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Final Report

Project Title: Bioinjury Implications of Pre-crash Safety Modeling and Intervention Investigators

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OVERVIEW

This is the Final Report of the Project

Bioinjury Implications of Pre-Crash Safety Modeling and Intervention

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Project Description

Project 4 will directly address the UTC's human physiology strategy. The goal will be to include bioinjury expertise in scenario generation, data collection, and human behavioral models so that research outcome metrics are closely aligned with the goal of improving safety.

In particular, we will investigate whether bioinjury data from a particular crash scenario can suggest particular evasive actions by the driver or the autonomous vehicle to minimize injury. We hypothesize that bioinjury data from a particular crash scenario can suggest situations in which the driver should not re-engage and assume control of the vehicle but rather leave the autonomous system in control, because human motor skill or reaction time would be insufficient to mitigate injury. Coupled with human behavioral models developed in Projects 2 and 3, we will be able to extrapolate situations beyond those for which data currently exist, and to test these extrapolated situations under Project 1.

We will also investigate how bioinjury data can inform the user community—both vehicle designers and vehicle safety policy makers—about the optimum position of the driver and the timing of passive restraints for given crash scenarios. As an example, recent data from airbag injury studies have suggested that the position of the driver's hands on the wheel should be modified to avert arm and wrist fractures when airbags are deployed. This information is expected to inform policy and safety procedures as well. As a second example, increasing vehicle autonomy for crash prevention increases the likelihood that the vehicle is braking hard at the time of impact, placing the driver and passengers in very different positions than those currently being employed in crash testing. The research on both driver behavior and autonomous vehicle behavior is expected to suggest alternative—and more relevant—safety testing procedures.

A primary resource for this research will be the crash data available from two national sources. The National Automotive Sampling System (NASS) Crashworthiness Data System (CDS) provides a broad range of data from crashes that occur in the United States. These data, largely based on police reports, focus on passenger vehicle crashes and are used to investigate injury

mechanisms. The database may be queried across several relevant variables, including primary direction of impact, object impacted, age and sex of occupants, safety restraints, and resulting injuries. The Crash Injury Research Engineering Network (CIREN) consists of detailed analyses of motor vehicle crashes, including both accident reconstruction and medical injury profiles. CIREN is University Transportation Centers Program more focused on specific crashes in which the occupant received a serious injury. The CIREN network brings together the first responders to the crash, the treating physicians, and a panel of bioinjury experts to examine each injury in detail and to document corresponding injury mechanisms. Similar to NASS CDS, CIREN cases may be searched across several relevant variables. The CIREN database is ideal for comparing bioinjury data across variations in a given crash scenario, such as different passive restraints or different occupant positions.

We will use the NASS CDS to define the most critical injury mechanisms related to each scenario to be considered in the UTC. We will also examine CIREN to document specific injury outcomes based on variations related to the automobile safety systems and to the driver's position and reaction. These analyses will be used to understand which variations lead to fewer or less severe injuries, providing valuable input to both human behavior influencing strategies and autonomous vehicle control strategies considered in other projects, with the goal of improving pre-crash safety. Information leading to improvements in passive restraint systems and more effective crash test protocols are also expected.

BACKGROUND

As a starting point and for the creation of a collaborative research project to investigate bio-injury mechanisms in crash imminent scenarios for automotive applications, the University Transportation Center (UTC) and the Injury Biomechanics Research Center (IBRC) at The Ohio State University chose three crash scenarios. Of NHTSA's 37 pre-crash scenarios, which are based on 6 million police reported crashes documented in the 2004 General Estimates System, they represent $26 billion of $120 billion in economic cost and 17% of the total functional years lost (Najm, 2007). The boundary conditions for the three crash scenarios were chosen to isolate common, yet relatively straight-forward crash physics. A population-based database (National Automotive Sampling System – Crashworthiness Data System (NASS-CDS)) and a real-world crash database (Crash Injury Research Engineering Network (CIREN)) were chosen as data sources. This study identified injury mechanisms and outcomes in lead vehicle stopped (LVS), near-side (NSI), and lane-change related (CLH) crashes and posed suggestions for ways that autonomous vehicle behaviors could be designed to mitigate injuries in crash-imminent scenarios.

Three Scenarios and their Importance to Safety Technology Research

Despite the many improvements seen in safety technology standards and implementation, lead vehicle stopped (LVS) and near-side impact (NSI) crash scenarios are among the top five traffic accidents in terms of frequency, years lost, or economic cost (Najm, 2007). Highway lane change (CLH) errors also frequently lead to complicated crashes and property damage (Najm, 2007). Together, these crashes represent $120 billion in economic cost and 3 million functional years lost. Current passive and active restraint technologies have focused on preventing occupant injuries

during a crash, but it may be possible to implement changes to crash-imminent scenarios, immediately before the impact to further improve safety.

In the LVS crash scenario a vehicle is going straight, at an intersection-related location and closes in on stopped lead vehicle (Figure 1) (Najm, 2007). LVS accidents represent 15 billion of the total economic cost and 9% of functional years lost (approximately 240,000 years). It is the most frequent of the 37 crash scenarios (Najm, 2007). The engine block/front of the car is most often the primary energy crash absorbing structure. The frontal airbag and seatbelt aid in controlling the deceleration of the occupant. Although these restraint systems have been shown to greatly reduce occupant injury, thoracic and abdominal injuries still occur in this crash modality. Rib injuries, for example, are often still caused by the restraint systems (Hendey, 1994) (Newgard, 2004). It is important to note the tradeoff: the restraint systems may cause injuries not previously observed because they prevented the death of the occupant. The occupant compartment is designed to resist intrusion by vehicle components (e.g. the car's windshield) and outside objects. When cars impact trucks or larger vehicles however, the height and mass difference of the vehicles may lead to increased occurrence of injury (Acierno, 2004). Furthermore, off-center impacts or driver reactions may result in angled lead vehicle stopped impacts, which allow the case vehicle to proceed forward following the initial impact and potentially impact other cars or objects.

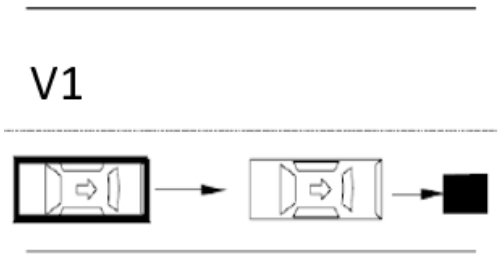

Figure 1 *Lead vehicle stopped (LVS) crash scenario (modified from Najm, 2007)*

The third most frequent and costly of NHTSA's 37 pre-crash scenarios are near side impact (NSI) crashes or t-bone type impacts (referred to as "vehicles turning at non-signalized junction" by NHTSA) (Figure 2). This type of pre-crash scenario accounts for 5% of the functional years lost and $7 billion in economic cost (Najm, 2007). In T-bone type crashes, there is not a lot of space in between the occupant and the intruding vehicle/door panel; in this case, intrusion may contribute to severe abdominal, thoracic and head injuries (Augenstein, 1999). Melocchi et al. utilized Crash Research Engineering Network to find the most frequently severely injured body regions in this crash scenario: thorax, lower extremity, and head (Figure 3) (Melocchi, 2010). Although it is standard to reinforce the doors to protect against these types of impacts, high delta-V crashes often result in significant intrusion levels. Additionally, oblique angle impacts can result in the occupant rebounding off of internal structures (e.g. steering wheel) that were not designed for near-side impacts (e.g. the frontal airbag is not available for the occupant during an oblique angle, near-side impact). Side airbags, when present, have been found to be effective in reducing injuries in side-impact crashes (Yoganandan, 2007).

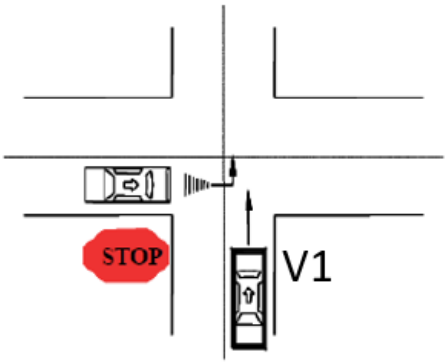

Figure 2 *Near side impact (NSI) crash scenario (modified from Najm, 2007)*

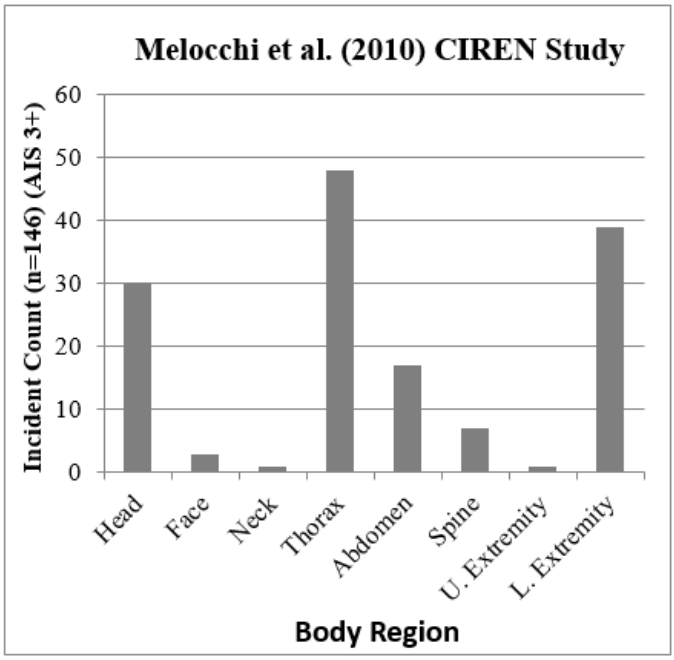

Figure 3 *The results of a study carried out by Melocchi et al show that the most frequently severely injured body regions in the NSI scenario are the Thorax, head, and lower extremity.*

CLH accidents occur when a vehicle attempts to merge or change lanes going at a high speed and encounters the front end of another vehicle (Figure 4). CLH crashes, although not as frequent or as costly as LVS and NSI crashes, represent a contribution to property loss and can result in complicated, multi-vehicle crashes (Wang, 2007). CLH crashes represent 3% of the functional years lost and $4 billion in economic cost to society (Najm, 2007). Due to the high delta-V and the potential presence of multiple impacts that may occur during this type of crash occupant compartment intrusion may potentially occur in any direction. The injuries that occur in this type of crash are therefore more diverse.

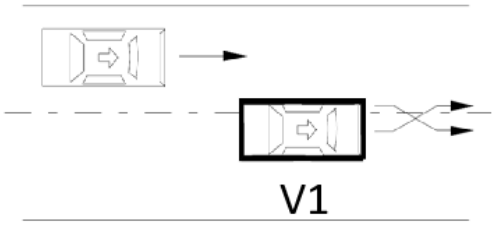

Figure 4 *Vehicles changing lanes on a highway or merging crash scenario (CLH) (modified from Najm, 2007)*

In each of these scenarios, once the initial crash occurs, vehicular crumple zones may be exhausted, safety technologies that deployed during the first impact are unavailable for subsequent impacts, and occupants may be out of position (Bahouth, 2005). This means that injuries sustained during the first impact may be exacerbated by secondary impacts (Bahouth, 2005). For example, multiple rear-end (LVS) impacts have been found to carry an elevated risk of injury compared to single rear-end impacts. Multiple LVS impacts are the most frequent and most harmful crash modality. Additionally, crash record analyses using NASS-CDS and CIREN have found that, the risk of an AIS 3+ injury to the head and trunk increase in multiple impact, NSI crashes compared to single impact crashes (Bahouth, 2005). Driver over-reaction, or lack of response to the crash could also contribute to crash outcomes (Staubach, 2009). For instance, once a frontal airbag deploys in a lead vehicle stopped crash, the occupant may not be able to further respond to mitigate the crash scenario. By studying the injuries that occur in each of these crash scenarios, it is possible to suggest focal points for improving autonomous vehicle behavior designs. Occupant-centric autonomous vehicle behavior designs would help to potentially, optimally align energy absorbing structures, reduce crash delta V and improve active and passive safety systems to reduce injuries.

Tasks-Research Objectives

Task 1: Lead vehicle stopped (LVS)

Aim: To better understand and communicate the injury mechanisms of LVS scenarios so that autonomous vehicle behaviors may be designed to reduce the occurrence of common and severe injuries.

Task 2: Near side impact (NSI)

Aim: To better understand and communicate the injury mechanisms of NSI scenarios so that autonomous vehicle behaviors may be designed to reduce the occurrence of common and severe injuries.

Task 3: Changing lanes on a highway or merging (CLH)

Aim: To better understand and communicate the injury mechanisms of CLS scenarios so that autonomous vehicle behaviors may be designed to reduce the occurrence of common and severe injuries.

Task 1: Lead Vehicle Stopped

Introduction

Lead vehicle stopped (LVS) impacts are among the top five traffic crashes in terms of frequency, years lost, or economic cost (Najm, 2007). In this crash scenario, a vehicle is going straight, at an intersection-related location and closes in on a stopped lead vehicle (Figure 7). Speeding and inattention are important factors in this impact type (Najm, 2007). Lead vehicle stopped impacts represent 12.84% of the economic cost of all crash scenarios (approximately 15 billion US dollars) and 8.69% of functional years lost (approximately 240,000 years) based on NHTSA's study of the 2004 General Estimates System. Both passive and active safety research in this area has been ongoing with respect to this crash scenario (NHTSA) (Brumbelow, 2015) (Lee, 2015) (Najm, 2007). Preventing and/or mitigating this type of motor vehicle crash would greatly decrease the overall cost of motor vehicle crashes and functional years lost.

