18 for rear and front seat occupants, respectively. Children seated in a child restraint system (CRS) were shown individually from adult occupants using a standard seatbelt. While a third of all rear seated crash exposed occupants were restrained in a CRS, their use was very rare in the front seats. When considering belted adults and CRS-restrained adolescents together as the restrained occupant population, rear seat occupants were restrained at a slightly lower rate than front seat occupants (96.8% and 98.6% belt use rate, respectively). In both occupant populations, those who sustained injury or fatality had much lower rates of seatbelt usage and were at substantially higher risks of serious injury and fatality. However, over half of rear seat occupants who were seriously-to-fatally injured were unrestrained (68.1% and 57.2%, respectively), as opposed to front seat occupants who were seriously-to-fatally injured and unrestrained less frequently (39.3% and 45.2%, respectively). As shown in Table 12, the absolute MAIS3+F injury risk for both rear- and front-seated occupants was significantly greater for unbelted occupants than for those who were restrained. Efforts to increase restraint use in the rear seat should be prioritized, including the addition of seat belt reminders to the rear seating positions.

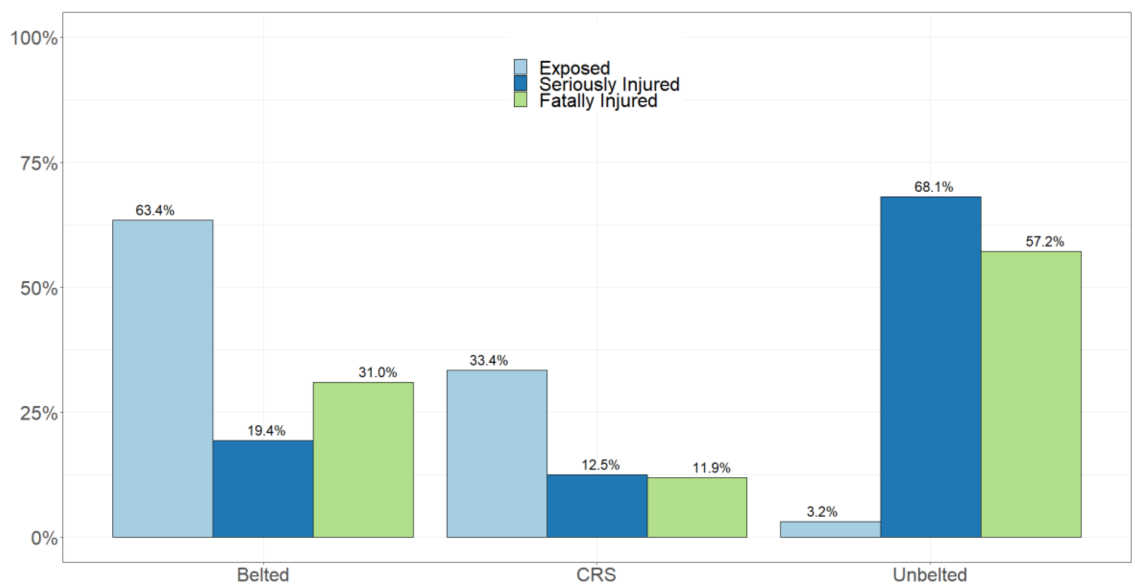


Figure 17. Restraint system use rates of crash-involved rear seated occupants.

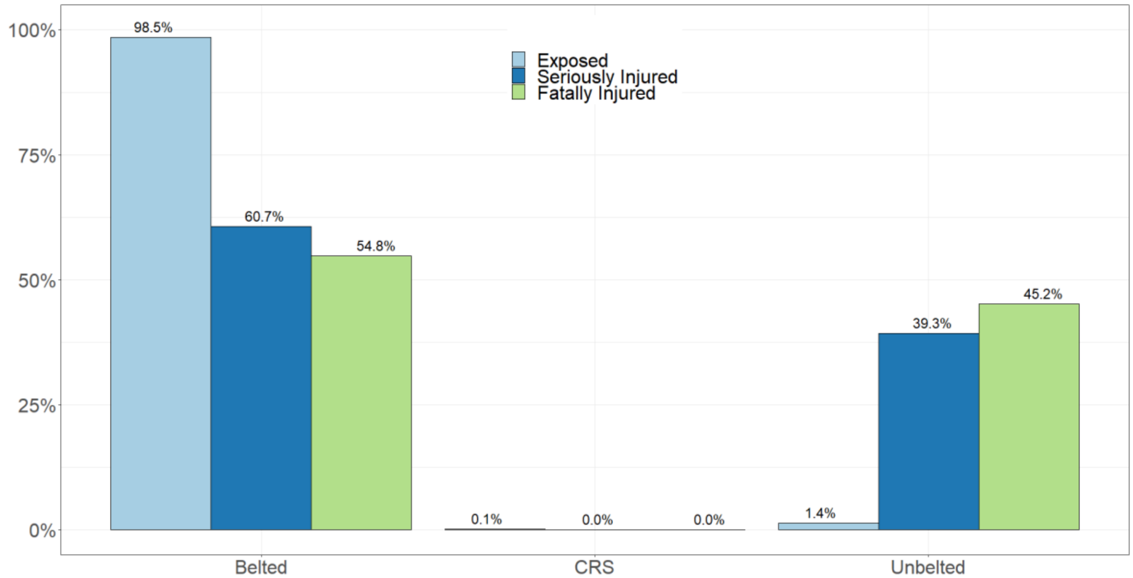


Figure 18. Restraint system use rates of crash-involved front seated occupants.

Table 12. Absolute risk of MAIS3+F injury by restraint use.

	Absolute Risk of MAIS3+F Injury (95% CI)	
Occupant Sex	**Rear**	**Front**
Belted	0.5% (0.3-0.8)	1.5% (1.1-1.9)
CRS	0.7% (0.0-1.4)	-
Unbelted	5.5% (3.1-7.9)	7.4% (5.3-9.6)

Figure 17 suggests that CRS use is associated with decreased injury and fatality risk, as those rates are overall lower than total crash exposure. This finding is consistent with prior research identifying CRSs as an effective means of preventing injury and fatality in the event of a crash [82-84]. NHTSA and the American Academy of Pediatrics (AAP) currently recommend that children aged 12 and below are restrained by an age- and size-appropriate CRS in the rear seats of passenger vehicles [85]. However, according to NHTSA reports in the mid-2000's, almost three-quarters (75%) of CRSs are being used incorrectly [86]. Further, compared with proper CRS use, inappropriate CRS use increases the risk of injury in the event of a crash, undermining the effectiveness of such a safety system [87]. While this collective work will not explicitly consider CRS misuse, it is important to note that within the CRS-restrained occupant populations studied herein, there is likely a sizeable portion who are incorrectly restrained, thus limiting the CRS safety benefit.

Today, there is only one type of seat belt commonly found in passenger vehicles – the three-point, or lap and shoulder, belt. However, in the past, two-point lap seat belts were common in the center rear seating position. In 2004, NHTSA issued a final rule requiring three-point seat belts for each rear seating position after lap belts were shown to cause certain injuries in the event of a crash. This new rule was included as part of FMVSS 208 and phase-in occurred between 2005 and 2007. Therefore, some vehicles in this study, which span back to model year 2000, may have been equipped with a lap belt only at the rear center seating position. Indeed, as shown in Figure 19, approximately 4% of all crash-exposed rear-seated occupants during the time period of study were wearing a lap belt only. Consistent with the motivation for requiring three-point belts, an increase in serious injury and fatality rates (11% and 6%, respectively) were seen for rear seated occupants wearing a lap belt only.

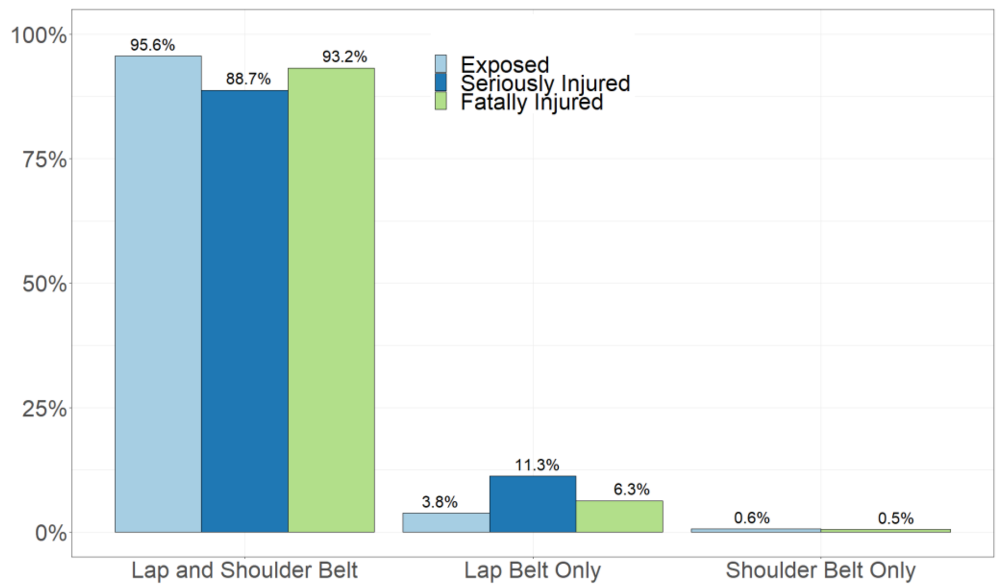


Figure 19. Seat belt type distribution of seat belt restrained rear seated occupants.

Although this study has primarily focused on seriously-to-fatally injured occupants, it was important to understand the complete injury severity distribution of all occupants, as only a select few in fact sustained serious-to-fatal injury. As shown in Figure 20, the majority of occupants in both the rear and front rows sustained no injury (MAIS 0) as a result of the crashes reported in CDS. However, there was a higher percentage of rear seat occupants who were uninjured than front seat occupants. Further, the incidence of serious-to-fatal injures for rear-seated occupants was less than that for front-seated occupants (1.5% and 2.3%, respectively).

Note that all fatally injured occupants were considered to be 'maximally' injured and thus were included in the MAIS6 category.

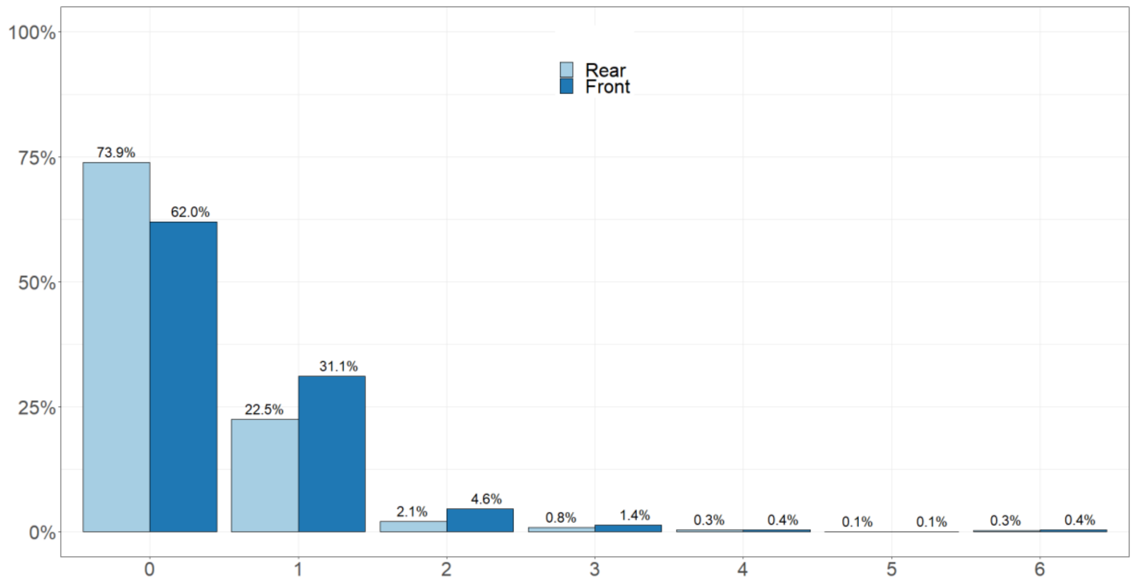


Figure 20. MAIS distribution of crash-involved rear and front seat occupants.

CONCLUSIONS

The conclusions of the analyses of the similarities and differences between crash, vehicle, and occupant characteristics across a range of injury levels and between rear and front seating positions were as follows:

1. During the 2011-2015 time period of study, 12.0% of all vehicle occupants were rear seated, and this rear seat occupancy rate has been relatively stable over time.

2. For both rear- and front-seated occupants, rear-end manner of collision crashes were the most frequent crash type (44.1% and 42.9%, respectively) and carries the lowest absolute MAIS3+F injury risk (0.5% and 0.6%, respectively).

3. Non-collision, or single-vehicle, crashes carry the greatest absolute risk of MAIS3+F injury for rear-seated occupants at 2.8%, followed closely by head-on crashes at 2.7%.

4. Crash-involved rear-seated occupants were traveling in cars and LTVs with approximately the same frequency. In contrast, crash-involved front-seated occupants were slightly more likely to be traveling in a car (57.8%). Absolute risk of MAIS3+F injury was the same for both rear- and front-seated occupants between vehicle body types.

5. Rear-seated occupants were traveling in vehicles comparable in model year to front-seated occupants. The mean and median model year of crash-involved vehicles containing rear-seated occupants was 2007, while the mean and median model year was 2006 and 2007, respectively, for crash-involved vehicles containing only front-seated occupants.

6. Rear-seated occupants may have been involved in lower severity crashes on average than all front-seated occupants. The mean total, or resultant, delta-v of crashes involving rear-seated occupants was 17 km/hr, while it was 18 km/hr for crashes involving only front-seated occupants.

7. An overwhelming majority (93.8%) of crash-involved rear-seated occupants were positioned in the 2nd row of a passenger vehicle. Further, there was a slight preference among rear-seated occupants for the right side seating position over the left side (47.5% vs. 38.6%). There was no significant difference in absolute MAIS3+F injury risk between rear rows or side seating position.

8. The majority of crash-involved rear-seated occupants were children between the ages of 0-12 (55.2%), while the most common age group of crash-involved front-seated occupants was 20-30 (27.4%).

9. For both rear- and front-seated occupants, absolute MAIS3+F injury risk increases with increasing occupant age.

10. Crash-involved rear-seated occupants were smaller on average than those who were front-seated. The 50th percentile height and weight of all rear-seated occupants were 150 cm and 39 kg, respectively. For front-seated occupants, the 50th percentile height and weight were 170 cm and 77 kg, respectively.

11. There was no significant difference in absolute MAIS3+F injury risk for either rear- or front-seated occupants based on sex. While crash-involved rear-seated men were exposed, seriously injured, and fatally injured at approximately the same rate as women, front-seated men make up a larger proportion of the fatally injured population than women (72.9%)

12. A third (33.4%) of crash-involved rear-seated occupants were restrained in a CRS while their use in the front seats was exceptionally rare per public safety recommendations (0.1%).

13. Both crash-involved rear- and front-seated occupants who were unbelted have a significantly greater absolute risk of MAIS3+F injury than their restrained counterparts (5.5% and 7.4% unbelted risk for rear and front seat, respectively).

14. Crash-involved rear-seated occupants were more likely to be uninjured than front-seated occupants (73.9% uninjured in the rear vs. 62.0% uninjured in the front). However, these absolute figures do not account for other factors such as crash mode, vehicle type, vehicle model year, or occupant demographics, all of which can affect overall injury risk. The chapters that follow will explore adjusted risks of injury in the rear seat by crash mode.

4. REAR IMPACTS AND INJURIES TO REAR SEATED OCCUPANTS

BACKGROUND

One of the most common crash modes on U.S. roadways are rear-end collisions. NHTSA has reported that approximately 2.1 million rear end crashes occurred in the US in 2015 [88]. Despite this large number of crash occurrences, rear impact crashes are often 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. A total of 757 (63%) 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?

FMVSS 301 and 305

Currently, there are two tests evaluating passenger vehicle crashworthiness in rear impacts. The first is the National Highway Traffic Safety Administration's (NHTSA) Federal Motor Vehicle Safety Standard (FMVSS) 301, Fuel System Integrity test [89]. In 2003 NHTSA issued a final rule to upgrade the 301 test, amending the prior standards in rear impacts. The motivation for such an upgrade was to reduce deaths and injuries occurring from post-crash fires that could result from fuel spillage during and/or after a crash event. FMVSS 301 previously required the entire rear of the subject vehicle to be hit by a 1,814 kg (4,000 lbs) moving rigid barrier at speeds up to 48 km/h (30 mph). The rear impact upgrade was to strike the rear of the subject vehicle at 80 km/h (50 mph) by a 1,368 kg (3,015 lbs) moving deformable barrier (MDB) at 70% overlap with the subject vehicle. These amended test conditions were designed to be more comparable with real-world crashes involving rear impact fires than the prior standards. Phase-in of this rear impact upgrade occurred during model years 2007 to 2009.

An analogous standard exists for electric vehicles – FMVSS 305, Electric-Powered Vehicles: Electrolyte Spillage and Electrical Shock Protection [90]. In this standard, the rear moving barrier impact test conditions are the same as applied in FMVSS 301, and they were therefore subject to the same 2003 upgrade. Instead of testing for a limitation of fuel spillage as in 301, 305 looks for electrolyte spillage, retention of propulsion batteries, and electrical isolation of the vehicle chassis from the high-voltage system during the crash event.

Although the FMVSS 301 and FMVSS 305 upgrades provide higher standards for evaluating the performance of vehicles in a rear impact condition, these standards are concerned primarily with preserving fuel and electrolyte system integrity during a rear impact crash event. The evaluation of occupant risk was not included as a criteria for these crash tests.

OBJECTIVE

The objective of this study is to investigate the characteristics of moderate-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.

METHODOLOGY

The data sources for this study were NASS-GES, NASS-CDS, and FARS. 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 later.
- 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 in which occupant seating positions were unknown 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 vehicles with 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 determine the effect that FMVSS 301 may have had on vehicle safety performance in the rear impact crash mode.

Our analysis classified injury severity by the MAIS injury sustained by an occupant. Depending on the analysis, either serious-to-fatal (MAIS3+F), moderate-to-fatal (MAIS2+F), or minor-to-fatal (MAIS1+F) injury cases were considered.

All analyses were performed in R and/or SAS v9.4 using NASS-GES and NASS-CDS sampling weights, unless otherwise noted.

Case Reviews

Evidence from the crash investigations and the injury data provided in CDS were used to determine what occurred during each crash where a serious-to-fatal (MAIS3+F) injury was sustained [91]. The evidence was reviewed to determine how each MAIS3+F injury could have been incurred. After thorough review, the most likely cause of injury, or injuries, was determined based on all the evidence provided on the crash and injuries. 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. While the results presented in this chapter discuss findings on a higher level, the details of each individual case review are provided in Appendix A.

Injury Model Development

The probability of both MAIS2+F and MAIS1+F injury in the studied rear-struck occupant population were estimated using logistic regression models. In this study, logistic regression was used to model the probability of both MAIS2+F and MAIS1+F injury as a function of EDR-reported delta-V, occupant age, occupant sex, and occupant seating row (front vs. rear). Occupant age, sex, and seating row were considered as binary, categorical variables. Age was classified as either 'young' (age 0-64) or 'elderly' (age 65+), where 'young' is considered to be the reference value. Sex was classified as either male or female, where female is considered to be the reference value. Finally, seat row was classified as either front (1st row) or rear (2nd or 3rd row), where rear is considered to be the reference value. These logistic regression models were constructed using the 'svyglm' function in the 'survey' package of R. The logistic models considered the stratified sampling scheme used by CDS. The logistic regression equation is shown in Equation 3.

$$Risk\ of\ Injury = \frac{1}{1 + e^{-(Intercept+\beta_{DeltaV}*DeltaV+\beta_{Elderly}*Elderly+\beta_{Male}*Male+\beta_{Front}*Front)}} \quad \text{Equation 3}$$

Odds ratios were calculated for each of the predictor variables in the logistic regression models in order to further parse out the influence of each parameter on injury outcome. The odds ratios were calculated using the logistic regression models in order to control for the other predictor variables. This method allows for the comparison of potential differences in the odds of injury for crashes of similar severity (delta-V) and other occupant characteristics.

RESULTS AND DISCUSSION

GES and FARS Dataset Composition

The composition of the GES and FARS datasets are presented in Table 13. The data were used to examine occupant deaths (FARS) in relation to total exposure (GES) in rear crashes. Data in Table 13 show that, between the years of 2010 to 2015, there were approximately 12.5 million crashes involving a rear struck passenger vehicle. In 2,912 of these crashes, at least one rear struck vehicle occupant was fatally injured.

Table 13. Compilation of GES and FARS Rear Crash Data

	All Crashes (GES 2010-2015)			**Fatal Crashes (FARS 2010-2015)**	
	Unweighted	Weighted	Annual Average	Frequency	Annual Average
Vehicles	90,276	12,572,654	2,095,442	2,912	485
Occupants	131,477	17,989,838	2,998,306	5,892	982
Fatalities	127	2,398	400	3,353	559

Characteristics of Rear Impact Crashes in the U.S.

As shown in Figure 21, the absolute number of rear impact crashes has been increasing. Figure 22 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. At least part of the reason for this increase is the increase in exposure for model year (MY) 2009+ vehicles over this period. As shown in Figure 23, MY 2000-2008 vehicles are over-represented in fatality outcome with 63% of rear struck vehicles and occupants but 77% of rear struck fatalities. This suggests that advances in MY 2009+ vehicles to meet FMVSS 301 have yielded at least some rear impact occupant protection improvements. To understand why rear impact fatalities persist, injury mechanisms in rear struck vehicle occupants must be further studied.

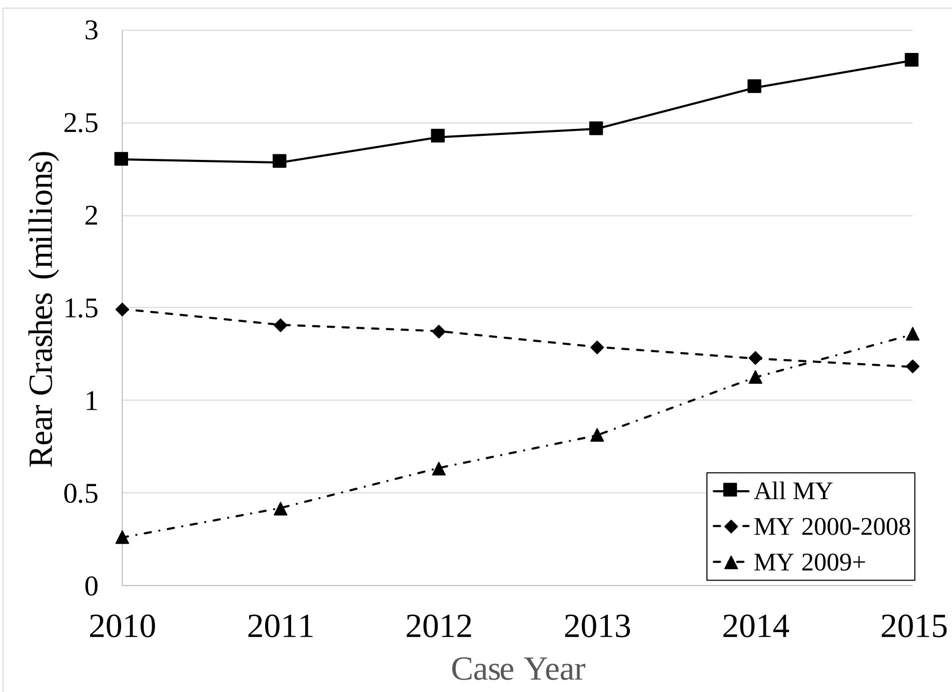


Figure 21. Absolute number of rear impact crashes in all model years, model year 2000-2008, and model year 2009+ passenger cars and LTVs (GES 2010-2015).

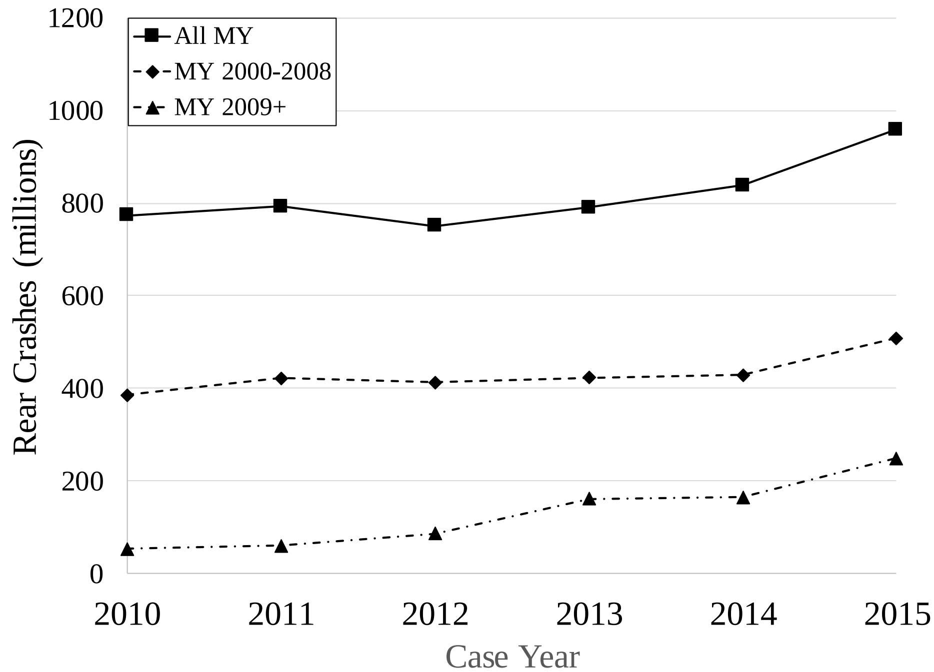


Figure 22. Absolute number of fatalities in rear struck vehicles in all model years, model year 2000-2008, and model year 2009+ passenger cars and LTVs (FARS 2010-2015).

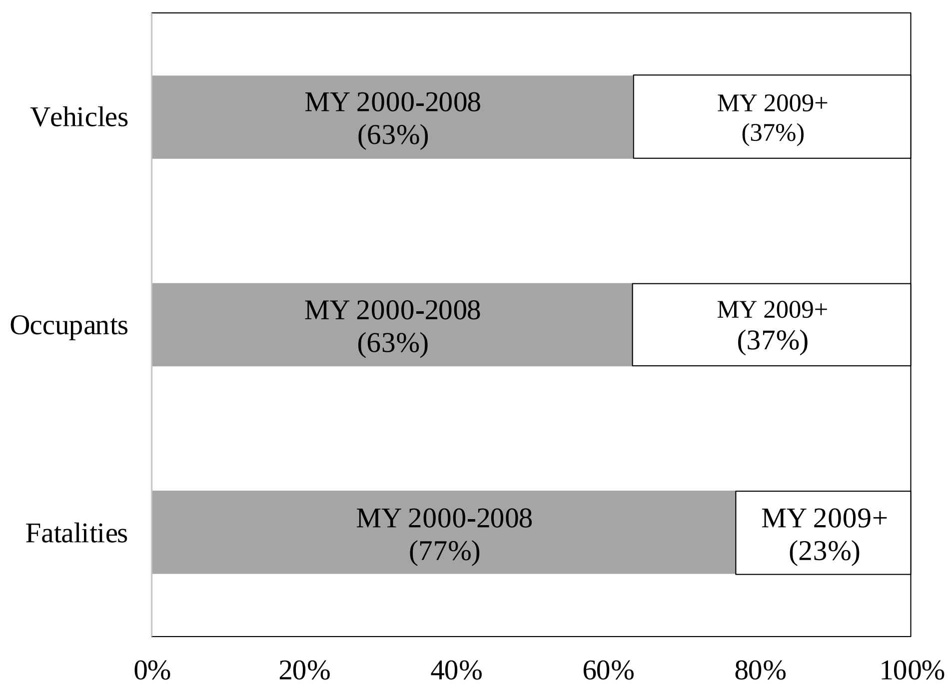


Figure 23. Proportion of all rear struck vehicles, occupants, and fatalities in model year 2000-2008 and model year 2009+ passenger cars and LTVs (GES and FARS 2010-2015).

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, Figure 24 shows 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 Figure 25. 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.

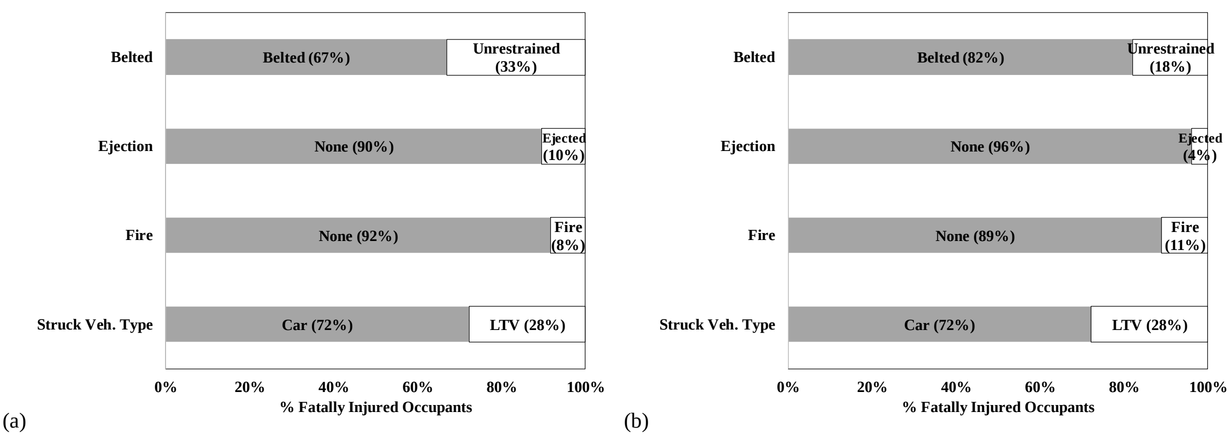


Figure 24. Incidence of seatbelt use, ejection, fire, and struck vehicle type in model year (a) 2000-2008 and (b) 2009+ passenger vehicles for fatally injured rear struck occupants (FARS 2010-2015).

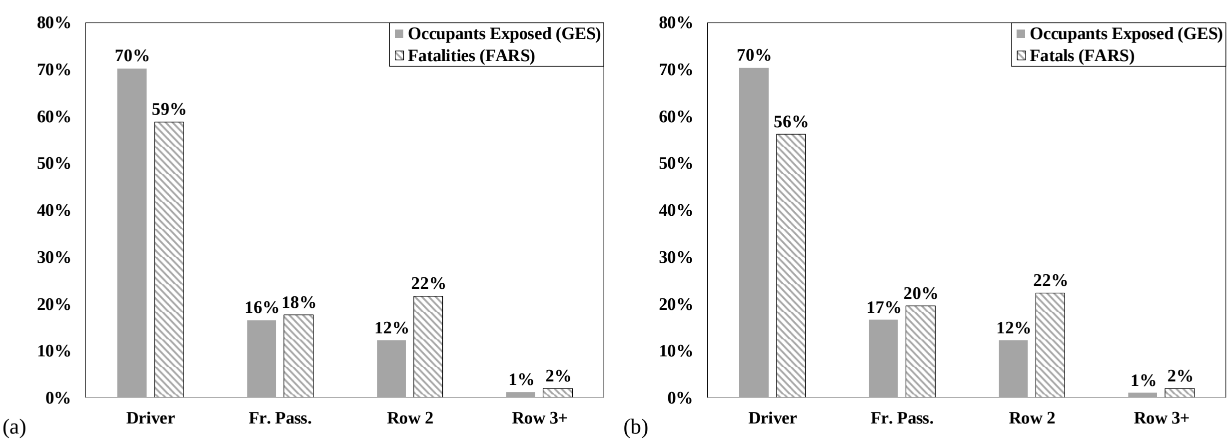


Figure 25. Rear struck vehicle occupant exposure and fatality distribution by occupant seat position in model year (a) 2000-2008 and (b) 2009+ passenger vehicles (GES and FARS 2010-2015).

CDS Dataset Composition

FARS includes no additional information detailing occupant injuries. To better understand these serious injuries, CDS was used to characterize injury patterns and their possible sources. As shown in Table 14, 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. The trends however are useful in guiding and narrowing future research efforts.

As shown in Figure 26, 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, Figure 27 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 14. 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

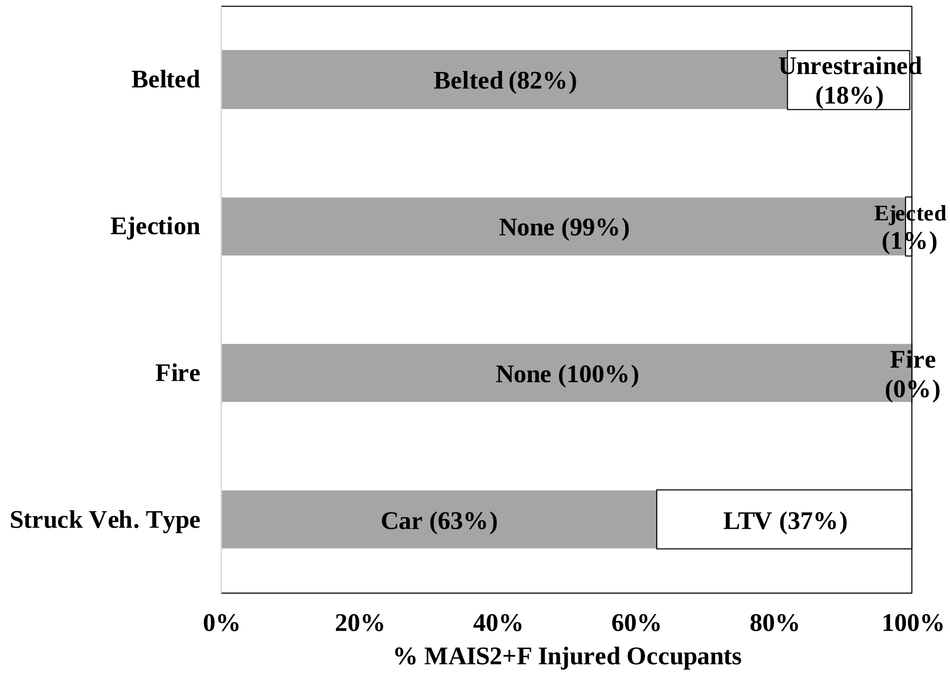


Figure 26. Incidence of seatbelt use, ejection, fire, and struck vehicle type in tow-away MAIS2+F injured rear struck vehicle occupants (CDS 2000-2015).

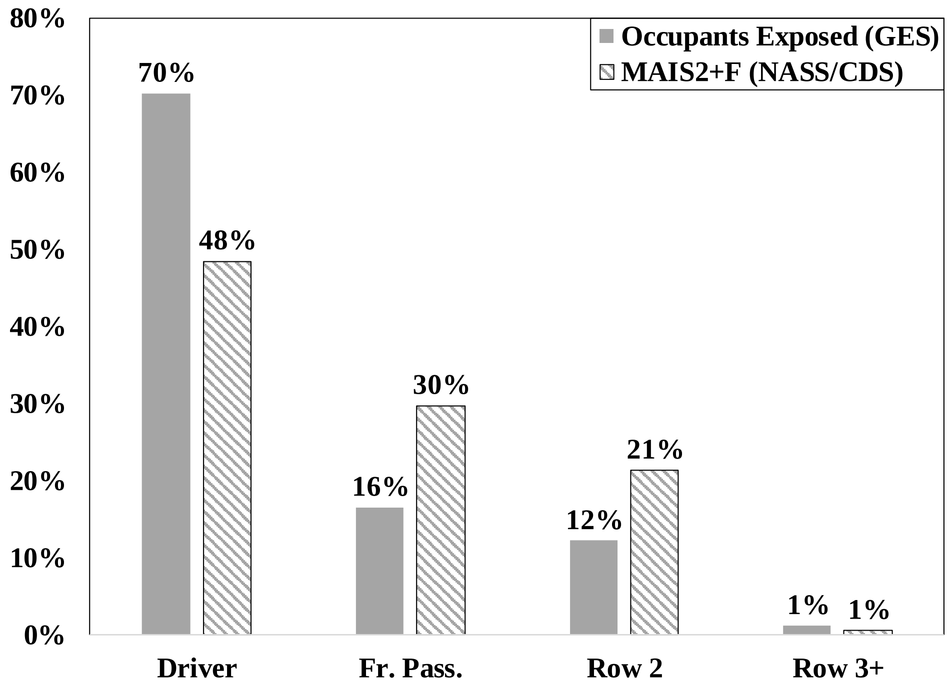


Figure 27. Occupant exposure and MAIS2+F distribution in tow-away rear struck vehicles by occupant seat position (GES 2010-2015 and CDS 2000-2015).

Fatal Injury Case Reviews

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 Figure 28. 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 likely been survivable. The driver and front right passenger experienced only AIS1 whiplash because of the crash. In fact, this deformation and subsequent fatality occurred at only a moderate reported delta-V of 30 km/hr. In all fatal injury cases involving compartment collapse, the average total delta-V was 43 km/hr with a range of 30-56 km/hr.

Figure 28. 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 (NASS-CDS 2010-43-051).

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. One hypothesis is that these massive compartment collapses are a result of cars being overridden by LTVs. While this is true in some cases, it was not a contributing factor in all of our sample cases. Four (4) of the fatal cases involved an LTV striking a car, 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 Figure 29.

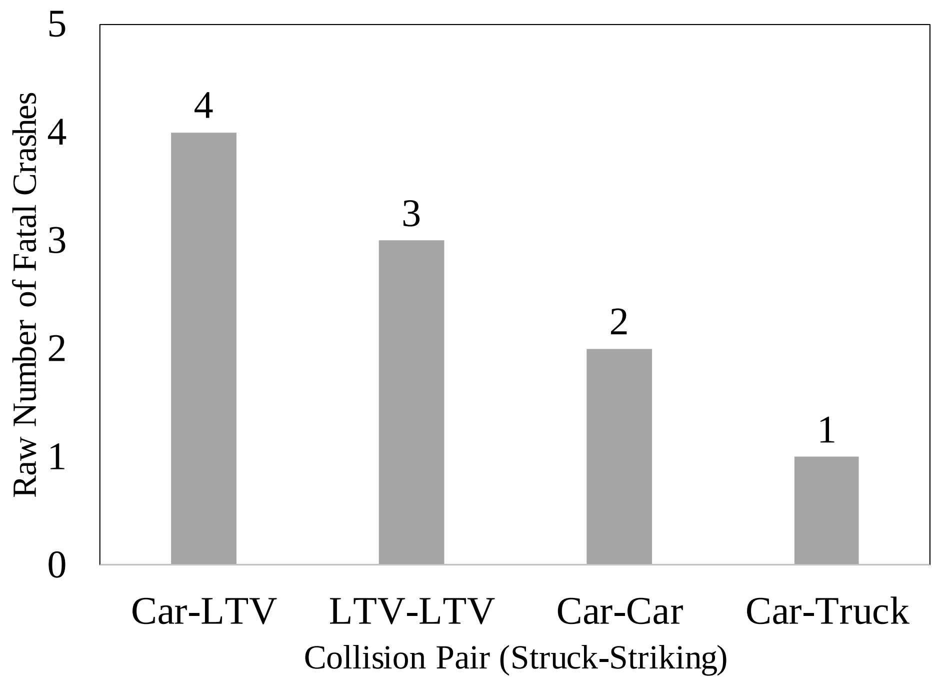


Figure 29. Collision pair (struck-striking vehicle) distribution in fatal rear impact crashes (CDS 2000-2015).

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) [92], as shown in Figure 30, 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. Figure 31 shows results by crash overlap configuration where full engagement corresponds to full vehicle frame interaction and moderate overlap correlated 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.

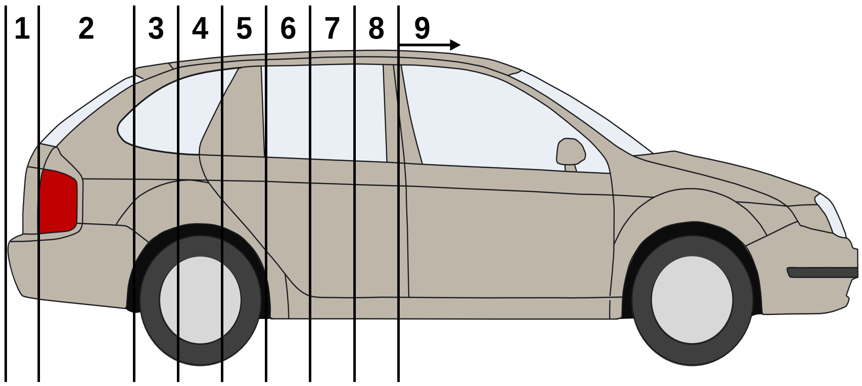


Figure 30. CDC damage extend codes, as mapped to a modern hatchback.