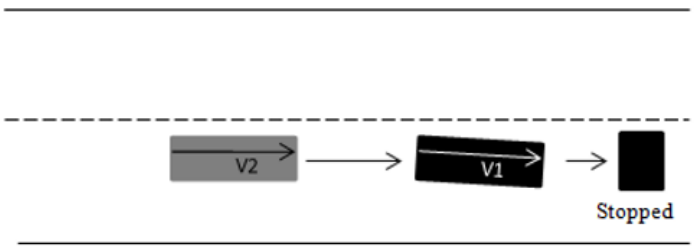

Figure 7 - *In a lead vehicle stopped scenario, the lead vehicle hits a slowed, or stopped vehicle.*

As technology improves and access to technology increases, distracted and out of position behaviors by the occupants may also increase. Distracted and possibly out of position drivers may not be able to optimally respond to pre-crash and crash scenarios. Bahouth et al. describes a study of belted drivers, and found that 48% of multiple impact crashes begin as a frontal impact (Bahouth, 2005). Furthermore, this study found that 17% of all multiple impact crashes involve a frontal followed by another frontal impact (Bahouth, 2005). This suggests that a veering or off-center impact allowed the vehicle to proceed into another object or vehicle. During the first impact, crumple zones may have been exhausted and the airbag may have deployed, leaving the occupant relatively vulnerable to injury further during the second impact. Togawa et al. described that the probability of higher injury levels is more likely to occur in multiple impact crashes than in single impact crashes (Togawa, 2011).

Additionally, an out of position and/or distracted occupant may not align with the vehicle's safety technology as they are currently tested in current laboratory and bench top environments. Hand position on the steering wheel, leg and pelvis position, and spinal alignment are all tested relatively consistently in laboratory crash tests. When the occupant is not in the expected position during the crash, the safety technologies may not be able to optimally protect the occupant from the impact. Unexpected rebounding of the occupant within the cabin may thus occur even in the absence of a veering event or an off-center crash. Furthermore, at-risk populations, such as small females and older occupants may not optimally align with safety technologies due to differences in their body proportions and natural posture. It is therefore necessary to expand the study of injury mechanisms and outcomes within these populations in order to explore the possibility of

more personalized safety technologies and autonomous vehicle behaviors. Semi-autonomous and autonomous vehicle behaviors could be used to optimize the deployment of passive and active safety measures in order to ensure the protection of the occupant in diverse impact scenarios. For example, air bag deployment timing and duration may be altered based on the movements of the vehicle in response to the impact scenario.

There were three main objectives of this study. The first was to identify which body regions were at risk for the most severe injuries in lead vehicle stopped crash scenarios. Next, patterns in injury mechanisms and outcomes were sought using a cohort of real-world, lead vehicle stopped crashes. Finally, these two results were analyzed to create suggestions for autonomous vehicle behavior design directions that could potentially mitigate the injury mechanisms found in the first two objectives.

Methods

A. Data Collection Methods

In order to identify the risk and patterns of injury caused in lead vehicle stopped impacts, the National Automotive Sampling System (NASS-CDS) was analyzed. The NASS is composed of two systems. The Crashworthiness Data System (CDS) focuses on passenger vehicle crashes. It may be used to investigate injury mechanisms to identify potential improvements to vehicle design (NHTSA). The second part, called the General Estimates System (GES) is geared towards problem size assessment and tracking bigger picture crash trends (NHTSA). The NASS-CDS is regarded as a population based sample, which allows for the calculation of risk figures. Crashes are collected from across the US.

The NASS-CDS dataset used in this study included crashes for the range 1998-2011, with vehicle model years from 1998 onwards. Drivers (seat position 1,1) over the age of 16 that encountered "crash types"20-31 (lead vehicle stopped and lead vehicle slowed) on a dry road were included. All belt statuses and crash changes in velocity (deltaV) were included. Pregnant occupants and end over end rollovers were excluded. Calculations were performed in Statistical Analysis System (SAS) 9.3 PROC SURVEYLOGISTIC (SAS Institute Inc., North Carolina, USA) workstation for Teaching and Research, which accounts for the sample weights for NASS-CDS using ratio inflation factor.

In order to investigate real-world injury mechanisms and outcomes, Crash Injury Research Engineering Network (CIREN) was surveyed via the public portal. CIREN is a public accessible database which is not population-based, but contains detailed injury mechanisms. Crash diagrams, pictures of the vehicles involved, and injury mechanisms are documented by teams of crash reconstructionists, engineers, physicians, nurses, and epidemiologists. Surveillance centers for CIREN are located in six centers across the US. Only crashes that resulted in a severe (AIS 3+ injury, or AIS 2+ articular injury) injury to the occupant were included in CIREN. The crashes entered into CIREN represent 12% of the crashes that comprise 77% of the nation's economic crash burden.

While surveying the CIREN data, the acceptance criteria for this lead vehicle stopped cohort included: an indicated principal direction of the force (PDOF) equal to 340-10 degrees for driver side impacts, drivers over the age of 16, front airbags on the case vehicle, dry road surface, and discernible injury causations. Occupant injury causations were organized by both AIS severity score and vehicle component contact points. This part of the study focused on AIS 3+ injuries, hereafter referred to as "severe". No longitudinal/end over end rollover crashes were included, but overturns (right/left) that did not contribute to AIS 3+ injuries were included. Pregnant occupants were excluded.

Because CIREN is not considered population-based, information about the demographic factors of the six catchment areas of CIREN were collected from the US census website (census.gov). The demographic factors of the study population were also documented when available within the CIREN cases. The overall US population (from the US census), the average population demographics of the six catchment areas of CIREN, and the demographic percent of the reporting population were compared in order to elaborate on any of the qualities of the injury mechanisms determined in this study.

B. Data Classification Methods

The abbreviated injury scale (AIS) is an anatomically-based, standardized, global severity scoring system that classifies injuries by body region according to its relative importance on a 6-point scale (1 being least severe, 6 being maximal). The body regions defined by AIS and analyzed in this study included: head, face, neck, thorax, abdomen, spine, upper extremity, and lower extremity (AIS 2005 Abbreviated Injury Scale 2005 Update 2008 Course Book). The pelvis is included in the lower extremity body region. The NHTSA injury coding manual for 2005 with the 2008 update was used to determine the injury severities to unify AIS severity codes when different versions of the dictionary were used in CIREN cases.

C. Statistical Methods

In order to determine which body regions were more frequently severely injured compared to all other body regions, chi-squared analyses were conducted. Injuries were grouped as AIS 3-6 (severe) and AIS 1-2 (not severe) into 6 chi-squared tables from the 6 body regions which had AIS 3+ injuries. Bonferroni corrections were made for the body regions' chi squared calculations depending on the number of body regions that had AIS 3+ injuries. Chi-squared analyses were also used to compare AIS 3-6 injury incidence to AIS 1-2 injury incidence (i) with or without airbag deployment and (ii) with or without seatbelt use. For these comparisons, a significance level of $\alpha=0.05$ was used.

Results

A. *NASS-CDS Results*

The analysis of occupants included in this part of the study was based on 6,143 raw cases from NASS CDS crash investigations representing 3,091,951 occupants with the national sampling weights applied. All of the analysis in this study used weighted data and not data from raw cases.

The projection of injury risks in LVS crashes from NASS-CDS is presented in Figure 8. The spine and upper extremity had the highest risk of AIS 1+ injury. However, when looking at AIS 2+ injuries, the highest risk of AIS 2+ injury (1.5%) was to the lower extremity body region. For AIS 3+, thorax, and lower extremity had the highest risk of injury.

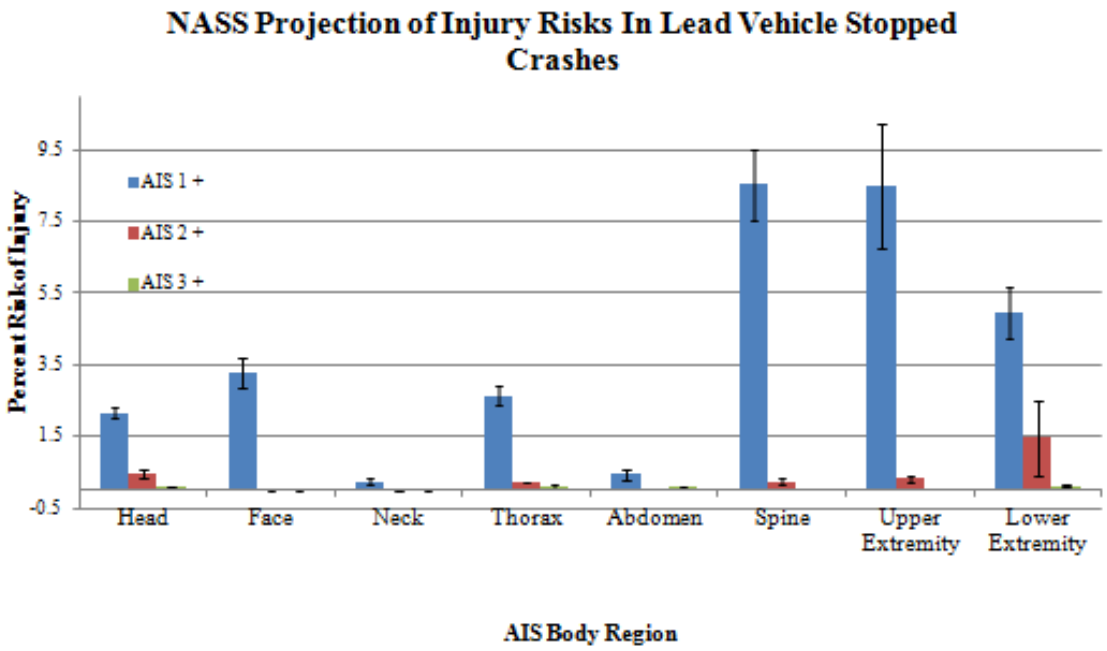

Figure 8 - *The NASS-CDS projection suggests that the head, thorax, spine, upper and lower extremity have a risk of AIS 2+ injury.*

B. *CIREN Results*

The study population differs from that of the US Census and average of the 6 catchment areas of CIREN (Figure 9). Fewer women were present in this sample. People over the age of 65 were overrepresented and people under the age of 18 were underrepresented. The Hispanic/Latino population is also much smaller than that of the US census. High school graduates were over represented within this population. A total of 52 cases were analyzed.

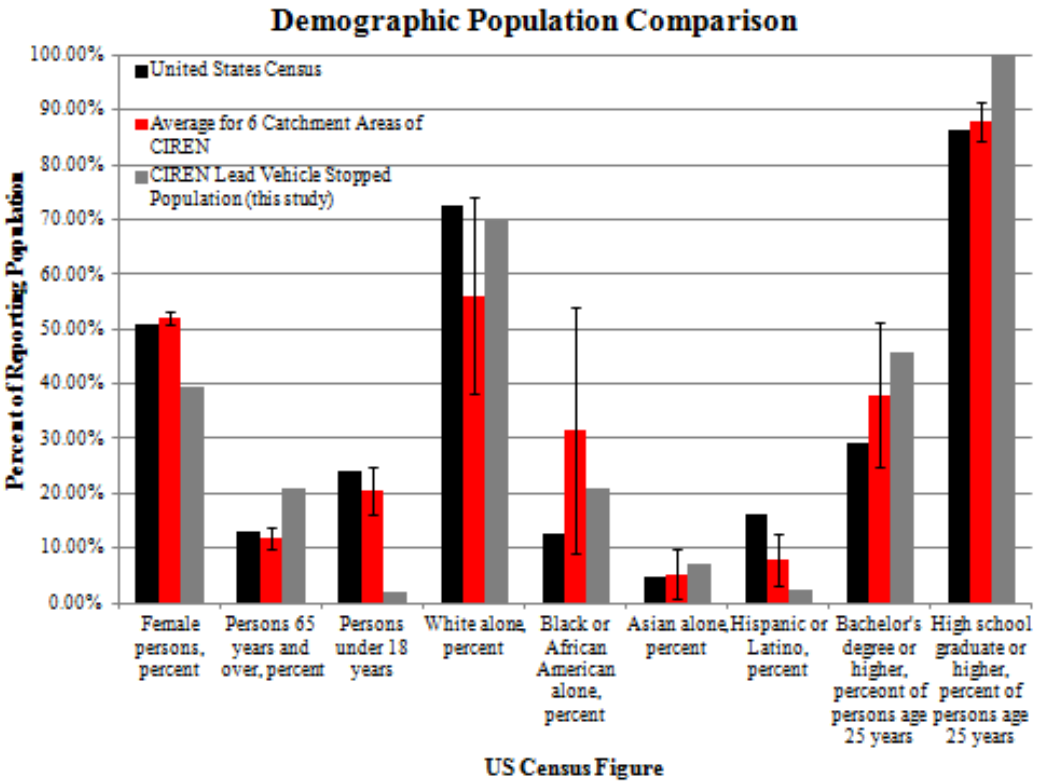

Figure 9 - *The United States Census data is compared to the population averages of the 6 catchment areas of CIREN as well as the current study population (where data was reported). There are fewer female people in the current study compared to the US Census figure.*

Within the lead vehicle stopped cohort, 58% of crashes involved a truck impact, rebounding and/or multiple impact crash. Veering during or after an impact offered in 32% of cases. Of the 53 occupants, 20 were unbelted. The frontal airbag deployed in all but 3 of the cases.

Within the distribution of AIS severities, 17% of injuries were categorized as AIS 3+. The distribution of AIS severities is given in Figure 10. The distribution of injuries by body region shows that the thorax and lower extremity body regions were significantly ($P<0.01$) different from the other body regions (Figure 10).

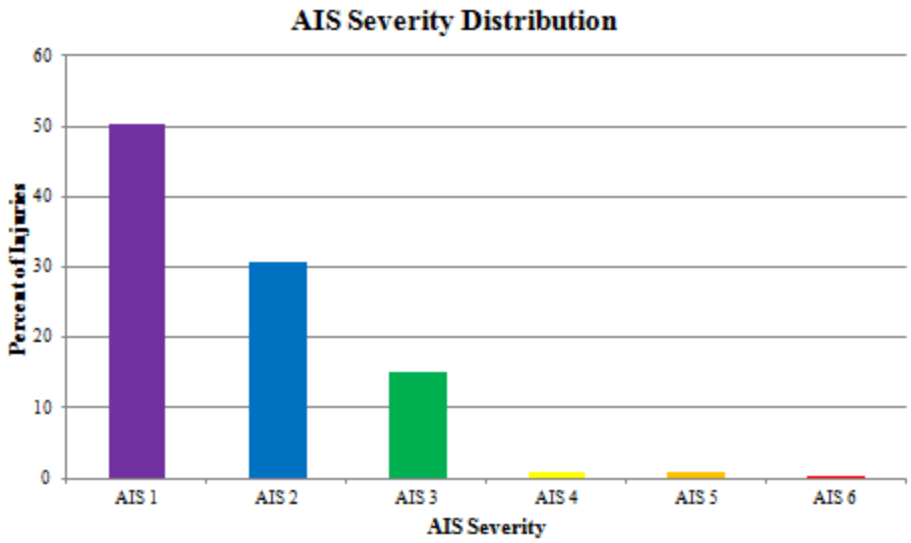

Figure 10 Less than 2% of the injuries were AIS 2. Nearly 20% of the injuries were AIS 3+.

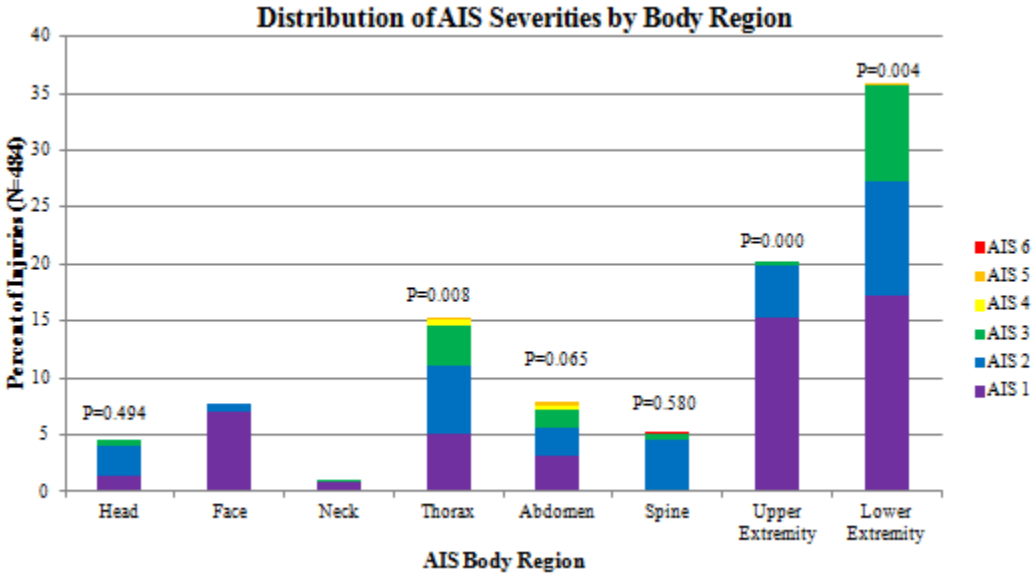

Figure 11 *-Within the lead vehicle stopped cohort, 6 body regions had AIS 3+ injuries. Chi-squared analyses were conducted comparing AIS 3-6 (severe injuries) to AIS 1-2 (not severe injuries) and the p-values for each body region are reported. Because 6 comparisons were carried out on this data, a Bonferroni correction was used. Within this restriction, p needs to be less than 0.05/6=0.008 (α) in order to be considered significant at the 0.05 level. The thorax, upper and lower extremities were below the necessary α level.*

Additionally, the upper extremity region had a AIS 3+ injuries and a significance level of P<0.01. Bonferroni corrections were made to the body-region calculations, where the significance level

corresponding to 95% confidence (α=0.05) was corrected to α=0.008 (0.05/6=0.008) in order to account for the 6 different body regions with severe injuries (Figure 11).

Of all injuries, 8% were AIS 3+ Lower extremity injuries. Lower extremity injuries were sourced to contact with the knee bolster and/or toe pan (76% and 17% respectively). Femur injuries were the most common lower extremity injury (40%) followed by pelvis (29%), and tibia (21%) injuries. The knee-thigh-hip complex is a linked chain and when contact with the knee bolster occurs via the distal end of the femur, failure may occur along the length of the femur, or at the acetabulum of the pelvis.

Of all injuries, 4.5% were AIS 3+ thorax injuries. Most of the thorax injuries (62%) were due to steering wheel contact sometimes through the airbag and/or seat belt contact. The seatbelt was sourced as the primary injury mechanism in 33% of thorax injuries. A majority of the AIS 3+ thorax injuries were to the ribs (67%). Of the occupants that experienced AIS 3+ thorax injuries, 43% were elderly (age 65+) and 52% were belted.

Abdomen injuries occurred in both belted and unbelted occupants predominantly due to steering wheel contact (82%). Seatbelt contact was sourced as the primary injury mechanism in 9% of abdomen injuries. Liver (36%), spleen (27%), and mesentery lacerations (18%) were the most common abdominal injuries. Of the cases that experienced AIS 3+ abdominal injuries, 81% collided with a truck. None of the occupants were elderly (age 65+).

Upper extremity injury mechanisms were diverse. Many were caused by contact with the interior of the vehicle when the hands were removed from the steering wheel during airbag deployment. In some cases, flying glass or instrument panel contact caused the upper extremity injury. The clavicle is included in the AIS 7 (upper extremity body region); the seatbelt was responsible for a few clavicle injuries. Different patterns of AIS 3+ injuries to the thorax, abdomen, spine, upper extremity, and lower extremity body regions were observed with seatbelt use. Seatbelt use was observed to significantly affect

injury severity at the 0.05 level and changed the distribution of injuries (Figure 12). Upper extremity injury percent increased in belted occupants compared to unbelted occupants. For the other body regions mentioned, the proportion of AIS 3+ injuries to AIS 1-2 injuries decreased with seat belt use. Additionally, AIS 3+ rib injury patterns varied with seatbelt use (Figure 13). Unbelted occupants had more even distributions of rib injuries compared to belted occupants.

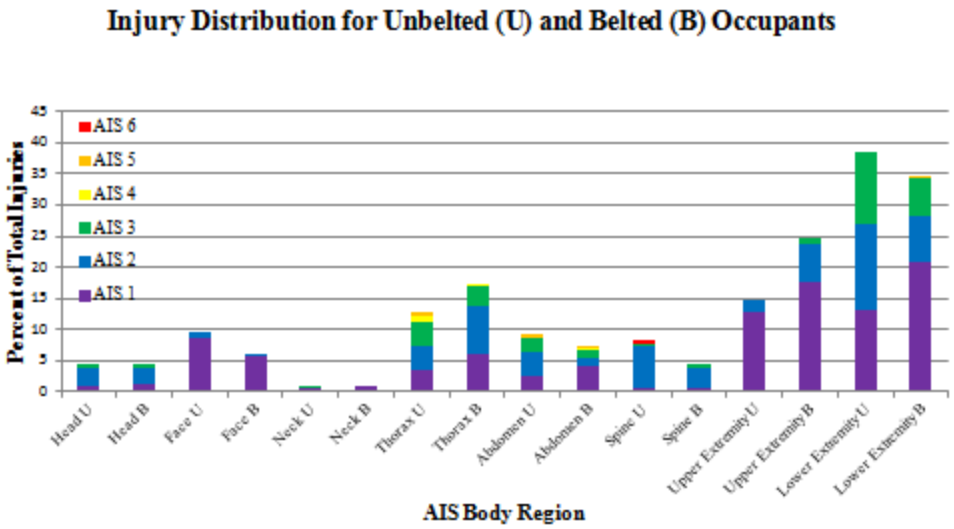

Figure 12 *- Seat belt use was observed to significantly reduce the overall severity of injuries ($p<0.05$). Additionally, the proportion of AIS 3+ injuries within each body region changed. This can be especially observed in the thorax, abdomen, and lower extremity body regions. Of the 53 occupants, 20 were unbelted.*

a) Unbelted Drivers (N=4)

	Thorax Side	
Rib Level	Right	Left
1	0.25	0
2	0.25	0
3	0.25	0.25
4	0.75	0.5
5	1	1
6	1	1
7	0.75	0.75
8	0.5	0.75
9	0	0.25
10	0	0
11	0	0
12	0	0

b) Belted Drivers (N=7)

	Thorax Side	
Rib Level	Right	Left
1	0.29	0.00
2	0.29	0.14
3	0.43	0.29
4	0.57	0.29
5	0.71	0.29
6	0.71	0.29
7	0.71	0.29
8	0.71	0.14
9	0.29	0.14
10	0.29	0.14
11	0.14	0.14
12	0.00	0.00

Figure 13 *Red represents more fractures and green represents fewer fractures. All numbers are percent occurrence among sample. Distribution of AIS 3+ rib injuries in a subset of a) unbelted and b) belted occupants.*

Rib injury percents are normalized to the number of occupants. Data was analyzed when it was present. Steering wheel (through airbag) loading accounted for the injuries in the unbelted occupants. Steering wheel and seatbelt loading combined occurred in many of the belted cases. Ribs 5 and 6, followed by ribs 4,7, and 8 fractured most in unbelted occupants. Ribs 5-8 on the right side of the occupant broke most often in belted occupants. The frontal airbag deployed in 6/7 belted cases and all of the unbelted cases. In the one case where the frontal airbag did not deploy, the deltaV was 12 kph, and all of the injuries were sourced to seatbelt contact. In the belted group, 5/7 cases sourced injuries to seatbelt contact; one rib fracture set was sourced to steering wheel contact and one rib fracture set was sourced to left forward upper door contact. Door contact occurred with PDOF of 350 degrees.

A. Case Reviews

In order to illustrate the potential for autonomous technologies, three case examples from this cohort will be presented in detail. The differences of the later two cases from the first case were meant to show how small variances in the expected condition, may result in different AIS 3+ injuries.

Case 1: 537106994

This crash involved a 39 year old (165 cm, 47 kg) female, unbelted driver that impacted the rear end of a Ford F250 extended cab pickup at a PDOF of 0 (Figure 14). The truck was stopped. The airbag deployed in response to the impact. Although the occupant, a 165cm, 47 kg, 39 year old female, was unbelted, her most severe injuries were to the lower extremity. She sustained AIS 3 fibula and tibia fractures, an AIS 2 talus fracture and an AIS 2 meniscal tear. Additionally, she sustained a loss of consciousness less than 1 hour (AIS 2). The case description states that the driver did not recognize that the lead vehicle had stopped.

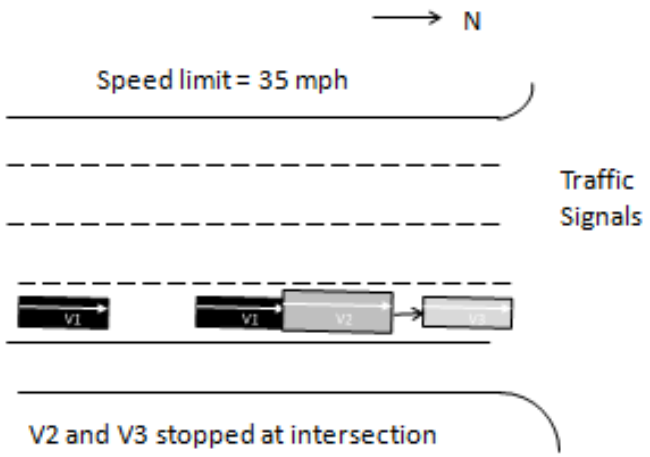

Figure 14 *CIREN case 537106994. The driver of V1 did not recognize that v2 was stopped and the front of V1 struck and under rode V2. V2 was then pushed into V3.*

Case 2: 338117581

This CIREN case describes a 47 year old (163 cm, 121kg) female, belted driver that impacted the rear end of a truck (Figure 15). The airbag deployed in response to the impact. The case occupant sustained an AIS 3 rib fracture due to steering wheel and seatbelt contact (with pneumothorax, AIS 2). She also sustained an AIS 2 foot injury due to toe panel contact and an AIS 2 sternum fracture due to steering wheel and seatbelt contact. Her upper extremity injuries include an ulna fracture, a radius fracture (both AIS 2), and a phalange fracture (AIS 1) and were sourced to contact with the left instrument panel.