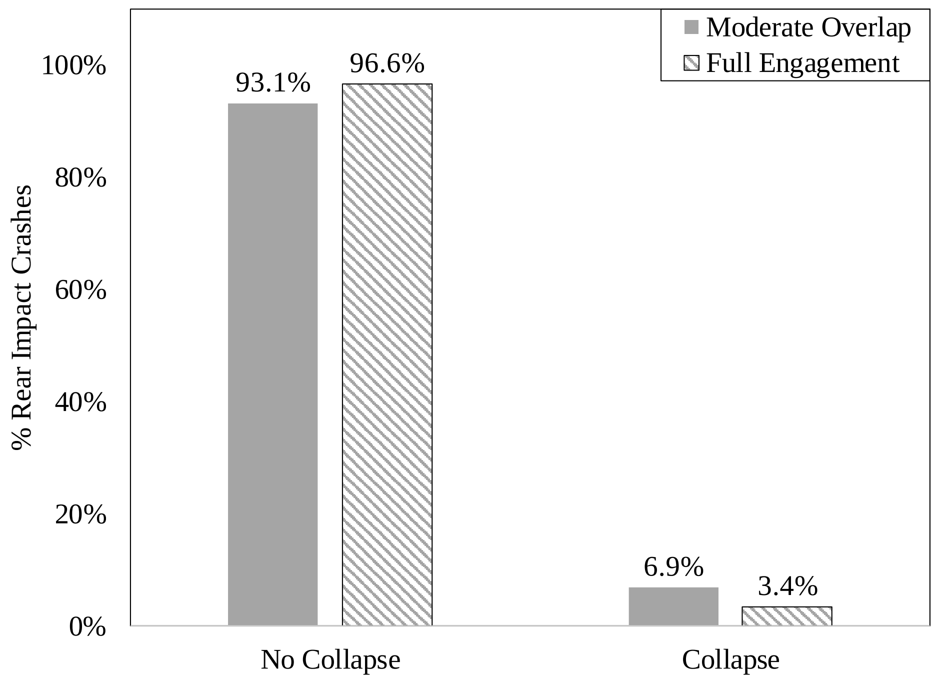


Figure 31. Incidence of rear struck vehicle occupant compartment collapse by crash overlap configuration (CDS 2000-2015).

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 likely due to inertial loading of the thorax in an elderly female occupant. The age range of fatally injured occupants was wide, from seven to 86 years with an average of 48 years. This is slightly older than the entire rear-struck occupant population where the average age of occupants is approximately 36 years old with a range from infancy to 93 years.

MAIS4-5 (Severe) Injury Case Reviews

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. Overall, the observed severe injury cases occurred at similar delta-V's as the fatality cases. The average delta-V of a crash yielding severe injury in this study was 42 km/hr with a range from 18-76 km/hr.

MAIS3 (Serious) Injury Case Reviews

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. These case reviews suggest that current seatback designs, especially their stiffness, 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. The observed serious injury cases generally involved lower total delta-V's than the fatality and severe injury cases. The average delta-V of a crash yielding serious injury in this study was 34 km/hr with a range from 15-61 km/hr.

MAIS2+F and MAIS1+F Injury Models

CDS/EDR Dataset Composition

For this study, EDR data was matched with CDS cases beginning in 2006. From 2006-2015, within the previously studied subset of rear impact cases, there were 238 occupant cases with corresponding complete EDR data. EDR data files were verified to be complete if the delta-V information converged to a constant velocity. If this stipulation is not met, the delta-V computations may be erroneous.

After matching the EDR data with CDS cases and verifying completeness, only 11 observed (1,887 estimated) of these cases included an MAIS2+F injury. While a logistic regression model can be developed on so few cases, the small sample size severely limits the statistical power of such a model. Therefore, MAIS1+F cases, or all injury cases, were considered for injury model development as well. From 2006-2015, within the previously studied subset of rear impact cases, there were 130 observed (48,988 estimated) cases involving a MAIS1+F injury.

MAIS2+F Injury Model

The estimated coefficient of each variable in the MAIS2+F model and their respective 95% confidence intervals are provided in Table 15. Based on the model, being elderly and/or male increases overall risk of MAIS2+F injury. Further, being front-seated decreases risk of injury.

Table 15. Logistic regression parameter estimates for the MAIS2+F model.

Variable	Coefficient Estimates	95% Confidence Limits	
Intercept	-7.15	-9.64	-4.67
Longitudinal Delta-V (β_{DeltaV})	0.14	0.09	0.18
Elderly ($\beta_{Elderly}$)	2.59	1.55	3.64
Male (β_{Male})	1.31	0.31	2.32
Front Seated (β_{Front})	-2.53	-4.11	-0.95

Using the parameter estimates in Table 15 and the logistic regression equation shown in Equation 3, the probability of MAIS2+F injury for an occupant can be estimated with respect to EDR-reported longitudinal delta-V, as shown in Figure 32. An elderly male who is rear-seated (the occupant characteristics with greatest risk of MAIS2+F injury based on the model, or 'worst case' scenario) has approximately a 50% risk of sustaining a MAIS2+F injury in the event of a crash with a delta-v of 24 km/hr. By comparison, an adult female who is front-seated must be in a much more severe crash (delta-v ≈ 71 km/hr) to have the same 50% risk of MAIS2+F injury.

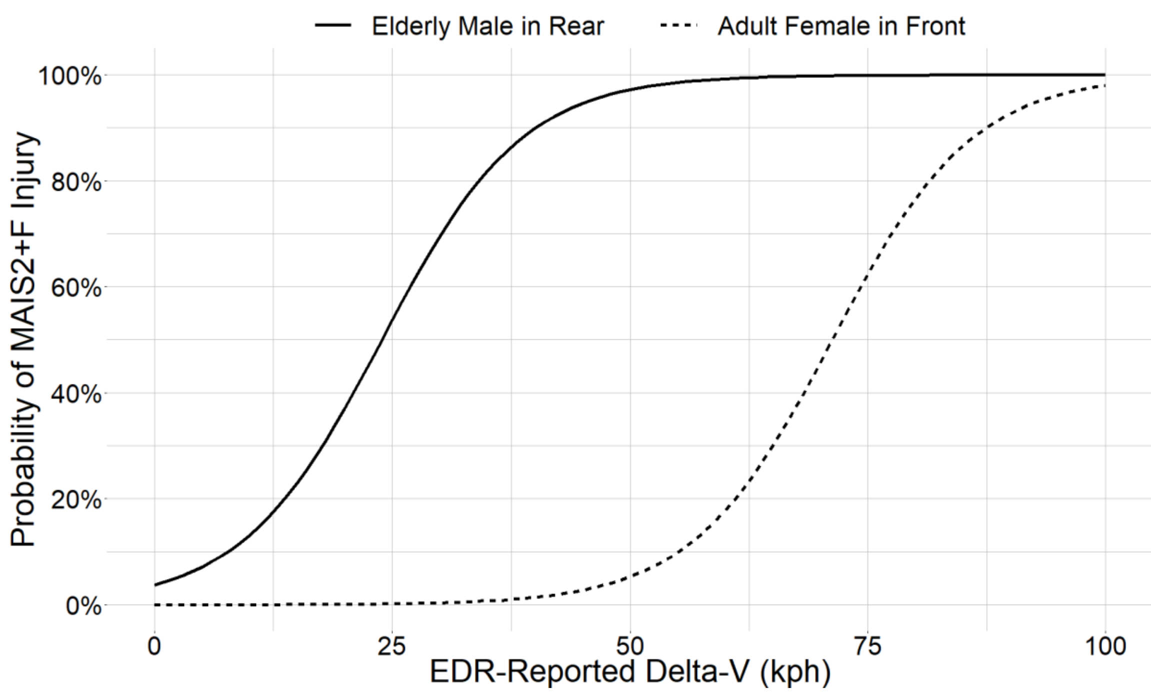


Figure 32. Risk of MAIS2+F injury for 1) an elderly male who is rear-seated and 2) an adult female who is front-seated.

Table 16 shows the odds ratio of MAIS2+F injury for all occupants in the CDS/EDR dataset. Occupants who are 'elderly' (aged 65+) present a greater odds of sustaining an MAIS2+F injury in the event of a rear impact than those who are younger. Specifically, compared to younger occupants, the elderly had over 13 times greater odds of MAIS2+F injury, which was statistically significant. Similarly, men had over 3 times greater odds of MAIS2+F injury than women. Finally, occupants who were front-seated at the time of a crash had lower odds of MAIS2+F injury than their rear-seated counterparts. In other words, based on this logistic regression model which controls for crash severity, occupant age, and occupant sex, rear-seated, rear-struck occupants exhibit a greater risk of MAIS2+F injury than their front-seated counterparts.

Table 16. Odds ratio of MAIS2+F injury from the logistic regression model.

Variable	Odds Ratio	95% Confidence Limits	
Elderly	13.4	4.7	38.0
Male	3.7	1.4	10.1
Front Seated	0.08	0.02	0.39

<u>MAIS1+F Injury Model</u>

The estimated coefficient of each variable in the MAIS1+F model and their respective 95% confidence intervals are provided in Table 17. Like in the MAIS2+F injury model, here the trend is that being elder and/or male increases risk of injury. In contrast, however, this MAIS1+F injury model suggests that front seated occupants are at an increased risk of injury.

Table 17. Logistic regression parameter estimates for the MAIS1+F model.

Variable	Coefficient Estimates	95% Confidence Limits	
Intercept	-2.59	-4.38	-0.80
Longitudinal Delta-V (β_{DeltaV})	0.06	-0.4	0.15
Elderly ($\beta_{Elderly}$)	0.15	-1.80	2.09
Male (β_{Male})	0.21	-1.17	1.59
Front Seated (β_{Front})	1.17	0.15	2.19

Using the parameter estimates in Table 17 and the logistic regression equation shown in Equation 3, the probability of MAIS1+F injury for an occupant can be estimated with respect to EDR-reported longitudinal delta-V, as shown in Figure 33. An elderly male who is front-seated (the occupant characteristics with greatest risk of MAIS1+F injury based on the model, or 'worst case' scenario) has a greater risk of sustaining a MAIS1+F injury in the event of a crash at the same total delta-v than an adult female who is rear-seated.

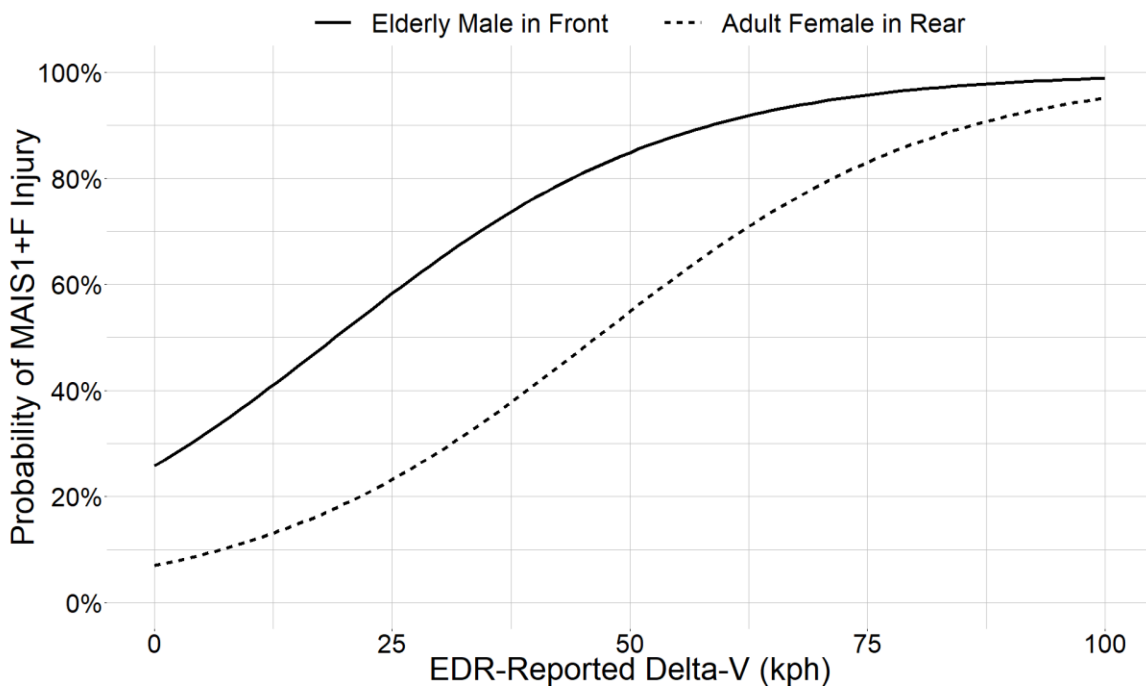


Figure 33. Risk of MAIS1+F injury for 1) an elderly male who is front-seated and 2) an adult female who is rear-seated.

The injury risk curves displayed in Figure 33 clearly show one of the limitations of using logistic regression for statistical modeling of injury outcomes, especially when using a relatively sparse data set. A logistic regression model does not guarantee that the predicted injury risk curve will pass through the origin, or zero risk of injury at zero total delta-v. Of course, having a non-zero risk of injury at zero delta-v (and therefore zero occupant load) is physically impossible in this context of vehicle crashes. While this can be remedied in some cases by constructing the injury risk curve with a parametric survival model using the Weibull distribution, this methodology is not appropriate here due to the observed distribution of injury outcomes and failure to meet Weibull distribution assumptions [93]. Therefore, while this model constructed using logistic regression is useful in understanding the overall trend in differences in injury risk between unique occupant populations, the statistical prediction of injury risk at a given delta-v is biased due to the large offset at the origin. In more suitable statistical models fitted to larger datasets with more even data spread, this offset is very small, making the analytical injury risk curves more reasonable representations of true empirical risk.

Table 18 shows the odds ratio of MAIS1+F injury for all occupants in the CDS/EDR dataset. No statistically significant difference in odds of MAIS1+F injury were found between occupant age groups or sex. Occupants who were front-seated present a greater odds of MAIS1+F injury than rear-seated occupants. Specifically, compared to rear-seated occupants, front-seated occupants had over 3 times greater odds of MAIS1+F injury.

Table 18. Odds ratio of MAIS1+F injury from the logistic regression model.

Variable	Odds Ratio	95% Confidence Limits	
Elderly	1.16	0.16	8.12
Male	1.24	0.31	4.92
Front Seated	3.23	1.17	8.95

While this work has developed preliminary MAIS2+F and MAIS1+F injury risk curves for occupants exposed to rear impacts based on real-world crash and corresponding EDR data – the first study of its kind – an important limitation of this study to note is that these models are based on small sample sizes and have not been validated. As more rear crash data becomes available, these models can (and should) be expanded and validated to increase their generalizability and utility.

CONCLUSIONS

This study has presented an 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. Given these findings, vehicle manufactures and/or regulatory agencies may consider undertaking a more comprehensive analysis of rear structural response and seat performance to gain a deeper understanding of the injury mechanisms in rear crashes, and to determine the priority for countermeasure development.

Using a logistic regression model, this study showed that for rear impacts, MAIS2+F injury outcome is significantly influenced by crash severity (total delta-v), occupant age, occupant sex, and occupant seat position. As crash severity and driver age increase, the risk of MAIS2+F injury increases. Men were at a higher risk of MAIS2+F injury in rear impacts than women. Finally, rear-seated occupants were at a higher risk of MAIS2+F injury than their front-seated counterparts. However, this trend did not hold true when widening the scope of injury prediction to MAIS1+F injuries.

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.

As previously discussed, the findings presented in this study are limited by the small sample of fatalities and injury outcomes in selected rear impact crashes, and should be revisited when a larger sample is available.

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.

5. FRONT IMPACTS AND INJURIES TO REAR SEATED OCCUPANTS

BACKGROUND

In any frontal collision – be it with another vehicle or into a roadside object – popular wisdom is that rear seated occupants are at a lower risk of injury in frontal crashes than their front seat counterparts. However, significant advances in passive safety countermeasures, such as advanced airbags, seatbelt pretensioners, and seatbelt load limiters, primarily benefit front seat occupants. In the U.S., regulatory emphasis in frontal crashes focuses exclusively on front seat occupants. With such safety advances and regulatory emphasis on front seat occupant protection, the differential injury risk between the front and rear seat should be revisited.

FMVSS 208 and the NCAP

The chief U.S. standard governing the frontal crash mode is Federal Motor Vehicle Safety Standard (FMVSS) 208, Occupant Crash Protection [94]. One component of this standard prescribes front crash test procedures. FMVSS 208 prescribes a full frontal crash test in which the subject vehicle is impacted into a fixed, rigid concrete barrier at a velocity of approximately 56 km/h (35 mi/h) with 100% overlap. The standard specifies performance requirements for ATDs seated in the tested vehicle. The standard prescribes multiple impact tests in the same frontal configuration with different ATD arrangements. Both front seats, the driver and right passenger seat, are either occupied by two 50th percentile male or two 5th percentile female ATDs. In each of these two ATD configurations, FMVSS 208 specifies both belted and unbelted tests.

FMVSS 208 also prescribes an offset frontal impact test. In this test, the subject vehicle is impacted into a deformable barrier at a 40% offset at a velocity of approximately 40 km/h (25 mi/h). Subject vehicles can be tested on either the driver or passenger side. An instrumented 5th percentile female Hybrid III dummy is seated on the impacted side. For both this offset test and the previously described full frontal impact test, there is no standard stipulating ATD performance requirements in the rear seats.

The aforementioned 208 full frontal test configuration of impacting the subject vehicle into a fixed, rigid concrete barrier at a velocity of approximately 56 km/h at 100% overlap is the same configuration used to rate vehicles in a frontal impact condition as part of the current U.S. New Car Assessment Program (NCAP) [95, 96]. However, in this NCAP test, only one ATD configuration is used. A 50th percentile male is seated in the driver's seat, and a 5th percentile female is seated in the right front passenger seat. Both ATDs are belted during the NCAP test. While this test does not currently evaluate rear seat occupant protection, NHTSA released a Request for Comments (RFC) regarding changes to NCAP [97]. One of the proposed changes is to add a 5th percentile female Hybrid III ATD placed in the rear (second row) seat behind the right front passenger seat in the full frontal impact test.

OBJECTIVE

Many previous studies on the performance of rear seat occupant restraint systems in the U.S. suggest that the difference in injury and fatality risk between the front and rear seats was elevated in more recent model year vehicles, but these studies were based on older crash data. The issue of relative rear seat safety has not been thoroughly investigated within the last decade. The most recent model year vehicles are not included in current literature. Therefore, the aim of this study was to use the most recent data available to quantify the difference in injury and fatality risk, if any, for front and rear seated occupants in frontal passenger vehicle crashes.

METHODOLOGY

The following study was based upon data from the NASS-CDS and the FARS. NASS-CDS is a U.S. nationally representative database that comes from a clustered, stratified, and weighted sample of police accident reports (PARs) involving passenger vehicles (cars, light trucks, and vans) in which at least one involved vehicle was towed from the crash scene [64]. NASS-CDS assigns a sampling weight to each case which represents the number of actual PARs filed in the U.S. that year which were similar to the selected case. FARS on the other hand is a national census of motor vehicle crashes yielding fatality. Having absolute fatality counts from FARS is invaluable to fatality risk research and can greatly supplement the data collected by NASS-CDS.

For this study, cases were extracted from case years 1999-2015 (inclusive) from both databases. All cases fulfilling the following criteria were included for subsequent analysis:

- Case vehicle was a passenger vehicle (passenger car, minivan, sport utility vehicle (SUV), or pick-up truck) of model year 2000 or newer.
- Vehicle age at the time of the crash was ten (10) or fewer years.
- Frontal impact crash [selected based on the greatest area of deformation in the most harmful crash event (GAD1) variable in NASS-CDS and the initial impact direction (IMPACT1) variable in FARS].
- Occupant is restrained, either by a vehicle equipped seat belt or a CRS.

The vehicle model year restriction of 2000 and later was imposed to help ensure that all vehicles in the resulting dataset were equipped with frontal airbags. Additionally, selected vehicles must have been within the most recent ten (10) model years relative to the crash year, as many crash details were not available in NASS-CDS for vehicles older than ten (10) years.

For analyses of injury risk, selected NASS-CDS cases were used exclusively, comprising both crash exposure counts and injury outcome counts. However, for analyses on fatality risk, FARS data on occupants involved in selected cases were substituted for the weighted sample of comparable NASS-CDS fatal cases in order to produce a combined dataset of all occupants exposed to a frontal crash with exact fatality counts. This method has been used previously [29], as it is known that NASS-CDS underreports total fatality counts in its weighted sampling scheme [98]. Replacing NASS-CDS fatality cases with FARS fatality cases will increase the accuracy of our computation of fatality risk. When computing fatality risk estimates, the combined CDS-FARS occupant dataset will comprise the exposure, and the exact fatality counts from FARS will comprise the outcome.

Variables of interest in this study that may affect the risk of injury to occupants include occupant age, occupant sex, vehicle model year, and vehicle type. All of these variables were treated as categorical in this study. Occupant age was categorized into eight (8) groups: 0-3 years, 4-8 years, 9-12 years, 13-19 years, 20-39, 40-54 years, 55-74 years, and 75+ years. These were chosen both for consistency with previous studies and to reflect the age groups that are recommended for different restraint systems, such as different types of child restraint systems (CRSs). Vehicle model years were categorized as 2000-2002, 2003-2006, and 2007-2016. These model year categorizations were chosen to reflect the airbag technology present in case vehicles.

Model year 2000-2002 vehicles were equipped with single stage airbags. Model year 2003-2006 vehicles reflect the phase in period for advanced, multi-stage airbags. By model year 2007, all vehicles were equipped with advanced airbags.

The intent of this study was in part to probe the effect that recent changes in vehicle restraint systems have had on injury risk. Therefore, occupants in this analysis were limited to those that were taking full advantage of a vehicle's safety systems by wearing their seat belt. This includes children seated in a CRS.

Injury Model Development

First, in order to determine the potential effect of seating position on MAIS2+F (moderate-to-fatal) injury outcome – that was if there was a difference in MAIS2+F injury risk between the front and rear seats – a logistic regression model was constructed to predict MAIS2+F injury outcome as a function of delta-V (DV, crash severity), occupant seating position (FvR, front vs. rear), occupant age, occupant sex, vehicle body type (BT), and vehicle model year (MY) as shown in Equation 4. Then, MAIS2+F injury outcomes were again modeled using logistic regression on the rear- and front-seated occupant populations separately. All covariates except occupant seating position were retained in these models to determine if some study variables influence injury in the rear seats but not in the front seats and vice versa. To account for the stratified sampling scheme used by CDS, the logistic regression model was constructed using 'svyglm' function in the 'survey' package of R.

$$Risk\ of\ MAIS2+F\ Injury = \frac{1}{1+e^{-(Intercept+\beta_{DV}*DV+\beta_{FvR}*FvR+\beta_{Age}*Age+\beta_{Sex}*Sex+\beta_{BT}*BT+\beta_{MY}*MY)}} \qquad \text{Equation 4}$$

Next, the combined CDS-FARS dataset was used to estimate the risk of fatality using another logistic regression model, as shown in Equation 5. The probability of fatality was modeled as a function of occupant seating position, occupant age, occupant sex, vehicle body type, and vehicle model year. In contrast to the MAIS2+F injury model, here, delta-V is omitted as a predictor as it is not reported in FARS. The logistic regression model was constructed using 'glm' function in R and the 'Logistic' function in SAS. These logistic modeling tools can consider the case weights present in the combined CDS-FARS dataset. The combination dataset retained the CDS sampling weights and set case weights in FARS to one (1) as FARS is a census database.

$$Risk\ of\ Fatality = \frac{1}{1 + e^{-(Intercept + \beta_{FvR} * FvR + \beta_{Age} * Age + \beta_{Sex} * Sex + \beta_{BT} * BT + \beta_{MY} * MY)}} \quad \text{Equation 5}$$

Odds ratios of fatality between the rear and front seats were further calculated across each fatality model covariate. In the following results, odds ratios from logistic regression were reported as adjusted RRs. Odds ratios are a good approximation of RRs when the outcome of interest is uncommon [99], as fatalities are in this study. RR was calculated between rear seat occupants and 1) all front seat occupants (both drivers and passengers), 2) drivers only, and 3) front passengers, i.e., non-drivers, only.

RESULTS

CDS Dataset Composition

The resulting CDS sample for analysis is provided in Table 19. During the time period of study from 1999-2015, there were 27,698 observed (11,319,068 estimated) restrained occupants involved in frontal impact tow-away crashes from NASS-CDS. Of those observed occupants, 4,595 (687,616 estimated) sustained an MAIS2+F injury.

Table 19. CDS data sample characteristics.

Sample Characteristic	Crash-Exposed Occupants observed (weighted %)		MAIS2+F Injured Occupants observed (weighted %)	
	Front Seat N = 24,147	**Rear Seat** N = 3,551	**Front Seat** N = 4,312	**Rear Seat** N = 283
Occupant Age				
0-3	11 (0.03)	735 (22.29)	-	40 (14.38)
4-8	91 (0.31)	800 (26.17)	9 (0.10)	31 (22.15)
9-12	225 (0.84)	458 (13.21)	15 (0.40)	29 (12.63)
13-19	2,877 (12.94)	683 (16.71)	355 (6.93)	75 (22.77)
20-39	10,980 (46.33)	546 (13.45)	1,729 (39.52)	61 (13.94)
40-54	5,229 (20.60)	128 (2.44)	991 (22.46)	17 (6.30)
55-74	3,566 (14.08)	111 (2.57)	884 (21.40)	21 (3.51)
75+	1,068 (4.40)	28 (0.53)	328 (9.15)	9 (4.31)
Unknown	100 (0.48)	62 (2.63)	1 (0.05)	-
Occupant Sex				
Male	11,938 (49.40)	1,686 (45.54)	2,060 (38.09)	137 (48.64)
Female	12,164 (50.45)	1,830 (53.97)	2,251 (61.90)	146 (51.36)
Unknown	45 (0.14)	35 (0.49)	1 (0.00)	-
Vehicle Model Year				
2000-2002	8,098 (32.33)	1,190 (35.36)	1,543 (36.95)	101 (33.78)
2003-2006	9,099 (36.60)	1,457 (37.91)	1,633 (34.15)	112 (43.07)
≥ 2007	9,288 (31.06)	10,556 (26.74)	1,136 (28.90)	70 (23.15)

An important occupant characteristic that was notably different between front and rear seat restrained occupants involved in frontal crashes was age. Since the introduction of airbags and CRSs, NHTSA and other public health agencies have strongly recommended that children should be seated in the rear row of vehicles in a CRS appropriate for the child's age and/or size [100]. This was reflected in the NASS-CDS occupant dataset, as over 60% of rear seated occupants were under the age of 13. In contrast, this age group makes up just over 1% of all front seated occupants. As expected, adults over the age of 20 comprise a vast majority of front row occupants at approximately 85%. However, adults make up a mere 19% of all rear seated restrained occupants experiencing a frontal crash. When looking at these age distributions in the MAIS2+F injured occupant population, adults over the age of 40 comprise higher rates of injury than those exposed in the rear seats. This was an indication that adults may be over-represented in injury outcome when rear seated. This may also speak to the effectiveness of CRSs and was an early clue that the adult population may be at a disproportionately high risk of injury when rear seated. Distributions of occupant sex reveal that women who were front-seated make up a higher proportion of those injured than men, though this trend was not present in the rear seats. The front and rear seat distributions of vehicle model year for all exposed occupants were relatively consistent with no great differences. Congruent with the finding in Chapter 1 that injured occupants tend to be traveling in slightly older vehicles, here the proportion of injured front and rear seat occupants was slightly higher in the older model year vehicle categories than those that are newer.

MAIS2+F Injury Model

In order to determine if there is a difference in MAIS2+F injury risk based on if an occupant if rear- or front-seated, the effect of each logistic regression model variable was evaluated. As shown in Table 20, total delta-v, occupant seating position, occupant age, and occupant sex significantly influenced MAIS2+F injury outcomes in the CDS dataset ($\alpha = 0.05$). To further understand where differences in MAIS2+F injury risk may be between the rear and front seats, the RR of MAIS2+F was derived from the logistic regression model for each significant model effect and are presented in Table 21.

Table 20. Test of CDS MAIS2+F model effects.

Variable	p-Value
Total Delta-V	**< 0.0001**
Occupant Seating Position	**0.0220**
Occupant Age	**< 0.0001**
Occupant Sex	**0.0485**
Vehicle Body Type	0.4383
Vehicle Model Year	0.8111

Table 21. Risk of MAIS2+F injury in frontal impacts for restrained rear seat passenger vehicle occupants and relative risk (RR) of MAIS2+F injury for rear vs. front seat restrained occupants by occupant age, occupant sex, and vehicle model year.

Sample Characteristic	Risk of MAIS2+F Injury in Rear Seat (95% CI)	Relative Risk (RR) of MAIS2+F Injury (95% CI) for Rear Seat Occupants vs.		
		All Front Seat Occupants	**Drivers**	**Front Seat Passengers**
Occupant Age				
0-3	1.32% (1.28-1.36)	-	-	-
4-8	1.76% (1.72-1.81)	-	-	0.34 (0.31-0.38)
9-12		-	-	0.52 (0.48-0.55)
13-19	2.81% (2.74-2.88)	0.95 (0.92-0.99)	0.92 (0.89-0.95)	1.09 (1.05-1.13)
20-39	2.17% (2.10-2.24)	0.62 (0.59-0.64)	0.63 (0.60-0.65)	0.57 (0.55-0.59)
40-54	5.44% (5.18-5.70)	0.83 (0.79-0.88)	0.86 (0.81-0.91)	0.64 (0.60-0.67)
55-74	2.87% (2.68-3.05)	0.23 (0.22-0.25)	0.23 (0.21-0.25)	0.24 (0.22-0.26)
75+	15.17% (14.35-16.00)	1.12 (1.04-1.21)	1.33 (1.23-1.44)	0.73 (0.67-0.79)
Occupant Sex				
Male	2.21% (2.17-2.25)	0.99 (0.93-1.06)	1.02 (0.96-1.09)	0.82 (0.77-0.88)
Female	1.97% (1.93-2.00)	1.06 (1.02-1.11)	1.28 (1.22-1.34)	0.65 (0.63-0.89)

In the rear seats, the risk of MAIS2+F injury generally increased with increasing occupant age. The risk of injury was much higher for occupants over the age of 75 than in any other age group. When considering the RR of injury between the rear and front seats, the risk is significantly higher for rear-seated occupants over the age of 75 for comparisons with all front seat occupants and drivers only. In all other age groups, the risk of injury is significantly lower in the rear seats.

Similarly in comparisons with all front seat occupants and drivers only, the RR of MAIS2+F injury was significantly greater for rear-seated women than those in the front. When making comparisons with just front seat passengers, the injury risk was significantly lower to rear seated occupants regardless of occupant sex.

A final set of MAIS2+F logistic regression models were used to model the risk of injury in the rear and front seats independently. The estimated coefficient of each covariate in the model and its respective standard error are provided in Table 22. For the rear seat model, total delta-v and occupant age significantly influence MAIS2+F injury outcomes in the CDS dataset (α = 0.05). While the front seat model also sees significant influence from delta-v and occupant age, occupant sex also contribute to injury risk significantly with women exhibiting a greater risk of injury than men in the front seats.

Table 22. Comparison of frontal impact MAIS3+F logistic regression models for rear- and front-seated occupants from CDS dataset.

Sample Characteristic	Rear Seat Model		Front-Seat Model	
	Coefficient Estimate (Std. Error)	p-Value	Coefficient Estimate (Std. Error)	p-Value
Intercept	-5.67 (0.66)	< **0.001**	-5.50 (0.32)	< **0.001**
Total Delta-V	00.09 (0.01)	< **0.001**	0.09 (0.005)	< **0.001**
Occupant Age				
0-3	-0.87 (0.51)	0.091	-11.43 (0.81)	< **0.001**
4-8	-1.05 (0.48)	**0.030**	-0.62 (0.92)	0.504
9-12	-0.10 (0.40)	0.799	0.04 (0.51)	0.938
13-19	0.11 (0.35)	0.762	-0.31 (0.17)	0.073
20-39	Reference		Reference	
40-54	1.12 (0.73)	0.127	0.60 (0.13)	< **0.001**
55-74	0.02 (0.80)	0.981	0.67 (0.14)	< **0.001**
75+	1.97 (0.57)	< **0.001**	1.58 (0.31)	< **0.001**
Occupant Sex				
Male	Reference		Reference	
Female	00.05 (0.31)	00.875	0.55 (0.09)	< **0.001**
Vehicle Body Type				
Minivan	Reference		Reference	
Passenger Car	0.14 (0.34)	0.694	0.34 (0.22)	0.128
Pickup Truck	-1.12 (0.90)	0.211	0.60 (0.30)	0.051
SUV	0.25 (0.45)	0.577	0.43 (0.26)	0.102
Vehicle Model Year				
2000-2002	-0.06 (0.33)	0.859	-0.00 (0.15)	0.988
2003-2006	-0.03 (0.30)	0.918	-0.08 (0.14)	0.571
≥ 2007	Reference		Reference	

Using the parameter estimates in Table 22 and the logistic regression equation shown in Equation 4, the probability of MAIS2+F injury for a rear-seated occupant can be estimated with respect to delta-V, as shown in Figure 34. The analytical models depicted represent the injury risk to a male occupant traveling in a model year 2007-2016 passenger car with varied age, the covariate which significantly affected MAIS2+F injury risk. As shown in the graph, there are indeed great differences in injury risk to a rear-seated occupant depending on their age. According to the logistic regression model, a 4-8 year old child has a 50% probability of MAIS2+F injury at a delta-v of approximately 70 km/hr. By comparison, a 75+ year old elder must experience a much less severe crash (delta-v = 38 km/hr) – almost half the crash severity – to have the same 50% chance of sustaining a MAIS2+F injury.

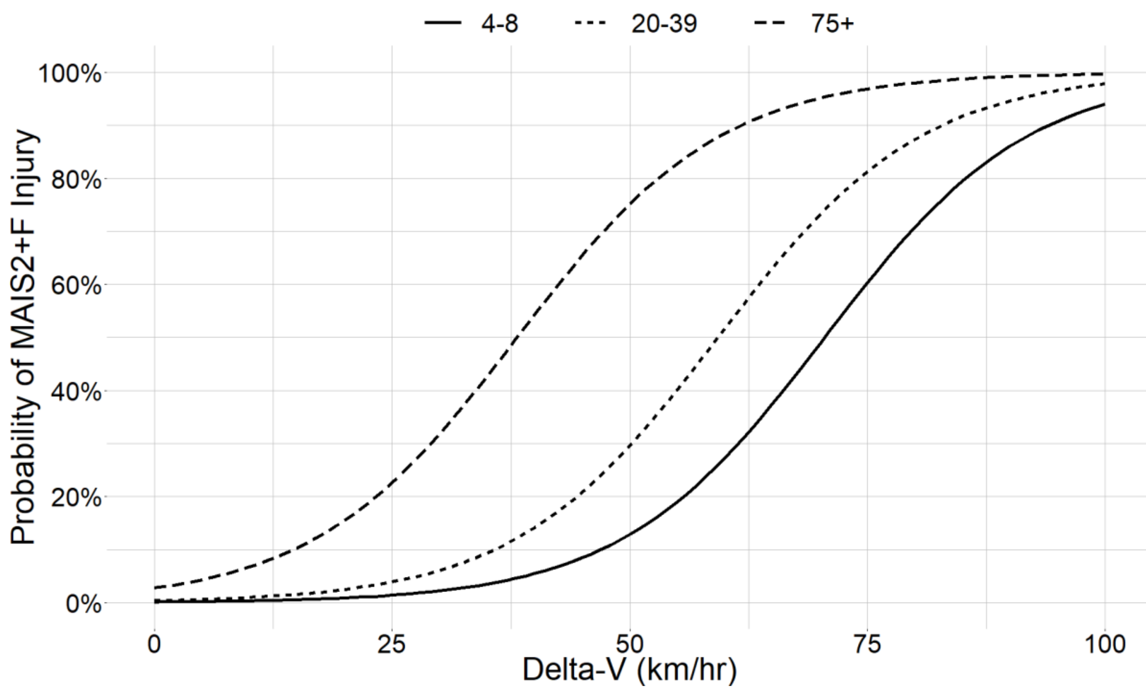


Figure 34. Probability of MAIS2+F injury by age group for a restrained, rear-seated male occupant traveling in a model year 2007-2016 passenger car.

FARS Dataset Composition

The resulting FARS sample for analysis is provided in Table 23. During the time period of study, there were 35,717 observed restrained occupants who sustained fatal injuries as a result of a frontal crash. Like in the exposed and injured occupant populations in CDS, occupant age was notably different between those who were fatally injured in the front and rear seats. Adults over the age of 20 comprise almost half of those fatally injured in the rear seats, but recall from Table 19 that they make up a mere 20% of all crash-exposed rear-seated occupants. This was a clear indication that adults were over-represented in fatality outcome when rear seated. Distributions of occupant sex show that men make up a higher proportion of those fatally injured in the front seats while women make up a higher proportion in the rear. Again, like in the exposed and injured populations, distributions of vehicle model year were relatively consistent.

Table 23. FARS data sample characteristics.

	Fatally Injured Occupants from FARS observed (%)	
	Front Seat N = 33,475	**Rear Seat** N = 2,242
Occupant Age		
0-3	28 (0.08)	390 (17.40)
4-8	80 (0.24)	341 (15.21)
9-12	82 (0.24)	158 (7.05)
13-19	2,139 (6.39)	286 (12.76)
20-39	10,253 (30.63)	289 (12.89)
40-54	6,775 (20.24)	143 (6.38)
55-74	8,635 (25.80)	319 (14.23)
75+	5,483 (16.38)	316 (14.09)
Unknown	-	-
Occupant Sex		
Male	19,914 (59.49)	970 (43.26)
Female	13,560 (40.51)	1,272 (56.74)
Unknown	1 (0.00)	0 (0.00)
Vehicle Model Year		
2000-2002	10,793 (32.24)	662 (29.53)
2003-2006	12,903 (38.55)	878 (39.16)
≥ 2007	9,779 (29.21)	702 (31.31)

Fatality Risk Model

Logistic regression was used to model the risk of fatality as a function of occupant seating position (front vs. rear), occupant age, occupant sex, vehicle body type, and vehicle model year. Based on this model, to further investigate the effect that being rear- or front-seated has on fatality outcome, the effect of each model variable was evaluated via a Wald test. As shown in Table 24, all model variables significantly influenced fatality outcome ($\alpha = 0.05$). In contrast to the MAIS2+F injury model, according to this fatality model, there was a statistically significant difference in fatality outcome based on if an occupant was rear- or front-seated.

Table 24. Test of combined CDS/FARS fatality model effects.

Variable	p-Value
Occupant Seating Position	**0.0017**
Occupant Age	**< 0.001**
Occupant Sex	**< 0.001**
Vehicle Body Type	**< 0.001**
Vehicle Model Year	**0.0412**

To further probe into the potential factors that may influence the RR of fatality between the rear and front seats, RRs were calculated for each model characteristic of interest. Estimates of the risk of fatal injury for the 2,242 restrained rear row occupants in the study are presented in Table 25 by age, sex, and vehicle model year. The RR of fatality for rear vs. front row restrained occupants is also provided. For occupants up to the age of 39, it appears that there was a benefit in being rear seated in the event of a frontal collision, as the RR of fatal injury for the rear seats was significantly lower than one (1). However, restrained rear seat occupants aged 40 and older, especially those over 75, display a significantly higher risk of fatal injury than their younger counterparts. In addition, occupants over the age of 40 exhibit significantly greater risk of fatal injury in the rear seats than the front seats. Again, this was exceptionally higher for elderly occupants over the age of 75.

Table 25. Risk of fatal injury in frontal impacts for restrained rear seat passenger vehicle occupants and relative risk (RR) of fatality for rear vs. front seat restrained occupants by occupant age, occupant sex, and vehicle model year.