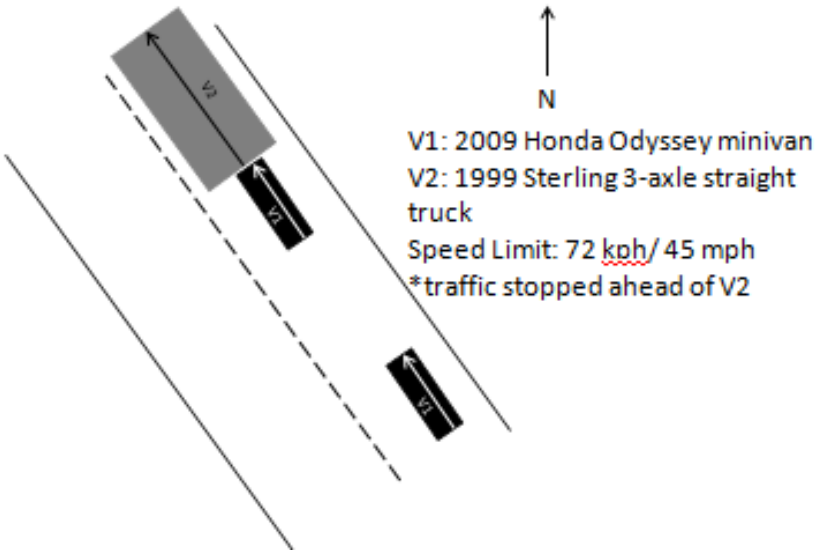

Figure 15 *CIREN case 338117581. V2 was stopped and waiting for traffic to proceed. The driver of V1 impacted the rear of V2 and under rode V2.*

Case 3: 904429225

This CIREN case describes a 46-year old (173cm, 109 kg) male, belted driver that was involved in a severe frontal impact (Figure 16). The airbag deployed in response to the impact scenario. Traffic had stopped in response to ducks obstructing the road. The crash sequence involved two impacts to the case vehicle. CIREN's crash diagram shows that the driver attempted to veer, but impacted the rear of another vehicle with a PDOF of 0 degrees. The driver sustained multiple lower extremity injuries, including a pelvic ring fracture (AIS 5), acetabulum fracture (AIS 2), hip dislocation (AIS 2), femur fracture (AIS 3), rib fractures with flail (AIS 4), sternum fracture (AIS 2), and upper extremity injuries (AIS 3). His upper extremity injuries included an open ulna fracture and an open humerus fracture. The lower extremity injuries were sourced to the lower instrument panel including knee bolster. The rib fractures were sourced to the left forward upper quadrant of the cabin and the sternum fracture was sourced to the seatbelt. The upper extremity injuries were sourced to the A-pillar and forward upper quadrant.

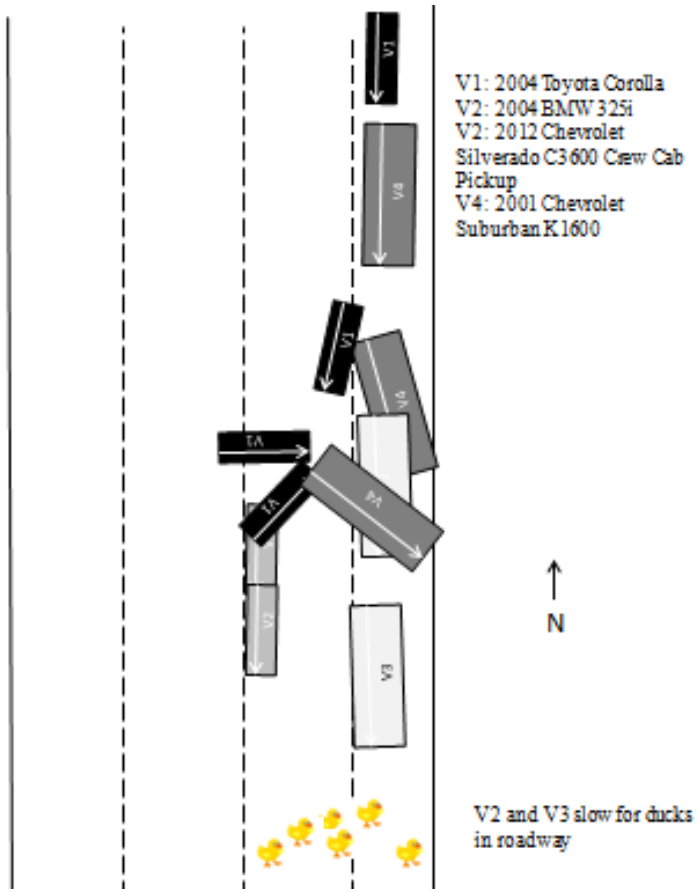

Figure 16 *CIREN Case 904429225, four events were documented as follows in order of occurrence. Ducks crossing the road caused V2 and V3 to slow down. V4 rear-ends V3. V1 rear-ends V4 (swiping impact). V4 strikes jersey barrier. V1 rotates and V1's right side impacts V2's back.*

Discussion

The case reviews showed that truck impacts, veering/off center impacts occur in many frontal impact scenarios that result in AIS 3+ injuries. NASS-CDS predicted that the head, thorax, and lower extremity regions have the highest risk of AIS 3+ injury. The CIREN data compares well to this prediction: the thorax and lower extremity body regions were the most frequently, severely injured compared to the other body regions ($P<0.01$). The injury patterns observed in the NASS-CDS and CIREN were consistent with the literature (Lee, 2015) (Brumbelow, 2015). CIREN's real-world crash records presented some potential avenues for the implementation of autonomous vehicle technologies in the mitigation of injuries in crash-imminent scenarios.

As autonomous vehicle technologies increase in prevalence, out of position seating and distracted driving behaviors may increase. Out of position seating could contribute to rebounding of the occupant around the cabin, even in the absence of multiple impacts. This study focused on the outcomes of frontal impacts. Multiple impacts initiated with a frontal impact have been found to account for a large proportion of crashes (about 24%) (Kildare, 2013). Offset impacts and

sideswipes or collisions with narrow objects have been found to carry higher rates of multiple frontal impacts when compared to single frontal impacts (Kildare, 2013). In multiple frontal impacts in which the most severe impact occurred first in the collision sequence, extremity injuries were seen more often than head/face/neck injuries compared with single frontal impacts. This contrasts with collisions where the second impact is the most severe; more head/face/neck injuries were seen in this type of collision (Kildare, 2013). The findings of this study compare well with the literature, where approximately half of the multiple frontal impacts had impacts after the initial collision (Togawa, 2011). The literature suggests that secondary impacts occur less than 2 seconds after the initial impact (Kildare, 2013). The proportion of kinetic energy remaining after the first impact has been identified as a possible predictor of the likelihood of multiple impacts (Kildare, 2013). Methodologies exist for the implementation of calculated semiautonomous breaking technologies (Kusano, 2010). Future work should investigate how autonomous vehicle may react to the pre-crash and crash scenario in order to better align energy-absorbing structures, and decrease veering/off-center crashes. Truck impacts and complicated crashes should not be overlooked in this endeavor (Abdel-Aty, 2004) (Gabler, 2000)).

Thorax injuries (specifically rib injury patterns) in belted and unbelted occupants were consistent with the literature (Lee, 2015). The seatbelt was found to mitigate the overall occurrence of AIS 3+ injuries within this cohort, but there is room for improvement. In belted occupants, rib fractures approximately followed the path of the seatbelt. Older occupants have been found to sustain more AIS 3+ rib fractures than younger occupants (Lee, 2015). Older occupants were over represented in this cohort, and 43% of the rib injuries occurred in older occupants. CIREN only contains crashes that result in severe injuries and has been reported to have more elderly occupant profiles compared to the general population. Nevertheless, this highlights the need for progress in protecting this at-risk population. Changes in seatbelt design and morphology may improve outcomes for this at risk group (Ekambaram, 2015) (Brown, 2013). Additionally, the timing of the airbag may be tuned using automated vehicle technologies already in use. Many of the injuries were found to occur even in the presence of a deployed airbag. For example, in Case 2 (338117581) the belted driver had the airbag deploy, but still sustained AIS 3 rib injuries. The fact that this was a collision with a truck could have played a role in both the severity of the crash and the timing of the airbag. Vehicles with semi-autonomous cruise control and self-parking functionality are able to sense their environment. This technology could be used to augment the deployment of passive safety technologies within the vehicle with respect to timing and duration of deployment. Smart braking and veering functionality could also be employed to minimize multiple impacts that occur as a result of a suboptimal maneuver by the driver.

Lower extremity injuries (AIS 2+) were present in both belted and unbelted occupants in this study. This was demonstrated in all three case reviews. The third case (904429225) showed that multiple impact crashes can result in more severe lower extremity injuries. Although information about the presence or absence of knee bolster airbags was not presence, there is evidence within the literature that this technology could alter the biomechanics of the knee thigh hip complex (Weaver, 2013) (Patel 2013). Occupants that are seated closer to the knee bolster, or in an out of position style may still be susceptible to AIS 2+ lower extremity injuries. The timing and deployment duration of knee bolster airbags should be tested to ensure that they are reducing knee-thigh-hip related injuries. Toward this goal, improvements to the anthropomorphic test devices' biofidelity could

be made to better predict knee-thigh-hip related injuries, as the literature suggests that improvement is needed in this area (Weaver, 2013) (Patel 2013).

Two regions of interest deserve further discussion: the abdomen, and the upper extremity regions. Abdominal injuries occurred in both older and younger occupants and regardless of belt status. The most often injured organs were the liver and spleen. The tuning of improved airbag timing and seatbelt characteristics may help to reduce the occurrence of these types of injuries. Additionally, this study highlighted that many upper extremity injuries occur in frontal crashes. Although few AIS 3+ upper extremity injuries occurred in comparison to the thorax and lower extremity, this body region was determined to be statistically significant ($P<0.05$). Hand position on the steering wheel is important in the injury potential of this body region (Huelke, 1994).

Laboratory crash testing with these automated technologies should be performed to represent diverse populations. This will allow for the tuning of safety technologies to better protect at-risk populations, such as elderly occupants, and those in "out of position" seating patterns. This study suggests that the thorax and lower extremity regions are most often severely injured in lead vehicle stopped crashes. Elderly occupants were over represented in the cohort. Additionally, truck collisions, complicated crashes, and veering events happened relatively frequently within this cohort, suggesting that vehicles should be prepared for non-traditional car-car collisions. Autonomous vehicle technologies could be employed to better detect truck collisions, and mitigate secondary impacts. Better alignment of the occupant with safety technologies and the vehicle during the impact scenario could improve injury outcomes.

The implications of this study are only based on the CIREN and NASS-CDS populations described. As CIREN is not a population-based sample, the findings of this study may only be expanded to the population within CIREN. CIREN is a sample of the crashes that resulted in the most severe injuries. The statistical significance of the upper extremity is based on very few AIS 3+ injuries to this region. Nevertheless, this study shows that, within this population that experienced a crash that resulted in serious injuries, there is room for improvement in the reduction of thorax and lower extremity injuries especially in elderly occupants.

Task 2: Near Side Impact

Introduction

Near-side impacts that occur at non-signalized intersections are the third most frequent crash type (Figure 17). They account for $7 billion in economic cost and 5% of functional years lost out of all of the National Highway Traffic Safety Administration's (NHTSA) 37 pre-crash scenarios based on the 2004 general estimates system (GES) (Najm, 2007). Additionally, the risk of a serious injury in a near-side impact is 83.8%, for change in velocity (deltaV) equal to 30 mph/48 kph (Augenstin, 2003). This is significantly elevated compared to all other crash types. Furthermore, a near-side impact has the potential to escalate. If the case vehicle does not optimally brake and/or veer, it could hit, or be hit by other vehicles, people, and/or structures before coming to rest. In some cases, even in the absence of a secondary impact, the physics of the crash can cause whipping or rebounding motions, which could potentially injure occupants.

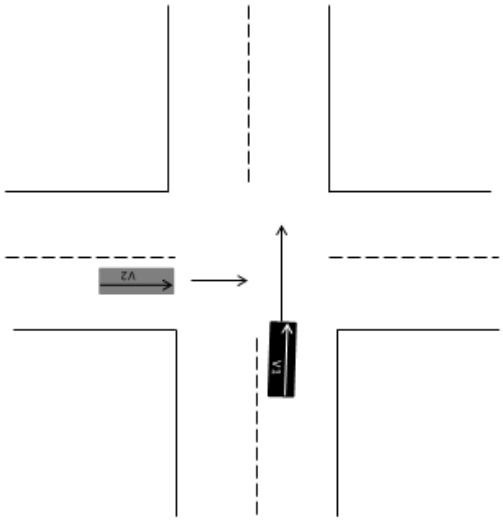

Figure 17 - *Near-side impacts that occur at non-signalized intersections are the third most frequent crash type according to NHTSA DOT HS 810 767.*

For multiple impact crashes with serious injuries, 15% of cases begin as a near-side impact (Bahouth, 2005). Multiple impact, near side crashes account for 35% of the Maximum Abbreviated Injury Scale (MAIS) 3+ injured, belted drivers from the cohort studied (Bahouth, 2005). Near-side impacts were found to be followed by another near side (6%), frontal (4%), and far-side (4%) impact (Bahouth, 2005). In a cohort of multiple impact crashes that produced serious injuries however, the 44.9% of initial impacts were found to be near side (Digges, 2003). Then, for this cohort that sustained serious injuries, the most serious secondary impact was side (48.4%) followed by frontal (27.5%) (Digges, 2003). The most harmful sequences were found to be side-side (27.7%) (Digges, 2003). An epidemiologic study conducted in the UK found that among two-

impact crashes with Abbreviated Injury Scale (AIS) 3+ injuries, the less severe impact is relevant to serious injury in around 10-12% of cases (Lenard, 2003). Once the initial crash occurs, vehicular crumple zones may be exhausted, passive safety technologies that deployed during the first impact are unavailable for subsequent impacts, and occupants may be out of position (Bahouth, 2003). Injuries sustained during the first impact may therefore be exacerbated by secondary impacts (Bahouth, 2003).