Sample Characteristic	Risk of Fatal Injury in Rear Seat (95% CI)	Relative Risk (RR) of Fatal Injury (95% CI) for Rear Seat Occupants vs.		
		All Front Seat Occupants	Drivers	Front Seat Passengers
Occupant Age				
0-3	0.14% (0.13-0.15)	-	-	0.22 (0.15-0.34)
4-8	0.10% (0.09-0.12)	-	-	0.47 (0.37-0.61)
9-12	0.10% (0.08-0.11)	-	-	0.92 (0.70-1.20)
13-19	0.14% (0.12-0.15)	0.87 (0.77-0.98)	0.92 (0.81-1.04)	0.78 (0.68-0.90)
20-39	0.17% (0.15-0.19)	0.83 (0.74-0.94)	0.86 (0.77-0.97)	0.70 (0.62-0.79)
40-54	0.47% (0.39-0.55)	1.64 (1.38-1.92)	1.70 (1.44-2.01)	1.44 (1.21-1.72)
55-74	0.99% (0.88-1.10)	1.83 (1.64-2.05)	2.06 (1.84-2.31)	1.16 (1.02-1.31)
75+	4.54% (4.05-5.03)	4.07 (3.62-4.57)	4.70 (4.17-5.29)	3.02 (2.66-3.42)
Occupant Sex				
Male	0.17% (0.16-0.18)	1.08 (1.00-1.17)	1.18 (1.09-1.28)	1.06 (0.98-1.16)
Female	0.19% (0.18-0.20)	1.41 (1.32-1.50)	1.70 (1.59-1.81)	1.05 (0.98-1.12)
Vehicle Model Year				
2000-2002	0.15% (0.14-0.16)	1.03 (0.94-1.12)	1.20 (1.10-1.30)	0.77 (0.70-0.85)
2003-2006	0.19% (0.17-0.20)	1.24 (1.15-1.34)	1.44 (1.33-1.56)	1.04 (0.96-1.13)
≥ 2007	0.21% (0.19-0.23)	1.65 (1.51-1.79)	1.84 (1.69-2.00)	1.58 (1.44-1.74)

Perhaps more importantly, there was significant evidence that restrained rear row occupants in model year 2007 and newer vehicles were at a higher risk of fatality than front row occupants. Among restrained rear row occupants, the absolute risk of fatality varied slightly by vehicle model year, with the oldest model year vehicles appearing to have the lowest risk of fatality. To further probe into this model year effect on the risk of fatal injury in the rear seats, a logistic regression model was run all restrained rear seat occupants in the study sample controlling for occupant age, gender, and vehicle type. Odds ratios were calculated for each of the model year groupings, using model years 2000-2002 as the reference in order to compare the influence of each model year range on fatality outcome. Compared to model years 2000-2003, restrained rear seat occupants in vehicle model years 2003-2006 and vehicle model years ≥ 2007 have the same odds of fatality (OR 1.000, 95% CI 0.998-1.003). Therefore, there was no statistically significant difference in the odds of fatality for restrained rear seat occupants between vehicle model years, suggesting that the overall safety of the rear seat has remained static over time.

When looking at the calculated RRs in Table 25, in the oldest model year vehicles with single stage airbags, model years 2000-2002, the front and rear seats pose a similar fatality risk (RR 1.03, 95% CI 0.94-1.12). However, during the phase-in of advanced airbags in model years 2003-2006, a difference in fatality risk arises, with a greater RR of fatal injury being seen in the rear seats (RR 1.24, 95% CI 1.15-1.34). The trend continues when looking at the newest model year vehicles where the RR of fatality becomes even higher in the rear seats (1.65, 95% CI 1.51-1.79). These findings are statistically significant and clearly show that the RR of fatal injury for rear vs. front seat occupants has been increasing in newer model year vehicles. Recall the finding shown in Table 25 that the risk of fatality in the rear seat was not statistically different for vehicle model years 2003-2006 and model years ≥ 2007. When considered jointly, these findings illustrate that the increase in RR of fatality for rear vs. front seat occupants was due to a lower fatality risk in the front seat – a sign of improved safety – rather than an increased risk in the rear. Finally, across all sample characteristics, the estimate of RR of fatal injury among rear seat occupants versus drivers was notably higher than the estimated risk for rear seat occupants versus front seat passengers.

Serious-to-Fatal Injury Case Studies

To further investigate how the types and sources of injury may differ between the rear and front seats, a subset of CDS cases involving MAIS3+F in our study were further examined, including the detailed injury data available in CDS. Having an understanding of these injury mechanisms may shed light on why the rear and front seats were displaying differences in fatality risk.

<u>Differences in Injury Patters Between the Rear and Front Seat</u>

For all restrained front- and rear-seated occupants with serious-to-fatal injuries in the CDS sample, Figure 35 shows the distribution of all AIS3+ injuries by body region. The rear-seated occupant population includes all who were restrained either by a traditional seatbelt or a CRS (the rear-seated population used in previous analyses). No front-seated, CRS-restrained occupants were injured at the AIS3+ level, so the front seat occupant population plotted here only includes those wearing a traditional seatbelt. It is most prudent when seeking to compare injury patterns that may be restraint-related between occupant populations to consider those who were similarly restrained. Therefore, Figure 36 further parses AIS3+ injuries occurring the rear seats by restraint type – either a traditional seatbelt or a CRS.

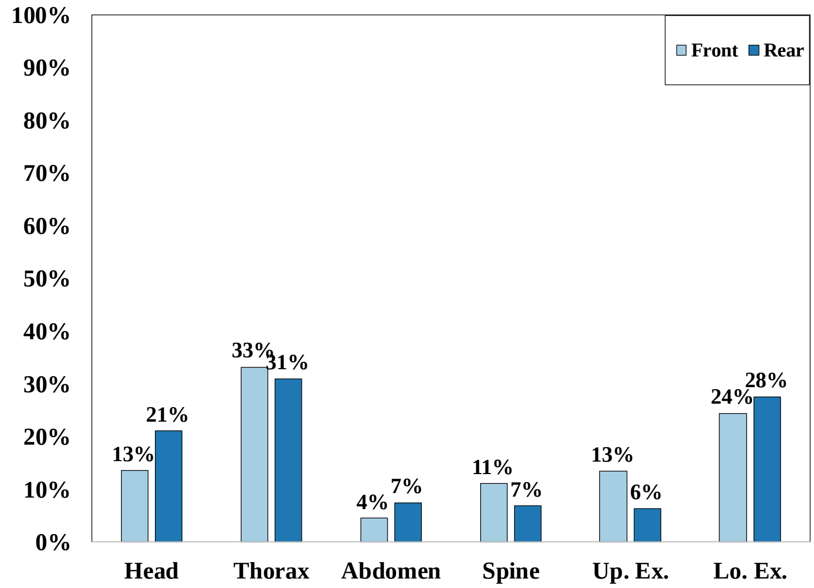


Figure 35. Distribution of AIS3+F injuries by body region for all restrained (both using vehicle seatbelt or CRS) front- and rear-seated occupants.

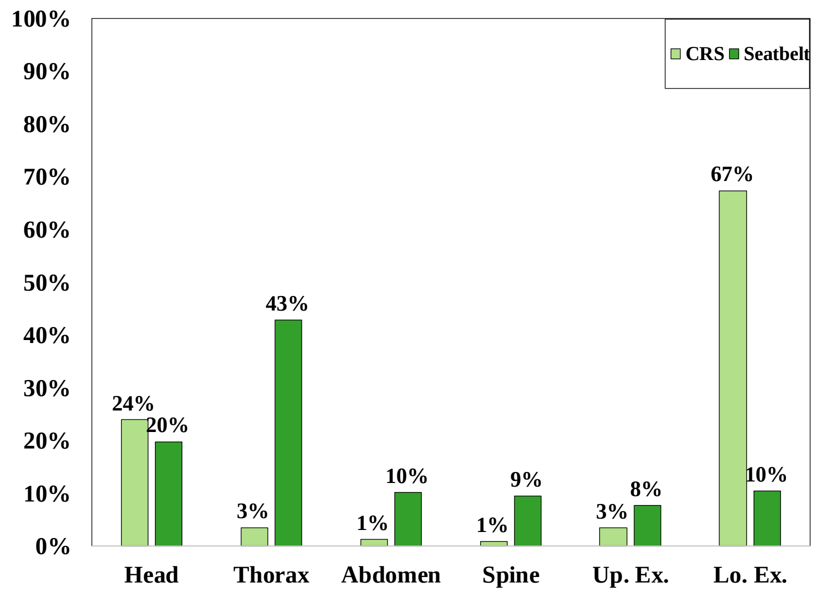


Figure 36. Distribution of AIS3+ injuries by body region for all rear-seated occupants by restraint type.

For the front- and both rear-seated occupant populations, the thorax was the most common seriously injured body region. In the rear seats, those occupants who were using a traditional seatbelt exhibit a much greater proportion of thorax injuries than those who were CRS restrained. For front-seated occupants, the least common seriously injured body region was the abdomen, while for rear-seated occupants who were seatbelt restrained it was the upper extremities. When considering how the AIS3+ injuries sustained by rear-seated occupants may be fundamentally different than those sustained by front-seated occupants, it was notable that all rear-seated occupants regardless of restraint type (either CRS or traditional seat belt) sustained both head and abdomen injuries more often than their front seat counterparts. Rear-seated occupants who were restrained by a traditional seat belt also sustained a greater proportion of thorax injuries than front-seated occupants. Rear-seated occupants who were CRS restrained sustained a much greater proportion of lower extremity injuries than those who were front-seated. While this topic has not been explored on real-world crash and injury data previously, these findings are consistent with studies of differences in ATD loading in the front and rear seats in full frontal vehicle crash tests. In the crash test, ATDs (both 50^{th}-percentile male and 5^{th}-percentile female) in the rear seats had considerably higher head/neck and thorax injury risks than occupants in the front seats [9]. What’s more, the injury measures recorded from the rear-seated ATDs often exceeded established injury risk thresholds.

Figure 37 shows adjusted rear versus front seat RR of AIS3+ injuries by body region. To produce these RRs, a logistic regression model was fitted to the selected seatbelt restrained occupants in order to control for the effect of crash severity (delta-V) alone. This model allowed a comparison of the RR of injury in crashes with and without AIS3+ injuries between rear- and front-seated occupants involved in crashes with the same severity. The small sample size of AIS3+ injuries within each body region in the selected dataset was not conducive to adjusting for other covariates, though this would be suggested given more injury data. Error bars have been added to show the 95% Wald confidence intervals on each RR.

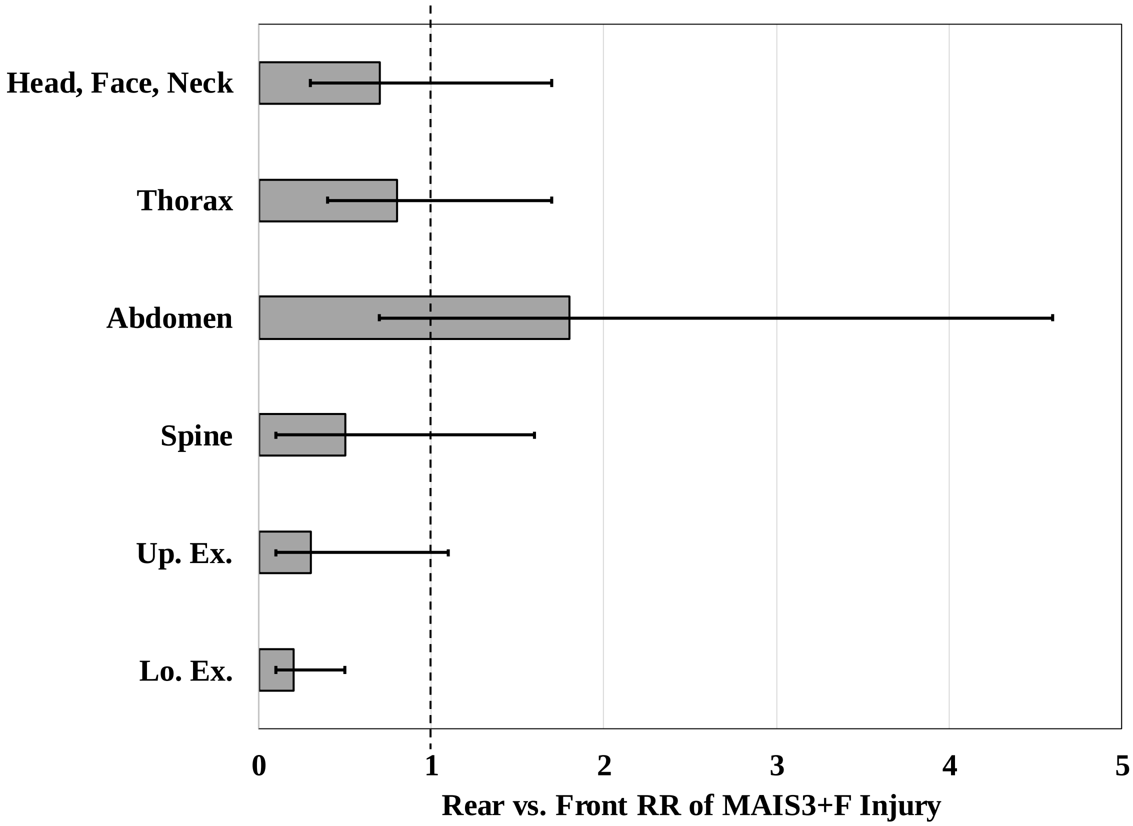


Figure 37. Delta-V adjusted rear vs. front seat RR of AIS3+F injury for belted occupants.

Given the same delta-V, rear-seated occupants have a greater RR of AIS3+ injuries to the abdomen. However, the 95% confidence interval of the RR was wide due to small sample sizes and suggests no statistically significant difference. In contrast, the RR of AIS3+ injuries to the lower extremities was statistically significant and less than one (1), suggesting that rear-seated occupants may be at a lower overall risk of serious lower extremity injuries than their front-seated counterparts. These findings agree with those previously presented in Figure 35 – that belted rear-seated occupants sustained more abdominal injuries and fewer lower extremity injuries than those who were belted and front-seated. Though proportionally rear-seated occupants appear to sustain more head and thorax injuries than their front-seated counterparts, the RR of MAIS3+ injury to these body regions when controlling for delta-v indicates that they may ultimately be at a lower risk, though, once again due to small sample sizes, these findings were not statistically significant.

MAIS3+F Injuries in the 9-12 Year Old Occupant Population

The adolescent population aged 9-12 years was notably the only aged occupant population under 40 years where the rear vs. front seat RR of fatality was not significantly below one (1), indicating no difference in risk between the front and rear seats. This was an unexpected finding, as children are recommended to be rear-seated through age 12 because it has been historically proven as the safest place for them to sit [100]. Table 25 shows that the risk of fatality to restrained 9-12 year olds in the rear seats was statistically similar to that of 0-3 year olds and 4-8 year olds, even though those two adolescent populations exhibit a significantly lower risk of fatality in the rear rows than in the front row. This suggests that there was a lower risk of fatality to restrained 9-12 year olds in the front passenger seat than the other adolescent populations. It was notable that relative to the other adolescent populations, 9-12 year olds made up a smaller proportion of rear seated occupants, so this finding/lack of statistical significance could simply be an abnormal statistical finding due to the small sample size.

That being said, children aged 9-12 were a particularly interesting adolescent population as this was the general age range when they were able to begin using a traditional seat belt instead of a CRS. It is recommended that a child remain in a booster seat until they are 'big enough' to wear a seat belt with proper fit. That is, the lap belt fits snugly over the lower hips, touching the thighs, and the shoulder belt lies comfortably across the shoulder and chest without touching the neck. Generally, this proper seat belt fit is achievable once a person reaches at least 4'9" (57 in. or 145 cm.). Although current recommendation is that children remain rear-seated through age 12 regardless of height, once a child reaches 4'9" they should be able to use either a rear or front seat belt properly.

In this study's dataset, none of the 9-12 year olds were restrained in a CRS but were instead using a traditional seatbelt at the time of the crash. However, 1 of the 5 (20%) and 8 of the 12 (67%) front- and rear-seated 9-12 year old occupants with a recorded height, respectively, were under 4'9" and should have been restrained in a booster seat per current child vehicle safety recommendations. In contrast, children in the other younger age groups were almost always CRS restrained. The high rate of seatbelt misuse among 9-12 year olds in the rear seat may explain why the 9-12 year old rear versus front RR is not statistically significant.

Table 26 shows the observed counts of AIS3+F injuries for belted front- and rear-seated adolescents aged 9-12 years. Due to the small sample size, weighted distributions were not considered. In this age group, the AIS3+F injuries in the front and rear seats were very different. While most injuries to front-seated 9-12 year olds were to the extremities, rear seat occupants much more commonly experienced head, thorax, and/or abdomen injuries. In fact, while abdomen and spine AIS3+F injuries occurred in the rear-seats, these injuries were absent in the 9-12 year old front-seated occupant population.

Table 26. Observed counts of AIS3+F injuries for all belted front- and rear-seated occupants aged 9-12.

Body Region	Observed # of AIS3+F Injuries	
	Front	Rear
Head	1	6
Thorax	1	5
Abdomen	-	4
Spine	-	1
Upper Extremity	3	1
Lower Extremity	2	3

Head injuries were the most common AIS3+F injury sustained in the rear seats, and all were traumatic brain injuries including hematoma/hemorrhage. Previous studies on restrained, rear-seated ‘older children’ similarly found that head injuries were common and have explored mechanisms of injury [101, 102]. In this study, of the six (6) brain injuries, all but one were direct contact injuries with interior vehicle structures. Four (4) of the six were attributed to contact with the front seat back. That is, upon frontal impact, the rear-seated occupants, even though they were belted, were propelled so far forward that their head contacted the back of the front seat before them. At times, especially in offset frontal impact, this motion occurs because the child’s torso ‘rolls out’ of the shoulder belt. Previous literature similarly cited the most common mechanism of head injury as head contact with the front seat back [102]. Further, this mechanism of injury appeared in both 9-12 year olds who were below and above 4’9” tall suggesting that this may not exclusively be an issue regarding CRS-use but perhaps includes a shortcoming of the vehicle-equipped seat belts themselves.

AIS3+F thorax injuries were also common in the rear seats. All were soft tissue injuries including lung contusions and lacerations. Of the five (5) thorax injuries, all but one were direct contact injuries with the seat belt. Three (3) of the five 9-12 year olds with thorax injuries were above 4'9" in height, the appropriate height to be using a vehicle-equipped seat belt. This again suggests that this injury mechanism was not exclusively an issue that may be resolved by proper CRS-use but rather points to a possible shortcoming of the seat belt technology itself.

In prior literature, abdominal injuries have commonly been identified in restrained, rear-seated younger occupants [33, 103, 104]. Abdominal injuries in this study exclusively occurred in the rear-seats, primarily as colon/jejunum-ileum/mesentery lacerations. Similar to thorax injuries, all AIS3+F abdominal injuries observed were attributed to direct contact with the seat belt, which was consistent with prior research. This injury mechanism often occurs when the lap portion of a seat belt is incorrectly placed over the stomach rather than the hips and upper thighs. With this belt configuration, an occupant is at increased risk of submarining – or sliding under the lap belt – in the event of a crash. This motion subjects the abdominal contents to immense forces under the lap belt, often resulting in serious injury. Children who are smaller in stature are especially vulnerable to this type of seat belt misplacement over the stomach. This is why booster seats are recommended until the height of 4'9" is reached. Premature 'graduation' to using an adult seat belt has previously been cited as a contributing factor to submarining and subsequent abdominal injuries in children [105, 106]. Of the four (4) 9-12 year olds sustaining an abdominal injury, height was only recorded for two (2) cases. One child was over 4'9" and one was under 4'9", again indicating that this injury mechanism may not exclusively be an issue regarding CRS-use but perhaps includes a shortcoming of the vehicle-equipped seat belts themselves. In addition to improper seat belt use, seat belt geometry and seat design have been shown to influence submarining and should additionally be considered as potential areas where design changes and innovations may improve abdominal injury outcomes in the rear seat occupant population [107, 108].

The one spinal injury observed in a rear-seated 9-12 year old was a lumbar spine fracture. Like the previously discussed abdominal injuries, this mechanism of spinal injury can occur when the occupant is wearing their seatbelt improperly over the stomach upon impact [109]. The lap portion of the seatbelt essentially acts as a fulcrum about which the body pivots, which directs great force toward the lumbar spine, possibly resulting in fracture. The shoulder portion of a seatbelt is designed to mitigate this, though misuse or occupant 'roll out' of the shoulder belt during impact nullify the intended protective effect. Along with this spinal injury, the occupant also sustained kidney contusions and abdominal abrasions from the seat belt, which is consistent with improper placement and possible submarining. This occupant was under 4'9" tall and should have been using a booster seat which may have avoided or lessened the severity of these injuries.

AIS3+F extremity injuries in the rear-seats were all fractures due to direct contact with some interior vehicle structure, often the front seat back or center console.

MAIS3+F Injuries in the Adult (40+ Years) Occupant Population

As shown previously in Table 19, , only about 5.5% of crash-exposed rear-seated occupants were aged 40 and over. However, this 5.5% of cases was overrepresented in both moderate injury and fatality outcomes, representing 14% of MAIS2+F injured rear-seated occupants and 35% of fatally injured rear-seated occupants. While the risk of injury and fatality similarly increases with age in the front seats, the effect is not as pronounced and begins at a later age (55 in the front seats vs. 40 in the rear). The huge jump in the RR of fatality between the rear and front seats for occupants over the age of 40 is a startling finding and warrants further investigation into the differences in injury characteristics between the front and rear seat populations.

Table 27 shows the composition of AIS3+F injuries for belted front- and rear-seated occupants aged 40 years old and over, and Figure 38 provides a visual of the weighted distribution of said injuries. Note that the provided figures are counts of body regions, not individual injuries. For example, if an occupant sustains five individual injuries to the thorax, this is only counted as one thorax case, not five. In frontal crashes, the overall body region trend for the AIS3+F injuries sustained in both the front and rear seats is the same. For adults aged 40 and over, the most commonly AIS3+F injured body region is the thorax, followed by the lower extremities, spine, and head, respectively. When comparing the body region distributions of AIS3+F injuries between front and rear seat occupants, it is notable that rear-seated occupants aged 40 and over sustained both thoracic and abdominal injuries more frequently than their front-seated counterparts.

Table 27. Observed counts and weighted distribution of AIS3+F injuries for all belted front- and rear-seated occupants aged 40 and over.

Body Region	Observed # of AIS3+F Injuries (Weighted %)	
	Front	Rear
Head	235 (12%)	7 (8%)
Thorax	489 (39%)	15 (58%)
Abdomen	88 (3%)	3 (7%)
Spine	149 (15%)	5 (8%)
Upper Extremity	203 (11%)	2 (2%)
Lower Extremity	366 (20%)	8 (17%)

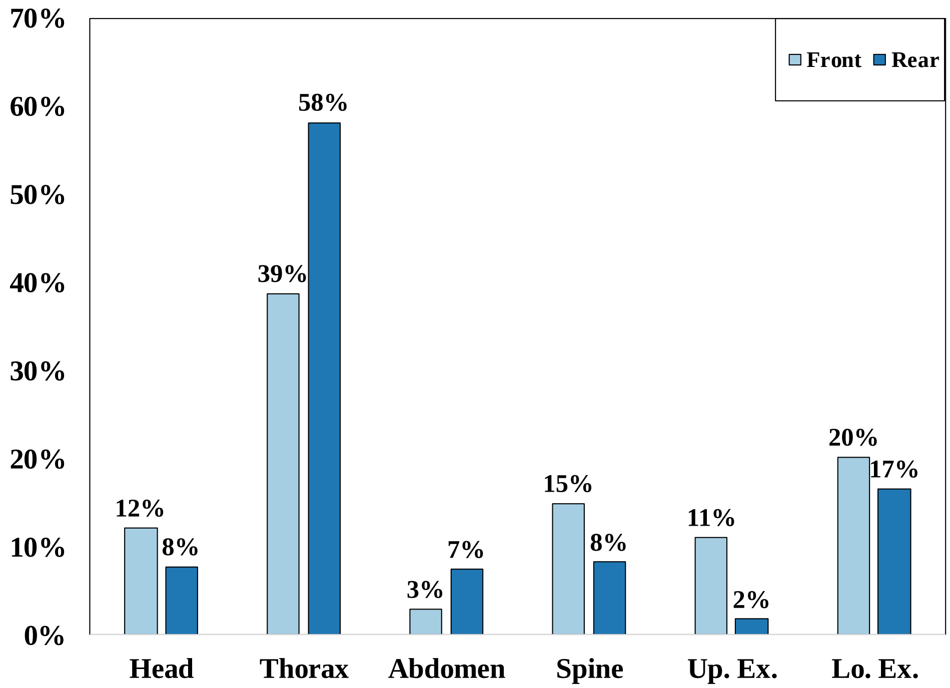


Figure 38. Distribution of AIS3+F injuries for all belted front- and rear-seated occupants aged 40 and over.

Of the seven (7) AIS3+F head injuries observed in the rear seats, most were traumatic brain injuries including hematoma/hemorrhage. One case included extended unconsciousness and one case included a skull fracture. Of the six (6) head injuries with a known injury source, three (3) were attributed to head-to-vehicle contact at a rigid point such as the B-pillar. This injury mechanism was primarily seen in front-to-front crashes that were classified as ‘angle’ type crashes instead of head-on crashes. This indicates that the impact was offset somewhat, likely leading to more lateral acceleration than a head-on crash would generate. In the absence of an airbag such as is provided to front seat occupants, rear seat occupant head excursion may be higher, possibly resulting in vehicle contact. Two (2) of the remaining head injuries were non-contact, and the remaining head injury was noted as resulting from indirect contact with the seat belt webbing/buckle.

Thoracic injuries made up a majority (58%) of injuries sustained by rear-seated occupants aged 40 and over. The proportion of AIS3+F thoracic injuries in belted rear-seated occupants in frontal crashes has been shown to increase with age [9], likely due to increased fragility of the thorax with aging [110-113]. Previous studies have also reported that in the elderly crash-involved population, thoracic injuries are most common [12]. Of the 15 occupants sustaining AIS3+F thorax injuries, all but one sustained multiple AIS3+F thorax injuries. Generally, occupants sustained an array of rib fractures accompanied by at least one soft tissue injury such as a lung contusion/laceration. Often times these injuries presented themselves coupled with hemo/pneumothorax. For each individual occupant, the source of all thorax injuries was consistent. Fourteen (14) of the 15 occupants sustaining AIS3+F thoracic injuries had a specified injury source. Ten (10) of the observed arrays of thoracic injuries were direct contact injuries with the seat belt. The remaining four (4) thorax injuries were attributed to contact with other internal vehicle structures, three of which were unspecified and one of which was the seat back.

The three (3) observed abdominal injuries were all different. One was a spleen laceration, one was a jejunum-ileum laceration, and the final was a colon/mesentery laceration. All injuries were attributed to direct seat belt contact. As discussed previously, this injury mechanism often occurs when the lap portion of a seat belt is incorrectly placed over the stomach rather than the hips and upper thighs, making an occupant more vulnerable to submarining in the event of a crash.

Of the five (5) observed AIS3+F spine injuries, four (4) were cervical spine injuries, three were contusions, and one was a fracture. Of the contusions, two (2) were noncontact injuries and one resulted from contact with the head restraint of the front seat directly before he occupant. The observed cervical spine fracture was similarly caused by contact with the back of the front seat. This mechanism of injury is akin to what was previously discussed regarding head injuries in the 9-12 year old occupant population. At times, upon frontal impact, a rear-seated occupant, even though they are belted, is propelled so far forward that their head contacts the back of the front seat before them. Depending on the angle of head-to-object contact, neck injuries may occur with hyper extension or flexion of the neck. Unlike for front-seated occupants, there is no airbag in the rear seats to prevent occupant contact with the vehicle interior in front of them, such as the front seat back. This type of occupant restraint – limiting head excursions and subsequent contact injuries – is entirely up to the seat belt. The final observed spine injury was a lumbar spine fracture due to seat belt contact. This injury pattern is consistent with inadequate seat belt positioning over the stomach.

AIS3+F extremity injuries in the rear-seats were all fractures due to direct contact with some interior vehicle structure, often the front seat back or center console. There were two (2) observed pelvis fractures, though one source of injury was unknown and the other was due to side door intrusion from a secondary impact.

DISCUSSION

It is clear from the injury and fatality risk results that children remain better protected in the rear versus front seats, displaying a lower risk of fatality in the rear seat than the front. Though occupants aged 39 and under benefit from being rear seated in a frontal crash, quite the contrary is true for their older counterparts. Considering all MAIS2+F injuries, elderly occupants, both front- and rear-seated are at a significantly greater risk than their younger counterparts. When looking at the rear versus front RR of injury, the elderly (75+ years) display a significantly greater injury risk when rear seated. When considering the RR of fatality, this difference in risk between the rear and front seats emerges at a younger age in mature adults (40+ years), who were at a significantly higher risk. when rear seated. Consistent with the findings of the injury model, this difference in rear versus front seat fatality risk is much more exaggerated in the elderly population (75+ years).

Vehicle model year was an insignificant predictor of MAIS2+F injury in all models when adjusting for total delta-v, occupant age, occupant sex, and vehicle body type, though when considering the absolute risk of MAIS2+F injury in the rear-seated occupant population it has significantly decreased in newer model year vehicles (≥ 2007) compared to older ones (2000-2002). These findings are, however, in stark contrast to the results of the fatality analysis. When considering these higher severity crashes involving a fatality, the absolute risk of fatality in the rear seat appears to be slightly lower in the oldest vehicle model year category of 2000-2002. However, the odds of fatality among model year groupings for all restrained rear seat occupants in our study sample showed no statistically significant difference. This finding suggests that the overall safety of the rear seats in preventing fatality has remained static across all model year vehicles. When considered together, the results of the injury and fatality analyses suggest that while rear-seat vehicle safety systems in newer vehicles have been effective at decreasing the overall risk of moderate-to-fatal injury, these systems may not have the same protective effect in the most serious crashes yielding fatality.

The results of the fatality analysis further shows that the RR of fatality for a restrained occupant involved in a frontal collision in a rear versus front seating position has significantly increased in newer model year passenger vehicles compared to older ones, which is again contrary to the findings of the MAIS2+F injury analysis. In the injury analysis, a decrease in MAIS2+F injury risk in the rear seats contributed to seeing a significantly lower RR of injury in the rear seats than the front seats in the newest model year vehicles. However, it was shown that the absolute risk of fatality in the rear seat was not changing with time, so the difference in fatality RR is likely a result of improved safety and subsequent reductions in fatality in the front seats. Again, this difference indicates that rear-seat safety advances may not be as effective in the most serious crashes, such as those documented in FARS, as front seat safety systems.

The findings of an increased fatality risk in the rear seats in the newest model year vehicles are consistent with prior research and continue to highlight the growing disparity in the crash protection afforded to occupants of front and rear rows of passenger vehicles. Current U.S. occupant protection regulation in a frontal impact condition (FMVSS 208) and the forward crash NCAP test do not consider the safety of occupants seated in the rear. This appears to be reflected in many current vehicle designs. For example, seatbelt reminders, pretensioners, and load limiters are all nearly standard equipment in the front seats of new vehicles today. However, in the U.S., these technologies are seldom carried into the rear seats.

The case reviews on AIS3+F injured rear-seated occupants aged 40 and over in this study provided evidence that seat belt-induced thoracic injuries were very common amongst that specific population. Even in the younger occupant population of 9-12 year olds, thorax injuries were present in a large fraction of cases. In the front seats, the combination of a pretensioner and load limiter have demonstrated injury-reducing benefits, especially thoracic injuries, in sled tests [114], crash tests [115], and in real-world crash data [116]. To date, there have been a much more limited number of studies on the effect of adding enhanced restraint systems to the rear seats. Both low speed (~29 km/hr) and high speed (~48 km/hr) sled tests on various ATDs and PMHS wearing pretensioner and load limiter equipped seat belts have shown that reductions in shoulder belt tension, chest deflection, spine acceleration, pelvic excursion, and femur excursion are possible [14, 117, 118]. Additionally in such tests, ATD loading is brought to below the injury assessment reference values (IARVs), whereas with traditional three-point belts these thresholds are almost always exceeded in the rear seats [119, 120].

That being said, implementation of advanced seat belt systems including a pretensioner and load limiter in the rear seats may not be exactly the same as in the front seats. In the rear seats especially, in part due to the lack of frontal airbags available to those seating positions, forward excursion of the occupant(s), especially the head, must be limited to avoid contact with interior vehicle surfaces such as the back of the front seat. In the case reviews of AIS3+F injuries in the 9-12 year old rear-seated occupant population, the majority of head injuries were from direct contact with the back of the front seat. While implementation of pretensioners would serve to mitigate this mechanism of injury by removing the slack from the seat belt upon impact, the incorporation of load limiters must be taken with care. Load limiters allow belt payout after a certain amount of force is being applied to the belt (and subsequently to the occupant), but automakers must ensure that payout is not so much that it will allow for an occupant to contact unwanted interior vehicle structures. In the aforementioned studies involving rear seat sled tests with pretensioner and load limiter equipped seat belts, results on head excursion were mixed. Some studies found reductions in head excursion (likely due to the pretensioner), some found no change in head excursion, and even then some found increases in head excursion (likely due to the load limiter). The balance between limiting occupant excursion while also limiting belt force is a complex issue, proving difficult even in the front seats [121]. The findings of this study's case reviews continue to highlight the challenge in designing rear seat vehicle safety systems for occupants of all ages, though the conclusions on types and sources of injury suggest that pretensioners and load limiters could be advantageous to both populations if implemented appropriately.

This issue of disparate front versus rear seat safety is not unique to the U.S. vehicle fleet. In an effort to improve restraint systems in the rear seats, the Euro NCAP added a frontal full width rigid barrier test in 2015 [122]. In this test, the subject vehicle is impacted into a rigid barrier at a velocity of approximately 50 km/h (31 mi/h) with 100% overlap. The test establishes performance requirements for two 5th percentile female dummies – one seated in the driver's seat and one seated in the rear passenger side (right side) seat. Just two years later in 2017, of the 51 new model year vehicles tested by Euro NCAP, 48 (94%) of the new vehicles had rear seat pretensioners and load limiters as standard equipment [123]. By contrast, in the U.S. in 2013, the National Transportation Safety Board (NTSB) reported that only 11 of the 35 (31%) common vehicle brands offered rear seat pretensioners and load limiters as either *optional* or standard equipment [124]. Currently, the U.S. NCAP is entertaining the idea of including a rear seated 5th percentile female Hybrid III dummy and corresponding injury criteria as part of their frontal crash test rating system [96, 125].

CONCLUSIONS

In newer model year passenger vehicles, the relative risk of fatality for a restrained occupant involved in a frontal crash is higher in the rear than the front seats. This appears to be an issue primarily for adults aged 40 and over, with a huge increase in both injury and fatality risk for those over the age of 75. Children aged 8 and under – who comprise a majority of rear seated occupants – continue to experience a great safety benefit in the event of a frontal crash by being rear seated. These results agree with previous studies and continue to highlight the challenge in implementing rear seat occupant protection systems that benefit all ages. Passenger vehicle safety systems have greatly improved over the last couple decades, but the increase in the RR of fatality between the rear and front seats in newer model year vehicles found here shows that rear seat occupants are not experiencing the same benefit as front seated occupants in the highest severity frontal crashes. Implementing advanced restraint systems such as seatbelts that are equipped with a pretensioner and a load limiter – commonplace in the front seats of passenger vehicles – into the rear row(s) of passenger vehicles would be a great first step towards more equitable occupant safety in frontal impacts.

6. SIDE IMPACTS AND INJURIES TO REAR SEATED OCCUPANTS

BACKGROUND

Side impacts are a challenging occupant protection problem chiefly due to the short distance between vehicle occupants and the possible side intruding structure(s). In comparison to front and rear impacts, there is very little vehicle crumple zone available in a side impact to dissipate loading to an occupant. While stronger side structures can help to reduce occupant compartment intrusion, occupant restraint systems such as airbags are also essential to aid in the absorption of collision energy. In the modern vehicle fleet, side head and torso airbags have been proven to be highly effective at supplementing vehicle structure in providing occupant protection in side crashes [60, 61]. Side curtains were initially designed to protect front row occupants, but have since been extended to rear seat occupants.

As shown in Figure 39, both near- and far-side impact fatalities have decreased by approximately a third between 1990 and 2015. This further attests to the effectiveness of side curtain airbags, however, these side airbags primarily benefit occupants on the near-side of impact. Even today, there are few countermeasures targeted at protecting any far-side occupant(s) [55, 126-128]. Since the great strides in side impact protection have been made over ten years ago, little has been published comparing the relative risk of injury and fatality between front and rear seat occupants in side crashes with and without these improved countermeasures.

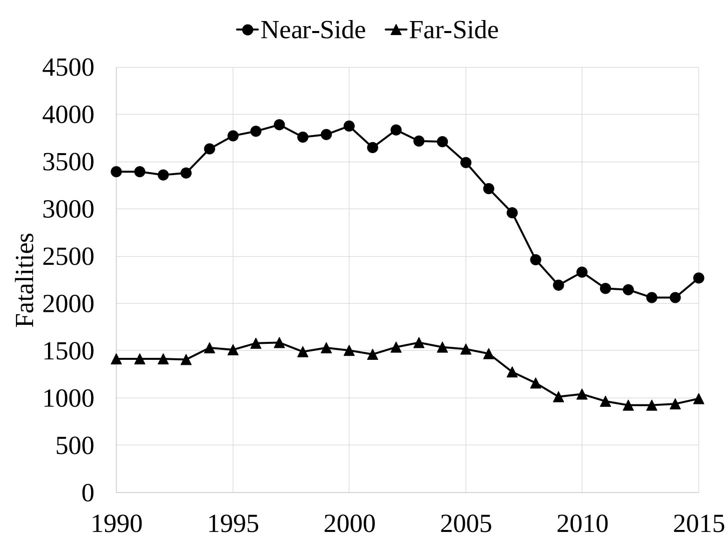


Figure 39. Passenger vehicle occupant fatalities in side impacts (FARS 1990-2015).

FMVSS 214

Federal Motor Vehicle Safety Standard (FMVSS) 214, Side Impact Protection, establishes minimum requirements for occupant protection in side crashes [129]. However, all prescribed tests, enumerated below, are near-side impacts.

Moving Deformable Barrier Test

This test was upgraded in 2007 with phase-in occurring from vehicle model years 2009 to 2012. The MDB test has always been designed to simulate a 90° side impact where the striking vehicle (the moving deformable barrier, or MDB) impacts the stationary target vehicle at approximately 53.9 kph (33.5 mph). The orientation and velocity of the MDB used in the test was chosen to simulate an impact where both vehicles would have been moving prior to impact such as in an intersection-type crash scenario. The test upgrade in 2007 was primarily to specify that vehicles would be tested with new, more advanced ATDs – the ES-2re, representing a 50th percentile male, and the SID-IIs, representing a 5th percentile female – than the side impact dummy (SID) that had been previously used. Two of the previously mentioned ATDs are seated in each target vehicle during this test. The ES-2reis positioned in the driver's seat and a SID-IIs is positioned in the left rear passenger seat (near side to impact). Head, thoracic, and pelvic protection was enhanced through the test upgrade and use of these ATDs. There are currently no U.S. requirements for far-side crash performance either in the front or rear seats in a dynamic side impact configuration.

Pole Test

This test, also phased-in from 2009 to 2012, is designed to simulate a side impact where the target vehicle is impacted into a fixed, rigid pole approximately 254 mm (10 in) in diameter at a speed of 32 kph (20 mph). The target vehicle may be tested on either the driver or right front passenger side. An option of ATD is provided for this test as well. Either a 50th percentile male ES-2re or 5th percentile female SID-IIs may be positioned in the front near side seating location to impact. There is no standard stipulating ATD performance requirements in a pole impact for the rear seating positions.

OBJECTIVE

The objective of this study is to examine occupant injury outcomes after a number of different side impact configurations including vehicle-to-vehicle near-side, vehicle-to-vehicle far-side, and vehicle-to-pole side impacts. The injury risk which each of these crash modes poses to vehicle occupants will be modeled with a focus on differences, if any, between rear and front seating positions.

METHODOLOGY

This study was based upon crashes extracted from NASS-CDS and FARS case years 2000 to 2015 (inclusive). In order to be included in the side impact study dataset, cases were first required to meet the following criteria:

- Case vehicle was either a car or a light truck, van, or sport utility vehicle (LTV)
- Case vehicle was of model year 2000 or newer
- No vehicle rollover
- Occupant was not fully ejected from the vehicle

Different methods were required for CDS and FARS case selection based on the desired side-impact crash modes for this study. A crash is made up of a series of events, and each crash event consists of a vehicle impact location and an object contacted or non-collision event (such as a rollover). Among a sequence of crash events are two notable points of interest – the first harmful event and the most harmful event. The first harmful event is the first injury and/or damage producing event of the crash. The most harmful event is the event that results in the most severe injury and/or the greatest vehicle damage during the crash sequence. In all single-event crashes and in some multi-event crashes, these two events are synonymous.

Within the CDS database, first harmful event for each crash-involved vehicle can be identified using the sequence of events catalogued in the 'EVENT' data set, where each vehicle impact location and object contacted/non-collision event are listed in order of occurrence. In the CDS vehicle exterior ('VE') data set, the most harmful crash event is characterized for each crash-involved vehicle by the highest deformation location (GAD1) and the highest object contacted (OBJCONT1). The delta-v (longitudinal, lateral, and total) for a crash-involved vehicle reported in CDS is derived from the most harmful crash event. In injury studies, the most harmful crash event is generally selected for analysis as it is responsible for the most serious injuries and has an associated measure of crash severity (delta-v).