Driver distraction or inattention has the potential to increase the risk of a serious crash (Young, 2013). Treat et al.'s study on crash-related factors found that some form of recognition failure by the driver was involved in 56% of the in-depth crash cases analyzed. The leading human direct causes were: improper lookout (looking, but not processing the information) (23%), excessive speed (17%), inattention (15%), improper evasive action (13%), and internal distraction (9%) (Treat, 1979). Cell phone usage, drowsiness, and secondary tasks (such as cabin condition adjustment) are some of the factors that contribute to driver distraction today (Wang, 1996)(DOT HS 819 594, 2006). Crashes were secondarily found to be caused by environmental factors, such as view obstructions and slick roads (Treat, 1979). Additionally, misuse of information errors (e.g. incorrect responses, orientation and expectation errors and misjudgments) by the driver have the potential to increase driver error and contribute to crash outcomes (Stauback, 2009). Serious injuries to the occupant also have the potential to significantly decrease driver awareness, alter occupant seating position, and or cause panic to the driver. During a crash sequence, these events could prevent a driver from reacting optimally to a crash scenario. If a misuse of information error occurs, a suboptimal crash configuration and/or secondary impacts can result from: confusion between brake and accelerator, overcorrection and/or errors in vehicle maneuvering.

Methods

A. Data Collection Methods

In order to identify the risk and patterns of injury caused in near-side impact crashes, The National Automotive Sampling System (NASS) Crashworthiness Data System (CDS) was analyzed. The NASS is composed of two systems. The CDS focuses on passenger vehicle crashes. It may be used to investigate injury mechanisms to identify potential improvements to vehicle design (NASS website). The second part, called the General Estimates System (GES) is geared towards problem size assessment and is used to track bigger picture crash trends (NASS website). The NASS-CDS is regarded as a population based sample, which allows for the calculation of risk figures. Crashes are collected from across the US.

A dataset of crashes from 1998-2011 from the NASS-CDS, with vehicle model years from 1998 onwards was pulled from the NASS-CDS. Drivers (seat position 1,1) over the age of 16 that encountered "crash type" 77 or 89 (near side) on a dry road were included. All belt statuses and crash changes in velocity (deltaV) were included. Pregnant occupants and end over end rollovers were excluded. Calculations were performed in Statistical Analysis System (SAS) 9.3 PROC SURVEYLOGISTIC (SAS Institute, Inc., North Carolina, USA) workstation for Teaching and Research.

In order to investigate real-world injury mechanisms and outcomes, Crash Injury Research Engineering Network (CIREN) was surveyed via the public portal. CIREN is a database which is not population-based, but contains detailed injury mechanisms. Crash diagrams, pictures of the vehicles involved, and injury mechanisms are documented by teams of crash reconstructionists, engineers, physicians, nurses, and epidemiologists. Surveillance centers for CIREN are located in six centers across the US. Only crashes that resulted in a severe (AIS 3+ injury, or AIS 2+ articular injury) injury to the occupant are included in CIREN. The crashes entered into CIREN represent 12% of the crashes that comprise 77% of the nation's economic crash burden (CIREN website).

Acceptance criteria for CIREN data included: an indicated principal direction of the force (PDOF) equal to 240-340 degrees for driver side impacts, drivers over the age of 16, front airbags on the case vehicle, dry road surface, and discernible injury causations. In order to include more near-side impacts, crashes that occurred at signalized junctions and/or merging ramps was included as long as discernible injury causations were present. No longitudinal/end over end rollover crashes were included, but overturns (right/left) that did not contribute to AIS 3+ injuries were included. A total of 134 cases were analyzed.

Because CIREN is not considered population-based, information about the demographic factors of the six catchment areas of CIREN were collected from the US census website (uscensus.gov). The demographic factors of the study population were also documented when available within the CIREN cases. The overall US population (from the US census), the average population demographics of the six catchment areas of CIREN, and the demographic percent of the reporting population were compared in order to elaborate on any of the qualities of the injury mechanisms determined in this study.

B. Data Classification Methods

The abbreviated injury scale (AIS) is an anatomically-based, standardized, global severity scoring system that classifies injuries by body region according to its relative importance on a 6-point scale (1 being least severe, 6 being maximal). The pelvis is included in the lower extremity body region. The NHTSA injury coding manual for 2005 with the 2008 update was used for this study. When assessing the severity of injuries, both the frequency and severity of the injury was taken into account.

C. Statistical Methods

In order to determine which body regions were more frequently severely injured compared to all other body regions, chi-squared analyses were conducted. Injuries were grouped as AIS 3-6 (severe) and AIS 1-2 (not severe) into 5 chi-squared tables from the 5 body regions which had AIS 3+ injuries. Bonferroni corrections were made to the body regions' chi-squared calculations depending on the number of body regions that had AIS 3+ injuries. Chi-squared analyses were also used to compare AIS 3-6 injury incidence to AIS 1-2 injury incidence with or without airbags and with or without seatbelts. For these comparisons, a significance level of $\alpha=0.05$ was used.

Results

A. NASS-CDS Results

The analysis of occupants included in this part of the study was based on 1,741 raw cases from NASS-CDS crash investigations representing 576,995occupants with the national sampling weights applied. All of the analysis in this study used weighted data from raw cases. The projection of injury risks in NSI crashes from NASS-CDS is presented in Fig. 3. The highest risk of AIS3+ injury is projected to occur to the Head, Face, Thorax, and Lower Extremity body regions.

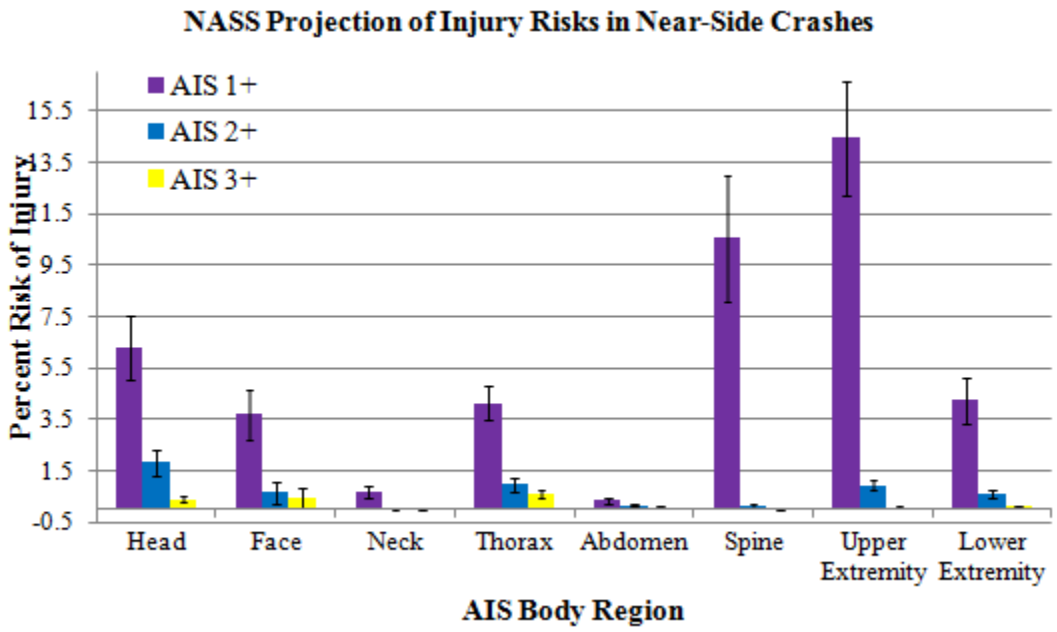

Figure 18 - *NASS projected risk of an AIS 1, AIS 2, and AIS 3+ injury in a nearside impact crash.*

A. CIREN Results

Within the study population (134 cases), 87% were belted. When available, race, age, level of education, and income of the occupants were collected from CIREN. The population of the 6 catchment areas of CIREN, and the study population were compared to US Census data (Figure 19) (census.gov). Overall, the study population consisted of more elderly people than the US population and the population of the catchment areas of CIREN. There are fewer Hispanic or Latino identifying people within the CIREN and study populations compared to the US average, but the study population compares well to the CIREN population average. There are more female persons within the study population compared to both the US average and the CIREN catchment area average. Persons that achieved a level of education of high school or higher are present at a higher population within the study population. All other factors fall within the 95% standard deviation bars of the average of the six CIREN catchment areas and are similar to the figures collected from the US Census (Figure 19).

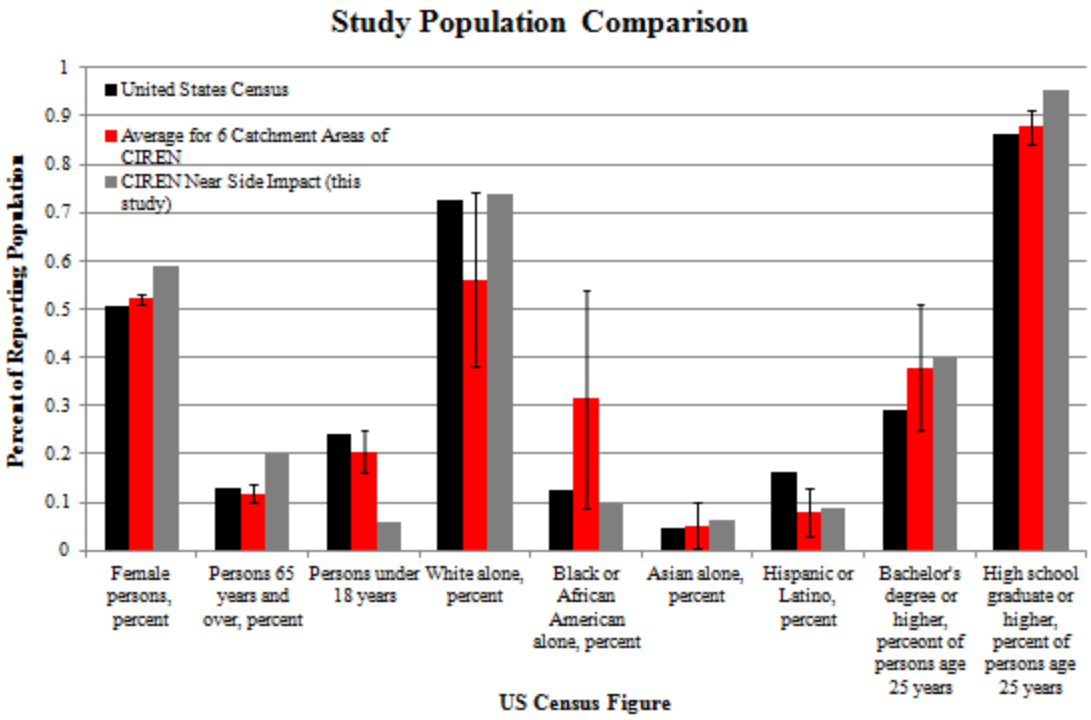

Figure 19 *Age and sex was always reported within the CIREN data. Individuals that specified racial identify and/or Hispanic or Latino identity (92/134) and level of education (63/134) were not universally present in the study population. Figures from the US Census were from the 2010 population.*

Most of the 134 occupants (87%) were using their available seatbelt at the time of the crash. Side airbags did not deploy in 75% of cases. In some cases, vehicles were equipped with side airbags, but the airbag did not deploy; in other cases, the vehicles did not have side airbags. A chi-squared analysis of the total number of injuries that occurred with or without a side airbag found no significant difference between the group where the side airbag deployed and the group where a side airbag did not deploy at the 0.05 level.

Most of the cases in this cohort experienced a PDOF of greater than 270 degrees (Figure 20). Additionally, most of the crash deltaVs were under 50 kph (Figure 21). Crashes that occurred at 320 (N=2) and 340 (N=1) had deltaVs equal to 48 kmph. Although over half of the crashes documented had only one event, 46% had two or more events. This includes: side slap, impact with another car, impact with an object, or a right/left rollover event. The initial nearside impact was described to be the source of all of the AIS 3+ injuries for this group of cases.

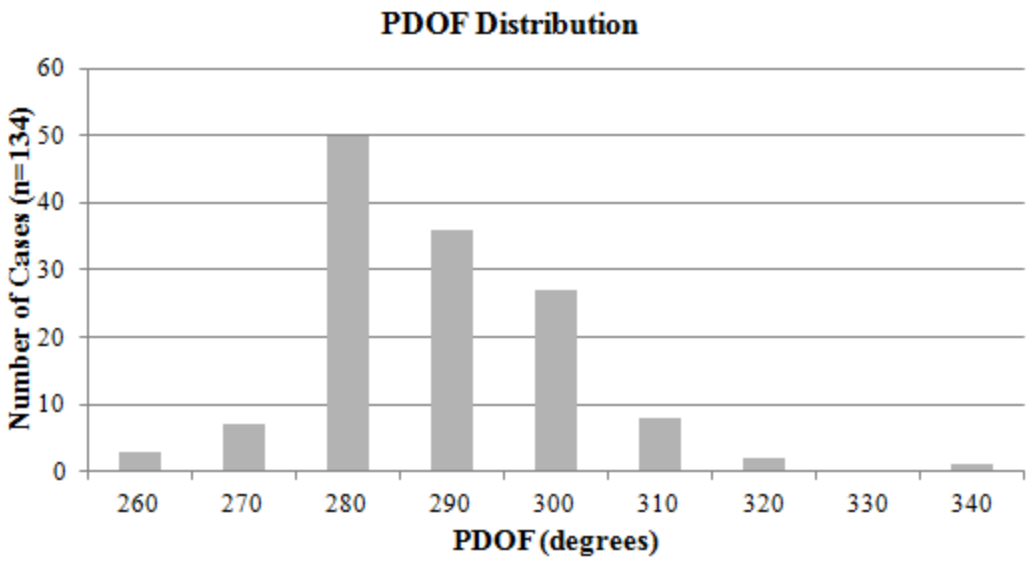

Figure 20 - *Most of the occupants sustained a crash PDOF of greater than 270 degrees.*

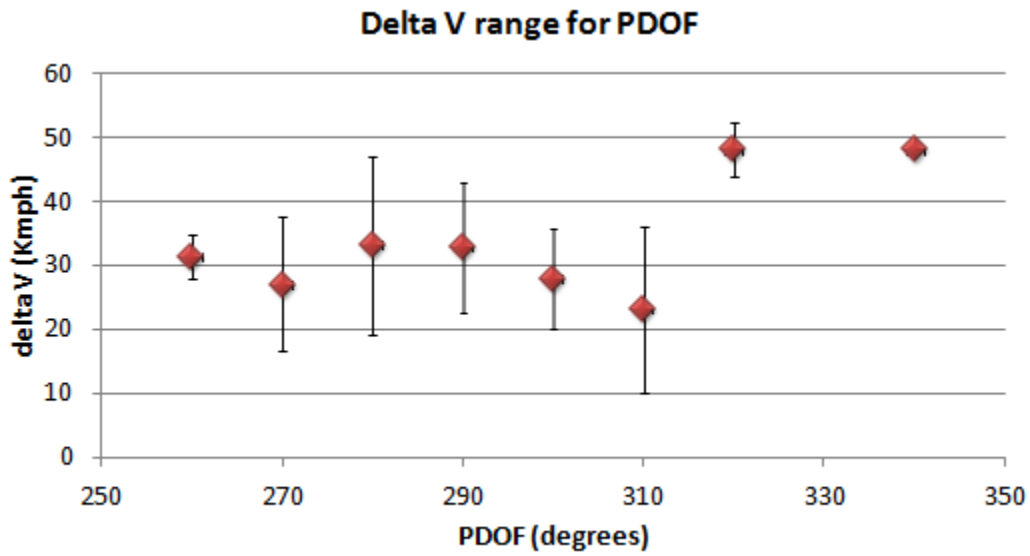

Figure 21 - *Distribution of average deltaVs by PDOF of reporting cases. Standard deviation bars are indicated. Most of the deltaVs are below 50 kph. Error bars represent standard deviation.*

In this NSI cohort, 24% of the injuries were AIS 3-6 severity. Less than 2% of these injuries were AIS 5-6 severity (Figure 22). The head, thorax, and lower extremity body regions were found to be severe compared to all the other body regions with a 0.05 significance level (Figure 23).

Bonferroni corrections were made to the body-region calculations, where the significance level corresponding to 95% confidence (α=0.05) was corrected to α=0.008 (0.05/5=0.01) in order to account for the 5 different body regions with AIS 3+ injuries. Of the all the injuries, 5% of the injuries were AIS 3+ head injuries, 8% of the injuries were AIS 3+ thorax injuries, and 7% of the injuries were AIS 3+ lower extremity injures (Figure 23).

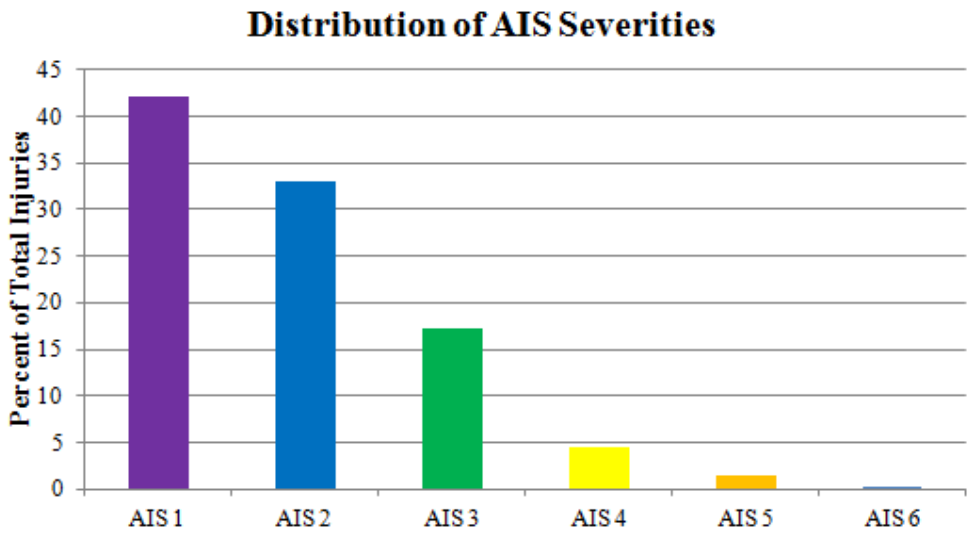

Figure 22 - *Of the injuries observed, 24% were categorized as AIS 3+. Less than 2% of the injuries are categorized as AIS 6.*

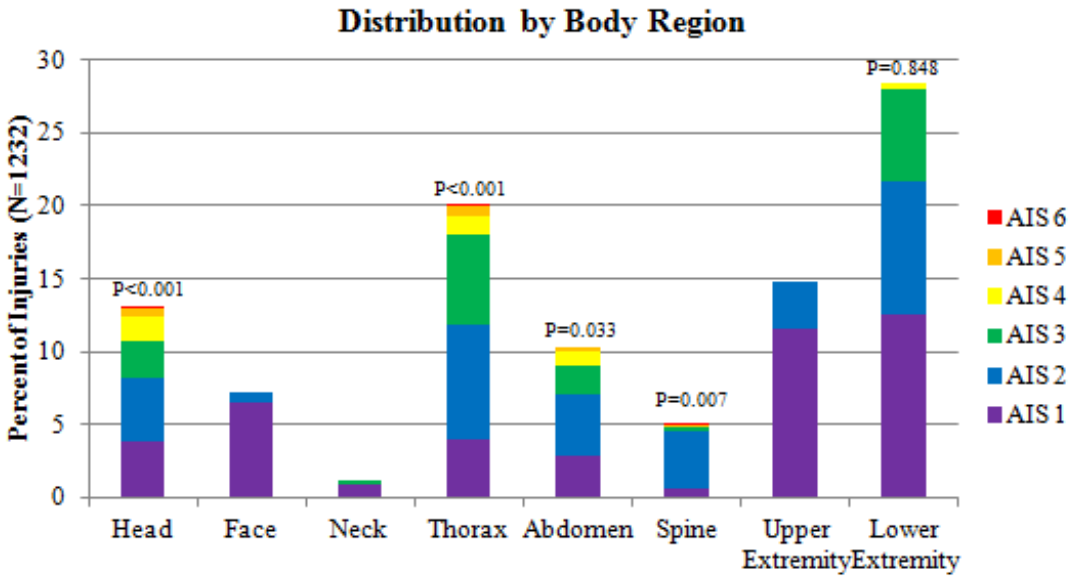

Figure 23 - *The 8 AIS body regions are described here. P-values for the chi-squared analyses are given above the 5 body regions that have AIS 3+ injuries. Note: AIS 3+ injuries are not common for all 8 body regions. An α value of less than 0.01 indicates significance following Bonferroni correction for multiple comparisons.*

Within the head injury category, 37% of the injuries were AIS 3+ and 72% of these severe injuries were brain injuries. This includes the cerebellum, cerebrum, and brain stem. Most of the skull and the brain injuries were due to door and b-pillar intrusion or door contact, even when an airbag was deployed. B-pillar contact or intrusion was specified for 26% of all AIS 3+ head injuries, 29% of AIS 3+ brain injuries, and 20% of AIS 3+ skull injuries.

Thoracic injuries (AIS 1-6) comprise 20% of all injuries; within the thorax body region, 40% of the thorax injuries were AIS 3+. Ribs were found to be the most frequently injured (47% of thorax injuries) AIS 3+ thorax component (Fig 8). This is followed by lung injuries (23% of AIS 3+ thorax injuries), aorta (10% of AIS 3+ thorax injuries), and diaphragm (8% of AIS 3+ thorax) injuries. AIS 3+ thorax injuries were due to intruding door contact (77%), b-pillar (19%) and/or door contact, even in the presence of a deployed airbag.

PDOF 270	Thorax Side	
Rib Level	Right	Left
1	0.00	0.00
2	0.00	0.00
3	0.00	1.00
4	0.00	1.00
5	0.00	1.00
6	0.50	1.00
7	0.00	0.50
8	0.00	0.50
9	0.00	0.50
10	0.00	0.50
11	0.00	0.00
12	0.00	0.00

PDOF 280	Thorax Side	
Rib Level	Right	Left
1	0.18	0.36
2	0.09	0.45
3	0.00	0.55
4	0.00	0.82
5	0.18	0.55
6	0.27	0.45
7	0.18	0.27
8	0.18	0.36
9	0.18	0.18
10	0.00	0.18
11	0.00	0.27
12	0.00	0.09

PDOF 290	Thorax Side	
Rib Level	Right	Left
1	0.00	0.10
2	0.20	0.20
3	0.10	0.60
4	0.10	0.60
5	0.10	0.70
6	0.10	0.40
7	0.20	0.60
8	0.10	0.50
9	0.10	0.50
10	0.10	0.30
11	0.10	0.20
12	0.00	0.10

PDOF 300	Thorax Side	
belted	Right	Left
1	0.17	0.50
2	0.17	0.50
3	0.17	0.67
4	0.33	0.67
5	0.17	0.50
6	0.17	0.50
7	0.00	0.50
8	0.00	0.67
9	0.00	0.67
10	0.00	0.50
11	0.00	0.17
12	0.00	0.17

Figure 24 - *Red signifies more fractures and green signifies fewer fractures. Percent fractured ribs among the samples are given. Rib fracture patterns grouped by PDOF. Information on rib level was collected when available. Note the fractures are more disperse in the 280, 290, and 300-degree groups compared to the 270-degree group. The occupant count is as follows for each group: N=2 for the 270 PDOF, an N=11 for the 280 PDOF, an N=290 for the 290 PDOF, and an N=6 for the 300 PDOF. All occupants included were belted.*

Within the abdomen body region, 31% of the injuries were AIS 3+. The spleen was the most injured, AIS 3+ abdominal organ; within the abdomen category, spleen injuries made up 52% of the injuries. Spleen injuries correlated with the PDOF distribution. In the oblique impacts that resulted in spleen injuries, the occupant was forced into the seatback/support by the intruding door or by rebounding off of the door structure. The second most injured abdominal organ was the bladder; it was injured in 20% of AIS 3+ abdominal injury occurrences.

Of the spinal injuries, 11% were AIS 3+. AIS 3+ spinal injuries include: cervical spine injuries (50% of AIS 3+ spinal injuries), vertebral body compressions (33% of AIS 3+ spinal injuries) and an odontoid fracture (16% of AIS 3+ injuries). These injuries were mainly attributed to a combination of forced flexion due to the acceleration of the crash and some intrusion. Half of the occupants with spinal cord injuries were over the age of 65.

Of the lower extremity injuries, 23% were categorized as AIS 3+. Most of the AIS 3+ injuries were to the pelvis (78% of AIS 3+ lower extremity injuries). Of the AIS 3+ injuries, femur and tibia injuries were 12%. AIS 3+ pelvic injuries were sourced to intrusion. This was described as compression between the intruding door and center console (23%), as well as door/side panel contact (77%). Femur and tibia injuries were attributed to contact with the knee bolster for 78% of the injuries; this injury mechanism occurred in both belted and unbelted individuals.