In FARS, the first harmful crash event is characterized by a combination of 1) the variable ‘IMAPCT1’ (reported in the vehicle and person data sets) which defines the vehicle’s initial contact point and 2) the variable ‘HARM_EV’ (reported in the accident, vehicle, and person data sets) which defines what the object contacted/non-collision event was. The most harmful event is available as ‘M_HARM’ in the vehicle data set, but this only provides the object contacted/non-collision event. The variable indicating what area on the vehicle corresponds to this most harmful crash event was discontinued in 2012. While all damaged areas to the crash-involved vehicle are available in the ‘damage’ data set, it is unclear which area was damaged as a result of the most harmful collision. Therefore, given the desired case years for this study (2000-2015), the first harmful event must be used in FARS analyses in order to identify a paired impact location and object contacted.

Given this, the CDS dataset was further selected based on the following criteria for each crash mode of interest:

- Vehicle-to-Vehicle (Most Harmful Event), from the vehicle exterior data set
    - GAD1 = ‘L’ (left vehicle side) or ‘R’ (right vehicle side)
    - OBJCONT1 = 1:11 (another motor vehicle in transport)

- Vehicle-to-Vehicle (First Harmful Event), from the event data set
    - ACCSEQ (accident sequence numeric indicator) = 1
    - GADEV1 (greatest area of damage during the first event) = ‘L’ or ‘R’
    - OBJCONT = 1:11 (another motor vehicle in transport)

- Vehicle-to-Pole (Most Harmful Event), from the vehicle exterior data set
    - GAD1 = ‘L’ or ‘R’
    - OBJCTON1 = 41:42 (trees), 50:53 (poles)

- Vehicle-to-Pole (First Harmful Event), from the event data set
    - ACCSEQ = 1
    - GADEV1 = ‘L’ or ‘R’
    - OBJCONT = 41:42 (trees), 50:53 (poles)

The FARS dataset was selected based on the following criteria for each cash mode of interest:

- Vehicle-to-Vehicle (First Harmful Event), from the vehicle or person table
    - IMPACT1 = 2:4, 8:10 (clock points around the vehicle), 61:63 (left side of vehicle), 81:83 (right side of vehicle)
    - HARM_EV = 12 (collision with another motor vehicle in transport)

- Vehicle-to-Pole (First Harmful Event), from the vehicle or person table
    - IMPACT1 = 2:4, 8:10 (clock points around the vehicle), 61:63 (left side of vehicle), 81:83 (right side of vehicle)
    - HARM_EV = 27:31 (poles), 42 (tree)

For analyses on MAIS2+F injury risk, selected NASS-CDS cases were used to obtain both crash exposure counts and injury outcome counts. The side-impact events used in these MAIS3+F injury analyses were all selected based on the most harmful crash event, primarily so that delta-v (crash severity) could be included as a model covariate. For analyses of fatality risk, from both CDS and FARS, cases that had been selected based on the first harmful crash event were used for analyses. This is the only feasible selection method in FARS for the time period of study, and case selection must be consistent from the two databases to allow for data combination. FARS data on occupants involved in selected cases were substituted for the weighted sample of comparable NASS-CDS fatal cases in order to produce a combined dataset of all occupants exposed to a frontal crash with exact fatality counts. This is the same combination method used previously in the analyses on frontal impacts. Additional details on the technique can be found in the 'Methodology' section of Chapter 5.

Variables of interest in this study that may affect the risk of injury to occupants include occupant age, occupant sex, occupant restraint use, vehicle model year, and crash compatibility. Each of these variables were treated as categorical in this study. Occupant age was categorized into four (4) groups: 0-8 years, 9-15 years, 16-54 years, and 55+ years. These groups were chosen to reflect both the age groups that are recommended for different CRS systems, the age groups that are more commonly front seated, and finally the age groups known to be overall more susceptible to injury due to frailty. Occupant restraint use was simply categorized as 'yes' or 'no' variable, where children who were seated in a CRS were included in the 'yes' (restrained) category.

Examining the availability and/or deployment status of curtain and seat/torso airbags and how that influences injury and fatality outcomes in side impacts would be ideal. However, the CDS data on airbag equipment and function during the crash in the selected dataset for this study is not robust enough to allow for meaningful statistical analysis. Since case year 2000, CDS has included 'airbag' tables indicating the availability and deployment status of all vehicle equipped airbags when such information is available. In over half (66%) of selected cases for this study, information on curtain and seat airbags was unavailable in these data tables. Therefore, as a substitute for the presence of these side impact safety systems, vehicle model year was used as a model covariate. For all side impact analyses, vehicle model years were categorized as 2000-2009 and 2010-2016 to reflect the model years affected by the FMVSS 214 side impact test upgrades, where the categorizations represent those vehicles manufactured pre-upgrade and those vehicles manufactured during the phase-in and post-upgrade, respectively. Presumably, vehicles designed for the upgraded tests would at least be equipped with curtain airbags if not seat airbags as well.

Finally, 'crash compatibility' refers to the difference in size between the two crash collision partners, which has been shown to significantly affect crash injury outcomes [130]. In this study, passenger vehicle sizes were classified as either a 'car' or a 'LTV,' yielding four possibilities for crash compatibility configuration – a car being struck by either 1) another car or 2) an LTV or a LTV being struck by either 3) a car or 4) another LTV.

Injury Model Development

Vehicle-to-Vehicle Side Impacts

First, in order to determine the potential effect of seating position on MAIS2+F (moderate-to-fatal) injury outcome in vehicle-to-vehicle side impacts, two logistic regression models were constructed to predict MAIS3+F injury outcome from the CDS datasets selected based on the most harmful crash event. One model was for near-side impacts and one was for far-side impacts. In both configurations, MAIS2+F injury outcome was modeled as a function of total delta-V (crash severity), occupant seating position (front vs. rear), occupant age, occupant sex, occupant restraint use, vehicle model year, and crash compatibility, as shown in Equation 6.

To account for the stratified sampling scheme used by CDS, the logistic regression model was constructed using the 'svyglm' function in the 'survey' package of R.

$$Risk\ of\ MAIS2+F\ Injury\ in\ Vehicle\ to\ Vehicle\ Side\ Impacts = \frac{1}{1+e^{-(Intercept+\beta_{DV}*DV+\beta_{FvR}*FvR+\beta_{Age}*Age+\beta_{Sex}*Sex+\beta_{Belt}*Belt+\beta_{MY}*MY+\beta_{CC}*CC)}}$$ Equation 6

Next, the combined CDS-FARS dataset of vehicle-to-vehicle side impacts, selected based on the first harmful crash event, was used to estimate the risk of fatality in this crash mode using another set of logistic regression models – one for near-side and one for far-side impacts. The probability of fatality was modeled as a function of occupant seating position (front vs. rear), occupant age, occupant sex, occupant restraint use, and vehicle model year as shown in Equation 6. Crash compatibility is omitted in this model as the vehicle body type of a collision partner is not readily available in FARS over the entire time period of study. The logistic regression model was constructed using 'glm' function in R and the 'Logistic' function in SAS. These logistic modeling tools can consider the case weights present in the combined CDS-FARS dataset. Again, the combination dataset retained the CDS sampling weights and set case weights in FARS to one (1) as FARS is a census database.

$$Risk\ of\ Fatality\ in\ Vehicle\ to\ Vehicle\ Side\ Impacts = \frac{1}{1+e^{-(Intercept+\beta_{FvR}*FvR+\beta_{Age}*Age+\beta_{Sex}*Sex+\beta_{Belt}*Belt+\beta_{MY}*MY)}}$$ Equation 7

Odds ratios of injury or fatality between the rear and front seats were further calculated across model covariates of interest. The comparison of presented ORs is between rear seat occupants and all front seat occupants (both drivers and passengers).

Vehicle-to-Pole Side Impacts

As reported in the following results, the sample size of vehicle-to-pole impacts in all selected data sets were exceptionally small. Therefore, analyses of this crash mode will focus exclusively on exposure and injury trends, as statistical modeling on so few cases does not yield meaningful results.

RESULTS AND DISCUSSION

Vehicle-to-Vehicle Side Impacts

CDS Dataset Composition

Table 28 and Table 29 present both the observed and estimated composition of the vehicle-to-vehicle side impact occupant dataset for both near- and far-side impacts, respectively. Both rear- and front-seated occupants are exposed to near- and far-side impacts with roughly the same frequency, which is consistent with previous literature [55, 131, 132]. When considering occupants sustaining moderate-to-fatal injuries, near-side impacts yield more of these outcomes than far-side impacts. Rear-seated occupants involved in vehicle-to-vehicle near- and far-side impacts accounted for 12% and 11% of all occupants exposed, respectively. This is consistent with the earlier finding in Chapter 3 that approximately 12% of all passenger vehicle occupants are rear-seated at the time of a crash. In other words, vehicles carrying rear-seated occupants are not more likely to be involved in vehicle-to-vehicle side impacts when compared to all crash modes. Further, these rear-seated cases appear to be underrepresented in injury outcomes. In near-side impacts, of the MAIS2+F injured occupant population, only 6% were rear-seated. Similarly, in far-side impacts, a mere 7% were rear-seated. That said, the differences in exposure and injury outcomes are relatively small, so further investigation is warranted to identify if rear-seated passenger vehicle occupants are actually at a different risk of serious injury in vehicle-to-vehicle side impacts than their front-seated counterparts.

Table 28. CDS most harmful event vehicle-to-vehicle near-side impact data sample characteristics.

Sample Characteristic	Crash-Exposed Occupants observed (weighted %)		MAIS2+F Injured Occupants observed (weighted %)	
	Front Seat N = 5,163	**Rear Seat** N = 724	**Front Seat** N = 1,129	**Rear Seat** N = 96
Occupant Age				
0-7	18 (0.33)	229 (37.46)	-	17 (20.37)
8-15	107 (2.50)	175 (21.12)	26 (1.99)	15 (15.43)
16-54	3,688 (71.40)	241 (33.93)	709 (57.28)	41 (49.69)
55+	1,314 (24.66)	59 (4.18)	393 (40.72)	22 (14.39)
Unknown	36 (1.12)	20 (3.31)	1 (0.00)	1 (0.12)
Occupant Sex				
Male	2,335 (46.16)	362 (47.59)	497 (39.01)	47 (43.33)
Female	2,814 (53.44)	352 (51.28)	632 (60.99)	49 (56.67)
Unknown	14 (0.40)	10 (1.13)	-	-
Restraint Use				
Yes (Belted)	4,476 (89.52)	547 (80.61)	919 (79.65)	54 (54.39)
No (Unbelted)	520 (7.86)	146 (13.75)	179 (19.05)	40 (45.02)
Unknown	167 (2.62)	31 (5.64)	31 (1.30)	2 (0.59)
Vehicle Model Year				
2000-2009	4,532 (86.40)	631 (82.58)	1,016 (88.11)	83 (91.33)
≥ 2010	631 (13.60)	93 (17.42)	113 (11.89)	13 (8.67)
Crash Compatibility				
Car ← Car	1,841 (36.45)	236 (33.23)	331 (30.67)	28 (22.25)
Car ← LTV	1,447 (25.79)	170 (24.88)	452 (33.79)	35 (40.68)
LTV ← Car	839 (17.00)	145 (17.87)	84 (12.82)	7 (5.60)
LTV ← LTV	680 (13.89)	120 (17.55)	136 (10.89)	15 (18.35)
Other / Unknown	356 (6.87)	53 (6.47)	126 (11.83)	11 (13.12)

Table 29. CDS most harmful event vehicle-to-vehicle far-side impact data sample characteristics.

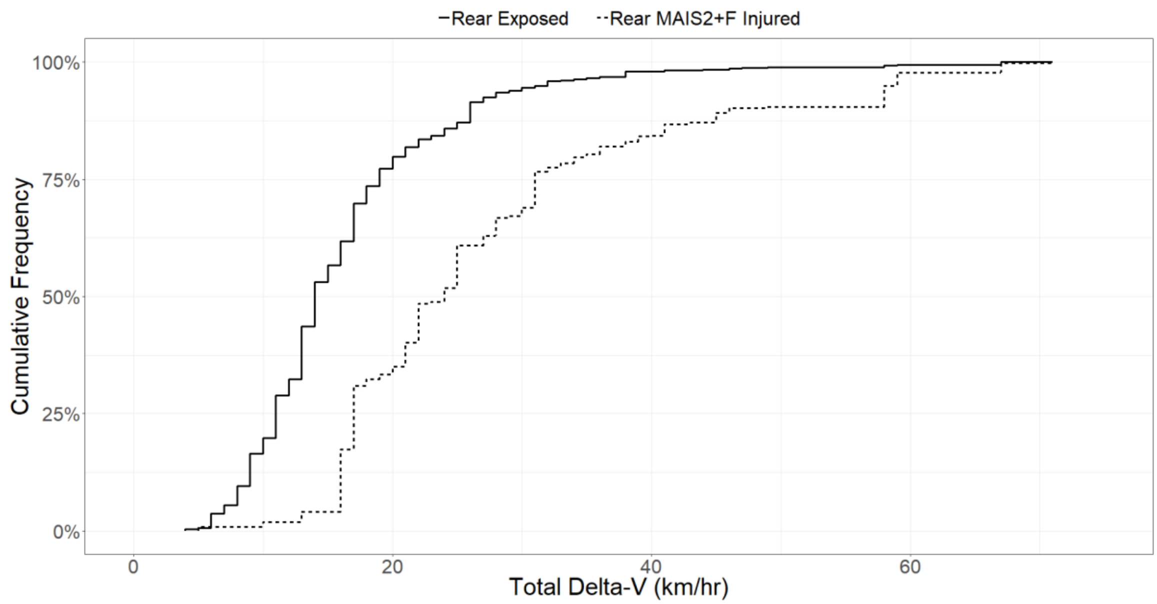
Sample Characteristic	Crash-Exposed Occupants observed (weighted %)		MAIS2+F Injured Occupants observed (weighted %)	
	Front Seat N = 4,574	**Rear Seat** N = 682	**Front Seat** N = 561	**Rear Seat** N = 51
Occupant Age				
0-7	13 (0.42)	237 (37.28)	2 (0.04)	9 (6.61)
8-15	136 (3.73)	155 (22.69)	11 (1.59)	11 (22.58)
16-54	3,278 (68.56)	228 (28.93)	345 (57.86)	23 (55.49)
55+	1,104 (25.80)	46 (5.88)	203 (40.51)	8 (15.32)
Unknown	43 (1.48)	16 (5.22)	-	-
Occupant Sex				
Male	2,072 (43.53)	321 (46.15)	264 (51.20)	19 (23.29)
Female	2,480 (55.64)	346 (48.85)	297 (48.80)	32 (76.71)
Unknown	22 (0.83)	15 (5.00)	-	-
Restraint Use				
Yes (Belted)	3,947 (89.96)	528 (81.57)	399 (64.85)	27 (49.18)
No (Unbelted)	487 (7.88)	126 (14.97)	144 (33.82)	21 (48.80)
Unknown	140 (2.16)	28 (3.47)	18 (1.34)	3 (2.02)
Vehicle Model Year				
2000-2009	4,002 (85.48)	603 (85.09)	502 (85.12)	49 (83.49)
≥ 2010	572 (14.52)	79 (14.91)	59 (14.88)	2 (16.51)
Crash Compatibility				
Car ← Car	1,679 (36.54)	212 (31.16)	175 (30.11)	14 (31.92)
Car ← LTV	1,278 (27.18)	166 (22.67)	223 (41.14)	18 (28.56)
LTV ← Car	751 (17.50)	141 (21.58)	44 (9.64)	6 (19.02)
LTV ← LTV	579 (13.13)	114 (16.48)	56 (9.35)	8 (12.93)
Other / Unknown	287 (5.65)	49 (8.11)	63 (9.76)	5 (7.57)

Further exploring the occupant composition by model covariates in Table 28 and Table 29 reveals that the age distribution of front- and rear-seated crash-exposed and injured occupants varied greatly. This is consistent with findings in previous chapters, where a majority of rear-seated crash-exposed occupants are children and adolescents. In both crash modes, while occupants under the age of 16 comprised almost 60% of the rear-seated occupant population, they made up less than 5% of the front-seated occupant population. For both front-and rear-seated occupants, those aged 55 and older are over-represented in MAIS2+F injury outcomes.

The other occupant population in both the front and rear seats that is notably over-represented in MAIS2+F injury outcome are those occupants who are unbelted at the time of the crash. While these occupants account for only 8-15% of all near- or far-side impact exposed occupants, they make up 19-49% of all MAIS2+F injured occupants. This over-representation is slightly more prominent in the rear-seated occupant population than their front-seated counterparts.

With respect to vehicle model year, as would be expected, at least for near-side impacts given the FMVSS 214 update, newer model year vehicles (2010+) account for fewer MAIS2+F injured occupants than those who are near-side crash exposed. Finally, when considering crash compatibility, the most notable difference between exposure and MAIS2+F injury rates are in crash cases involving a car struck by an LTV. These cases are over-represented in MAIS2+F injury outcome, which is consistent with the prior research previously discussed.

Near- and far-side crash involved vehicles' total, or resultant, delta-v's are shown in Figure 40 and Figure 41, respectively, as cumulative distributions for both rear- and front-seated occupants. The trends in total delta-v between rear- and front-seated crash-exposed occupants are very similar in both near- and far-side impacts. For crash-exposed rear-seated occupants, the median total delta-v in both near- and far-side impacts was 14 km/hr, and for MAIS2+F injured rear-seated occupants it was 24 km/hr in near-side impacts and 23 km/hr in far-side impacts. Crash-exposed front-seated occupants experienced delta-v's of 15 and 16 km/hr in near- and far-side impacts, respectively. For injured front-seated occupants, the mean delta-v was 24 and 27 km/hr in near- and far-side impacts, respectively.



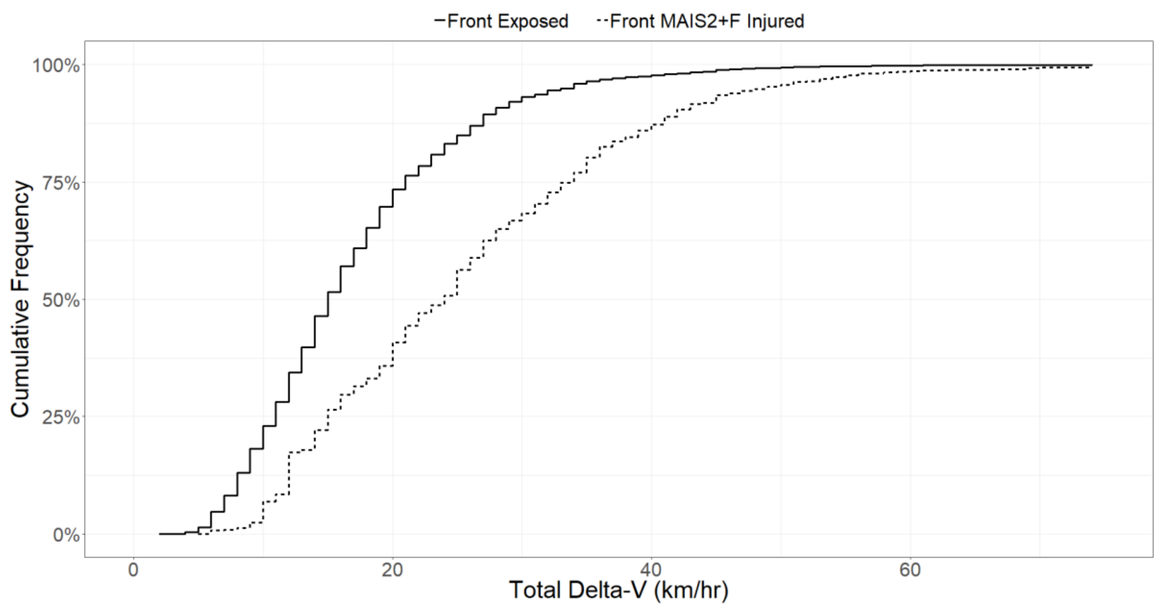


Figure 40. Cumulative distribution of total, or resultant, delta-v (km/hr) for near-side impact rear-seated (top) and front-seated (bottom) occupants.

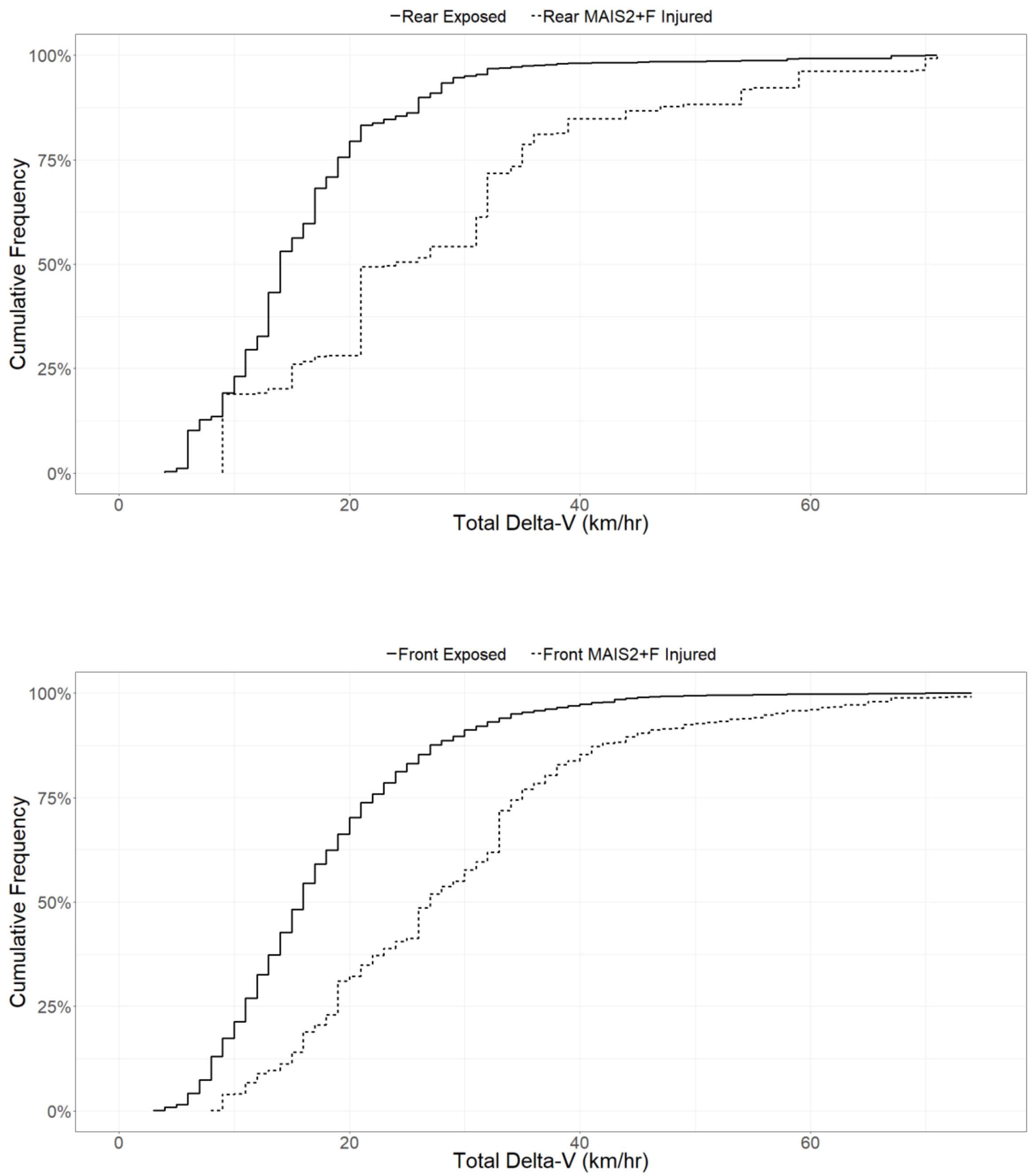


Figure 41. Cumulative distribution of total, or resultant, delta-v (km/hr) for far-side impact rear-seated (top) and front-seated (bottom) occupants.

<u>Comparison of MAIS2+F Injuries in the Rear and Front Seats</u>

Figure 42 shows the distribution of MAIS2+ injuries sustained by both front and rear seated occupants in vehicle-to-vehicle near-side impacts, which are relatively similar. For both rear and front seat occupants, most MAIS2+ injuries in near-side impacts were head/face/neck injuries, followed by thorax and lower extremity injuries. This finding is consistent with prior research [133, 134]. The greatest differences in injury patterns between front- and rear-seated occupants were seen in the spine and upper extremities. Rear-seated occupants sustained MAIS2+F spine injuries more frequently than their front-seated counterparts, while front-seated occupants were more likely to sustain upper extremity injuries. In all near-side impacts, previous literature suggests that most injuries regardless of body region are attributable to intrusion and/or direct contact to the vehicle wall/door.

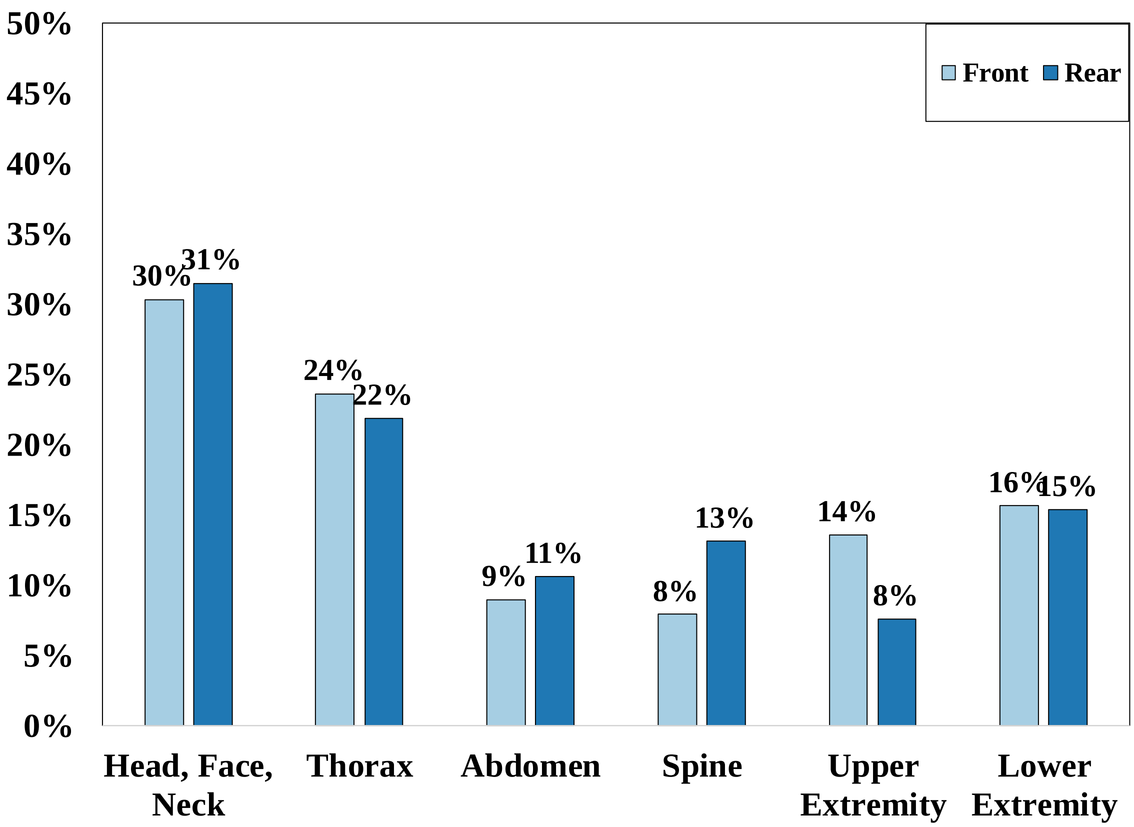


Figure 42. Distribution of MAIS2+F injuries sustained in near-side vehicle-to-vehicle side impacts for both front and rear seat occupants.

Considering far-side impacts, Figure 43 shows the distribution of MAIS2+ injuries sustained by both front and rear seated occupants. Far-side crashes most frequently led to head/face/neck injuries followed by upper extremity injuries, which, again, is consistent with prior literature [55, 135]. In these far-side crashes, rear-seated occupants were more likely to sustained head/face/neck, abdomen, and spine injuries, whereas front-seated occupants more commonly sustained thorax and lower extremity injuries than those who were rear-seated.

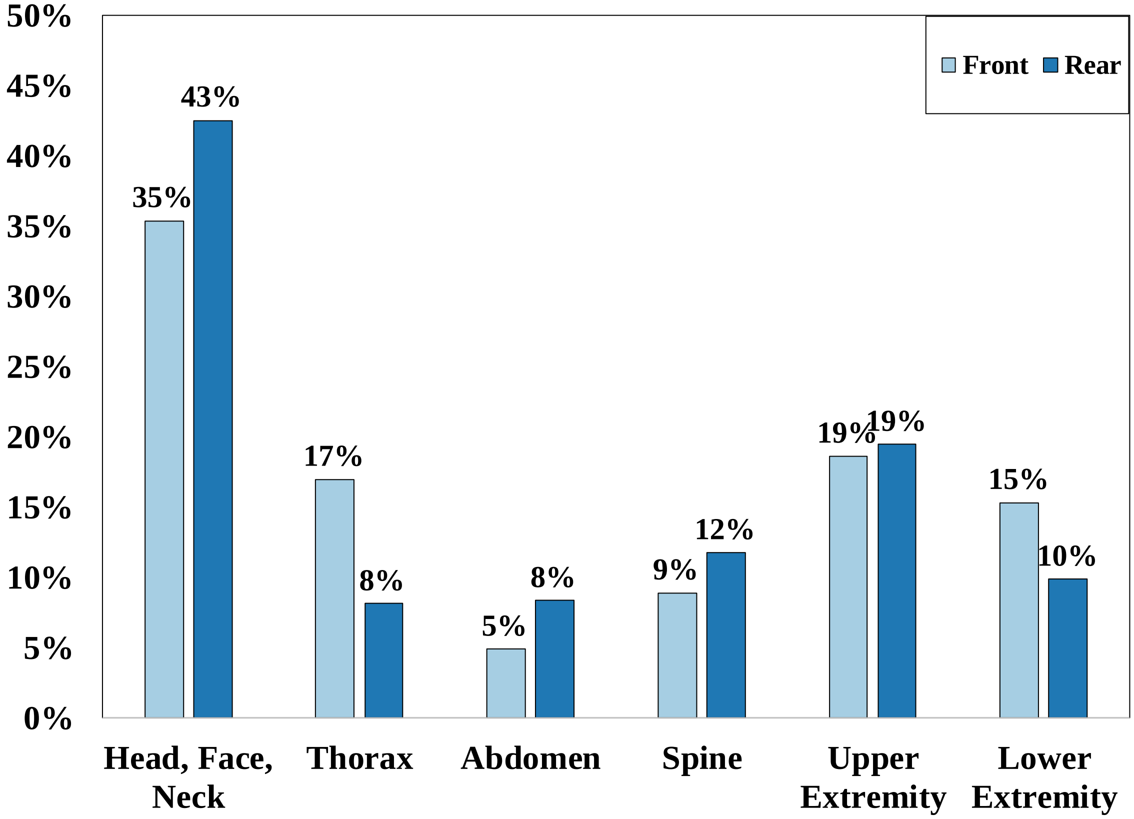


Figure 43. Distribution of MAIS2+F injuries sustained in far-side vehicle-to-vehicle side impacts for both front and rear seat occupants.

MAIS2+F Injury Models

In order to determine if there is a statistical difference in overall MAIS2+F injury risk based on if an occupant is rear- or front-seated in vehicle-to-vehicle side impacts, the effect of numerous logistic regression model covariates was evaluated. Two separate models were constructed – one for near-side and one for far-side impacts, the results of which are presented in Table 30. In both models, total delta-V, occupant age, and occupant restraint use were statistically significant in influencing MAIS2+F injury outcome ($\alpha = 0.05$). However, in both models, whether an occupant was rear- or front-seated did not have a statistically significant effect on injury outcome. This suggests that there is no difference in the overall moderate-to-fatal injury risk between the front and rear seats in vehicle-to-vehicle side impacts, both near- and far-side, when adjusting for delta-V, occupant age, occupant sex, restraint use, vehicle model year, and crash compatibility.

Table 30. Near- and far-side impact MAIS2+F logistic regression model parameter estimates from CDS dataset.

Sample Characteristic	Near-Side Model		Far-Side Model	
	Coefficient Estimate (Std. Error)	**p-Value**	**Coefficient Estimate (Std. Error)**	**p-Value**
Intercept	-4.92 (0.49)	< **0.001**	-5.78 (0.51)	< **0.001**
Total Delta-V	0.09 (0.01)	< **0.001**	0.09 (0.01)	< **0.001**
Seat Position				
Front	Reference		Reference	
Rear	-0.39 (0032)	0.223	-0.04 (0.65)	0.948
Occupant Age				
0-7	-0.69 (0.59)	0.241	-2.17 (0.88)	**0.015**
8-15	-0.92 (0.39)	0.018	-0.62 (0.57)	0.280
16-54	Reference		Reference	
55+	0.83 (0.23)	< **0.001**	1.07 (0.25)	< **0.001**
Occupant Sex				
Male	Reference		Reference	
Female	0.35 (0.23)	0.122	0.17 (0.24)	0.469
Restraint Use				
No (Unbelted)	1.08 (0.32)	< **0.001**	2.13 (0.33)	< **0.001**
Yes (Belted)	Reference		Reference	
Vehicle Model Year				
2000-2009	0.18 (0.37)	0.633	-0.19 (0.47)	0.682
≥ 2010	Reference		Reference	
Crash Compatibility				
Car ← Car	Reference		Reference	
Car ← LTV	0.09 (0.20)	0.633	0.22 (0.32)	0.500
LTV ← Car	0.05 (0.41)	0.895	0.28 (0.37)	0.452
LTV ← LTV	-0.01 (0.29)	0.959	-0.69 (0.36)	0.057

As in rear and frontal impacts, occupant demographics were found to significantly influence serious injury outcomes. The finding that older occupants are more likely than younger occupants to be seriously injured is again not surprising in this analysis. Previous studies using

CDS to examine injury risk in side impacts have shown that elderly occupants were three times as likely as younger occupants to be seriously injured [56]. This analysis of vehicle-to-vehicle side impacts agrees with those findings. Table 31 shows the odds ratios of MAIS2+F injury for all occupants in both near- and far-side impacts derived from the previously presented logistic regression models. Occupants who are older (55+) exhibit greater odds of MAIS3+F injury than those who are younger. Specifically, compared to occupants aged 16-54, older occupants had over 2 times greater odds of MAIS2+F injury in both near- and far-side impacts, which are both statistically significant.

Table 31. Odds ratios of MAIS2+F injury for all vehicle-to-vehicle near- and far-side impacted occupants.

Sample Characteristic	Near-Side Model		Far-Side Model	
	Odds Ratio	**(95% CI)**	**Odds Ratio**	**(95% CI)**
Seat Position				
Front	Reference		Reference	
Rear	0.68	(0.36, 1.27)	0.96	(0.27, 3.45)
Occupant Age				
0-7	0.50	(0.16, 1.58)	0.11	(0.02, 0.65)
8-15	0.40	(0.19, 0.85)	0.54	(0.18, 1.65)
16-54	Reference		Reference	
55+	**2.30**	(1.46, 3.63)	**2.93**	(1.79, 4.78)
Occupant Sex				
Male	Reference		Reference	
Female	1.42	(0.91, 2.22)	1.19	(0.74, 1.90)
Restraint Use				
No (Unbelted)	**2.94**	(1.56, 5.55)	**8.46**	(4.39, 16.30)
Yes (Belted)	Reference		Reference	
Vehicle Model Year				
2000-2009	1.19	(0.58, 2.45)	0.82	(0.33, 2.08)
≥ 2010	Reference		Reference	
Crash Compatibility				
Car ← Car	Reference		Reference	
Car ← LTV	1.10	(0.75, 1.62)	1.24	(0.66, 2.34)
LTV ← Car	1.06	(0.47, 2.37)	1.32	(0.64, 2.72)
LTV ← LTV	0.99	(0.56, 1.74)	0.50	(0.25, 1.02)

The same previous logistic regression study on the odds of MAIS2+F injury in side impacts found that seat belt use was advantageous in both near- and far-side impacts, which agrees with the findings of this study [56]. Occupants who are unbelted presented statistically significant greater odds of MAIS2+F injury than those who are belted. Our study shows significance of belt use for both impact configurations, though it is more advantageous to the occupant in far-side impacts. In a far-side impact, there is more room for occupant excursion than in near-side impacts where occupant motion is limited by door contact. A seat belt helps keep an occupant in place during far-side impacts, limiting this excursion which may aid in injury prevention. Based on the model in this study, the adjusted odds of MAIS2+F injury to an unbelted occupant in near- and far-side impacts compared to a belted occupant are over 3 and 8 times greater, respectively.

Finally, although not statistically significant likely due to small sample sizes, the trend is that, on average, occupants traveling in older model year vehicles (2000-2009) exhibit slightly greater odds of MAIS2+F injury (1.19 times) than those who are traveling in newer vehicles when involved in near-side impacts. This result is expected due to the introduction of the aforementioned countermeasures such as side curtain airbags that began becoming more standard in vehicles with the FMVSS 214 upgrades. This trend is not however seen in far-side impacts, though occupants involved in far-side impacts stand to benefit less from these types of countermeasures as they do not interface with them as frequently.

CDS/FARS Dataset Composition

In contrast to the previous CDS dataset, for the CDS-FARS combination dataset, cases were selected based on the first harmful event instead of the most harmful event as explained in the methodology. In CDS, 46% of the most harmful event vehicle-to-vehicle side impacts are first events, and 89% of first event vehicle-to-vehicle side impacts are the most harmful event. That is, in 11% of the cases studied in the following section, there was a more severe crash event (determined by injury and/or property damage outcome) that occurred after the vehicle-to-vehicle side impact, which may have been responsible for the injuries studied here, an important limitation of this methodology to note.

The resulting CDS and FARS cases that were selected and combined are presented in Table 32 for near-side impacts and Table 33 for far-side impacts. The overall occupant trends were similar to what was observed in the CDS dataset selected on most harmful event. While a majority of front-seated occupants are aged 16 and older, a majority of rear-seated occupants are under the age of 16. Older occupants over the age of 55 are greatly over-represented in fatality outcome in both the front and rear seats. Women are over-represented in fatality outcome in the rear seats in both near- and far-side impacts. Rear-seated occupants, both crash-exposed and fatally injured, were more likely to not be wearing a seat belt. In far-side impacts, unbelted occupants are notably over-represented in fatality outcome, though this trend is not clear in near-side impacts. This in part may be due to the high rate of 'unknown' seat belt use in the selected FARS dataset. Finally, older model year vehicles (2000-2009) are over-represented in fatality outcome compared to their rate of crash-exposure in both near- and far-side impacts.

Table 32. Combined CDS/FARS first harmful event vehicle-to-vehicle near-side impact data sample characteristics.

Sample Characteristic	**Crash-Exposed Occupants (CDS)** observed (weighted %)		**Fatally Injured Occupants (FARS)** observed (%)	
	Front Seat N = 2,606	**Rear Seat** N = 140	**Front Seat** N = 14,685	**Rear Seat** N = 1,346
Occupant Age				
0-7	11 (0.52)	48 (38.16)	42 (0.29)	291 (21.62)
8-15	62 (2.59)	34 (24.49)	230 (1.57)	215 (15.97)
16-54	1,833 (70.08)	41 (29.13)	6,891 (46.93)	484 (35.96)
55+	678 (25.92)	11 (4.77)	7,522 (51.21)	356 (26.45)
Unknown	22 (0.89)	6 (3.45)	-	-
Occupant Sex				
Male	1,185 (49.36)	76 (65.00)	7,157 (48.74)	638 (47.40)
Female	1,409 (49.96)	60 (32.76)	7,526 (51.26)	708 (52.60)
Unknown	12 (0.67)	4 (2.23)	2 (0.00)	-
Restraint Use				
Yes (Belted)	2,238 (90.51)	101 (78.86)	11,291 (76.89)	774 (57.50)
No (Unbelted)	290 (7.62)	31 (16.60)	1,162 (7.91)	206 (15.30)
Unknown	78 (1.87)	8 (4.54)	2,232 (15.20)	366 (27.20)
Vehicle Model Year				
2000-2009	2,320 (86.72)	95 (60.21)	13,682 (93.17)	1,239 (92.05)
≥ 2010	286 (13.28)	45 (39.79)	1,003 (6.83)	107 (7.95)

Table 33. Combined CDS/FARS first harmful event vehicle-to-vehicle far-side impact data sample characteristics.