Discussion

Fatalities are avoided with the use of seatbelts and airbags (DOT HS 812 218) (Kahane, 2000) (NHTSA, 1996). With the advent of these life-saving technologies, more people are surviving car crashes and the injuries observed in crashes are changing. It can be expected that energy-absorbing structures (e.g. seatbelt, airbag) cause some low AIS severity injuries during automobile crashes (Dineen, 1989) (Kulowsky, 1956) (Hendy, 1994) (Mohamed, 1998). It is important to observe these injuries so that seatbelts and airbags may be improved further. More severe AIS severity injuries tend to occur due to structural failure of the vehicle due to intrusion, or failure of energy absorbing structures to cushion occupants from forces present at the time of the crash (Hendy, 1994)(Mohamed, 1998)(Augenstein, 1999)(Otte, 1984). Additionally, the deltaV and PDOF of the crash will heavily influence the injury biomechanics. For the near-side impact scenario studied, most severe injuries were found to occur in the head, thorax, and spinal regions. Intrusion of another vehicle/door intrusion, and b-pillar and/or door contact caused a majority of these AIS 3+ injuries. The presence of side airbags and/or seatbelts was not observed to significantly affect the severity of the injury outcomes. These findings correlate well with similar studies of the NASS-CDS and CIREN databases (Brumbelow, 2015) (Stadter, 2008). Additionally, in some cases occupants were observed to be impacting vehicle interior components through airbags. This suggests that the timing and/or placement of the airbags could be improved. Furthermore, it was observed that 46% of the cases had two or more impacts or contacts during their crash sequence. Due to the timing of the impacts and the deployment of safety technologies, coupled with movements of the vehicle following the initial impact there could be secondary or rebounding impacts of the occupant within the cabin. Even when safety technology deploys correctly, secondary impacts and/or rebounding could be occurring following initial deployment of safety technology, when the occupant could be out of position due to the first impact (Newgard, 2005).

A. PDOF and Delta V

Active safety components are in early stages of development; both active and passive safety components could be enhanced by autonomous vehicle technologies. One of the primary design considerations for active safety features is to avoid and/or mitigate crashes. Injury frequencies and severities vary with the use of safety technologies. For example, side airbags have the potential to reduce injuries in near side crashes, but have been found to deploy in only 43% of near-side impacts where a side airbag is available (Stadter, 2008). The airbag deployment varies with crash deltaV; a higher crash deltaV was correlated with a decreased side airbag deployment. Sensors on

autonomous vehicles could augment the ability of these passive safety systems to detect an incoming crash by improving deployment timing and duration. Furthermore, the current study and others show that oblique PDOF crashes may lead to increased injuries (Brumbelow, 2015). The concept of improving safety feature deployment timing, and duration has also been proposed by (Brumbelow, 2015). The shape of the airbags may also be explored further. Active safety features (autonomous vehicle behaviors) could potentially enhance the ability of passive safety features to decrease injuries that occur in oblique angle crashes.

Although side airbags have been projected to decrease the risk of thorax injuries, this is not being observed, and the risk of a thorax injury has been shown to increase for occupants above the age of 50 (Augenstein, 2003) (Griffin, 2012). This is, in part, due to the larger intrusion into the occupant compartment present in near side crashes. Thorax injuries also tend not to occur in isolation for AIS 4+ severities; thorax injury prevention could therefore prevent injuries to other body regions (Scarboro, 2007) (Yoganandan, 2007). For example, it is common to find lung injuries, such as pneumothorax, associated with rib fractures. Relevant to other body regions, laboratory tests have shown that out of position occupants can sustain more severe craniocervical loads and chest deflections compared to occupants in normal seating positions (Yoganandan, 2007). Furthermore, airbag coverage and energy absorbing vehicle structures may not be optimized for every PDOF (Brumbelow, 2015). Airbag deployment timing may also need improvement to account for variances in PDOF and deltaV.

Consistent with the literature, the crashes in this CIREN cohort were below the deltaV of those performed in many laboratory tests (e.g. IIHS's crash test protocol with movable deformable barrier 31 mph/50 kph) (Brumbelow, 2015). This suggests a larger contribution of PDOF to the injury outcomes than deltaV. Even though the near-side impacts included in this study were at a lower deltaV than crash tests, 46% of the vehicles travelled into two or more vehicles or objects following the initial impact (this includes a side slap event). Avoiding secondary impacts would not only minimize damage to people, vehicles, and objects in the vicinity of the case vehicle, but could minimize movement of the case occupant about the cabin during the crash. Each of the crashes here produced AIS 2+ injuries, which could distract or disable the driver; distracted and/or disabled drivers may be unable to optimally stop or veer to avoid secondary impacts. Examples of cases from CIREN where optimal braking and/or veering did not occur is shown in Figure 25.

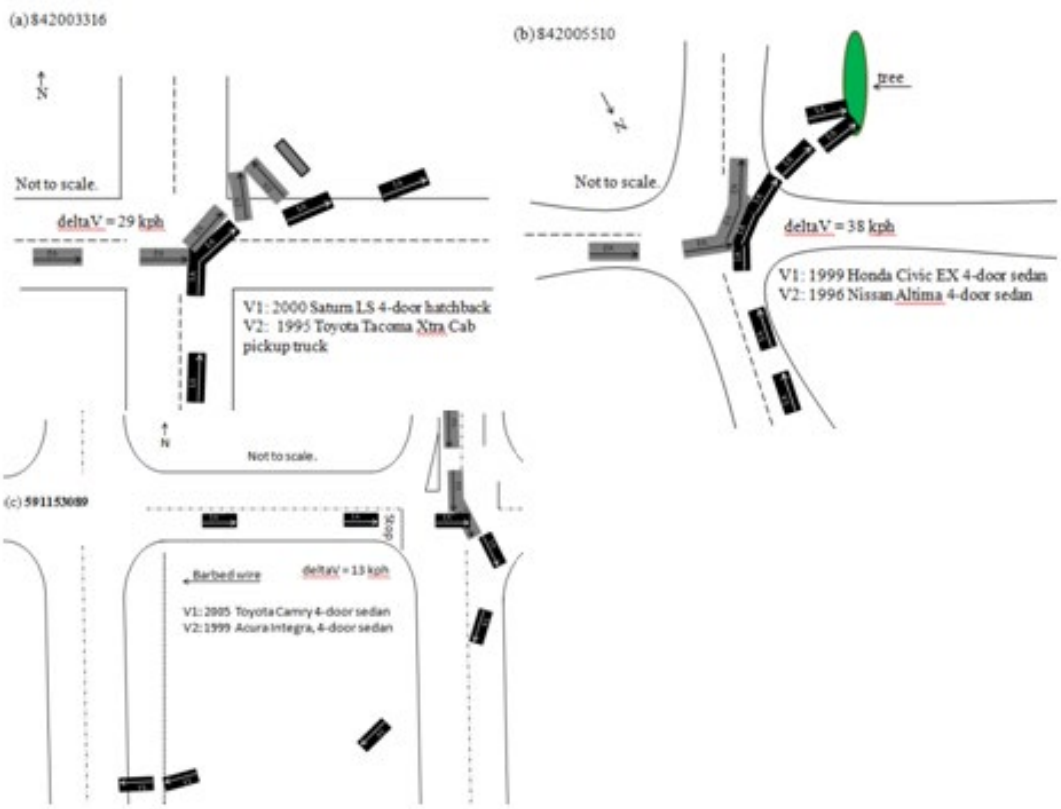

Figure 25 *- CIREN cases (a) 842003316, (b) 842005510, and (c) 591153089 are examples of multiple impact crashes. (a) This is a 2-event crash with an initial PDOF of 300 degrees. The crash sequence resulted in cervical spine facet fracture due to A-pillar contact and AIS 2 rib fractures due to steering wheel contact. The frontal airbag deployed. (b) B-pillar contact as a result of the initial impact caused numerous AIS 3+ head injuries, an aortic injury, and multiple rib fractures. The case vehicle then impacted a tree. (c) The initial impact caused an AIS 3+ brain and lower extremity injuries. The crash was fatal. Note the trajectory of the vehicle off the road and through a barbed wire fence. Figures are drawn from CIREN database.*

Corrections in the vehicle's velocity and PDOF in crash-imminent, pre-crash scenarios could be programmed to reduce driver overcorrection and/or error in response to the pre-crash scenarios and primary impacts as seen in Figure 25. This study showed that oblique angle crashes occur more often than perpendicular crash configurations. In addition to expanding upon these laboratory test conditions and modifying safety technologies accordingly, autonomous vehicle technologies have the potential to mitigate the severity of both primary and secondary impacts by using braking and steering sequences to better align energy absorbing structures and reduce driver error in response to the crash configuration described here.

B. Injury Distribution

Head, thorax, and lower extremity injuries were overwhelmingly caused by door contact, even in the presence of an airbag. Pelvic injuries may be caused by door intrusion, or crush between the door and the center console. These findings are consistent with the literature (Brumbelow, 2015) (Stadter, 2008) (Nirula, 2008) (Tencer, 2005). In cases where an airbag deployed, injuries often occurred through the airbag. Airbag deployment could be tailored to better respond to impending impacts using sensors employed by autonomous capabilities. Side-airbags, can alter the distribution of injuries across body regions, but studies show that there is room for improvement in this area (Brumbelow, 2015) (Stadter, 2008). For example, Scarboro et al. show that side airbags designed for thorax injury mitigation may not be very effective in preventing AIS 3+ severity thorax injuries. One possible explanation (given by Scarboro) is multi-trauma injury patterns, where one body region may benefit from side airbag availability, but others do not (Scarboro, 2007). Side airbags also do not perform as well in guarding against head injuries in oblique angle, near side crashes (Brumbelow, 2015) (Scarboro, 2007). The Insurance Institute for Highway Safety has also suggested that vehicles rated well for side impact are not adequately protecting occupants as would be expected for conditions that differ from those of current laboratory tests (e.g. oblique angles) (Brumbelow, 2015). These findings may explain what was observed in this case review and the lack of significant effect of the airbag in this crash mode.

Also consistent with the literature, crashes included in this study were mostly oblique angle crashes (greater than 270 degrees). The spleen was the most injured abdominal organ. The spleen is anatomically located on the left side of the abdomen, towards the back of an occupant. A spleen injury in a side impact crash suggests an oblique angle impact or intrusion, which would force the occupant backwards into a seat-back/support structure. Altering the PDOF of the crash using an autonomous vehicle behavior, or an airbag function could possibly be used to decrease the severity of this type of injury. In order to verify this finding, crash tests should be altered to better replicate occurring variety of PDOFs instead of just one (270 degree). Brumbelow et al. advocate for the expansion of crash test PDOFs, as well as changes that include: impacting the vehicle farther forward, greater test severity, and more restrictive injury criteria.

This study is limited to entries within CIREN. Because CIREN has a minimum requirement for severe injuries the data presented only represents severe crash scenarios. As the focus of safety research is to reduce the occurrence of severe injuries, this feature makes CIREN a good candidate for studying injury mechanisms. Literature studies of the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS), driver behavioral studies (e.g. driving simulation studies) and other NHTSA data as a means for comparing these findings to those of other researchers. The findings of the study may only be extended to severe crash scenarios. The study population was found to consist of more older adults, and more females than the US census and CIREN catchment areas would suggest. It is not possible to have an AIS 3+ injury in every body region, but the distribution of AIS 3+ injuries by body region compares well to a similar study conducted in 2010 (Melocchi, 2010).

Task 3: Changing Lanes on Highway or Merging

Introduction

"Vehicle(s) changing lanes-same direction" (here referred to as CLH) is sixth in terms of frequency (for light-vehicle crashes) out of 37 pre-crash scenarios described in the Department of Transportation 810 767 report (Najm, 2007). Ideal lane change-related crashes, involving two cars, usually result in loss of property and not injury, however when they take place at high speeds these scenarios have the potential to turn into multi-vehicle crashes (Figure 26) (Najm, 2007)(Wang, 1994)(Sen, 2003). The National Highway Traffic Safety Administration (NHTSA) reported that highway lane change crashes represent $4 billion in economic cost and 3% of functional years lost based on a review of the 2004 General Estimates System (Najm, 2007). Multi-vehicle crashes that occur on the highway may start out as lane-change or merging crashes and evolve into near side impacts, frontal impacts, and rollover crashes. Multiple impact crashes have been shown to have higher risk of injury than single impact crashes (Bahouth, 2005).

Varying levels of vehicle autonomy will co-exist on U.S. roadways for decades to come (IIHS, 2016). According to the Society of Automotive Engineers (SAE) out of the 6 levels of defined vehicle autonomy; human drivers should be ready to intervene in case of vehicle failure from levels 0 through 3. Level 4 automation specifies that an automated system may maintain control even if a human driver does not respond appropriately to a request to intervene. Level 4 automation is regarded as "high automation" and is one level below "full automation" (Appendix A) (SAE J3016_201609, 2014). During this time when vehicles on the road are not networked with each other and while many still rely on human drivers; human error could result in crashes. Even if the human driver is aware of an impending crash, the driver may not be able to process information about his/her surroundings fast enough to react optimally. Also, human errors in surrounding vehicles (e.g. path cutoff or veering to avoid an object) could lead to situations where even automated vehicles cannot completely evade a crash. This suggests that relinquishing control of the vehicle over to a potentially distracted driver in case of automation failure could result in more severe injuries for the occupants. During the crash, airbag(s) and debris could potentially obscure the driver's view and an injury could incapacitate the driver.

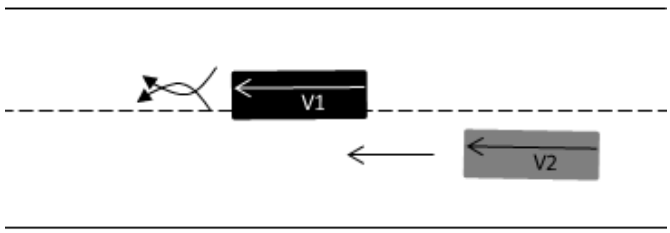

Figure 26 - *Lane-change or merging related crashes on the highway occur when a vehicle attempts to switch lanes, or deviates from its lane.*

Following the crash, when crumple zones and safety technologies have deployed, the potentially injured driver may not be able to optimally stop the vehicle or maneuver to avoid further harm from additional impacts.