Sample Characteristic	Crash-Exposed Occupants (CDS) observed (weighted %)		Fatally Injured Occupants (FARS) observed (%)	
	Front Seat N = 2,557	**Rear Seat** N = 123	**Front Seat** N = 6,390	**Rear Seat** N = 551
Occupant Age				
0-7	6 (0.94)	50 (37.52)	6 (0.09)	105 (19.06)
8-15	68 (3.52)	29 (34.72)	48 (0.75)	82 (14.88)
16-54	1,829 (71.48)	34 (22.13)	3,581 (56.04)	199 (36.12)
55+	623 (22.21)	6 (3.92)	2,755 (43.12)	165 (29.94)
Unknown	31 (1.85)	4 (1.72)	-	-
Occupant Sex				
Male	1,159 (45.28)	58 (44.98)	3,305 (51.72)	237 (43.01)
Female	1,380 (53.57)	60 (53.19)	3,085 (48.28)	314 (56.99)
Unknown	18 (1.16)	5 (1.82)	-	-
Restraint Use				
Yes (Belted)	2,201 (91.09)	90 (86.19)	4,346 (68.01)	308 (55.90)
No (Unbelted)	297 (7.25)	25 (9.53)	759 (11.88)	78 (14.16)
Unknown	59 (1.66)	8 (4.28)	1,285 (20.11)	165 (29.94)
Vehicle Model Year				
2000-2009	2,252 (84.82)	87 (67.87)	5,950 (93.11)	489 (88.75)
≥ 2010	305 (15.18)	36 (32.13)	440 (6.89)	62 (11.25)

Fatality Injury Models

In addition to the factors which are significant in influencing MAIS2+F injury outcomes in vehicle-to-vehicle side impacts, there is also interest in the variables which may affect the fatal outcomes observed in FARS. The fatality logistic regression model derived from the combined CDS-FARS data set selected based on vehicle-to-vehicle side impact first harmful event crashes is shown in Table 34. Occupant age was statistically significant in influencing fatality outcome in both the near- and far-side models ($\alpha = 0.05$). Further, in the near-side model, vehicle model year had a significant effect, with older model year vehicles (2000-2009) exhibiting an increased fatality risk. This is the same trend that was seen in the MAIS2+F injury model, and provides more evidence that new side impact occupant protection countermeasures are having a positive effect in preventing injury. Finally, also in the near-side model, seat position is a statistically significant predictor with rear-seated occupants exhibiting a greater risk of fatality, suggesting that rear-seated occupants may not be as well protected in the most severe vehicle-to-vehicle side impacts compared to their front-seated counterparts.

Table 34. Near- and far-side impact fatality logistic regression model parameter estimates from the combined CDS/FARS dataset selected based on the first harmful crash event.

Sample Characteristic	Near-Side Model		Far-Side Model	
	Coefficient Estimate (Std. Error)	p-Value	Coefficient Estimate (Std. Error)	p-Value
Intercept	-5.79 (0.29)	< **0.001**	-6.43 (0.62)	< **0.001**
Seat Position				
Front	Reference		Reference	
Rear	0.97 (0.35)	**0.005**	1.44 (0.80)	0.072
Occupant Age				
0-7	-0.50 (0.58)	0.39	-1.47 (1.45)	0.309
8-15	-0.22 (0.48)	0.650	-1.38 (1.31)	0.291
16-54	Reference		Reference	
55+	1.28 (0.15)	< **0.001**	1.05(0.34)	**0.002**
Occupant Sex				
Male	Reference		Reference	
Female	0.13 (0.14)	0.356	-0.19 (0.33)	0.569
Restraint Use				
No (Unbelted)	0.21 (0.24)	0.377	0.81 (0.46)	0.077
Yes (Belted)	Reference		Reference	
Vehicle Model Year				
2000-2009	0.92 (0.27)	< **0.001**	0.85 (0.60)	0.155
≥ 2010	Reference		Reference	

Vehicle-to-Object Side Impacts

The FMVSS 214 pole test further challenges occupant protection systems in a side impact configuration. Compared to vehicle-to-vehicle side impacts, side impacts with narrow objects such as poles and trees may yield a greater magnitude of vehicle crush, though over a smaller area. This is a unique impact configuration that is currently only evaluated on the front seating positions. The incidence of such an impact configuration to the rear seats and the subsequent injury risk it carries for rear-seated occupants is currently unknown.

CDS Dataset Composition

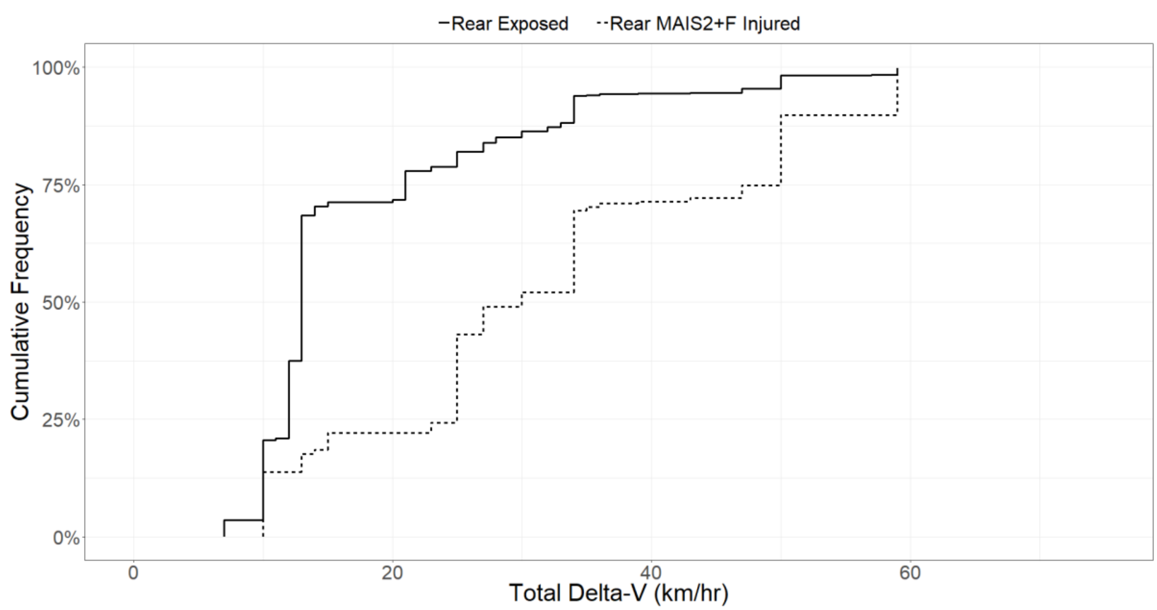
As shown in Table 35, the dataset of CDS vehicle-to-pole crashes based on the most harmful crash event included 1,061 near-side occupants, of which, 951 and 110 were front- and rear-seated, respectively. Overall, this impact mode was rarely experienced by rear-seated occupants. Of all vehicle-to-pole side impact exposed occupants, a mere 6% were rear-seated, and this proportion is consistent in the MAIS2+F injured occupant population at 5%.

Table 35. CDS most harmful event vehicle-to-pole near-side impact data sample characteristics.

Sample Characteristic	**Crash-Exposed Occupants** observed (weighted %)		**MAIS2+F Injured Occupants** observed (weighted %)	
	Front Seat N = 951	**Rear Seat** N = 110	**Front Seat** N = 448	**Rear Seat** N = 44
Occupant Age				
0-7	2 (0.38)	13 (18.89)	-	1 (2.83)
8-15	20 (1.98)	11 (6.28)	8 (0.85)	6 (20.60)
16-54	830 (81.94)	80 (67.88)	405 (91.39)	35 (75.62)
55+	89 (13.01)	3 (0.32)	35 (7.76)	2 (0.94)
Unknown	10 (2.69)	3 (6.64)	-	-
Occupant Sex				
Male	631 (64.27)	66 (35.93)	307 (57.96)	30 (82.03)
Female	314 (34.01)	41 (57.43)	141 (42.04)	14 (17.97)
Unknown	6 (1.71)	3 (6.64)	-	-
Restraint Use				
Yes (Belted)	625 (77.36)	57 (65.82)	246 (59.33)	16 (31.63)
No (Unbelted)	278 (16.46)	49 (33.78)	176 (37.59)	26 (66.79)
Unknown	48 (6.18)	4 (0.40)	26 (3.08)	2 (1.58)
Vehicle Model Year				
2000-2009	917 (93.28)	106 (95.52)	434 (98.80)	42 (98.98)
≥ 2010	34 (6.72)	4 (4.48)	14 (1.20)	2 (1.02)

In the vehicle-to-pole occupant dataset the age distribution of front- and rear-seated crash-exposed and injured occupants is more similar compared to previous analyses in this and other chapters. Older teens and adults aged 16-54 made up a majority of both front- and rear-seated occupants who were both crash-exposed and injured (67-91%). Like in the vehicle-to-vehicle side impact analyses, both unbelted front- and rear-seated occupants were notably over-represented in MAIS2+F injury outcome compared to those who were restrained at the time of the crash. While these occupants account for only 16-34% of all crash exposed occupants, they make up 37-67% of all MAIS2+F injured occupants. With respect to vehicle model year, again as would be expected, newer model year vehicles (2010+) account for fewer vehicle-to-pole side impact MAIS2+F injured occupants than those who are crash exposed.

Figure 44 presents the cumulative distribution of total delta-v for both rear- and front-seated occupants involved in vehicle-to-pole near-side impacts. The mean delta-v for crash-exposed rear-seated occupants was 13 km/hr, while this was slightly higher for front-seated occupants at 16 km/hr. In contrast, the mean delta-v for injured rear-seated occupants was 28 km/hr, while this was lower for front-seated occupants at 25 km/hr. Further, these delta-v's are comparable to those observed in vehicle-to-vehicle side impacts.



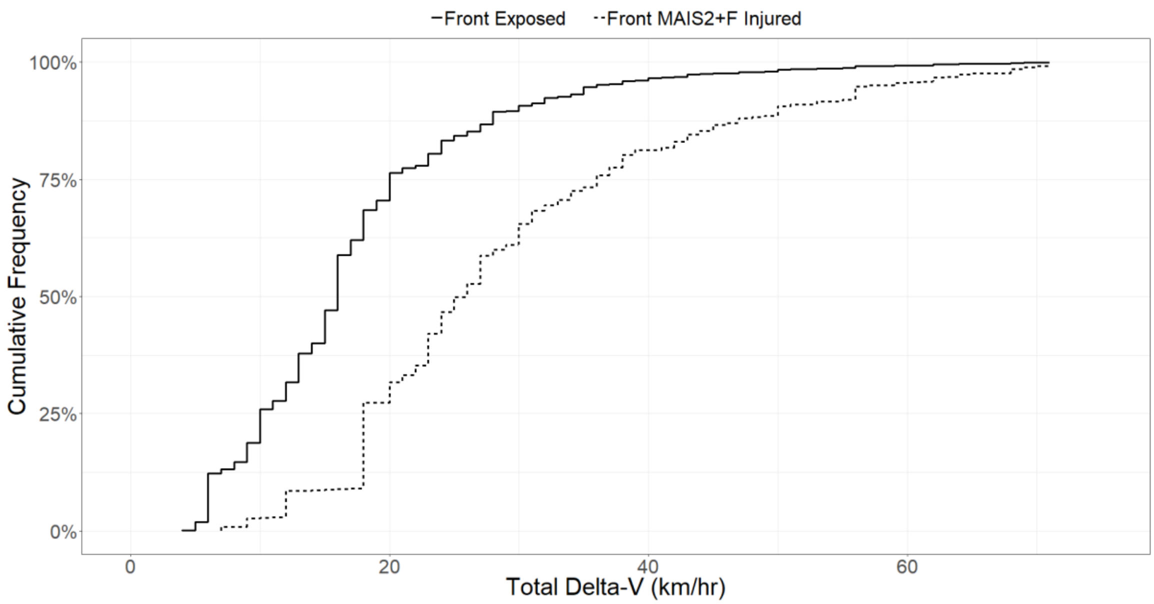


Figure 44. Cumulative distribution of total, or resultant, delta-v (km/hr) for vehicle-to-pole near-side impact rear-seated (top) and front-seated (bottom) occupants.

Comparison of MAIS2+F Injuries in the Rear and Front Seats

In vehicle-to-vehicle near-side impacts, the head/face/neck was the most commonly injured body region for both front- and rear-seated occupants. When looking at the injuries sustained in vehicle-to-pole near-side impacts, as shown in Figure 45, the head/face/neck remains the most commonly injured body region for front-seated occupants, but for rear-seated occupants, lower extremity injuries were most prominent. Compared to front-seated occupants, those who were rear-seated sustained more spine, upper extremity, and lower extremity injuries.

Like in vehicle-to-vehicle crashes, the main mechanism of injury in vehicle-to-pole crashes discussed in previous literature is intrusion into the occupant space. The body region of injury generally correlated to the area of intrusion. Poles are much more narrow than the front of an impacting vehicle. Because of this, vehicle-to-pole impacts yield smaller surface areas (though not necessarily extent/depth) of intrusion than vehicle-to-vehicle crashes. In vehicle-to-vehicle side impacts, it is more likely that the striking vehicle will engage a majority of the side vehicle panel, subjecting both rear- and front- seated occupants to more similar intrusions than may be produced by a vehicle-to-pole side impact. These differences in intrusion locality may contribute to the fact that the body region injury distributions were more similar between rear- and front-seated occupants in vehicle-to-vehicle side impacts than vehicle-to-pole impacts.

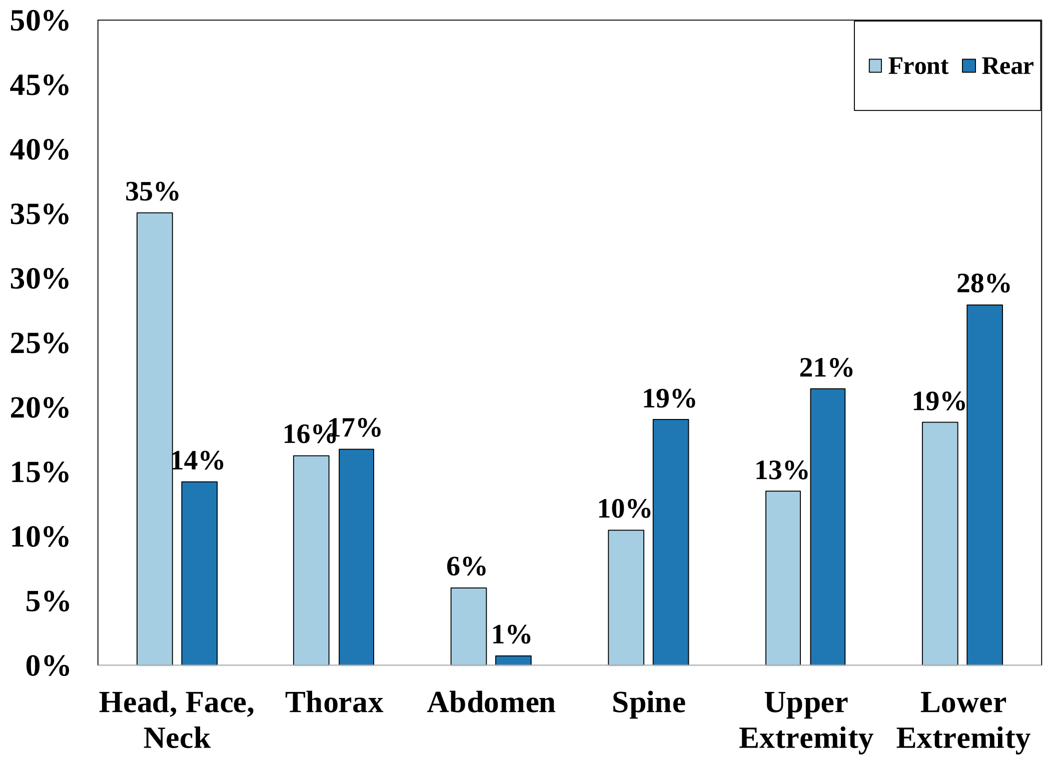


Figure 45. Distribution of AIS2+ injuries sustained in vehicle-to-pole side impacts for both front and rear seat occupants.

<u>CDS/FARS Dataset Composition</u>

In the vehicle-to-pole crash mode in CDS, 48% of most harmful event vehicle-to-pole side impacts are the first event, and 63% of the first harmful events studies here are also the most harmful event. That is, in 37% of the cases studied in the following section, there was a more severe crash event (determined by injury and/or property damage outcome) that occurred after the vehicle-to-pole side impact, which may have been responsible for the injuries studied here. Compared to vehicle-to-vehicle side impacts, these vehicle-to-pole impacts are less frequently both the first and most harmful event.

As shown in Table 36, the resulting CDS and FARS datasets of vehicle-to-pole impacts are relatively small, with the rear-seated CDS cases being exceptionally so. Most fatally injured occupants in this vehicle-to-pole side impact crash mode were older teens and adults aged 16-54, though in the rear seats a comparatively high proportion of children were fatally injured. In both the front and rear seats, men were more commonly fatality injured than women, though this is not abnormal, as the findings in Chapter 3 revealed that across all crash modes men are most commonly fatally injured. While a majority of front-seated fatally injured occupants in the vehicle-to-pole side impact crash mode were belted, most fatally injured rear-seated occupants were unbelted. Finally, there are no great differences in fatality outcome in this crash model between the front and rear seats based on vehicle model year.

Table 36. Combined CDS/FARS first harmful event vehicle-to-pole near-side impact data sample characteristics.

Sample Characteristic	Crash-Exposed Occupants (CDS) observed (weighted %)		Fatally Injured Occupants (FARS) observed (%)	
	Front Seat N = 285	**Rear Seat** N = 8	**Front Seat** N = 2,168	**Rear Seat** N = 164
Occupant Age				
0-7	-	3 (75.34)	5 (0.23)	26 (15.85)
8-15	9 (2.61)	2 (13.37)	28 (1.29)	15 (9.15)
16-54	239 (83.35)	3 (11.29)	1,833 (84.55)	113 (68.90)
55+	35 (12.33)	-	302 (13.93)	10 (6.10)
Unknown	2 (1.71)	-	-	-
Occupant Sex				
Male	172 (60.07)	7 (28.49)	1,522 (70.20)	94 (57.32)
Female	112 (38.44)	1 (71.51)	646 (29.80)	69 (42.07)
Unknown	1 (1.49)	-	-	1 (0.61)
Restraint Use				
Yes (Belted)	222 (83.01)	6 (94.27)	1,151 (53.09)	61 (37.20)
No (Unbelted)	55 (14.15)	2 (5.73)	847 (39.07)	91 (55.49)
Unknown	8 (2.84)	-	170 (7.84)	12 (7.31)
Vehicle Model Year				
2000-2009	278 (99.22)	8 (100.00)	1,996 (92.07)	149 (90.85)
≥ 2010	7 (0.78)	-	172 (7.93)	15 (9.15)

CONCLUSIONS

This study has presented an analysis of injury outcomes in side impacts which compares the differences between injury outcomes of front and rear seat occupants. In vehicle-to-vehicle side impacts, rear seat occupants are slightly under-represented in MAIS2+F injury outcomes compared to front seat occupants. However, when controlling for factors including total delta-v, occupant age, occupant sex, vehicle model year, and crash compatibility no statistically significant difference in MAIS2+F injury risk is apparent between rear- and front-seated occupants. However, when considering the most severe vehicle-to-vehicle side impact crashes yielding fatality, it appears as though rear-seated occupants are at a greater risk of fatality than their front seated counterparts. While the injury and fatality models provide evidence that there have been improvements to vehicle safety systems in the newest model year vehicles, it is possible that rear-seated occupants are not experiencing the same benefit as those who are front seated.

Vehicle-to-pole side impacts were very rare in CDS, especially involving rear-seated occupants. In these types of crashes, there are no obvious differences in overall MAIS2+F injury risk between front- and rear-seated occupants by looking at differences in crash-exposure and injury outcomes. In combination, the results of this study attempt to provide an initial understanding of the differences in crashworthiness vehicles may exhibit between the front and rear rows in both vehicle-to-vehicle and vehicle-to-pole side impact configurations. These analyses suggest that no significant difference in MAIS2+F injury risk currently exists, though in the most severe near-side impacts yielding fatality, rear-seated occupants may be at a slightly higher risk than their front seated counterparts.

7. REAR SEAT BELT REMINDER SYSTEMS

BACKGROUND

Since 1968, per the requirements of the Federal Motor Vehicle Safety Standard (FMVSS) 208, 'Occupant Crash Protection,' all new vehicles have been manufactured with seat belts, one of the most effective injury countermeasures in vehicle crashes that saved an estimated 14,955 lives in 2017 [136]. Recall from Chapter 3 - Figure 17, Figure 18, and Table 12 – that those passengers, both front- and rear-seated, who sustained injury or fatality in a crash had much lower rates of seatbelt usage. In other words, that who did not wear their seat belt were at substantially higher risks of serious injury and fatality in the event of a crash. Over half of rear seat occupants who were seriously-to-fatally injured were unrestrained, and the absolute MAIS3+F injury risk for an unrestrained rear-seated occupant was nine (9) times that of a restrained rear-seated occupant. Unfortunately, seat belt usage rates for the rear seats has continued to be consistently below those for the front seats. In 2017, front and rear seat belt use was 89.7% and 75.4%, respectively, based on observational studies [137], and self-reported seat belt use has remained lower for rear seat passengers than those who are front seated [138].

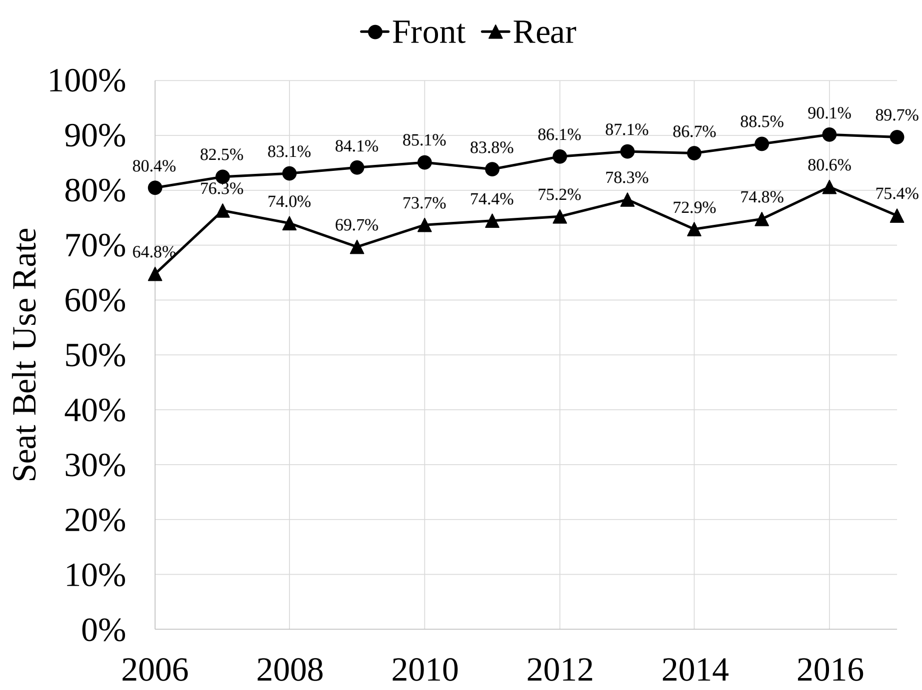


Figure 46. Seat belt usage rates in the U.S. [137]

While the importance of seat belt use was identified long ago and has been heavily emphasized as a crash countermeasure for over 50 years, the employment of state and federal legislation encouraging seat belt use remains drastically different between the front and rear seats. The first state seat belt use laws were introduced in 1984, and since then, a number of either primary or secondary seat belt laws have been enacted. A primary law allows enforcement officers to ticket a person for not wearing a seat belt without any other traffic offense taking place. On the other hand, a secondary law only allows enforcement officers to ticket a person for not wearing a seat belt only when there is another citable traffic violation. State seat belt laws not only differ by the type of enforcement but also by the seating positions that are regulated. Today, for front seat occupants, 34 states and DC have primary seat belt laws, while 15 states have secondary laws. For rear seat occupants, 19 states and DC have primary seat belt laws, 11 states have secondary laws, and 20 states do not have laws enforcing rear seat belt use. The seat belt enforcement laws for each state are shown in Figure 47.

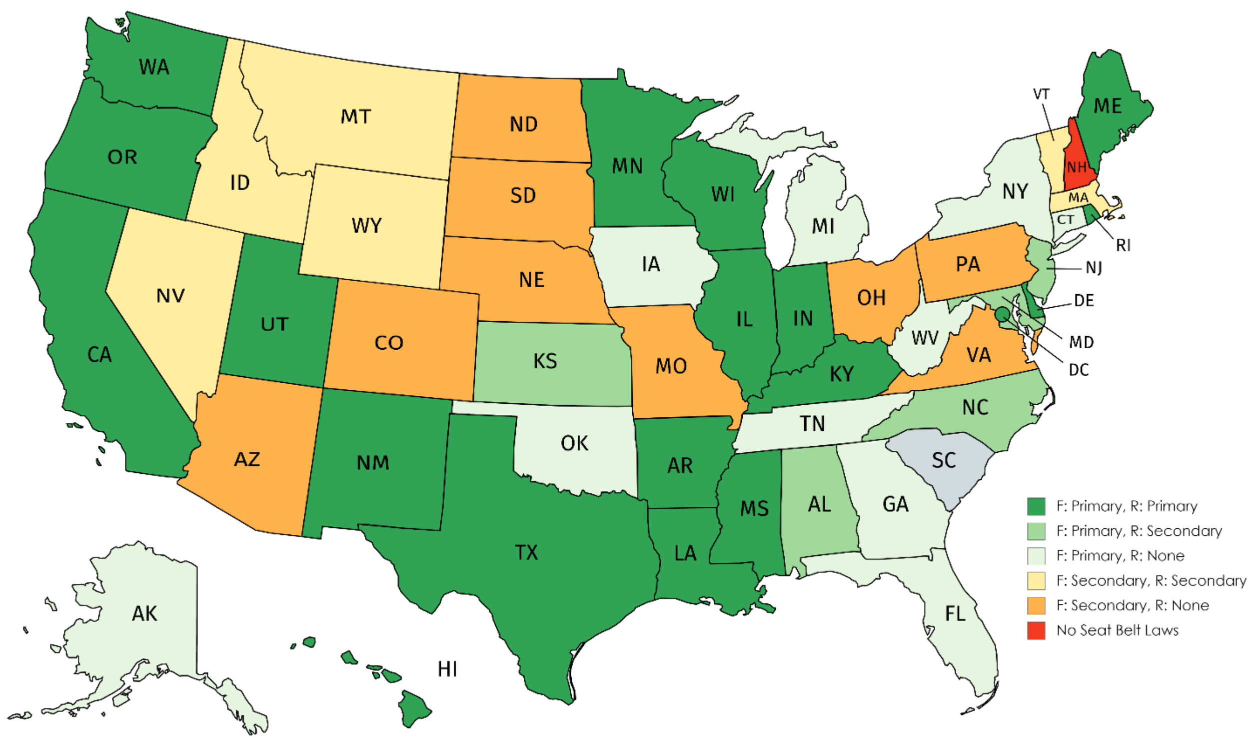


Figure 47. Seat belt law enforcement by state, where 'F' indicates front seating position enforcement and 'R' indicates rear seating position enforcement.

In addition to this state legislation promoting seat belt use, the National Highway Traffic Safety Administration (NHTSA) has enacted regulatory legislation requiring vehicle-based strategies aimed at increasing seat belt use. Since 1974, FMVSS 208 requires a seat belt warning system for the driver's seat, and, although not formally required by the FMVSS, a vast majority of vehicle manufacturers today also equip the front passenger seat with such a system. However, not many vehicle manufactures extend this seat belt reminder technology to the rear seats. According to NHTSA's New Car Assessment Program (NCAP) data, only 13% of new (model year 2019+) vehicles sold in the U.S. come equipped with a rear seat belt reminder (RSBR) system. These systems almost universally consist of a display visible to the driver that indicates which rear seat belts are in use and, in the event of a 'change-of-status,' i.e. a rear-seated occupant unbuckles, a reminder is triggered with visual and audible components.

In 2012, as part of the Moving Ahead for Progress in the 21st Century Act (MAP-21), NHTSA was directed to initiate a rulemaking proceeding to amend the FMVSS 208 to require a rear 'seat belt use warning system.' Currently, NHTSA is continuing with this proceeding, most recently releasing an Advance Notice of Proposed Rulemaking (ANPRM) on the subject in September 2019. Any regulatory decision such as this must have justified benefits, so research that attempts to forecast what the potential benefits of RSBR systems may be are of great importance and value, especially to NHTSA during this ongoing rulemaking process. Therefore, the final portion of the research objective for this collective work is to investigate what the benefits, in terms of injuries prevented, of RSBR systems would be in a future vehicle fleet.

Prior Research on Seat Belt Reminder Systems

There has been prior research on the difference in seat belt usage rates and subsequent injury prevention expected and observed from seat belt reminder systems. In this section, the major findings and methodologies from a selection of these past studies will be summarized.

Since driver seat belt reminders were mandated so long ago, there are few studies, and certainly no recent studies, on the effect of implementing a seat belt reminder system versus no system in the front seats of a vehicle. However, NHTSA has researched the effectiveness and acceptance of 'enhanced' seat belt warnings via both an observational study and an experimental/focus group based study. An 'enhanced' seat belt warning is a system in which the required reminder exceeds the minimum requirements set forth in FMVSS 208. The observational study investigated the seat belt use of front seat occupants in a large, geographically diverse sample of registered passenger vehicles both with and without 'enhanced' seat belt warning systems [139]. Findings were that the belt use rates of drivers in vehicles equipped with an 'enhanced' seat belt reminder system was 3-4% higher than drivers of vehicles without such a system.

The experimental study focused on seat belt reminder system features to determine which system configurations drivers found to be most annoying versus desirable [140]. The 'enhanced' seat belt reminder systems tested were all perceived to be more effective than the currently required minimum reminder by FMVSS 208. More 'aggressive' displays and more frequent repetition patterns were perceived to make the systems most effective, with auditory warnings having a greater effect than visual displays. However, findings also showed that the system components deemed most effective were also frequently those that drivers indicated were annoying. Opinions on if an effective but annoying system would be a desirable vehicle feature varied among the study participants. Based on these findings, NHTSA has published a set of recommendations for effective 'enhanced' seat belt reminder design [141].

Discussions regarding the possible implementation of gearshift interlocks based on seat belt use have recently reemerged. Before the current requirements on seat belt reminder systems were enacted, one FMVSS 208 compliance option was to use an interlock system that would prevent the vehicle's engine from starting if any of the front seat belts were not fastened and an occupant was present. The introduction of this technology in the early 1970s was not well received by the public. The interlock was deemed too annoying, and many consumers disabled or figured out ways to circumvent the system. In response, Congress passed a provision prohibiting NHTSA from prescribing a FMVSS that required, or permitted, seat belt interlocks or an audible warning lasting longer than eight (8) seconds. However, as part of MAP-21, the restriction on allowing interlocks as an optional means of compliance was removed.

In a recent study by the Insurance Institute for Highway Safety (IIHS), the belt use of 32 part-time belt users with a recent seat belt citation and 16 full-time belt users was observed for 2 weeks, during which time half of the part-time belt users and all of the full-time belt users were exposed to a gearshift interlock based on belt use in addition to an enhanced seat belt reminder system [142]. Among the part-time belt users, relative to an enhanced seat belt reminder, the interlock system increased belt use by 16%. It is notable that six (6) of the part-time users circumvented the interlock by either sitting on the buckled seat belt, waiting for the interlock to deactivate, or unbuckling during travel after the interlock had deactivated. These findings highlight the importance of designing an interlock system that can better prevent circumvention. In addition to increasing belt use among the part-time users, the full-time belt users found the addition of the interlock to be ‘acceptable.’

A continuation of this research observed the belt use of 49 part-time belt users with a recent seat belt citation for one (1) week, during which time the participants were exposed to a variety of audible seat belt reminders and/or a speed-limiting interlock [143]. The data from these participants was combined with the data collected during the previously discussed gearshift interlock study for analysis. The study found that relative to three intermittent 7-second audible reminders, seat belt use was increased 30% by a 90-second audible reminder, 34% by an indefinite audible reminder, and 33% by a speed-limiting interlock. A survey of the participants post-study indicated that the audible reminders were more acceptable than the interlocks.

As a final study in this IIHS series, 28 volunteers drove on a closed course in six vehicles with differing belt reminder and/or interlock systems [144]. Participants either completed the drive unbelted or had to complete a task that led to unbelted driving. After each test drive, an opinion survey was administered on the seat belt technology experienced. Results of the surveys revealed that interlocks were perceived by study participants as being more effective than reminders at increasing belt use, and they were additionally perceived as no more or less acceptable than reminders. However, safety concerns were raised regarding the speed-limiting interlocks which could affect their overall acceptance.

While this large body of work on front seat belt reminder system effectiveness, especially how effectiveness varied with system design, is invaluable to inform how future seat belt reminder systems should be employed, it still does not answer what the effectiveness and/or benefits of the addition of a rear seat belt reminder system would be in the United States versus having no such system at all. That being said, beginning in 2002, the Euro NCAP has awarded points for front and rear seat belt reminder systems when they were not otherwise required by any regulation. Then, in 2009, the Economic Commission for Europe (ECE) Regulation No. 16, the European Union vehicle regulation on seat belts, required a seatbelt reminder system for the driver’s seat in all vehicles manufactured from 2011 on. Further, just recently in September

2019, ECE No. 16 was updated again to require a rear seat belt warning. This warning must consist of a visual indicator of any rear seating position in which the seat belt is unfastened as well as a visual and auditory change-of-status warning. Given the evolution of these European seat belt reminder system regulations, there has been a larger body of research conducted in Europe on the effectiveness of seat belt reminder systems both in the rear and front seats, and the studies often have more clear pre- and post- seat belt reminder system implementation populations.

One of the first seat belt use studies regarding seat belt reminders in Europe was conducted as an observational study in Sweden [145]. Seat belt use was collected via field observation of drivers in cars both with and without a seat belt reminder system. More than 3,000 drivers with known seat belt usage and vehicle seat belt reminder system equipment were recorded. Belt use rates were found to be 82.3% and 98.9% in cars without and with a seat belt reminder system, respectively (statistically significant difference). This study was continued to be larger-scale and inclusive of more European cities outside of Sweden [146]. The change in seat belt use for drivers was further evaluated via additional data collection in six (6) more European cities. This additional data was combined with that from the previous study to make a total data collection from 11 different European cities. The study yielded an observed 10,237 drivers with known belt usage and vehicle seat belt reminder system equipment. Based on statistical tests comparing the proportion of seat belt usage rates between drivers in vehicles with and without a seat belt reminder system, it was found that the driver seat belt reminder system increased seat belt use among nonusers by 82.2% (± 8.6%).

To date in the U.S., the most recent study on RSBR effectiveness was conducted by NHTSA in 2015. This research gauged the perceived effectiveness and consumer acceptance of rear seat belt warnings via a consumer survey. A noticed increase in rear seat belt use was reported by 23-28% of drivers in vehicles with a rear seat belt warning system, and of all drivers surveyed, a vast majority (80%) were overall satisfied with the system. It was reported that 'the rear seat belt warning made it easier to encourage rear seat passengers to buckle up' by 65% of surveyed drivers. Almost half (49%) of surveyed drivers had experienced a 'change of seat belt status alert' [an activation of the RSBR system if a rear-seated occupant unbuckles their seatbelt during vehicle operation], and, of those drivers, 77% said that the unbuckled passenger did eventually refasten their seat belt, which is at least partially attributable to the RSBR system. Regarding their next vehicle purchase, 55% of surveyed drivers indicated that it would be important that their next vehicle be equipped with a RSBR system.

OBJECTIVE

The objective of this study is to forecast the number of rear-seated occupant injuries that would be prevented if a RSBR system were to be deployed throughout the future U.S. vehicle fleet.

METHODOLOGY

The following study is based upon data from NASS-CDS case years 2000-2015. All occupant cases fulfilling the following criteria were included for subsequent analysis:

- Total crash delta-v is known.
- Case vehicle was a passenger vehicle [passenger car, minivan, sport utility vehicle (SUV), or pick-up truck] of model year 2000 or newer.
- Case vehicle greatest area of deformation (GAD) due to the most harmful crash event is known.
- Rear-seated occupant with known belt use and injury outcome (even if the outcome was no injury).

Injury Model Development

The hypothesis used in this study is that the addition of a RSBR system will lead to an increase in rear seat belt use, subsequently yielding reduction in injury given that a crash occurs. In order to predict the reduction in injury expected from a RSBR system, binary logistic regression models were developed that predict MAIS2+F injury outcome given crash severity and occupant characteristics including belt use. Occupant age and sex were included occupant characteristics as these have often been shown to influence injury outcomes in previous chapters of this work. The models were developed using CDS rear seat occupant cases that had known age, sex, and injury outcome as well as available data on crash severity and impact configuration. After case selection, the final dataset of crash-involved rear-seated occupants was divided into impact configurations of interest. Impact configurations included front, near-side, far-side, rear, and rollover, as defined by the vehicle's GAD from the most harmful crash event with reference to the occupant's seating position. All crashes including at least one-quarter turn rollover were included in the rollover category regardless of GAD.

The probability of MAIS2+F injury occurrence among the selected rear-seated occupant population was then estimated for each impact configuration. Specifically, the injury models used crash severity (CS), occupant age, occupant sex, and occupant belt use as predictors for injury given that a crash occurred, as shown in Equation 8. Crash severity was defined as total, or resultant, delta-v for all impact configurations except for rollovers, where crash severity was alternatively characterized by number of quarter turns. Delta-v, number of quarter turns, and occupant age were input as a continuous covariates while occupant sex and belt use were modeled as categorical predictors. 'Unbelted' was used as a binary covariate to indicate occupant restraint use where a value of one (1) indicated the occupant was unbelted and zero (0) indicated the occupant was belted. To account for the stratified sampling scheme used by CDS, the logistic regression model was constructed using the 'svyglm' function in the 'survey' package of R.

$$Risk\ of\ Injury = \frac{1}{1 + e^{-(Intercept + \beta_{CS} * CS + \beta_{Age} * Age + \beta_{Sex} * Sex + \beta_{Belt} * Belt)}} \qquad \text{Equation 8}$$

Rear Seat Belt Reminder Benefit Calculations

Two different approaches were taken to calculate fleet-wide RSBR system benefits. The first calculation involved replacing belt use conditions from the statistical models developed herein to assume that all rear seated occupants would be belted. This simulation model used the developed injury risk curves to predict RSBR system benefits. The injury benefits of the RSBR system were calculated as shown in Equation 9. The number of injuries without a RSBR system was determined from the real-world CDS data, and the number of predicted injuries with a RSBR system was the result of the previously described computational simulation. All injury benefits subsequently reported were annualized over the 10 year time period of study.

$$Injury\ Benefits = \frac{\#\ Injuries\ without\ RSBR - \#\ Injuries\ with\ RSBR}{\#\ Injuries\ without\ RSBR} \qquad \text{Equation 9}$$

Since the assumption that a RSBR system would yield 100% rear seat belt use is a lofty assumption, these benefits estimations can be considered an 'upper bound' of the possible injury reductions expected from such a system. To provide a bit more realistic estimation, the second benefits calculation involved assuming that the effectiveness of seat belt reminders reported in the previous literature review could be applied to the rear seat occupant population studied here. Given the estimated injuries prevented with 100% rear seat belt use due to a RSBR system calculated previously, these subsequent calculations simply take the benefits to be a proportion of those estimated with universal seat belt use given the reported increase in seat belt use observed in selected studies.

RESULTS AND DISCUSSION

Dataset Composition

Table 37 summarizes the number of all impact configurations and rear-seated occupant belt use in the study CDS dataset. Both belted and unbelted occupants have approximately the same proportion of crash impact configurations with respect to all crashes. The majority of crashes in this study were frontal impacts (58-60%), the crash type – along with rollovers – in which seat belts are most effective at occupant protection.

Table 37. Rear-seated occupants in selected study cases, where the 'observed' number is the raw count of study cases and the 'estimated' number is the sum of weighted cases.

Impact Configuration	Belted			Unbelted		
	Observed	Estimated (% of Total)	Annualized Average	Observed	Estimated (% of Total)	Annualized Average
All Crashes	3,084	963,456	60,216	1,073	200,852	12,553
Front	1,848	578,460 (60)	36,154	672	117,490 (58)	7,343
Rear	316	140,146 (15)	8,759	69	19,419 (10)	1,214
Near-Side	375	112,288 (12)	7,018	134	25,637 (13)	1,602
Far-Side	364	103,474 (11)	6,467	109	23,781 (12)	1,486
Rollover	181	29,088 (2)	1,818	89	14,525 (7)	908

MAIS2+F Injury Models

Table 38 shows the results from the logistic regression model fits to the chance of a rear-seated occupant sustaining an MAIS2+F injury. Crash severity was a significant predictor of rear-seated occupant injury in all models except for the rollover impact configuration, though this impact mode had a comparatively small sample size limiting its statistical power. In the MAIS2+F injury models, occupant age was a significant predictor of injury in all impact modes except rear crashes. Occupant sex was insignificant in all models. Finally, occupant belt use was a significant predictor of injury in all models regardless of impact configuration.

Table 38. Logistic regression model coefficient estimates and belt use odds ratios for rear-seated occupant MAIS2+F injury where * indicates statistically significant coefficients.

Sample Characteristic	Impact Configuration				
	Front	Rear	Near-Side	Far-Side	Rollover
Intercept	-6.64*	-6.65*	-6.73*	-6.93*	-3.66*
Crash Severity	0.10*	0.08*	0.10*	0.08*	0.23
Occupant Age	0.03*	0.02	0.03*	0.03*	0.03*
Occupant Sex *Female (Ref = Male)*	0.01	-0.28	1.13	1.37	0.37
Belt Use *Unbelted (Ref = Belted)*	1.53*	2.52*	2.66*	1.69*	1.15*
Belt Use Odds Ratio (95% CI)	4.6 (2.9, 7.4)	12.5 (2.5, 62.5)	14.3 (4.5, 45.4)	5.4 (1.6, 18.3)	3.2 (1.1, 8.8)

Estimated Benefits of Rear Seat Belt Reminder Systems

Without a RSBR system, the CDS simulation dataset accounted for an annualized, weighted 3,146 MAIS2+F injured occupants in the rear seats of passenger vehicles with known crash delta-v, occupant age, occupant sex, and occupant belt use. Across all impact modes studied, the simulation estimated 1,345 of these MAIS2+F injuries could have been prevented annually if the vehicles were equipped with a RSBR system that had 100% effectiveness. This yields an overall 43% RSBR system effectiveness at preventing moderate-to-fatal injuries.

The benefits model also estimated RSBR benefits given more conservative system effectiveness measures at increasing rear seat belt usage. In Europe, after vehicle manufacturers began implementing driver's seat belt reminder systems, one study suggested that the belt use rate in that seating position increased among non-users by 82% [146]. If this effectiveness would hold true for a RSBR system, rear seat passengers would have avoided MAIS2+F injuries in 1,103 crash cases based on the overall CDS figures accounting for all crash modes. These figures yield an estimated 35% effectiveness regarding MAIS2+F injuries. The most conservative RSBR effectiveness at increasing seat belt usage used for these benefits calculations comes from the NHTSA survey of driver's who currently own a vehicle equipped with a RSBR system. Approximately 25% of drivers reported noticing an increase in rear seat belt usage due to their vehicle being equipped with a RSBR system. If this effectiveness would hold true for all RSBR systems, the effectiveness values across all crash modes would be an 11% reduction in MAIS2+F injury.

Table 39 summarizes the annualized, fleet-wide, predicted RSBR system benefits for each of the described calculation methods and individual impact configurations. As would be expected, the lower seat belt use rates even with a RSBR system resulted in lower overall effectiveness of such a system.

Table 39. Annualized, fleet-wide RSBR system benefits estimations based on CDS 2006-2015.

	Impact Configuration				
	Front	**Rear**	**Near-Side**	**Far-Side**	**Rollover**
Injured Occupants without a RSBR System	1,512	238	676	292	428
Injured Occupants with a RSBR System Given:					
100% Belt Use	960	111	266	177	287
82% Belt Use	1,059	134	340	198	312
25% Belt Use	1,374	206	574	263	393
RSBR System Effectiveness Given:					
100% Belt Use	37%	53%	61%	39%	33%
82% Belt Use	30%	44%	50%	32%	27%
25% Belt Use	9%	13%	15%	10%	8%

It is important to reiterate the assumptions and note the limitations of this study and the simulation approach. One key assumption made in regard to a RSBR system and the first benefits calculations was that this system would lead to 100% rear seat belt use. As discussed in the previous literature, a RSBR system is not likely to yield this rate of belt use. Thus, these benefits estimations should be treated as an 'upper bound' on the possible number of injuries that could be prevented annually by such a system.

In production systems, there will likely be variability in the design of the RSBR warning system. There will likely be an increase or decrease in effectiveness based on the design. The previously discussed literature provided a snapshot of the wide breath of seat belt reminder system design and subsequent effectiveness observed today and in hypothetical future systems. In the study yielding an 82% increase in belt use rates after the implementation of a seat belt reminder system [146], the seat belt reminder systems were all presumably at least what is typical of a driver's seat belt reminder system in the United States. Such an audiovisual signal is a more 'aggressive' warning system, and, in newer vehicles, generally one that does not deactivate unless the seat belt in question is buckled. On the other hand, the RSBR systems currently being employed in the U.S. are usually a visual display to the driver indicating rear seat belt status, and a – usually temporary – audible warning only activates if a rear seat belt is unbuckled during travel. These systems yielded the perceived 25% increase in rear seat belt use reported by surveyed drivers of RSBR equipped vehicles. In this system, the RSBR is only effective if the driver takes action to encourage the unbelted rear seat occupants to buckle up.

On a similar theme, another assumption playing into the seat belt use rates seen post-RSBR implementation include driver and passenger acceptance. People are not always accepting of safety systems if they are deemed too annoying or too much of an inconvenience. Previously, this was discussed briefly with regards to the disastrous introduction of gearshift interlocks based on seat belt use in the early 1970's. Recent studies by IIHS show that this perception may not have waned much, as study participants at times circumvented interlock systems by either sitting on a buckled seat belt, waiting for the interlock to deactivate, or unbuckling during travel after the interlock had deactivated. The fleet-wide benefits model presented here assumes every vehicle in the U.S. will be equipped with a RSBR system, the system will remain activated, and occupants will not circumvent the system. Vehicle owners who disable the system due to annoyance or occupants who circumvent the system will gain no benefits. Of course, if NHTSA proceeds with rulemaking on RSBR systems in the future, such systems will not be able to be deactivated, but the issue of circumvention will likely remain.

CONCLUSIONS

Rear-seated injury risk models were derived for front, rear, side (near- and far-), and rollover crashes based on crash delta-v, occupant age, occupant sex, and occupant seat belt use. Using these models, the benefits of the fleet-wide implementation of a RSBR system were estimated. This study predicts that RSBR systems could prevent 8-61% of all MAIS2+F injuries sustained by rear-seated occupants depending on both impact configuration and RSBR system design/seat belt use effectiveness. As expected, lower effectiveness figures were found for lower seat belt use rates elicited by the hypothetical RSBR systems, highlighting the importance and great influence of RSBR system design to expected benefits. The results of these studies are directly applicable to regulators and vehicle manufacturers who are performing analysis of proposed RSBR systems.

8. CONCLUSIONS AND CONTRIBUTION TO THE FIELD OF AUTOMOTIVE SAFETY

The overall research objective of this dissertation was to address the current injury risk to rear seated occupants in passenger vehicles across multiple crash modes. The dissertation presents the first large-scale study of its kind, investigating the factors that lead to rear-seated occupant injury and/or fatality in passenger vehicle crashes through retrospective studies on several impact configurations. The overall goal was to provide a better understanding of the injury risk and mechanisms to rear seated occupants under a variety of crash conditions, which can benefit automakers who seek to improve the effectiveness of rear seat safety systems as well as regulatory agencies seeking to improve vehicle tests targeting rear seat passenger vehicle safety. To this end, several important research objectives have been attained, including:

1. Characterize the population of rear seat occupants involved in passenger vehicle crashes in the United States vehicle fleet.
2. Investigate the characteristics of serious-to-fatal rear crashes, and identify the underlying crash features that may lead to serious or fatal injury for occupants seated in rear-impacted vehicles.
3. Determine the injury risk to rear seated occupants in frontal impacts, and quantify the difference in injury risk for rear versus front seated occupants.
4. Evaluate the injury risk to rear seated occupants in side impacts, both vehicle-to-vehicle and vehicle-to-object, and compare the difference in injury risk for rear versus front seated occupants in both near- and far-side impact configurations.
5. Forecast the number of rear-seated occupant injuries that would be prevented if a rear seat belt reminder system were to be deployed throughout the future U.S. vehicle fleet.

A summary of the primary findings for each of these research objectives is detailed in the discussion which follows.

CHARACTERISTICS OF CRASH-INVOLVED REAR SEATED OCCUPANTS IN THE U.S.

The objective of this study was to determine the characteristics which may influence the risk of injury and/or fatality in crashes involving rear-seated occupants in the United States and how these characteristics may differ from the front seat occupant population. To achieve this objective, this study identified the crash conditions, types of vehicles, and occupants which were typical of crashes of all severity, serious-to-fatal injury severity, and fatal injury severity. These characteristics were evaluated in the context of all rear-seated occupants as well as all front-seated occupants so that comparisons could be made between the two occupant populations. This approach allowed for an understanding of characteristics unique to serious injury and fatality outcomes crashes, as compared to characteristics of all crashes, as well as characteristics that were significantly different between the rear- and front-seated occupant populations.

This study was based on crashes extracted from NASS-GES case years 2011-2015, NASS-CDS case years 2006-2015, and FARS case years 2011-2015. In order to be included in the dataset, occupants from these databases were required to be traveling in a passenger vehicle of model year 2000 or newer and have a front or rear (second through fifth row) seating position. For this study, all occupants with a known row position were included for analysis.

This study showed that the most common type of crash that both rear- and front-seated occupants were exposed to were rear-end crashes. However, for both occupant populations, injury and fatality were most commonly sustained in non-collision crashes (such as a rollover). Overall, the greatest risk of serious injury to both rear- and front-seated occupants was present in these non-collision crashes and head-on crashes.

Rear-seated occupants were exposed to crashes in cars and LTVs with roughly the same frequency, but front-seated occupants were more commonly exposed to crashes in cars. Generally, it was found that minivans and SUVs have higher occupancy rates than cars, suggesting that these vehicle body types may be more likely to contain rear-seated occupants. For both rear- and front-seated occupants, the serious injury risk was the same regardless whether the occupant was traveling in a car or LTV. Rear- and front-seated occupants were exposed to crashes in vehicles of comparable model year (median 2007), though both occupant populations were MAIS3+F and fatally injured in slightly older model year vehicles. Crash severity, measured by total delta-v, was comparable for all rear- and front-seated occupants exposed to crashes. However, rear-seated occupants were MAIS3+F and fatally injured at lower crash severities than their front-seated counterparts.

Rear-seated passenger vehicle occupants were most commonly positioned in the 2nd vehicle row, partially because most vehicles only have two passenger rows. The right seating position was the most commonly occupied rear seat, followed by the left and middle, respectively. There was no significant difference in absolute risk of MAIS3+F injury between any rear seating position.

The age distribution of rear- and front-seated occupants varied significantly. While a majority of rear-seated occupants were children under the age of 13, most front-seated occupants were aged 20 and older. In both the rear- and front-seats, the absolute risk of MAIS3+F injury was greatest for occupants aged 76+. Consequent to these differences in age, the average rear-seated occupant was smaller in both height and weight than the average front-seated occupant. The average size of a non-CRS restrained rear seat occupant was greater than the 5th percentile female Hybrid III ATD (59 inches tall and 108 lbs), which is the dummy most commonly used when evaluating rear seating positions in crash tests. Seeing that those injured were even larger than the exposed population further suggests that the challenge in rear seat occupant protection may not necessarily be small individuals. That being said, the average rear seat height and weight presented here were still smaller than the 50th percentile male Hybrid III (69 inches tall and 172 lbs). Finally, the distribution of all crash-exposed, seriously injured, and fatally injured rear-seated occupants was consistent among the sexes. Front-seated men were more likely than women to be fatally injured.

A majority of all rear- and front-seated occupants were belted at the time of the crash, and in the rear seats CRS use was common while this was a rare occurrence in the front seats. A higher proportion of rear-seated occupants were unbelted at the time of the crash than their front-seated counterparts. In both the rear and front seats, unbelted occupants were at a significantly greater risk of serious injury than those where were otherwise restrained.

Finally, while both rear- and front-seated occupants sustained no injury as a result of a crash in a majority of cases, a greater proportion of rear-seated occupants were uninjured.

Further, the incidence of serious-to-fatal injures for rear-seated occupants was less than that for front-seated occupants (1.5% and 2.3%, respectively).

REAR IMPACTS AND INJURIES TO REAR SEATED OCCUPANTS

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

This study was based on rear crashes extracted from NASS-GES case years 2010-2015, NASS-CDS case years 2000-2015, and FARS case years 2010-2015. The GES and FARS cases for analysis were selected to meet the following criteria:

- Struck vehicle was either a car or LTV of model year 2000 or later.
- 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 NASS-CDS cases that met the following criteria were selected for 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 in which occupant seating positions were unknown were excluded.
- Cases in which injury outcomes were unknown were excluded.
- Crashes with zero sampling weights or sampling weights over 5000 were excluded.

This study showed that the absolute number of rear impact crashes has been increasing, as have fatalities in this crash mode. A majority of both injured (MAIS2+F) and fatal rear-struck passenger vehicle occupants were belted at the time of the crash, not ejected from the vehicle during the crash sequence, not involved in a vehicle fire, and were traveling in cars rather than LTVs. While only 13% of rear crash-exposed occupants were rear-seated, they accounted for 22-24% of those injured and/or killed in this crash mode. This over-representation of rear-seated occupants in fatality outcomes given a rear crash indicates that this population was at a higher risk than their front-seated counterparts.

Three mechanisms of serious-to-fatal injury in rear impacts were identified through detailed crash case reviews. A majority of fatal cases studied were a direct result of catastrophic occupant compartment collapse, which was present in 3.4% of full overlap rear impacts and 6.9% of moderate overlap rear impacts. In many of the conducted case reviews, if the compartment had not collapsed, the crash would have likely been survivable. Rear-seated occupants who were fatally injured as a result of compartment collapse often had front-seated counterparts who sustained only minor injuries. That said, there were also cases where the extent of compartmental collapse was so great that front-seated occupants were affected as well.

The second mechanism of injury was head contact with a rigid interior vehicle object(s), such as the B- or C-pillar. Occupants are thrust backwards in the event of a rear impact, and if they do not make contact with the headrest as designed, this head-to-other object contact was likely. At higher severity rear impacts, this contact can be made at relatively high speeds and yield serious brain injury.

The third and final injury mechanism was thoracic loading from the seat, often leading to rib fractures and, at times, spinal injury. Current seatback stiffness may not be appropriate in all crash modes and for occupants of all ages and/or sizes. Most rib fractures observed from seat loading occurred in occupants over the age of 55, who are known to be more susceptible to injury due to frailty.

Using a logistic regression model, this study showed that for rear impacts, MAIS2+F injury outcome was significantly influenced by crash severity (total delta-v), occupant age, occupant sex, and occupant seat position. As crash severity and driver age increase, the risk of MAIS2+F injury increases. Men were at a higher risk of MAIS2+F injury in rear impacts than women. Finally, rear-seated occupants were at a higher risk of MAIS2+F injury than their front-seated counterparts.

In summary, this study 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. Older occupants, men, and rear-seated occupants were at significantly greater risks of injury in the rear impact crash mode. There are currently no US regulations to evaluate the potential for occupant injury in rear impacts. Given that so many individuals succumb to 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. This 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.

FRONT IMPACTS AND INJURIES TO REAR SEATED OCCUPANTS

The objective of this study was to use the most recent data available to quantify the difference in injury and fatality risk, if any, for front and rear seated occupants in frontal passenger vehicle crashes. Many previous studies on the performance of rear seat occupant restraint systems in the U.S. have suggested that the difference in injury and fatality risk between the front and rear seats was elevated in more recent model year vehicles, but these 'recent model years' considered include vehicles manufactured over a decade ago due to the age of said studies and availability of crash data at the time. The issue of relative rear seat safety has not been thoroughly investigated within the last decade, so the most recent model year vehicles released in the last decade were not yet included in current literature. This study sought to fill that gap in knowledge and either verify or deny that this trend of disparate front and rear seat safety in frontal impacts is continuing.

This study was based on front crashes extracted from NASS-CDS and FARS case years 1999-2015. All cases fulfilling the following criteria were included for analysis:

- Case vehicle was a passenger vehicle (passenger car, minivan, SUV, or pick-up truck) of model year 2000 or newer.
- Vehicle age at the time of the crash was ten (10) or fewer years.

- Frontal impact crash [selected based on the greatest area of deformation in the most harmful crash event (GAD1) variable in NASS-CDS and the initial impact direction (IMPACT1) variable in FARS].

Using a logistic regression model, this study showed that MAIS2+F injury outcome in frontal impacts was influenced by crash severity (total delta-v), occupant age, occupant sex, and occupant seating position. Consistent with the conclusions of the rear impact study, in frontal impacts, as crash severity and occupant age increases, the risk of MAIS2+F injury increases. Women displayed a higher risk of MAIS2+F injury in frontal impacts than men when controlling for other model covariates, though men displayed a greater absolute risk of injury. Finally, rear-seated occupants exhibited a higher risk of injury than those who were front-seated.

Looking at the RR of MAIS2+F injury between the rear and front seats reveals that this issue of disparate injury risk depends greatly on occupant age and sex. Elderly occupants aged 75 and older displayed a significantly higher risk of MAIS2+F injury when rear-seated than when front-seated. However, occupants younger than this were better protected in the rear when considering MAIS2+F injury outcomes. Again here, women show a significantly greater rear versus front seat RR of MAIS2+F injury. However, when considering vehicle model year, the absolute risk of MAIS2+F injury risk has decreased in the newest model year vehicles (≥ 2007) than those vehicles that were older. Further, the rear versus front RR of MAIS2+F injury was also significantly lower in these newest model year vehicles.

However, looking at fatal injury outcomes instead of MAIS2+F injury outcomes yields some different results. Using another logistic regression model, this study shows that fatal injury outcome in frontal impacts was not only influenced by crash severity, occupant age, occupant sex, and seating position as in the MAIS2+F model, but vehicle body type and model year also have a significant effect. Like in the MAIS2+F model, the risk of fatality increases with increasing occupant age. The rear versus front RR of fatality reveals however that this disparate risk becomes evident at a much younger age when considering fatality instead of MAIS2+F injury. While children and young adults remain better protected when considering fatality outcome in the rear seats, occupants aged 40 and over displayed a significantly greater risk of fatality when rear-seated.

Perhaps most interestingly, when considering vehicle model year, the rear versus front RR of fatality has significantly increased in newer model year vehicles. This was in contrast to the finding of the MAIS2+F injury model. Together, these results suggest that rear seat occupant safety has improved in more recent model year vehicles at preventing all moderate-to-fatal injuries. However, these protective effects were not seen in the most serious crashes that yield fatality.

The adolescent population aged 9-12 years was notably the only occupant age group under 40 years where the rear vs. front seat RR of fatality was not significantly below one (1), indicating no difference in risk between the front and rear seats. In this study's dataset, none of the 9-12 year olds were restrained in a CRS but were instead using a traditional seatbelt at the time of the crash. However, 1 of the 5 (20%) and 8 of the 12 (67%) front- and rear-seated 9-12 year old occupants with a recorded height, respectively, were under 4'9" and should have been restrained in a booster seat per current child vehicle safety recommendations. In contrast, children in the other younger age groups were almost always CRS restrained. The high rate of seatbelt misuse among 9-12 year olds in the rear seat may explain why the 9-12 year old rear versus front RR was not statistically significant. In the 9-12 year old rear-seated occupant population, head injuries where most common followed by the thorax and abdomen, respectively. Mechanisms of injury to these body regions were consistent with seat belt misuse.

The huge jump in rear versus front seat RR of fatality for occupants aged 40 and over was similarly intriguing as this was a younger age than past literature suggests injury risk begins to increase appreciably. For rear-seated occupants aged 40 and older, the thorax was the most commonly injured body region, present in over half of all injured occupant cases in this age group. Compared to front-seated occupants aged 40 and older, those who were rear-seated sustained greater proportions of both thorax and abdomen injuries. Generally, these injuries were caused by direct seat belt contact.

In summary, given that a frontal crash occurred and an occupant was restrained, while the risk of all moderate-to-fatal injuries has decreased in the newest model year passenger vehicles, the relative risk of fatality was higher in the rear than the front seats. This appears to be an issue primarily for adults aged 40 and over, with a huge increase in both injury and fatality risk for those over the age of 75. Children aged 8 and under – who comprise a majority of rear seated occupants – continue to experience a great safety benefit in terms of both injury and fatality outcomes in the event of a frontal crash by being rear seated. These results agree with previous studies and continue to highlight the challenge in implementing rear seat occupant protection systems that benefit all ages.

Passenger vehicle safety systems have greatly improved over the last couple decades, but the increase in the RR of fatality between the rear and front seats in newer model year vehicles found here shows that rear seat occupants were not experiencing the same benefit as front seated occupants in the highest severity frontal crashes. Implementing advanced restraint systems such as seatbelts that are equipped with a pretensioner and a load limiter – commonplace in the front seats of passenger vehicles – into the rear row(s) of passenger vehicles would be a first step towards more equitable occupant safety in frontal impacts.

SIDE IMPACTS AND INJURIES TO REAR SEATED OCCUPANTS

The objective of this study was to examine occupant injury outcomes resulting from a number of different side impact configurations including vehicle-to-vehicle near-side, vehicle-to-vehicle far-side, and vehicle-to-pole side impacts. The injury risk each of these crash modes poses to vehicle occupants was modeled with a focus on differences between rear and front seating positions.

This study was based on side crashes extracted from NASS-CDS and FARS case years 2000 to 2015. In order to be included in the side impact study dataset, cases were required to meet the following criteria:

- Case vehicle was either a car or LTV of model year 2000 or newer.
- No vehicle rollover.
- Occupant was not fully ejected from the vehicle.
- Side impact configuration determined for both:
    - Most harmful event side crashes based on:
        - NASS-CDS: Greatest area of deformation (GAD) and object contacted to yield said deformation.

- First harmful event side crashes based on:
  - NASS-CDS: Greatest area of deformation (GAD) in the first crash event and the object contacted during said first event.
  - FARS: First vehicle impact location and the corresponding object contacted.

Using a logistic regression model, this study showed that for both near- and far-side vehicle-to-vehicle impacts, MAIS2+F injury outcomes were influenced by crash severity, occupant age, and occupant restraint use. Consistent with previous chapters' findings on rear and side impacts, the risk of MAIS2+F injury increases with increasing crash severity and occupant age. A significant difference in MAIS2+F injury outcome was present between occupants who were belted and unbelted at the time of a vehicle-to-vehicle side crash, with unbelted occupants displaying a greater risk of injury. However, there was no significant difference in injury outcome between front- and rear-seated occupants. The distribution of AIS2+ injured body regions were very similar both near- and far-side impacts, with head/face/neck injuries being the most common.

When considering fatality outcomes in vehicle-to-vehicle side impacts, for near-side crashes, fatality outcome was significantly influenced by occupant age, vehicle model year, and occupant seat position. The risk of fatality was greater in older model year vehicles (2000-2009) not required to meet the last FMVSS 214 upgrades. This indicates that in the newer model year vehicles likely equipped with enhanced countermeasures for this side impact crash mode, these occupant protection systems were likely having a positive effect at preventing fatality. Finally, based on this model, rear-seated occupants exhibit a greater risk of fatality than those who were front seated in near-side impacts. However, the same cannot be said for far-side impacts, where fatality outcome was only significantly influenced by occupant age.

Vehicle-to-pole crashes were a rare occurrence in both NASS-CDS and FARS. Compared to vehicle-to-vehicle side impacts, the distributions of AIS2+ injured body regions were more varied between the front and rear seats. In all crash modes, if intrusion occurs, the body region of occupant injury generally correlated to the area of intrusion. In vehicle-to-vehicle side impacts, it is more likely that the striking vehicle will engage a majority of the side vehicle panel, subjecting both rear- and front- seated occupants to more similar intrusions than may be produced by a vehicle-to-pole side impact. These differences in intrusion locality may contribute to the fact that the body region injury distributions were more similar between rear- and front-seated occupants in vehicle-to-vehicle side impacts than vehicle-to-pole impacts.

In summary, in vehicle-to-vehicle side impacts, rear seat occupants were slightly under-represented in MAIS2+F injury outcomes compared to front seat occupants. However, when controlling for factors including total delta-v, occupant age, occupant sex, vehicle model year, and crash compatibility no statistically significant difference in MAIS2+F injury risk was apparent between rear- and front-seated occupants. However, when considering the most severe vehicle-to-vehicle side impact crashes yielding fatality, it appears as though rear-seated occupants were at a greater risk of fatality than their front seated counterparts. In vehicle-to-pole side impacts, there were no obvious differences in overall MAIS2+F injury risk between front- and rear-seated occupants by looking at differences in crash-exposure and injury outcomes. In combination, the results of this study attempt to provide an initial understanding of the differences in crashworthiness vehicles may exhibit between the front and rear rows in both vehicle-to-vehicle and vehicle-to-pole side impact configurations. These analyses suggest that no significant difference in MAIS2+F injury risk currently exists, though in the most severe vehicle-to-vehicle near-side impacts yielding fatality, rear-seated occupants may be at a slightly higher risk than their front seated counterparts.

ESTIMATED BENEFITS OF REAR SEAT BELT REMINDER SYSTEMS

The objective of this study was to forecast the number of rear-seated occupant injuries that would be prevented if a RSBR system were to be deployed throughout the future U.S. vehicle fleet.

This study was based on crash data from NASS-CDS case years 2000-2015. All occupant cases fulfilling the following criteria were included for analysis:

- Total crash delta-v was known.
- Case vehicle was a passenger vehicle [passenger car, minivan, SUV, or pick-up truck] of model year 2000 or newer.

- Case vehicle greatest area of deformation (GAD) due to the most harmful crash event was known.
- Rear-seated occupant with known belt use and injury outcome (even if the outcome was no injury).

A general rear-seated injury risk model was derived for each crash mode of interest using logistic regression based on crash delta-v, occupant age, occupant sex, and occupant seat belt use. Using these models, the benefits of the fleet-wide implementation of a RSBR system were estimated. This study predicts that RSBR systems could prevent 8-61% of all MAIS2+F injuries sustained by rear-seated occupants depending on both impact configuration and RSBR system design/seat belt use effectiveness. As expected, lower effectiveness figures were found for lower seat belt use rates elicited by the hypothetical RSBR systems, highlighting the importance and great influence of RSBR system design to expected benefits. The results of these studies are directly applicable to regulators and vehicle manufacturers who are performing analysis of proposed RSBR systems.

PUBLICATION SUMMARY

A summary of publications and supplementary conference presentations in support of this dissertation:

Chapter	Title	Publication Venue	Year
4	Preliminary Analysis of Serious-to-Fatal Injury in Rear Impact Crashes in the United States	IRCOBI Conference Proceedings	2017
5	Differential Fatality Risk Between Rear and Front Seat Passenger Vehicle Occupants in Frontal Crashes	IRCOBI Conference Proceedings	2019
5	Differential Injury Risk Between Rear and Front Seat Passenger Vehicle Occupants in Frontal Crashes	Traffic Injury Prevention	proposed
7	Estimated benefits of Rear Seat Belt Reminders	AAAM Conference Proceedings	proposed

REFERENCES

[1] L. Evans and M. C. Frick, "Seating position in cars and fatality risk," *American Journal of Public Health*, vol. 78, no. 11, pp. 1456-1458, 1988/11/01 1988.

[2] L. Evans and M. C. Frick, "Relative fatality risk in different seating positions versus car model year," *Accident Analysis & Prevention*, vol. 21, no. 6, pp. 581-587, 1989.

[3] K. M. Smith and P. Cummings, "Passenger seating position and the risk of passenger death or injury in traffic crashes," *Accident Analysis & Prevention*, vol. 36, no. 2, pp. 257-260, 2004.

[4] K. Smith and P. Cummings, "Passenger seating position and the risk of passenger death in traffic crashes: a matched cohort study," *Injury Prevention*, vol. 12, no. 2, pp. 83-86, 2006.

[5] K. D. Kusano and H. C. Gabler, "Comparison of expected crash and injury reduction from production forward collision and lane departure warning systems," *Traffic injury prevention*, vol. 16, no. sup2, pp. S109-S114, 2015.

[6] D. Holmes, H. Gabler, and R. Sherony, "Estimating Benefits of LDW Systems Applied to Cross-Centerline Crashes," SAE Technical Paper0148-7191, 2018.

[7] J. M. Scanlon, R. Sherony, and H. C. Gabler, "Preliminary potential crash prevention estimates for an Intersection Advanced Driver Assistance System in straight crossing path crashes," in *2016 IEEE Intelligent Vehicles Symposium (IV)*, 2016, pp. 1135-1140: IEEE.

[8] T. I. Gorman, K. D. Kusano, and H. C. Gabler, "Model of fleet-wide safety benefits of Lane Departure Warning systems," in *16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013)*, 2013, pp. 372-377: IEEE.

[9] S. Kuppa, J. Saunders, and O. Fessahaie, "Rear seat occupant protection in frontal crashes," in *19th International Conference on the Enhanced Safety of Vehicles*, 2005: Citeseer.

[10] E. S. Esfahani and K. Digges, "Trend of rear occupant protection in frontal crashes over model years of vehicles," SAE Technical Paper0148-7191, 2009.

[11] L. E. Bilston, W. Du, and J. Brown, "A matched-cohort analysis of belted front and rear seat occupants in newer and older model vehicles shows that gains in front occupant safety have outpaced gains for rear seat occupants," *Accident Analysis & Prevention*, vol. 42, no. 6, pp. 1974-1977, 2010/11/01/ 2010.

[12] C. Parenteau and D. C. Viano, "Field Data Analysis of Rear Occupant Injuries Part I: Adults and Teenagers," 2003. Available: http://dx.doi.org/10.4271/2003-01-0153

[13] R. Kent, J. Forman, D. Parent, and S. Kuppa, "Rear seat occupant protection in frontal crashes and its feasibility," in *20th International Conference on the Enhanced Safety of Vehicles*, 2007.

[14] J. Forman, J. Michaelson, R. Kent, S. Kuppa, and O. Bostrom, "Occupant restraint in the rear seat: ATD responses to standard and pre-tensioning, force-limiting belt restraints," presented at the Annals of Advances in Automotive Medicine/Annual Scientific Conference, 2008.

[15] M. Blanco *et al.*, "FMVSS Considerations for Vehicles with Automated Driving Systems: Phase 1, Volume 2 Final Report " Virginia Tech Transportation Institute, Washington, DC2019.

[16] M. J. Trowbridge and R. Kent, "Rear-seat motor vehicle travel in the US: Using national data to define a population at risk," *American journal of preventive medicine,* vol. 37, no. 4, pp. 321-323, 2009.
[17] D. Bose, J. Crandall, J. Forman, D. Longhitano, and C. Arregui-Dalmases, "Epidemiology of injuries sustained by rear-seat passengers in frontal motor vehicle crashes," *Journal of Transport & Health,* vol. 4, pp. 132-139, 2017.
[18] S. O.-R. A. V. S. Committee, "Taxonomy and definitions for terms related to on-road motor vehicle automated driving systems," *SAE Standard J,* vol. 3016, pp. 1-16, 2014.
[19] T. Litman, "Autonomous vehicle implementation predictions: Implications for transport planning," 2015.
[20] B. Grush, J. Niles, and E. Baum, "Ontario Must Prepare for Vehicle Automation: Automated vehicles can influence urban form, congestion and infrastructure delivery," 2016.
[21] S. Koppel *et al.*, "Seating configuration and position preferences in fully automated vehicles," *Traffic Injury Prevention*, pp. 1-7, 2019.
[22] M. Krafft, A. Kullgren, and C. Tingvall, "Crash pulse recorders in rear impacts-real life data," in *ESV Conference, Windsor, Ontaria, Canada*, 1998, pp. 1256-1262.
[23] T. J. Szabo *et al.*, "Human Occupant Kinematic Response to Low Speed Rear-End Impacts," 1994. Available: http://dx.doi.org/10.4271/940532
[24] G. Wusk and H. Gabler, "Evaluation of Vehicle-Based Crash Severity Metrics Using Event Data Recorders," in *25th International Technical Conference on the Enhanced Safety of Vehicles (ESV) National Highway Traffic Safety Administration*, 2017.
[25] A. H. Tsoi and H. C. Gabler, "Evaluation of vehicle-based crash severity metrics," *Traffic injury prevention,* vol. 16, no. sup2, pp. S132-S139, 2015.
[26] V. Eis, R. Sferco, and P. A. Fay, "A Detailed Analysis of the Characteristics of European Rear Impacts," *Proceedings: International Technical Conference on the Enhanced Safety of Vehicles,* vol. 2005, pp. 9p-9p, 2005.
[27] D. C. Viano and C. S. Parenteau, "Fatalities by Seating Position and Principal Direction of Force (PDOF) for 1st, 2nd and 3rd Row Occupants," 2008. Available: http://dx.doi.org/10.4271/2008-01-1850
[28] E. R. Braver, R. Whitfield, and S. A. Ferguson, "Seating positions and children's risk of dying in motor vehicle crashes," *Injury Prevention,* 10.1136/ip.4.3.181 vol. 4, no. 3, p. 181, 1998.
[29] D. R. Durbin *et al.,* "Rear seat safety: Variation in protection by occupant, crash and vehicle characteristics," *Accident Analysis & Prevention,* vol. 80, pp. 185-192, 2015/07/01/ 2015.
[30] G. Nilson, M. Y. Svensson, P. Lovsund, Y. Haland, and K. Wiklund, "Rear-End Collisions, the Effect of the Seat Belt and the Crash Pulse on Occupant Motion," in *Proceedings of the 14th Conference on the Enhanced Safety of Vehicles, Munich, Germany, May 23-26, 1994*, 1994, p. 1994.
[31] M. B. James, C. E. Strother, C. Y. Warner, R. L. Decker, and T. R. Perl, "Occupant Protection in Rear-end Collisions: I. Safety Priorities and Seat Belt Effectiveness," 1991. Available: http://dx.doi.org/10.4271/912913
[32] M. L. Edwards, C. S. Parenteau, and D. C. Viano, "Front-Seat Occupant Injuries in Rear Impacts: Analysis of the Seatback Incline Variable in NASS-CDS," 2009. Available: http://dx.doi.org/10.4271/2009-01-1200

[33] C. Parenteau and D. C. Viano, "Field Data Analysis of Rear Occupant Injuries Part II: Children, Toddlers and Infants," 2003. Available: http://dx.doi.org/10.4271/2003-01-0154
[34] G. Bhat, L. Beck, G. Bergen, and M.-j. Kresnow, "Predictors of rear seat belt use among U.S. adults, 2012," *Journal of Safety Research,* vol. 53, pp. 103-106, 2015/06/01/ 2015.
[35] (2018). *Seat Belt Laws*. Available: https://www.ghsa.org/state-laws/issues/seat%20belts
[36] D. C. Viano and C. S. Parenteau, "Ejection and Severe Injury Risks by Crash Type and Belt Use With a Focus on Rear Impacts," *Traffic Injury Prevention,* vol. 11, no. 1, pp. 79-86, 2010/01/29 2010.
[37] D. C. Viano and C. S. Parenteau, "Serious Injury in Very-Low and Very-High Speed Rear Impacts," 2008. Available: http://dx.doi.org/10.4271/2008-01-1485
[38] D. C. Viano and C. S. Parenteau, "Field Accident Data Analysis of 2nd Row Children and Individual Case Reviews," 2008. Available: http://dx.doi.org/10.4271/2008-01-1851
[39] S. L. Evans, M. L. Nance, K. B. Arbogast, M. R. Elliott, and F. K. Winston, "Passenger compartment intrusion as a predictor of significant injury for children in motor vehicle crashes," *Journal of Trauma and Acute Care Surgery,* vol. 66, no. 2, pp. 504-507, 2009.
[40] J. Saunders, L. N. Molino, and F. McKoy, "Performance of seating systems in a FMVSS No. 301 rear impact crash test," in *18th Enhanced Safety of Vehicles (ESV) Conference*, 2003.
[41] J. Padmanaban, R. Burnett, and A. E. Levitt, "Relationship between Seatback Stiffness/Strength and Risk of Serious/Fatal Injury in Rear-Impact Crashes," 2009.
[42] R. Burnett, J. Carter, V. Roberts, and B. Myers, "The influence of seatback characteristics on cervical injury risk in severe rear impacts," *Accident Analysis & Prevention,* vol. 36, no. 4, pp. 591-601, 2004/07/01/ 2004.
[43] D. C. Viano, "Role of the Seat in Rear Crash Safety," 2002.
[44] C. Y. Warner, C. E. Stother, M. B. James, and R. L. Decker, "Occupant Protection in Rear-end Collisions: II. The Role of Seat Back Deformation in Injury Reduction," 1991. Available: http://dx.doi.org/10.4271/912914
[45] D. C. Viano, C. S. Parenteau, P. Prasad, and R. Burnett, "Occupant Responses in High-Speed Rear Crashes: Analysis of Government-Sponsored Tests," 2008. Available: http://dx.doi.org/10.4271/2008-01-0188
[46] D. C. Viano, C. S. Parenteau, P. Prasad, and R. Burnett, "Stiff versus Yielding Seats: Analysis of Matched Rear Impact Tests," 2007. Available: http://dx.doi.org/10.4271/2007-01-0708
[47] D. C. Viano and C. S. Parenteau, "NASS-CDS Analysis of High Retention Seat Performance in Rear Impacts," *Traffic Injury Prevention,* vol. 16, no. 5, pp. 491-497, 2015/07/04 2015.
[48] D. C. Viano, "Effectiveness of High-Retention Seats in Preventing Fatality: Initial Results and Trends," 2003. Available: http://dx.doi.org/10.4271/2003-01-1351
[49] D. Viano, "The Debate Between Stiff and Yielding Seats: A New Generation of Yielding Seats with High Retention in Rear Crashes. SAE Book PT-106," *Society of Automotive Engineers, Warrendale PA*, 2003.
[50] P. Prasad, A. Kim, D. P. V. Weerappuli, V. Roberts, and D. Schneider, "Relationships Between Passenger Car Seat Back Strength and Occupant Injury Severity in Rear End Collisions: Field and Laboratory Studies," 1997. Available: http://dx.doi.org/10.4271/973343

[51] D. C. Viano, "Fracture-Dislocation of the Thoracic Spine in Extension by Upright Seats in Severe Rear Crashes," 2011. Available: http://dx.doi.org/10.4271/2011-01-0274
[52] D. C. Viano, C. S. Parenteau, R. A. Burnett, and M. B. James, "Influence of Seating Position on Dummy Responses with ABTS Seats in Severe Rear Impacts," 2009. Available: http://dx.doi.org/10.4271/2009-01-0250
[53] E. Sahraei, D. Soudbakhsh, and K. Digges, "Protection of rear seat occupants in frontal crashes, controlling for occupant and crash characteristics," SAE Technical Paper2009.
[54] R. J. Mitchell, M. R. Bambach, and B. Toson, "Injury risk for matched front and rear seat car passengers by injury severity and crash type: An exploratory study," *Accident Analysis & Prevention,* vol. 82, pp. 171-179, 2015/09/01/ 2015.
[55] H. C. Gabler, K. Digges, B. N. Fildes, and L. Sparke, "Side impact injury risk for belted far side passenger vehicle occupants," SAE Technical Paper0148-7191, 2005.
[56] C. M. Farmer, E. R. Braver, and E. L. Mitter, "Two-vehicle side impact crashes: the relationship of vehicle and crash characteristics to injury severity," *Accident Analysis & Prevention,* vol. 29, no. 3, pp. 399-406, 1997.
[57] D. Lestina, P. Gloyns, and S. Rattenbury, "Fatally injured occupants in side impact crashes," in *Proceedings: International Technical Conference on the Enhanced Safety of Vehicles*, 1993, vol. 1993, pp. 701-707: National Highway Traffic Safety Administration.
[58] R. R. Samaha and D. S. Elliott, "NHTSA side impact research: motivation for upgraded test procedures," in *Eighteenth International Technical Conference on the Enhanced Safety of Vehicles, Paper*, 2003, no. 492.
[59] C. Laberge-Nadeau, F. Bellavance, S. Messier, L. Vézina, and F. Pichette, "Occupant injury severity from lateral collisions: a literature review," *Journal of safety research,* vol. 40, no. 6, pp. 427-435, 2009.
[60] A. T. McCartt and S. Y. Kyrychenko, "Efficacy of side airbags in reducing driver deaths in driver-side car and SUV collisions," *Traffic injury prevention,* vol. 8, no. 2, pp. 162-170, 2007.
[61] G. McGwin Jr, J. Metzger, and L. W. Rue III, "The influence of side airbags on the risk of head and thoracic injury after motor vehicle collisions," *Journal of Trauma and Acute Care Surgery,* vol. 56, no. 3, pp. 512-517, 2004.
[62] F. Zhang and C.-L. Chen, "NASS-CDS: sample design and weights," 2013.
[63] NHTSA, "National Automotive Sampling System-General Estimates System, 1988-2015 Analytical User’s Manual," 2016.
[64] NHTSA, "National Automotive Sampling System–Crashworthiness Data System, 2015 Analytical User’s Manual," 2016.
[65] A. Daniello and H. C. Gabler, "Fatality risk in motorcycle collisions with roadside objects in the United States," *Accident Analysis & Prevention,* vol. 43, no. 3, pp. 1167-1170, 2011.
[66] D. E. Lefler and H. C. Gabler, "The fatality and injury risk of light truck impacts with pedestrians in the United States," *Accident Analysis & Prevention,* vol. 36, no. 2, pp. 295-304, 2004.
[67] S. M. Duma and M. V. Jernigan, "The effects of airbags on orbital fracture patterns in frontal automobile crashes," *Ophthalmic Plastic & Reconstructive Surgery,* vol. 19, no. 2, pp. 107-111, 2003.

[68] B. Claytor, P. A. MacLennan, G. McGwin Jr, L. W. Rue III, and J. S. Kirkpatrick, "Cervical spine injury and restraint system use in motor vehicle collisions," *Spine,* vol. 29, no. 4, pp. 386-389, 2004.
[69] R. Nirula, R. Kaufman, and A. Tencer, "Traumatic brain injury and automotive design: making motor vehicles safer," *Journal of Trauma and Acute Care Surgery,* vol. 55, no. 5, pp. 844-848, 2003.
[70] K. D. Kusano and H. C. Gabler, "Comprehensive target populations for current active safety systems using national crash databases," *Traffic injury prevention,* vol. 15, no. 7, pp. 753-761, 2014.
[71] H. C. Gabler, J. A. Hinch, and J. Steiner, *Event Data Recorders: A Decade of Innovation*. 2008.
[72] *Event Data Recorders,* 563, 2012.
[73] A. Tsoi, J. Hinch, R. Ruth, and H. Gabler, "Validation of event data recorders in high severity full-frontal crash tests," *SAE International Journal of Transportation Safety,* vol. 1, no. 1, pp. 76-99, 2013.
[74] A. Tsoi, N. Johnson, and H. Gabler, "Validation of event data recorders in side-impact crash tests," *SAE International journal of transportation safety,* vol. 2, no. 1, pp. 130-164, 2014.
[75] P. Niehoff, H. C. Gabler, J. Brophy, C. Chidester, J. Hinch, and C. Ragland, "Evaluation of event data recorders in full systems crash tests," in *Proceedings of the Nineteenth International Conference on Enhanced Safety of Vehicles, Paper,* 2005, no. 05-0271, pp. 6-9.
[76] T. A. Gennarelli and E. Wodzin, *Abbreviated injury scale 2005 : update 2008*. Barrington, Ill.: Association for the Advancement of Automative Medicine, 2008.
[77] H. C. Gabler, A. A. Weaver, and J. D. Stitzel, "Automotive field data in injury biomechanics," in *Accidental Injury*: Springer, 2015, pp. 33-49.
[78] S. P. Baker, B. o'Neill, W. Haddon Jr, and W. B. Long, "The injury severity score: a method for describing patients with multiple injuries and evaluating emergency care," *Journal of Trauma and Acute Care Surgery,* vol. 14, no. 3, pp. 187-196, 1974.
[79] NHTSA, "Fatality Analysis Reporting System (FARS), Analytical User's Manual, 1975-2017," 2018.
[80] R. Kent, M. Trowbridge, F. J. Lopez-Valdes, R. H. Ordoyo, and M. Segui-Gomez, "How many people are injured and killed as a result of aging? Frailty, fragility, and the elderly risk-exposure tradeoff assessed via a risk saturation model," in *Annals of Advances in Automotive Medicine/Annual Scientific Conference*, 2009, vol. 53, p. 41: Association for the Advancement of Automotive Medicine.
[81] G. Li, E. R. Braver, and L.-H. Chen, "Fragility versus excessive crash involvement as determinants of high death rates per vehicle-mile of travel among older drivers," *Accident Analysis & Prevention,* vol. 35, no. 2, pp. 227-235, 2003.
[82] L. Blincoe, A. Seay, A. Zaloshnja, T. Miller, E. Romano, and S. Luchter, "Department of Transportation (US), National Highway Traffic Safety Administration," *The economic impact of motor vehicle crashes,* 2000.
[83] E. Hertz, "Revised estimates of child restraint effectiveness," *NHTSA Research Note,* 1996.

[84] T. M. Rice and C. L. Anderson, "The effectiveness of child restraint systems for children aged 3 years or younger during motor vehicle collisions: 1996 to 2005," *American Journal of Public Health*, vol. 99, no. 2, pp. 252-257, 2009.
[85] V. Committee on Injury and P. Prevention, "Child passenger safety," *Pediatrics,* vol. 127, no. 4, pp. 788-793, 2011.
[86] L. E. Decina, K. H. Lococo, and A. W. Block, "Misuse of child restraints: results of a workshop to review field data results," United States. National Highway Traffic Safety Administration. Office of …2005.
[87] D. R. Durbin, I. Chen, R. Smith, M. R. Elliott, and F. K. Winston, "Effects of seating position and appropriate restraint use on the risk of injury to children in motor vehicle crashes," *Pediatrics,* vol. 115, no. 3, pp. e305-e309, 2005.
[88] "Traffic Safety Facts 2015: A Compilation of Motor Vehicle Crash Data From the Fatality Analysis Reporting System and the General Estimation System," NHTSA, Washington, DC2017.
[89] *Fuel System Integrity,* 571.301, 1975.
[90] *Electric-powered vehicles: electrolyte spillage and electrical shock protection,* 571.305, 2000.
[91] W. Tatem and H. Gabler, "Preliminary Analysis of Serious-to-Fatal Injury in Rear Impact Crashes in the United States," in *IRCOBI Conference Proceedings,* 2017.
[92] *Collision Deformation Classification,* J224 MAR80, 1980.
[93] N. Yoganandan *et al.*, "Deriving injury risk curves using survival analysis from biomechanical experiments," *Journal of biomechanics,* vol. 49, no. 14, pp. 3260-3267, 2016.
[94] *Occupant Crash Protection,* 571.208, 1971.
[95] *Laboratory Test Procedure for New Car Assessment Program Frontal Impact Testing,* 2012.
[96] "Creating a Global Market for Vehicle Safety," in "Activities of New Car Assessment Programmes and how they operate in different countries and regions," Global NCAP2017.
[97] *New Car Assessment Program,* N. H. T. S. Administration, 2015.
[98] E. R. Braver, A. T. McCartt, C. P. Sherwood, D. S. Zuby, L. Blanar, and M. Scerbo, "Front Air Bag Nondeployments in Frontal Crashes Fatal to Drivers or Right-Front Passengers," *Traffic Injury Prevention,* vol. 11, no. 2, pp. 178-187, 2010/03/31 2010.
[99] D. W. Hosmer Jr, S. Lemeshow, and R. X. Sturdivant, *Applied logistic regression*. John Wiley & Sons, 2013.
[100] D. R. Durbin, V. Committee on Injury, and P. Prevention, "Technical report—Child passenger safety," *Pediatrics,* pp. peds. 2011-0215, 2011.
[101] J. F. García-España and D. R. Durbin, "Injuries to belted older children in motor vehicle crashes," *Accident Analysis & Prevention,* vol. 40, no. 6, pp. 2024-2028, 2008.
[102] K. Bohman, K. B. Arbogast, and O. Boström, "Head injury causation scenarios for belted, rear-seated children in frontal impacts," *Traffic injury prevention,* vol. 12, no. 1, pp. 62-70, 2011.
[103] D. Bergqvist, H. Hedelin, B. Lindblad, and T. Mätzsch, "Abdominal injuries in children: an analysis of 348 cases," *Injury,* vol. 16, no. 4, pp. 217-220, 1985.

[104] D. R. Durbin, K. B. Arbogast, and E. K. Moll, "Seat belt syndrome in children: a case report and review of the literature," *Pediatric emergency care,* vol. 17, no. 6, pp. 474-477, 2001.

[105] N. Lutz, K. B. Arbogast, R. A. Cornejo, F. K. Winston, D. R. Durbin, and M. L. Nance, "Suboptimal restraint affects the pattern of abdominal injuries in children involved in motor vehicle crashes," *Journal of pediatric surgery,* vol. 38, no. 6, pp. 919-923, 2003.

[106] M. L. Nance *et al.*, "Optimal restraint reduces the risk of abdominal injury in children involved in motor vehicle crashes," *Annals of surgery,* vol. 239, no. 1, p. 127, 2004.

[107] D. Adomeit, "Seat design—a significant factor for safety belt effectiveness," *SAE Transactions,* pp. 3326-3337, 1979.

[108] J. D. Horsch and W. E. Hering, "A kinematic analysis of lap-belt submarining for test dummies," SAE Technical Paper0148-7191, 1989.

[109] A. K. Abbas, A. F. Hefny, and F. M. Abu-Zidan, "Seatbelts and road traffic collision injuries," *World Journal of Emergency Surgery,* vol. 6, no. 1, p. 18, 2011.

[110] R. F. Neathery, C. K. Kroell, and H. J. Mertz, "Prediction of thoracic injury from dummy responses," SAE Technical Paper0148-7191, 1975.

[111] R. Kent, D. Lessley, G. Shaw, and J. Crandall, "The utility of Hybrid III and THOR chest deflection for discriminating between standard and force-limiting belt systems," SAE Technical Paper2003.

[112] R. Kent, B. Henary, and F. Matsuoka, "On the fatal crash experience of older drivers," in *Annual Proceedings/Association for the Advancement of Automotive Medicine*, 2005, vol. 49, p. 371: Association for the Advancement of Automotive Medicine.

[113] T. R. Laituri, P. Prasad, K. Sullivan, M. Frankstein, and R. S. Thomas, "Derivation and evaluation of a provisional, age-dependent, AIS3+ thoracic risk curve for belted adults in frontal impacts," SAE Technical Paper0148-7191, 2005.

[114] R. W. Kent, J. R. Crandall, J. Bolton, P. Prasad, G. Nusholtz, and H. Mertz, "The influence of superficial soft tissues and restraint condition on thoracic skeletal injury prediction," SAE Technical Paper2001.

[115] M. Walz, "NCAP test improvements with pretensioners and load limiters," *Traffic injury prevention,* vol. 5, no. 1, pp. 18-25, 2004.

[116] J. Foret-Bruno *et al.*, "Thoracic injury risk in frontal car crashes with occupant restrained with belt load limiter," *SAE Transactions,* pp. 2955-2975, 1998.

[117] J. Forman *et al.*, "Rear seat occupant safety: an investigation of a progressive force-limiting, pretensioning 3-point belt system using adult PMHS in frontal sled tests," SAE Technical Paper2009.

[118] B. Beck, J. Brown, and L. E. Bilston, "Assessment of vehicle and restraint design changes for mitigating rear seat occupant injuries," *Traffic injury prevention,* vol. 15, no. 7, pp. 711-719, 2014.

[119] J. Hu, K. Fischer, P. Lange, and A. Adler, "Effects of crash pulse, impact angle, occupant size, front seat location, and restraint system on rear seat occupant protection," SAE Technical Paper0148-7191, 2015.

[120] J. Hu, M. P. Reed, J. D. Rupp, K. Fischer, P. Lange, and A. Adler, "Optimizing seat belt and airbag designs for rear seat occupant protection in frontal crashes," SAE Technical Paper2017.

[121] M. L. Brumbelow, B. C. Baker, and J. M. Nolan, "Effects of seat belt load limiters on driver fatalities in frontal crashes of passenger cars," in *International Technical Conference on the Enhanced Safety of Vehicles, Paper*, 2007, no. 07-0067.
[122] *Full Width Frontal Impact Testing Protocol*, 2018.
[123] "2017 - The Year in Numbers," Euro NCAP2018.
[124] "Rear Seat Safety in Passenger Vehicles," National Transportation Safety Board, Washington, DC2017.
[125] "Laying the Groundwork for Safety Improvements for Back-seat Occupants," IIHS, Status Report 2014, vol. 49.
[126] K. H. Digges and H. C. Gabler, "Opportunities for reducing casualties in far-side crashes," SAE Technical Paper0148-7191, 2006.
[127] B. Fildes, M. Fitzharris, H. C. Gabler, K. Digges, and S. Smith, "Chest and abdominal injuries to occupants in far side crashes," in *The 20th International Technical Conference on Enhanced Saefty of Vehicles Proceedings. Lyon, France*, 2007.
[128] O. Bostrom, H. C. Gabler, K. Digges, B. Fildes, and C. Sunnevang, "Injury reduction opportunities of far side impact countermeasures," in *Annals of Advances in Automotive Medicine/Annual Scientific Conference*, 2008, vol. 52, p. 289: Association for the Advancement of Automotive Medicine.
[129] *Side Impact Protection*, 571.214, 2007.
[130] H. C. Gabler and W. T. Hollowell, "The aggressivity of light trucks and vans in traffic crashes," *SAE transactions*, pp. 1444-1452, 1998.
[131] B. Fildes *et al.*, "Occupant protection in far side crashes," in *Proceedings of the Nineteenth International Conference on Enhanced Safety of Vehicles, Washington, DC, USA*, 2005.
[132] M. L. Brumbelow, B. C. Mueller, and R. A. Arbelaez, "Occurrence of serious injury in real-world side impacts of vehicles with good side-impact protection ratings," *Traffic injury prevention*, vol. 16, no. sup1, pp. S125-S132, 2015.
[133] P. Thomas and R. Frampton, "Injury patterns in side collisions-a new look with reference to current test methods and injury criteria," 1999.
[134] N. Yoganandan, F. A. Pintar, J. Zhang, and T. A. Gennarelli, "Lateral impact injuries with side airbag deployments—a descriptive study," *Accident Analysis & Prevention*, vol. 39, no. 1, pp. 22-27, 2007.
[135] N. Yoganandan *et al.*, "Crash characteristics and injury patterns of restrained front seat occupants in far-side impacts," *Traffic injury prevention*, vol. 15, no. sup1, pp. S27-S34, 2014.
[136] "Lives Saved in 2017 by Restraint Use and Minimum Drinking Age Laws," in "Traffic Safety Facts Crash Stats," National Center for Statistics and Analysis, National Highway Traffic Safety Administration, Washington, DCMarch 2019.
[137] H. R. Li and T. M. Pickrell, "Occupant Restraint Use in 2017: Results From the NOPUS Controlled Intersection Study," 2019.
[138] N. L. Taylor and M. Daily, "Self-reported factors that influence rear seat belt use among adults," *Journal of Safety Research*, vol. 70, pp. 25-31, 2019/09/01/ 2019.
[139] M. Freedman, S. Levi, P. Zador, J. Lopdell, and E. Bergeron, "The effectiveness of enhanced seat belt reminder systems–Observational field data collection methodology and findings," 2007.

[140] N. Lerner, J. Singer, R. Huey, and J. Jenness, "Acceptability and potential effectiveness of enhanced seat belt reminder system features," *Report No. DOT HS,* vol. 810, p. 848, 2007.
[141] M. Freedman, N. Lerner, P. Zador, J. Singer, and S. Levi, "Effectiveness and acceptance of enhanced seat belt reminder systems: Characteristics of optimal reminder systems," 2009.
[142] D. G. Kidd, J. Singer, R. Huey, and L. Kerfoot, "The effect of a gearshift interlock on seat belt use by drivers who do not always use a belt and its acceptance among those who do," *Journal of safety research,* vol. 65, pp. 39-51, 2018.
[143] D. G. Kidd and J. Singer, "The effects of persistent audible seat belt reminders and a speed-limiting interlock on the seat belt use of drivers who do not always use a seat belt," 2019.
[144] D. G. Kidd and J. Singer, "Consumer acceptance of enhanced seat belt reminders, a gearshift interlock, or different speed-limiting interlocks to encourage seat belt use following a brief hands-on experience," *Safety Science,* vol. 120, pp. 617-624, 2019.
[145] M. Krafft, A. Kullgren, A. Lie, and C. Tingvall, "The use of seat belts in cars with smart seat belt reminders—results of an observational study," *Traffic Injury Prevention,* vol. 7, no. 2, pp. 125-129, 2006.
[146] A. Lie, M. Krafft, A. Kullgren, and C. Tingvall, "Intelligent seat belt reminders—Do they change driver seat belt use in Europe?," *Traffic injury prevention,* vol. 9, no. 5, pp. 446-449, 2008.

APPENDIX A. CHAPTER 4, IN-DEPTH REAR IMPACT CASE REVIEWS

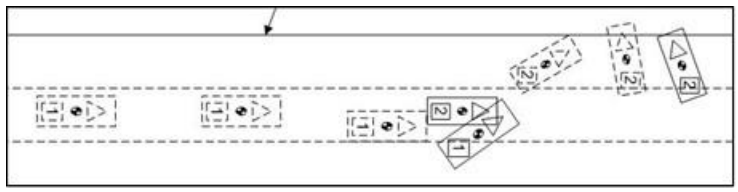
FATALITY CASES

Case Number: NASS/CDS 2001-49-263
Outcome: Fatality **Body Region of Injury:** whole body
Probable Injury Cause: ejection

Crash Scenario

Case Vehicle	
Year	2001
Make	Ford
Model	Explorer
Striking Vehicle	1999 Chevy Pickup
Delta-V (struck, striking)	56, 55 kph
PDOF (struck, striking)	180, 0
Case Occupant	Driver
Age/Gender	21 / Female
Belt Used	No
Other Occupants	Yes
Other MAIS	RRP, 1

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior

Case Summary

The pickup was traveling west in the 3rd lane of a 4 lane divided roadway. The Explorer was traveling in the same land and direction, on the same roadway. The Explorer completely stopped in the middle lane. The pickup's front impacted with the Explorer's rear end. It caused the Explorer to move into the 1st lane and rotate counter clockwise. The driver of the Explorer was completely ejected and struck by another vehicle in a separate event. The rear passenger of the Explorer was transported to a hospital. The driver of the Explorer was hospitalized and deceased within the next 13 days due to the injuries suffered in this and following crash.

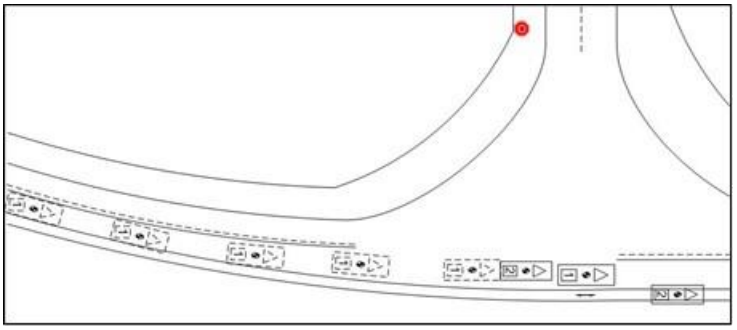
Case Number: NASS/CDS 2002-12-115

Outcome: Fatality **Body Region of Injury:** spine/thorax
Probable Injury Cause: seat loading (G-based)

Crash Scenario

Case Vehicle	
Year	2001
Make	Pontiac
Model	Trans Sport/Montana
Striking Vehicle	2000 Chevrolet G-Series Van
Delta-V (struck, striking)	22, 22 kph
PDOF (struck, striking)	180, 0
Case Occupant	Driver
Age/Gender	72 / Female
Belt Used	Yes
Other Occupants	No
Other MAIS	-

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior (Driver's Seat)

Case Summary

V1 and V2 were heading north on a 2 lane, 2 way, dry, asphalt roadway that curves left. V2, a 2001 Pontiac Montana, was stopped at an intersection to make a left hand turn. As V1, a 2000 Chevrolet G1500 Express van, came around the curve the front of the vehicle contacted the back of V2 causing moderate damage to both vehicles. Both vehicles were towed due to damage. The driver of V1 sought no treatment for minor injuries. All occupants in V1 were wearing their safety belts and the frontal air bags did deploy. The occupant of V2 was wearing her lap and shoulder belt. The vehicle was equipped with front and side air bags, none of which deployed in this rearward impact. She was transported to a local trauma center where she later died of her injuries.

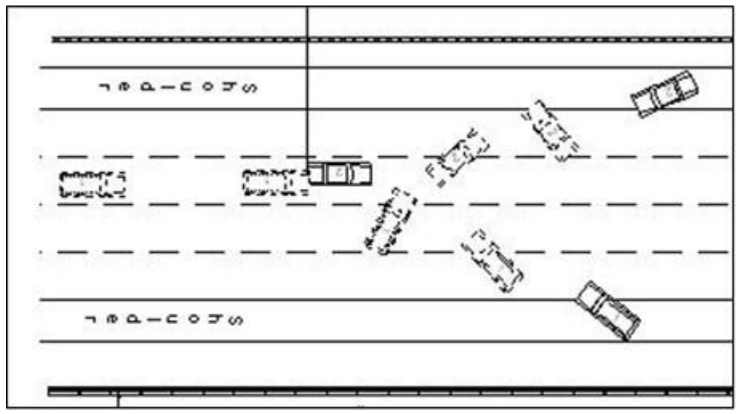
Case Number: NASS/CDS 2006-09-168

Outcome: Fatality **Body Region of Injury:** head (brain stem laceration)
Probable Injury Cause: occupant compartment collapse

Crash Scenario

Case Vehicle	
Year	2004
Make	Ford
Model	Taurus
Striking Vehicle	1997 Ford Expedition
Delta-V (struck, striking)	43, 35 kph
PDOF (struck, striking)	180, 0
Case Occupant	RRP
Age/Gender	54 / Male
Belt Used	Yes
Other Occupants	Yes
Other MAIS	Driver, 1
	RFP, 2
	LRP, 1
	MRP, 2

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior (Rear Seat)

Case Summary

The Expedition was traveling north in lane 3 of a 4 lane divided roadway with positive barriers. The Taurus was stopped in the same lane just ahead of the Expedition. The Expedition's front contacted the Taurus's back plane. The Expedition was towed due to damage and contained a driver and 1 passenger, both of whom were transported. The Taurus was also towed due to damage and contained a driver and 4 passengers all of whom were transported except the right rear passenger (RRP) who was pronounced dead at the scene.

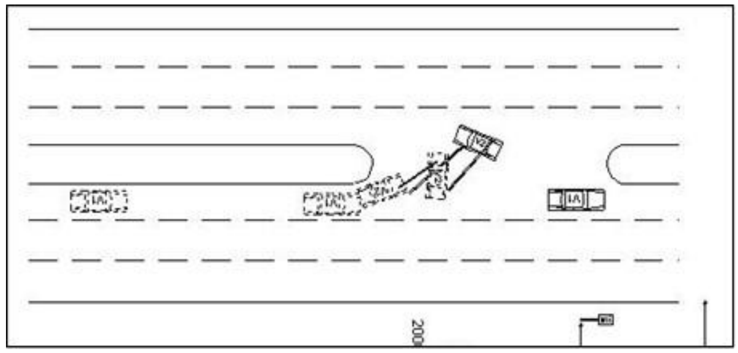
Case Number: NASS/CDS 2006-50-068

Outcome: Fatality **Body Region of Injury:** head (cerebellum subarach. hemorrhage)
Probable Injury Cause: contact w/ rigid vehicle object (B-pillar)

Crash Scenario

Case Vehicle	
Year	2003
Make	Toyota
Model	MR2
Striking Vehicle	2002 Honda Civic
Delta-V (struck, striking)	23, 18 kph
PDOF (struck, striking)	200, 0
Case Occupant	Driver
Age/Gender	63 / Male
Belt Used	No
Other Occupants	Yes
Other MAIS	RFP, 0 (uninjured)

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior (Driver Side B-Pillar)

Case Summary

The Civic was traveling northbound in the 3rd lane of a 3-lane, divided roadway. The MR2 was ahead of the Civic in the same lane. The MR2 came to a stop in the roadway, and the front of the Civic impacted the back of the MR2. Both vehicles were towed due to damage. The unrestrained driver of the MR2 was fatally injured and died in the ER.

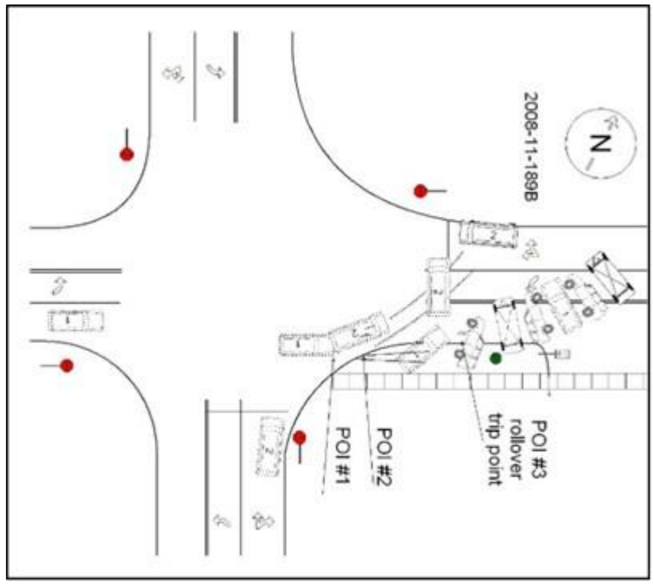
Case Number: NASS/CDS 2008-11-189

Outcome: Fatality **Body Region of Injury:** head (brain stem compress)
Probable Injury Cause: occupant compartment collapse

Crash Scenario

Case Vehicle	
Year	2002
Make	Chrysler
Model	Town & Country
Striking Vehicle	2008 Jeep Grand Cherokee
Delta-V (struck, striking)	31, 31 kph
PDOF (struck, striking)	200, 0
Case Occupant	RR(3rd row)P
Age/Gender	7 / Male
Belt Used	Yes
Other Occupants	Yes
Other MAIS	Driver, 1 RFP, 0 LR(2nd row)P, 0 RR(2nd row)P, 0 LR(3rd row)P, 1

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior (3rd Row, R Seat)

Case Summary

The Cherokee was traveling northeast. The T&C was traveling northwest, turning right to go northeast. The front of the Cherokee contacted the back of the T&C. The Cherokee left the roadway on the right and rolled 6 quarter turns to the right. It then returned to the roadway on the right and came to rest in the northeast bound lane facing northwest on its roof. The T&C rotated counterclockwise, crossed the center line and came to rest against the curb facing southwest. The occupant in the right seat of the 3rd row of the T&C was fatally injured.

Case Number: NASS/CDS 2008-43-091

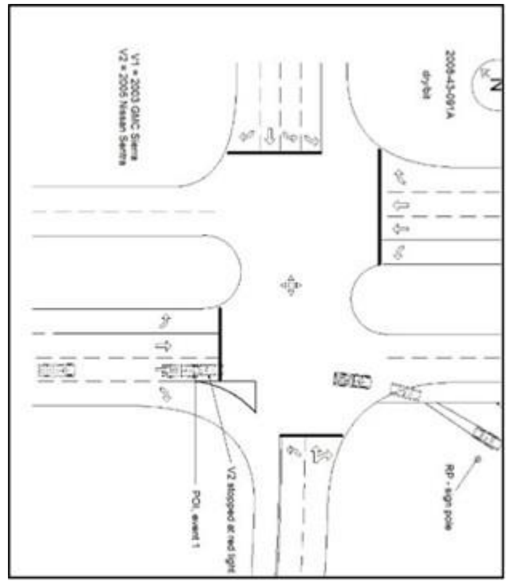
Outcome: Fatality **Body Region of Injury:** thorax

Probable Injury Cause: occupant compartment collapse

Crash Scenario

Case Vehicle	
Year	2005
Make	Nissan
Model	Sentra
Striking Vehicle	2003 GMC Sierra
Delta-V (struck, striking)	unknown
PDOF (struck, striking)	180, 0
Case Occupant	RRP
Age/Gender	26 / Female
Belt Used	No
Other Occupants	Yes
Other MAIS	Driver, 1
	RFP, 3 (see Appendix C)

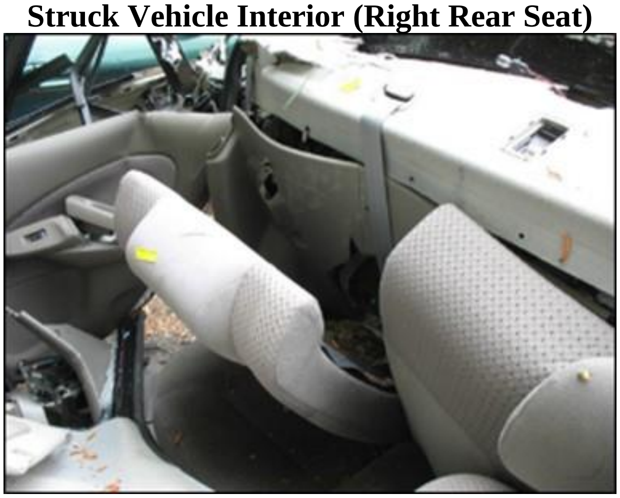
Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior (Right Rear Seat)



Case Summary

The Sierra was eastbound in lane 2 of a 4-lane divided roadway. The Sentra was stopped at a red light facing east in lane 2 of the same roadway. The front of the Sierra contacted the rear of the Sentra.

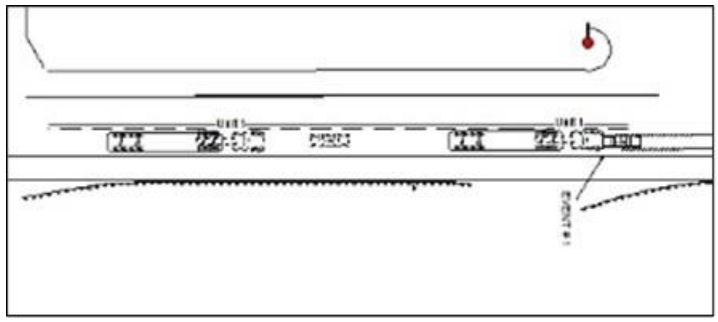
Case Number: NASS/CDS 2010-02-115

Outcome: 2 fatalities **Body Region of Injury:** head, thorax (for both occupants)
Probable Injury Cause: compartment collapse (for both occupants)

Crash Scenario

Case Vehicle	
Year	2004
Make	Honda
Model	Civic
Striking Vehicle	2007 International Harvester
Delta-V (struck, striking)	unknown
PDOF (struck, striking)	180, 0
Case Occupants	Driver, RFP
Age/Gender	83 / Female, 86 / Male
Belt Used	Yes, No
Other Occupants	No
Other MAIS	-

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior (Driver/Rear Seats)

Case Summary

The Civic and the commercial truck were traveling east with the Civic ahead of the truck. The back of the Civic was contacted by the front of the truck.

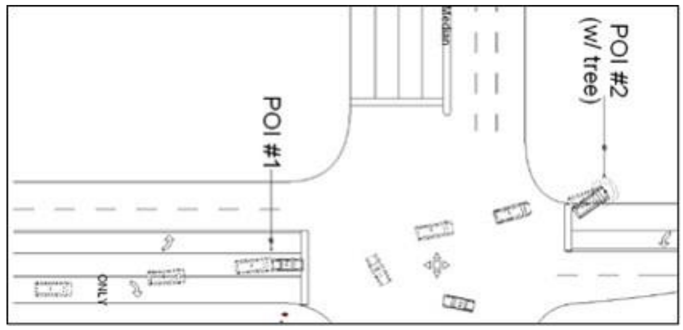
Case Number: NASS/CDS 2010-41-031

Outcome: Fatality **Body Region of Injury:** spine (complete thoracic cord laceraction)
Probable Injury Cause: occupant compartment collapse

Crash Scenario

Case Vehicle	
Year	2001
Make	Honda
Model	Prelude
Striking Vehicle	2005 Ford E-Series Van
Delta-V (struck, striking)	unknown
PDOF (struck, striking)	180, 0
Case Occupant	Driver
Age/Gender	55 / Male
Belt Used	unknown
Other Occupants	Yes
Other MAIS	Driver, 4 (See MAIS 4-5) RFP, 2

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior

No Interior Images

Case Summary

The van was traveling east in lane 1, approaching an intersection. The Prelude was stopped for a red light at the same intersection, facing east in lane 2. The van traveled over the left lane line, into lane 2. The front of the van made contact with the back of the Prelude. The Prelude came to final rest in the intersection. The van continued through the intersection, leaving the roadway on the northeast corner of the intersection. The front of the van made contact with a tree. The van apparently rolled back into the first lane of the intersection to final rest.

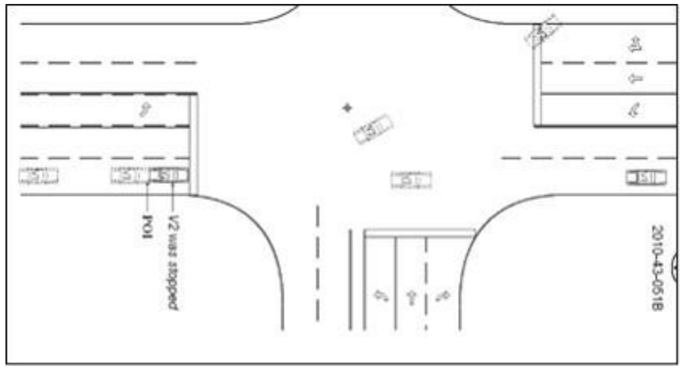
Case Number: NASS/CDS 2010-43-051

Outcome: Fatality **Body Region of Injury:** head
Probable Injury Cause: occupant compartment collapse

Crash Scenario

Case Vehicle	
Year	2006
Make	Scion
Model	TC
Striking Vehicle	2007 Mazda 3
Delta-V (struck, striking)	30, 36 kph
PDOF (struck, striking)	180, 0
Case Occupant	RRP
Age/Gender	24 / Male
Belt Used	No
Other Occupants	Yes
Other MAIS	Driver, 1
	RFP, 1

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior (R Rear Seat)

Case Summary

The Scion and the Mazda were both traveling southbound in lane 1 of a 5-lane undivided roadway. The Scion was stopped and ahead of the Mazda. The front end of the Mazda struck the back end of the Scion.

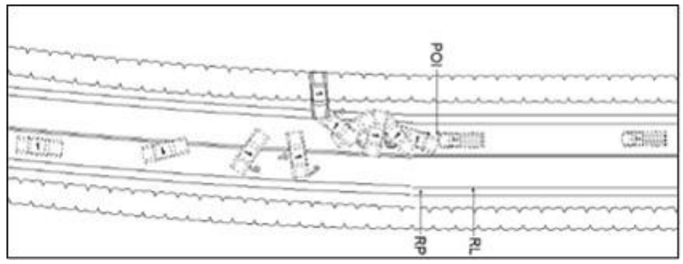
Case Number: NASS/CDS 2013-11-092

Outcome: Fatality **Body Region of Injury:** head (brain stem laceration)
Probable Injury Cause: occupant compartment collapse

Crash Scenario

Case Vehicle	
Year	2005
Make	Ford
Model	Taurus
Striking Vehicle	2009 GMC Canyon
Delta-V (struck, striking)	56, 53 kph
PDOF (struck, striking)	290, 0
Case Occupant	Driver
Age/Gender	38 / Female
Belt Used	Yes
Other Occupants	No
Other MAIS	-

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior (Driver Seat)

Case Summary

The Taurus was eastbound negotiating a left hand curve. The Canyon was westbound approaching the curve. The Taurus went into a counterclockwise yaw while entering the westbound lane. The back right of the Taurus contacted the front of the Canyon.

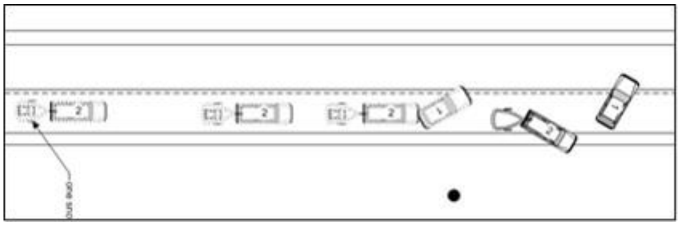
MAIS 4-5 (SEVERE INJURY) CASES

Case Number: NASS/CDS 2000-11-009
Outcome: MAIS 5 **Body Region of Injury:** head (vertebral artery, head laceration)
Probable Injury Cause: occupant compartment collapse

Crash Scenario

Case Vehicle	
Year	2000
Make	Ford
Model	Focus
Striking Vehicle	1996 Jeep Cherokee
Delta-V (struck, striking)	33, 17 kph
PDOF (struck, striking)	200, 350
Case Occupant	Driver
Age/Gender	43 / Female
Belt Used	Unknown
Other Occupants	No
Other MAIS	-

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior (Driver Seat)

Case Summary

V1, a 2000 Ford Focus, was travelling west on a 2 lane rural roadway. V2, a 1996 Jeep Cherokee, was travelling east on the same roadway, while hauling a trailer with a snowmobile. V1 lost control on the roadway due to icy roadway conditions. The back of V1 contacted the front of V2 in the east bound lane. Both vehicles were towed due to damage. The driver of V1 was transported and hospitalized. The driver of V2 was listed on the PAR as not receiving any injuries.

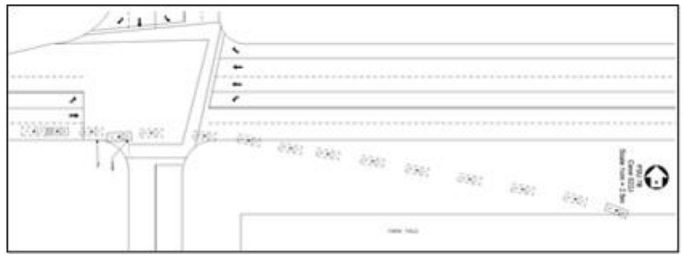
Case Number: NASS/CDS 2003-78-022

Outcome: MAIS 4 **Body Region of Injury:** head (cerebrum hematoma)
Probable Injury Cause: contact w/ rigid surface (rear header)

Crash Scenario

Case Vehicle	
Year	2001
Make	Ford
Model	Ranger
Striking Vehicle	2001 Ford F-Series Pickup
Delta-V (struck, striking)	51, 41 kph
PDOF (struck, striking)	180, 0
Case Occupant	RFP
Age/Gender	70 / Female
Belt Used	Yes
Other Occupants	Yes
Other MAIS	Driver, 1

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Veh. Interior (Front Passenger Seat)

Case Summary

The F-Series was traveling eastbound in the 1st lane approaching an intersection on a 5-lane, level, straight, dry, bituminous, urban roadway. The Ranger was stopped in the same lane at the intersection. The front of the F-Series struck the back of the Ranger. The F-Series came to final rest in the 1st lane in the middle of the intersection facing east. The Ranger traveled off the roadway to the right and came to final rest on a small embankment facing in an easterly direction. The Ranger's restrained driver was hospitalized overnight for observation and released with a scalp laceration. The Ranger's front restrained passenger was hospitalized with a small brain hemorrhage. The Ranger was equipped with front airbags which did not deploy.

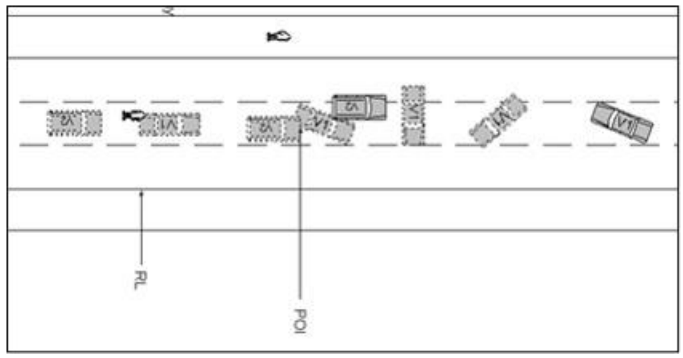
Case Number: NASS/CDS 2008-41-175

Outcome: MAIS 4 **Body Region of Injury:** head (cerebrum hematoma)
Probable Injury Cause: occupant compartment collapse

Crash Scenario

Case Vehicle	
Year	2002
Make	Ford
Model	Taurus
Striking Vehicle	2008 Ford Escape
Delta-V (struck, striking)	unknown
PDOF (struck, striking)	160, 0
Case Occupant	Driver
Age/Gender	22 / Female
Belt Used	No
Other Occupants	No
Other MAIS	-

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior (Driver Seat)

Case Summary

The Taurus was disabled in the center lane of an interchange high volume/high occupancy roadway. The passenger was trying to push the vehicle off the roadway to the right when the Escape's front contacted the back of the Taurus, pushing it approximately 200 feet while rotating clockwise making final rest facing northbound.

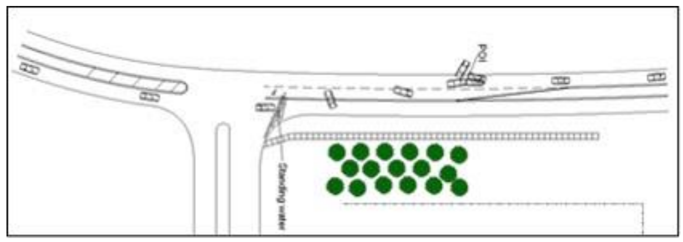
Case Number: NASS/CDS 2008-43-249

Outcome: MAIS 5 **Body Region of Injury:** neck (C spine fracture)
Probable Injury Cause: head restraint contact

Crash Scenario

Case Vehicle	
Year	2002
Make	Honda
Model	Accord
Striking Vehicle	2002 Nissan Sentra
Delta-V (struck, striking)	76, 83 kph
PDOF (struck, striking)	170, 350
Case Occupant	Driver
Age/Gender	20 / Male
Belt Used	Yes
Other Occupants	No
Other MAIS	-

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior (Driver Seat)

Case Summary

The Accord was traveling west in lane 1 of a 3 lane roadway. The Sentra was traveling east in lane 1 of the same roadway. It was raining and there was standing water on the roadway. The Accord contacted standing water in the roadway and started rotating counter clockwise and crossed the center lane to the left. The front of the Sentra contacted the rear of the Accord.

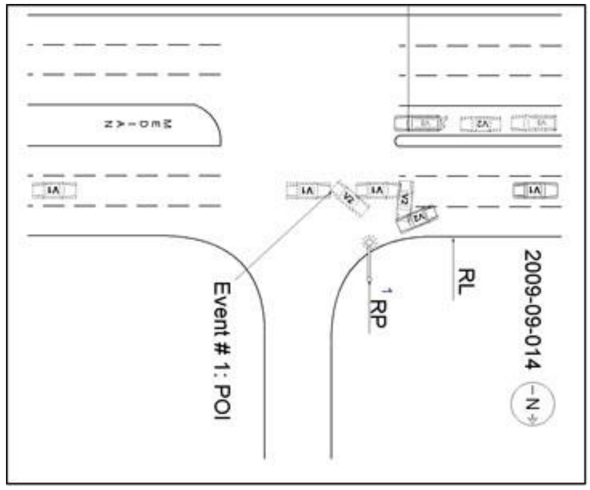
Case Number: NASS/CDS 2009-09-014

Outcome: MAIS 5 **Body Region of Injury:** head (cerebrum hematoma)
Probable Injury Cause: head contact w/ rigid surface (B-pillar)

Crash Scenario

Case Vehicle	
Year	2004
Make	Kia
Model	Optima
Striking Vehicle	2001 Mercedes Benz S Class
Delta-V (struck, striking)	18, 17 kph
PDOF (struck, striking)	140, 0
Case Occupant	Driver
Age/Gender	36 / Male
Belt Used	No
Other Occupants	Yes
Other MAIS	RFP, 1

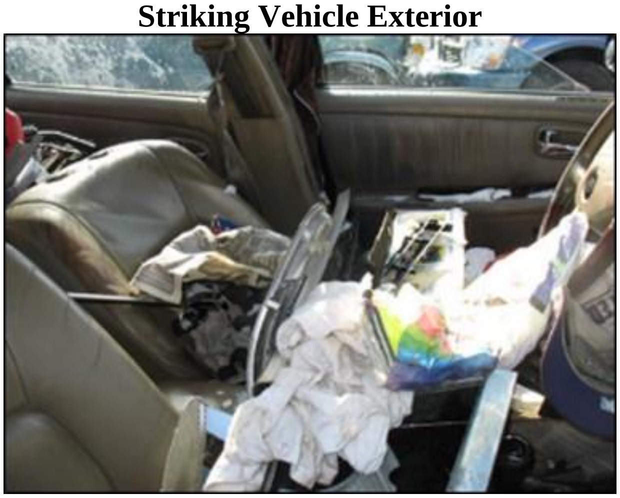
Crash Scene



Struck Vehicle Exterior

Struck Vehicle Interior

Striking Vehicle Exterior



Case Summary

The Mercedes was traveling westbound in lane 2. The Kia was traveling eastbound in lane 4. The Kia began a U-turn when the Mercedes front end plane contacted the Kia's back plane.

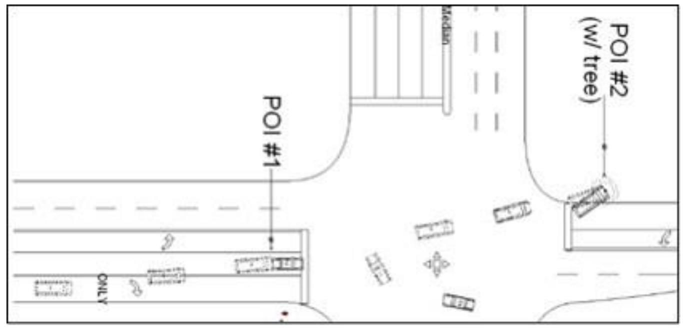
Case Number: NASS/CDS 2010-41-031

Outcome: MAIS 4 **Body Region of Injury:** head (cerebrum hematoma)
Probable Injury Cause: contact w/ rigid object (other occupant)

Crash Scenario

Case Vehicle	
Year	2001
Make	Honda
Model	Prelude
Striking Vehicle	2005 Ford E-Series Van
Delta-V (struck, striking)	unknown
PDOF (struck, striking)	180, 0
Case Occupant	Driver
Age/Gender	21 / Female (pregnant, 2nd trimester)
Belt Used	Unknown
Other Occupants	Yes
Other MAIS	RFP, 2 RRP, fatal (see fatal cases)

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior

No Interior Images

Case Summary

The van was traveling east in lane 1, approaching an intersection. The Prelude was stopped for a red light at the same intersection, facing east in lane 2. The van traveled over the left lane line, into lane 2. The front of the van made contact with the back of the Prelude. The Prelude came to final rest in the intersection. The van continued through the intersection, leaving the roadway on the northeast corner of the intersection. The front of the van made contact with a tree. The van apparently rolled back into the first lane of the intersection to final rest.

Case Number: NASS/CDS 2010-41-053

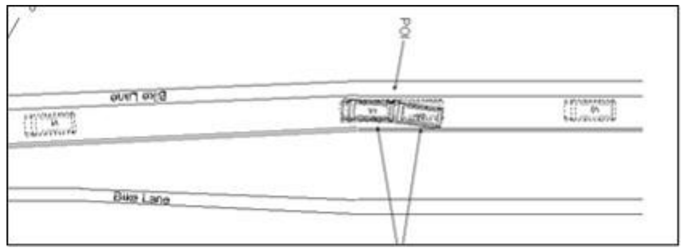
Outcome: MAIS 4 **Body Region of Injury:** head (cerebrum hematoma)

Probable Injury Cause: contact w/ rigid object (roof top)

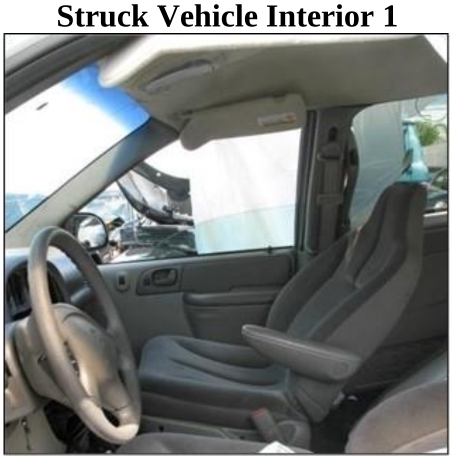
Crash Scenario

Case Vehicle	
Year	2002
Make	Dodge
Model	Caravan
Striking Vehicle	2001 GMC Safari
Delta-V (struck, striking)	50, 38 kph
PDOF (struck, striking)	180, 0
Case Occupant	RFP
Age/Gender	23 / Female
Belt Used	No
Other Occupants	Yes
Other MAIS	Driver, 1

Crash Scene



Struck Vehicle Interior 1



Struck Vehicle Interior 2

Struck and Striking Vehicles at Final Rest

Case Summary

The Caravan was traveling northbound in reverse in the southbound lane. The Safari was traveling southbound in the same lane. As the Caravan approached the Safari, the back of the Caravan contacted the front of the Safari.

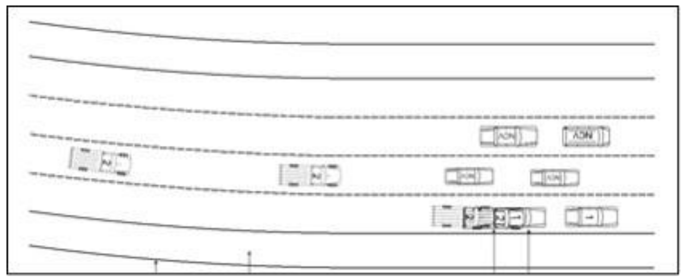
Case Number: NASS/CDS 2011-43-177

Outcome: MAIS 4 **Body Region of Injury:** head (cerebrum hematoma)
Probable Injury Cause: occupant compartment collapse

Crash Scenario

Case Vehicle	
Year	2007
Make	Toyota
Model	Camry
Striking Vehicle	2001 Ford Ranger
Delta-V (struck, striking)	unknown
PDOF (struck, striking)	180, 0
Case Occupant	RRP
Age/Gender	33 / Female
Belt Used	No
Other Occupants	Yes
Other MAIS	Driver, 1 RFP, 1 LRP, 2

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior (Rear Seat)

Case Summary

The Camry was traveling eastbound in lane 1 of a 4-lane highway. It was stopped in its lane. The Ranger was traveling eastbound in lane 2 of the same 4-lane highway. It changed lanes and its front end struck the back end of the Camry.

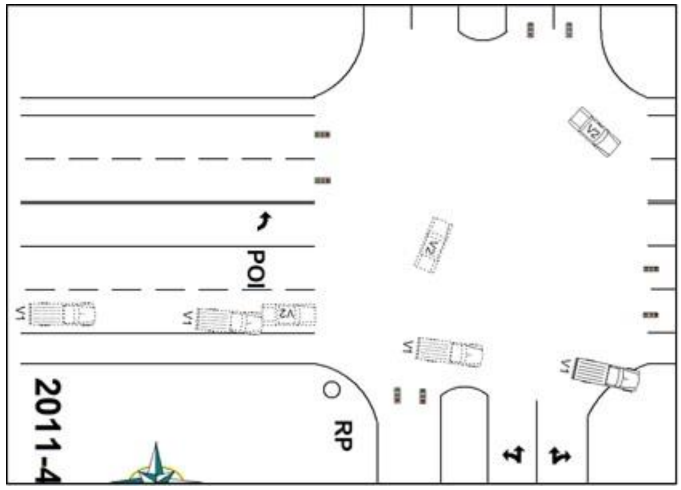
Case Number: NASS/CDS 2011-45-091

Outcome: MAIS 4 **Body Region of Injury:** head (cerebrum hematoma)
Probable Injury Cause: (probable) head contact w/ rigid surface (unspecified injury source)

Crash Scenario

Case Vehicle	
Year	2009
Make	Hyundai
Model	Elantra
Striking Vehicle	1997 Ford F-Series Pickup
Delta-V (struck, striking)	26, 18 kph
PDOF (struck, striking)	190, 0
Case Occupant	Driver
Age/Gender	26 / Male
Belt Used	Yes
Other Occupants	No
Other MAIS	-

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior (Driver Seat)

Case Summary

The pickup and the Elantra were both westbound on a 5-lane road. The Elantra was stopped at a traffic signal. The pickup's front contacted the Elantra's rear.

MAIS 3 (SERIOUS INJURY) CASES

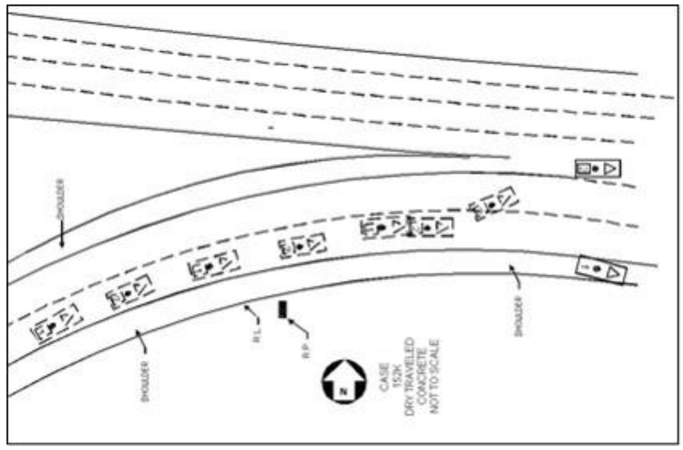
Case Number: NASS/CDS 2005-49-152

Outcome: MAIS 3 **Body Region of Injury:** upper extremity (humerus fracture – open)
Probable Injury Cause: arm contact w/ rigid surface (seat back)

Crash Scenario

Case Vehicle	
Year	2001
Make	Chevrolet
Model	Cavalier
Striking Vehicle	1990 Lexus LS
Delta-V (struck, striking)	47, 34 kph
PDOF (struck, striking)	170, 0
Case Occupant	Driver
Age/Gender	42 / Male
Belt Used	Yes
Other Occupants	No
Other MAIS	-

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior (Driver Seat)

Case Summary

V1, a 1990 Lexus LS400, was traveling eastbound in the 1st lane of a 2-lane, 1-way service road, merging with an expressway. V2, a 2001 Chevrolet Cavalier, was traveling eastbound in the same lane, ahead of and slower than V1. The front of V1 impacted the back of V2. V1 left the road to the right and came to rest on the paved shoulder. V2 crossed the pained median and came to rest on the expressway. Both vehicles were towed due to damage. The restrained driver of V1 was not injured. The restrained driver of V2 was hospitalized with an upper arm fracture. V1 was equipped with a first-generation driver's frontal airbag, which deployed. V2 was equipped with dual frontal airbags, which did not deploy.

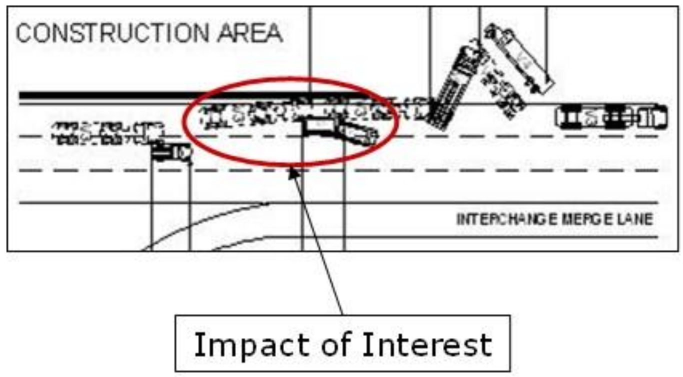
Case Number: NASS/CDS 2007-09-046

Outcome: MAIS 3 **Body Region of Injury:** head (cerebrum subarachnoid hemorrhage)
Probable Injury Cause: probable contact w/ rigid surface (B-pillar), although coded as head restraint

Crash Scenario

Case Vehicle	
Year	2007
Make	Chrysler
Model	Town & Country
Striking Vehicle	1998 Freightliner
Delta-V (struck, striking)	unknown
PDOF (struck, striking)	180, 0
Case Occupant	Driver
Age/Gender	62 / Male
Belt Used	Yes
Other Occupants	Yes
Other MAIS	RFP, 1

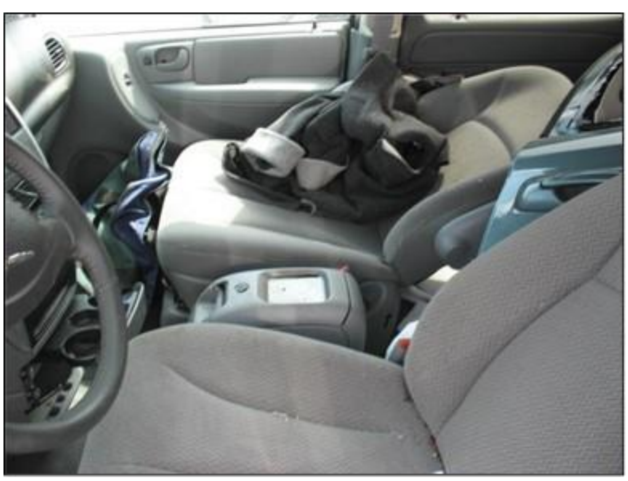
Crash Scene



Struck Vehicle Exterior 1

Struck Vehicle Exterior 2

Struck Vehicle Interior (Front Seats)



Case Summary

V2, a 2007 Chrysler T&C, was stopped in lane 3 of a 4-lane, divided roadway facing west. V1 was stopped in lane 4 of this same roadway. Both vehicles were stopped for V4, a fire truck, which was responding to a crash on the other side of the concrete traffic barrier. V3, a 1998 Freightliner, traveled westbound in lane 4, approached the stopped traffic and began to merge to its right when it crossed paths with V1. V1's left side-plane made contact with the Freightliner. **The Freightliner then returned to lane 4 and come into contact with the rear end-plane of the T&C with its front end-plane (impact of interest to this case review).** The Freightliner continued forward and struck the fire truck in the left-side plane with its front-end plane.

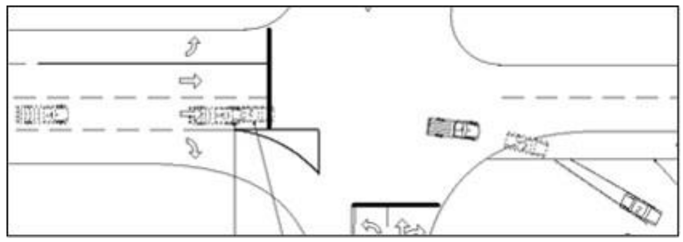
Case Number: NASS/CDS 2008-43-091

Outcome: MAIS 3 **Body Region of Injury:** neck (C spine fracture)
Probable Injury Cause: occupant compartment collapse

Crash Scenario

Case Vehicle	
Year	2005
Make	Nissan
Model	Sentra
Striking Vehicle	2003 GMC Pickup
Delta-V (struck, striking)	unknown
PDOF (struck, striking)	180, 0
Case Occupant	RFP
Age/Gender	22 / Female
Belt Used	Yes
Other Occupants	Yes
Other MAIS	Driver, 1
	RRP, fatal (see Appendix A)

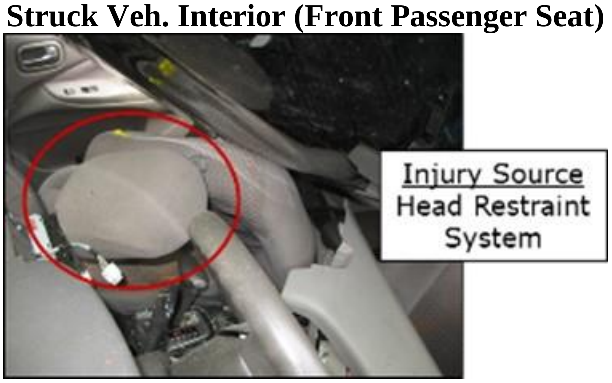
Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Veh. Interior (Front Passenger Seat)



Case Summary

The pickup was eastbound in lane 2 of a 4-lane divided highway. The Sentra was stopped at a red light facing east in lane 2 of the same roadway. The front of the pickup contacted the rear of the Sentra.

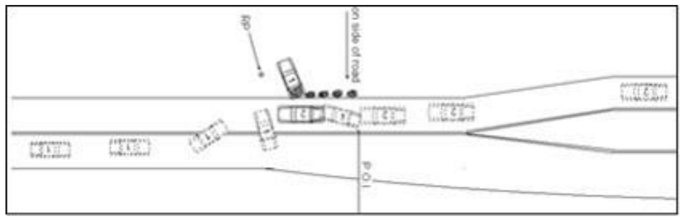
Case Number: NASS/CDS 2009-11-017

Outcome: MAIS 3 **Body Region of Injury:** upper extremity (radius fracture – open)
Probable Injury Cause: arm contact w/ rigid surface (hardware in left rear lower vehicle quadrant)

Crash Scenario

Case Vehicle	
Year	2003
Make	Honda
Model	Civic
Striking Vehicle	1997 Chevrolet Lumina
Delta-V (struck, striking)	56, 42 kph
PDOF (struck, striking)	160, 350
Case Occupant	Driver
Age/Gender	27 / Male
Belt Used	Yes
Other Occupants	No
Other MAIS	-

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior (Driver Seat)

Case Summary

The Civic was traveling northbound in lane 1. The Lumina was traveling southbound in lane 1. The Civic rotated 180 degrees counterclockwise and crossed the centerline. The front of the Lumina contacted the back of the Civic.

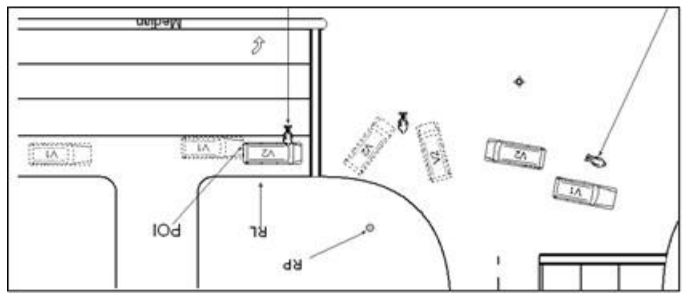
Case Number: NASS/CDS 2009-41-256

Outcome: MAIS 3 **Body Region of Injury:** upper extremity (humerus fracture - open)
Probable Injury Cause: ejection (landed on hood of striking vehicle)

Crash Scenario

Case Vehicle	
Year	2002
Make	Ford
Model	E-Series Van
Striking Vehicle	2007 Chevrolet Suburban
Delta-V (struck, striking)	31, 47 kph
PDOF (struck, striking)	180, 0
Case Occupant	Passenger (unknown position, likely sitting in cargo hold of van)
Age/Gender	58 / Female
Belt Used	No
Other Occupants	Yes
Other MAIS	Driver, 1

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior (Cargo Door)

Case Summary

The Suburban was traveling westbound approaching a 4-way intersection. The van was stopped directly in front of the Suburban. The Suburban's front made contact with the back of the van. The van rotated counter-clockwise, making final rest in the middle of the intersection facing eastbound. Occupant 2 (the passenger in question) of the van was ejected out of the back of the van.

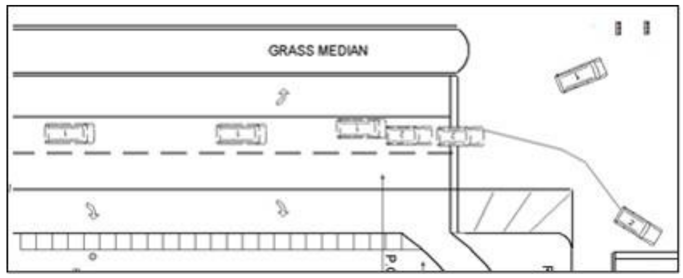
Case Number: NASS/CDS 2009-45-054

Outcome: MAIS 3 **Body Region of Injury:** thorax (rib cage fracture – 4 ribs, left side)
Probable Injury Cause: 2 possibilities – 1) hard surface contact [driver strikes door], or 2) seat loading [G-based]

Crash Scenario

Case Vehicle	
Year	2005
Make	Ford
Model	Escape
Striking Vehicle	2005 Buick Rendezvous
Delta-V (struck, striking)	61, 56 kph
PDOF (struck, striking)	180, 0
Case Occupant	Driver
Age/Gender	19 / Female
Belt Used	Yes
Other Occupants	No
Other MAIS	-

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior (Driver Seat)

Case Summary

The Buick was traveling on the 4-lane southbound section of a roadway that has a center grass divider in the inside travel lane. The Ford was stopped in the inside travel lane on the same roadway. The Buick's front struck the back of the Ford.

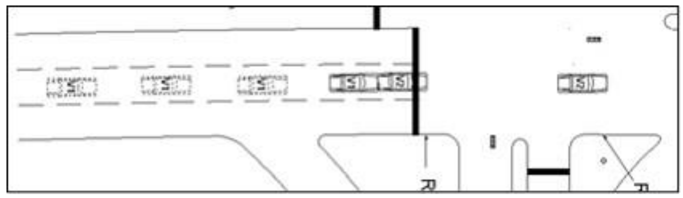
Case Number: NASS/CDS 2010-48-118

Outcome: MAIS 3 **Body Region of Injury:** head (cerebrum subarachnoid hemorrhage)
Probable Injury Cause: probable head contact w/ rigid surface (C-pillar), although coded as head restraint

Crash Scenario

Case Vehicle	
Year	2004
Make	Chevrolet
Model	Malibu
Striking Vehicle	1990 Nissan Maxima
Delta-V (struck, striking)	29, 33 kph
PDOF (struck, striking)	180, 0
Case Occupant	LRP
Age/Gender	46 / Female
Belt Used	No
Other Occupants	Yes
Other MAIS	Driver, 1 RFP, 1

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior (L Rear Seat)

Case Summary

The Maxima and the Malibu were traveling west in the middle lane approaching an intersection with the Maxima behind the Malibu. The Malibu stopped at a traffic light. The front of the Maxima contacted the rear plane of the Malibu. The Maxima stopped facing west at the traffic light for final rest. The Malibu was pushed through the intersection and stopped in the same lane facing west just passed the light. Both vehicles were towed due to disabling damage.

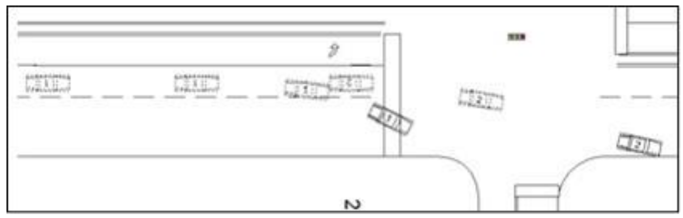
Case Number: NASS/CDS 2010-73-016

Outcome: MAIS 3 **Body Region of Injury:** neck (C spine fracture)
Probable Injury Cause: head restraint contact

Crash Scenario

Case Vehicle	
Year	2001
Make	Oldsmobile
Model	Aurora
Striking Vehicle	1998 Buick Lesabre
Delta-V (struck, striking)	15, 16 kph
PDOF (struck, striking)	180, 0
Case Occupant	Driver
Age/Gender	59 / Male
Belt Used	Yes
Other Occupants	No
Other MAIS	-

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior (Driver Seat)

Case Summary

The Buick was southbound in lane 2 of a 5-lane, 2-direction roadway approaching a traffic signal controlled intersection. The Oldsmobile was stopped at the traffic signal in the same lane as the approaching Buick. The front of the Buick impacted the back of the Oldsmobile.

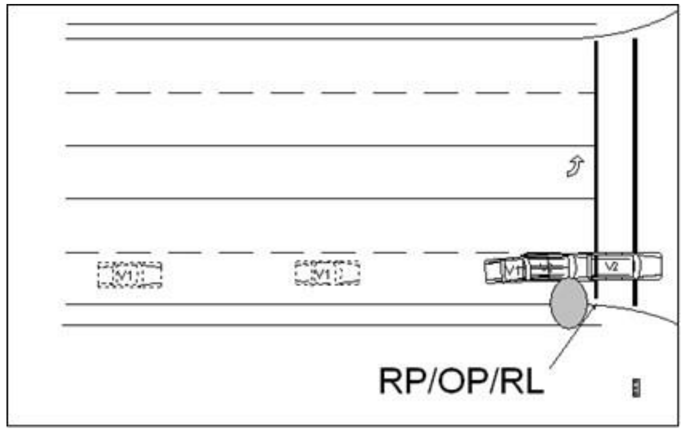
Case Number: NASS/CDS 2010-78-143

Outcome: MAIS 3 **Body Region of Injury:** thorax (rib fracture – 3 ribs, left side)
Probable Injury Cause: seat loading (G-based)

Crash Scenario

Case Vehicle	
Year	2002
Make	Chevrolet
Model	Trailblazer
Striking Vehicle	2009 Toyota Corolla
Delta-V (struck, striking)	unknown
PDOF (struck, striking)	180, 0
Case Occupant	RFP
Age/Gender	58 / Male
Belt Used	Yes
Other Occupants	Yes
Other MAIS	Driver, 1 RRP, 1

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Striking Vehicle Exterior

Case Summary

The Trailblazer was stopped at a traffic signal facing east and the Corolla was traveling east behind the Trailblazer. The front of the Corolla contacted the back of the Trailblazer.

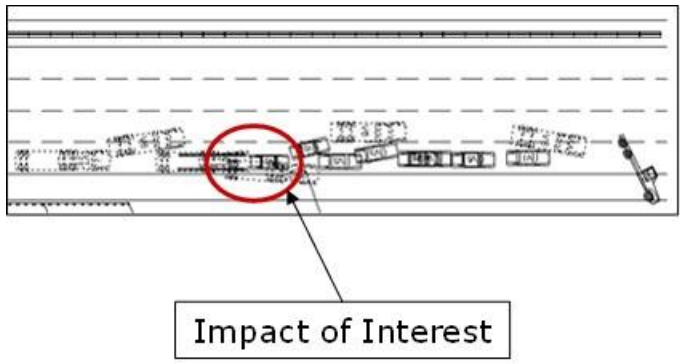
Case Number: NASS/CDS 2011-49-064

Outcome: MAIS 3 **Body Region of Injury:** abdomen (spleen laceration, moderate)
Probable Injury Cause: unknown; Injuries and photos appear consistent with a side impact. Case appears to be a rear impact followed by a side impact (possible miscode in NASS/CDS).

Crash Scenario

Case Vehicle	
Year	2011
Make	Ford
Model	Fiesta
Striking Vehicle	2010 Peterbilt Medium/Heavy CBE
Delta-V (struck, striking)	unknown
PDOF (struck, striking)	180, 0
Case Occupant	Driver
Age/Gender	54 / Male
Belt Used	Yes
Other Occupants	No
Other MAIS	-

Crash Scene



Struck Vehicle Exterior 1

Struck Vehicle Exterior 2

Struck Vehicle Interior (Driver Seat)

Case Summary

All vehicles were traveling east on a highway in the right lane. V6 was traveling in the same lane ahead of the Peterbilt truck. The Fiesta, V3, V4, V5, and V7 were stopped ahead of the Peterbilt truck and V6. V6 attempted to merge into the left lane. The front of the Peterbilt truck struck the back of V6. **The front of the Peterbilt truck then struck the back of the Fiesta, pushing the Fiesta into the lane to its left (impact of interest to this case).** The front of V3 struck the back of V4. V4 moved forward and struck the back of V5 with its front. While V6 was moving east traveling in the next lane to the left, the right side of V6 struck the left side of V3. The right side of V6 struck the left side of V7. V6 rotated clockwise and rolled one quarter turn to the left.

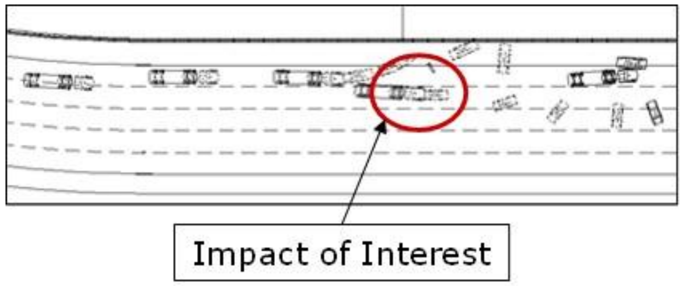
Case Number: NASS/CDS 2011-74-048

Outcome: MAIS 3 **Body Region of Injury:** thorax (rib fracture – 7 ribs, right side)
Probable Injury Cause: 2 possibilities: 1) contact w/ rigid surface [driver strikes adjoining seat w/ right side of chest], or 2) seat loading [G-based]

Crash Scenario

Case Vehicle	
Year	2005
Make	Toyota/Scion
Model	XB
Striking Vehicle	2006 Volvo Truck
Delta-V (struck, striking)	unknown
PDOF (struck, striking)	180, 0
Case Occupant	Driver
Age/Gender	41 / Male
Belt Used	Yes
Other Occupants	No
Other MAIS	-

Crash Scene



Struck Vehicle Exterior 1

Struck Vehicle Interior 1 (Across Front Row)

Struck Vehicle Interior 2 (Driver Seat)

Case Summary

All vehicles were travelling west on an interstate. V1 (not the Scion) was in the left-most lane when a pedestrian entered the roadway to retrieve a saw that flew out of his vehicle. V1 slowed down to avoid the pedestrian when it was struck in the back by the truck. V1 struck the pedestrian then departed the road, where its front struck a concrete barrier. V1 rotated counter-clockwise as it re-entered the road. **The truck veered right and its front struck the back of the Scion (impact of interest to this case).** The truck returned to the left-most lane as V1 was re-entering the road, and the left side of V1 contacted the left side of the truck.

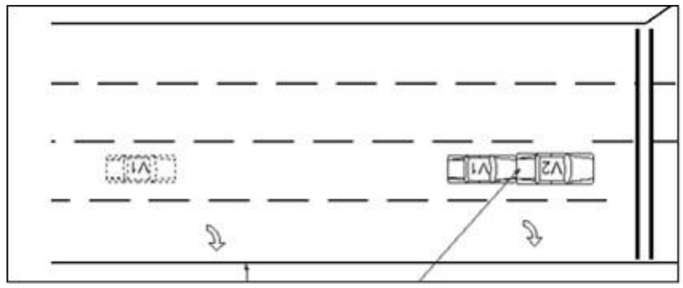
Case Number: NASS/CDS 2012-09-014

Outcome: MAIS 3 **Body Region of Injury:** lower extremity (femur fracture)
Probable Injury Cause: leg entrapment

Crash Scenario

Case Vehicle	
Year	2008
Make	Ford
Model	Mustang
Striking Vehicle	2003 Kia Rio
Delta-V (struck, striking)	19, 19 kph
PDOF (struck, striking)	180, 0
Case Occupant	Driver
Age/Gender	50 / Female
Belt Used	Yes
Other Occupants	No
Other MAIS	-

Crash Scene



Struck Vehicle Exterior

Struck Vehicle Interior

Striking Vehicle

No Kia Rio Pictures

Case Summary

The Rio was traveling eastbound in lane 2. The Mustang was stopped for a traffic light in lane 2 when the Rio's front contacted the Mustang's back.

Case Number: NASS/CDS 2012-76-096

Outcome: MAIS 3 **Body Region of Injury:** head (cerebrum subarachnoid hemorrhage)
Probable Injury Cause: probable contact w/ rigid surface (B-pillar), although coded as head restraint

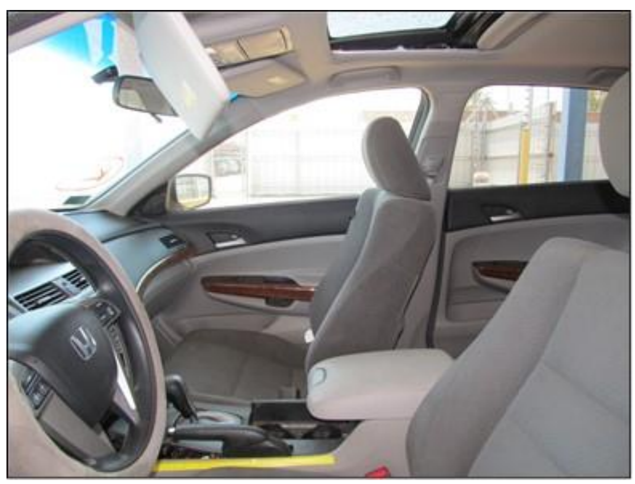
Crash Scenario

Case Vehicle	
Year	2011
Make	Honda
Model	Accord
Striking Vehicle	2002 Honda CR-V
Delta-V (struck, striking)	23, 18 kph
PDOF (struck, striking)	180, 0
Case Occupant	RFP
Age/Gender	79 / Female
Belt Used	No
Other Occupants	Yes
Other MAIS	Driver, 1 RRP, 1

Crash Scene

Struck Vehicle Exterior

Struck Vehicle Interior



Striking Vehicle

No Honda CR-V Pictures

Case Summary

The CR-V was northbound on a divided traffic way. The Accord was northbound in front of the CR-V. The front of the CR-V struck the back of the Accord.

Case Number: NASS/CDS 2012-76-137

Outcome: MAIS 3 **Body Region of Injury:** thorax (rib fracture – 4 ribs, right side)
Probable Injury Cause: seat loading (G-based)

Crash Scenario

Case Vehicle	
Year	2008
Make	Buick
Model	Lacrosse
Striking Vehicle	2007 GMC Acadia
Delta-V (struck, striking)	22, 17 kph
PDOF (struck, striking)	180, 0
Case Occupant	RFP
Age/Gender	82 / Female
Belt Used	Yes
Other Occupants	Yes
Other MAIS	Driver, 0 (uninjured)

Crash Scene

Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Veh. Interior (Front Passenger Seat)

Case Summary

The Acadia was northbound in the 1st lane behind the Lacrosse, which was also northbound in the 1st lane, when the front of the Acadia struck the back of the Lacrosse.

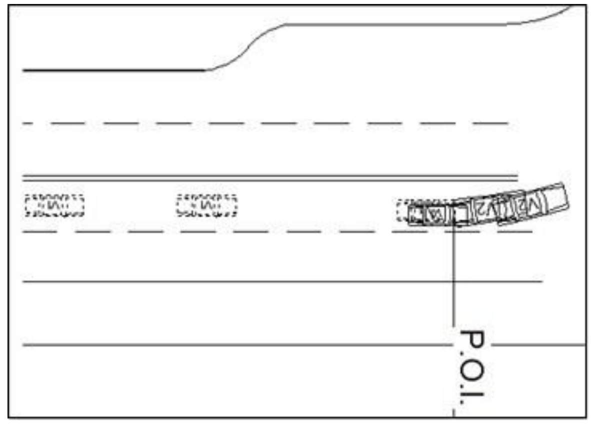
Case Number: NASS/CDS 2013-12-101

Outcome: MAIS 3 **Body Region of Injury:** head (cerebrum contusion)
Probable Injury Cause: head contact w/ rigid surface (seat belt mount, see photos)

Crash Scenario

Case Vehicle	
Year	2004
Make	Buick
Model	Lesabre
Striking Vehicle	2006 Pontiac G6
Delta-V (struck, striking)	29, 31 kph
PDOF (struck, striking)	190, 350
Case Occupant	Driver
Age/Gender	34 / Female
Belt Used	Yes
Other Occupants	No
Other MAIS	-

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior

Case Summary

The Buick was stopped facing northbound waiting to turn left. The Pontiac was traveling northbound intending on going in a straight path. The Buick's front impacted the rear of the Pontiac.

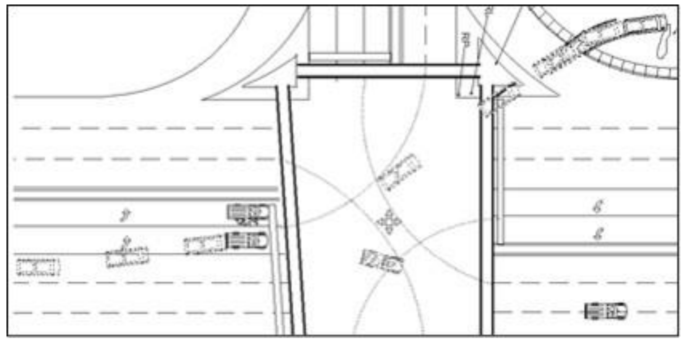
Case Number: NASS/CDS 2013-75-078

Outcome: MAIS 3 **Body Region of Injury:** thorax (rib fracture – 5 ribs, right side)
Probable Injury Cause: seat loading (G-based)

Crash Scenario

Case Vehicle	
Year	2010
Make	Dodge
Model	Ram
Striking Vehicle	2000 Ford E-Series Van
Delta-V (struck, striking)	46, 37 kph
PDOF (struck, striking)	170, 0
Case Occupant	Driver
Age/Gender	68 / Male
Belt Used	Yes
Other Occupants	No
Other MAIS	-

Crash Scene



Struck Vehicle Exterior

Striking Vehicle Exterior

Struck Vehicle Interior (Driver Seat)

Case Summary

The van was traveling northbound, approaching an intersection. The Dodge was stopped ahead of the van in the lane to the van's left. V3 was stopped next to the Dodge, to its left. The van moved left across the lane line as it approaches the stopped traffic, and the front of the van stuck the back of the Dodge. Debris from the impact struck the right side of V3. The van continued forward to the northwest and departed the road onto a raised island by the northwest corner, damaging the left front wheel against the curb. The van's front struck a delineator post as it traversed the island. The van continued forward and departed the road over the northwest curb, where it came to rest.

Case Number: NASS/CDS 2014-78-015

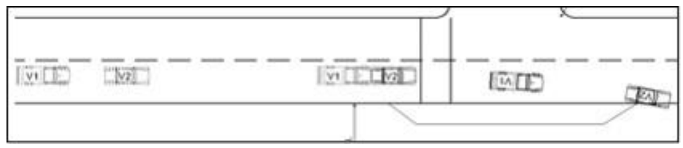
Outcome: MAIS 3 **Body Region of Injury:** thorax (rib fracture – 4 ribs, right side)

Probable Injury Cause: seat loading (G-based)

Crash Scenario

Case Vehicle	
Year	2013
Make	Nissan
Model	Altima
Striking Vehicle	2013 Ford F-Series Pickup
Delta-V (struck, striking)	34, 23 kph
PDOF (struck, striking)	180, 0
Case Occupant	RRP
Age/Gender	62 / Female
Belt Used	Yes
Other Occupants	Yes
Other MAIS	Driver, 0
	RFP, 0
	LRP, 0

Crash Scene



Struck Vehicle Exterior

Struck Vehicle Interior

Struck Vehicle Interior (R Rear Seat)

Case Summary

The pickup was southbound on an undivided roadway. The Altima was southbound in front of the pickup. The Altima stopped and the front of the pickup struck the back of the Altima.