It is critical that autonomous vehicle crash-imminent behaviors be occupant protection centric in design, meaning they take into account the capabilities of the vehicle's safety technology to crash in a way that best protects the occupant. In order to project body regions of interest, the National Automotive Sampling System (NASS) was analyzed. Next, to better determine how injuries occur in lane change and merging related crashes, the Crash Injury Research Engineering Network (CIREN) was searched for real-world lane-change crashes with discernible injury mechanisms. This case review provides some insight into injury mechanisms and outcomes of lane-change and merging related crashes.

Methods

National Automotive Sampling System

The National Automotive Sampling System (NASS) Crashworthiness Data System (CDS) database was used to identify the frequency and patterns of injuries occurring in lane change crashes. The occupants who sustained injuries to a specific body region were compared to the occupants involved in a similar crash with no injuries to that body region.

Data from 1998 through 2011 (13 case years) were used in this study including occupants of passenger vehicles of model years 1998 and later. Only crashes corresponding to lane change on a traffic way (Crash Type = 46 or 47) were included. Occupants were restricted to drivers of ages 16 and over only and pregnant occupants were excluded from this analysis. The database was analyzed using SAS 9.3 PROC SURVEYLOGISTIC (SAS Institute Inc., North Carolina, USA) which accounts for the sample weights for NASS CDS using ratio inflation factor.

Crash Injury Research and Engineering Network

There are six CIREN centers located across the US. The crashes entered into CIREN represent 12% of the crashes that comprise 77% of the nation's economic crash burden (Stauback, 2009). CIREN is not considered a population-based sample. For this case review, the injuries were pooled. Regions of interest were identified based on their frequency and severity of injury. In order to be included in CIREN, adult occupants must have sustained a serious or disabling injury based on the AIS. This means an AIS 2+ articular or other AIS 3+ injury must have occurred. Vehicles in CIREN are no more than 6 years old from the current manufacturing year. Single event crashes are preferred (Stauback, 2009).

CIREN was manually surveyed for lane change and merging crash scenarios via the public portal (Young, 2013). Specifically, cases were selected based on the impact scenario. Crash scenarios that began as lane change impacts between two cars were include. Injury mechanisms that resulted from lane change or merging – related impacts were included. Acceptance criteria included: occupant age of 16 or older, front airbags on the case vehicle, dry road surface, and discernible injury causations. In order to include more cases, crashes that occurred at or merging ramps were included as long as discernible injury causations were present. Only drivers were considered for this study because it provides a worst-case scenario; the steering wheel is an additional vehicle component that the occupant may impact during a crash. Both belted and unbelted occupants were

included in this study. A total of 19 cases were analyzed. Occupant injury causations were organized by both AIS severity score and vehicle component contact points.

Data Classification Methods

The abbreviated injury scale (AIS) is an anatomically-based, standardized, global severity scoring system that classifies injuries by body region according to its relative importance on a 6-point scale (1 being least severe, 6 being maximal) (AIS manual 2005 with 2008 update). The consensus-driven descriptors for the severity scores are in Table 3. AIS scores also define the body region affected. In AIS, eight separate body regions are defined and were analyzed in this study: head, face, neck, thorax, abdomen, spine, upper extremity, and lower extremity. The NHTSA injury coding manual for 2005 with the 2008 update was used for this study.

Table 3. Example Injury Descriptions and Corresponding AIS Severity Scores (AIS Course Manual).

Injury Description	AIS Severity Scale
Minor	1
Moderate	2
Serious	3
Severe	4
Critical	5
Maximal	6

Results

NASS Predictions

The NASS results predicted a risk of an AIS 2+ injury to the head, thorax, spine, upper extremity, and lower extremity during a lane change impact event (Figure 27).

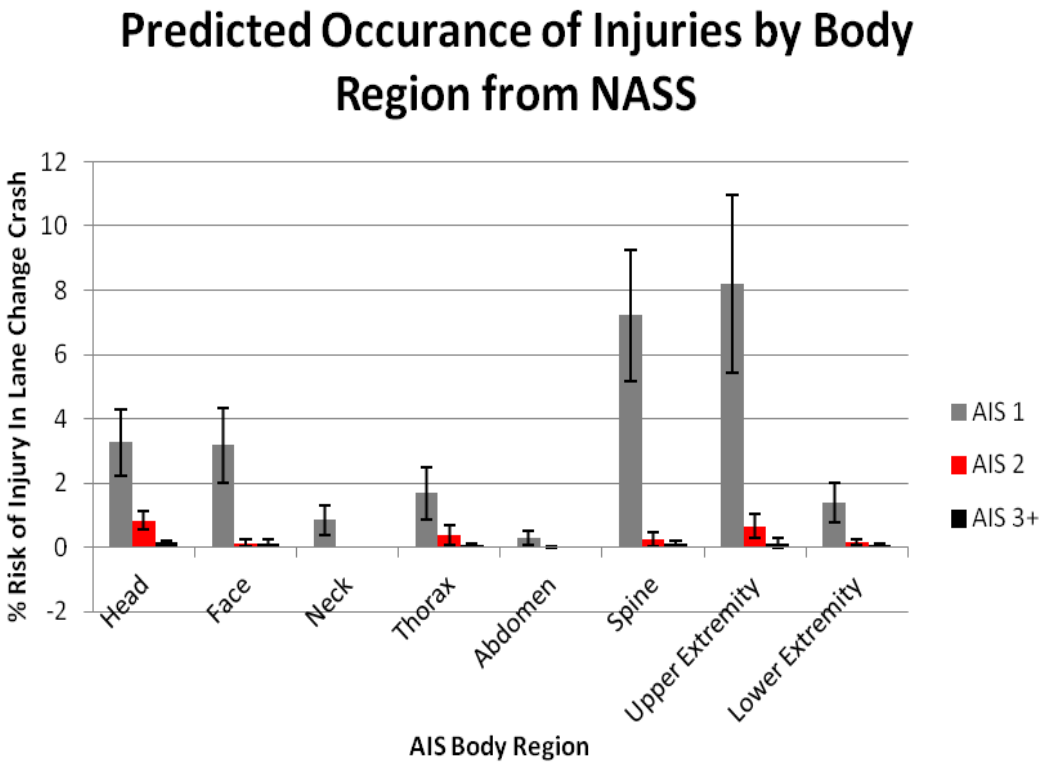

Figure 27 *- There is a risk of injury to all body regions, but the error bars for the AIS 3+ injuries overlap zero.*

CIREN Overview

Lane change crashes often result in property damage and minor injuries to the occupant. When these crashes occur at high speeds however, an abrupt yaw caused by a lane change may result in secondary impacts (e.g. near side or frontal) and/or loss of control of the vehicle. Loss of control of the vehicle may result in impacts with other vehicles and/or objects. The following cases were chosen because they demonstrate how initial lane change crashes can escalate into multiple impact crashes using real-world examples from CIREN.

Of the 148 documented injuries, 26 were AIS 3+ in severity. Injuries are described as percent of total injuries (Figure 28). Severe thorax injuries accounted for 6% of all the injuries. Door and/or b-pillar contact caused most of these thorax injuries, which were mainly injuries to the ribs and lungs. The case reviews and discussion will elaborate on some of injury mechanisms and possible sequelae of lane change related primary impacts. Driver over reaction, or lack of reaction played a part in the outcome of these cases.

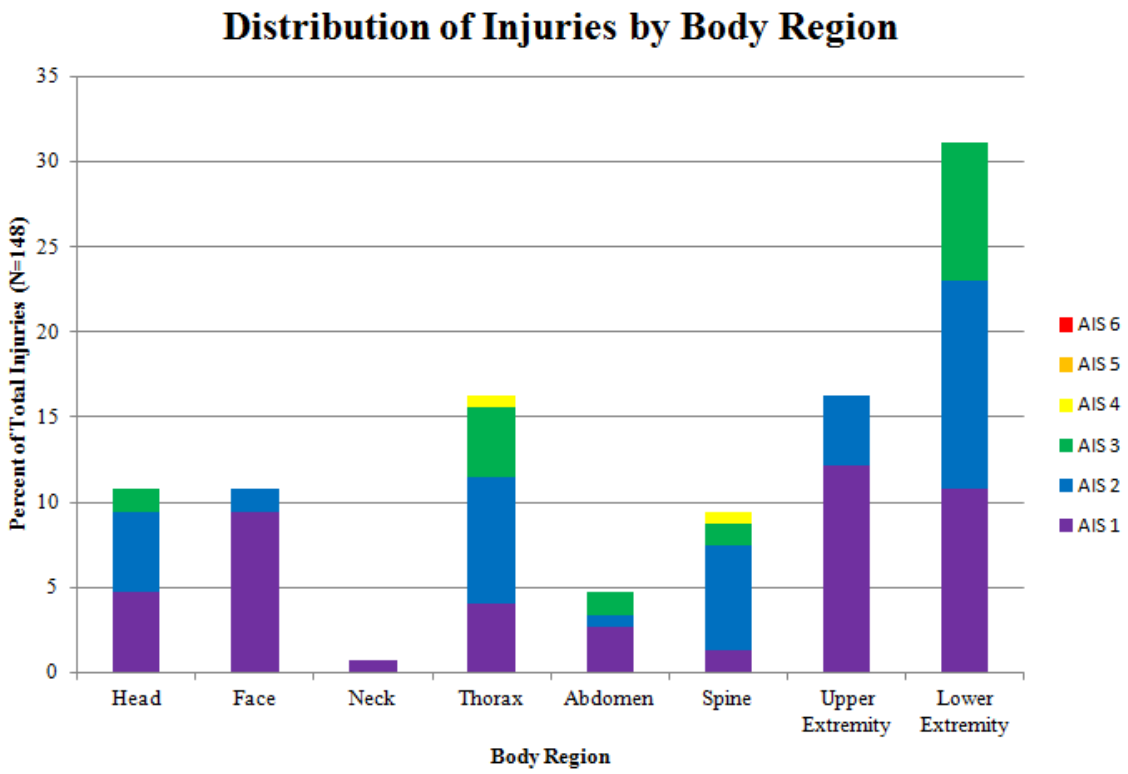

Figure 28 - *For the 19 Cases studied, there were 148 total injuries; 122 of the injuries were categorized as not severe (AIS 1-2) while 26 were categorized as severe (AIS 3-6). Of the severe injuries 7 were to the thorax and 12 were to the lower extremity.*

A. CIREN Case 1 - 120380

As the case vehicle reached a convergence area with a posted speed limit of 70 mph, the driver merged suddenly to his left and into the path of another vehicle (Fig. 29). The other driver was unable to avoid the case vehicle and the front of the other vehicle struck the left side of the case vehicle. This impact caused the case vehicle to rotate counterclockwise approximately 250 degrees while continuing to travel downstream and partially enter the lane that contained a third vehicle. This third vehicle was also unable to avoid the case vehicle and struck the right, rear end of the case vehicle. All three of these vehicles were towed due to disabling damage.

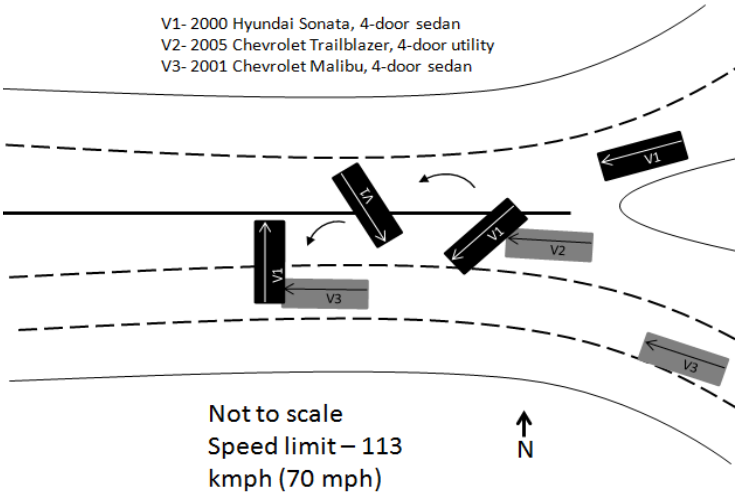

Figure 29 - *The initial impact for CIREN case 120380 was to the left rear of the vehicle by V2 in an oblique L-type configuration. The second impact was to the right rear of the vehicle by V3 also in an L-type configuration. The total deltaV of this crash was 24 kmph.*

The case occupant was a 39 year old, 183 cm, 91 kg male driver of a 2000 Hyundai Sonata, 4-door sedan. The available seat belt was being utilized at the time of the crash**.** The setback-mounted side-impact air bag deployed as a result of the impact. The case occupant sustained a loss of consciousness from contact with the air bag (AIS 2). He also sustained six left rib fractures (#4-9) posterior-lateral (AIS 3) probably from contact with the air bag. Additionally, he sustained five right posterior rib fractures (#3-7) (AIS 3) probably from contact with the center armrest. He sustained a multiple thoracic and lumbar vertebral fractures (AIS 2) from torso lateral bending over the center armrest and torso rotation.

The impact to the left side of the case vehicle most likely resulted in the severe injuries. Rotation and lateral bending may also have occurred at this time. While the case occupant was being injured, he may not have been able to optimally control the vehicle and a second impact occurred.

CIREN Case 2 - 590123577

A vehicle merged left into the eastbound number-one lane just as the case vehicle changed lanes to the right (Fig. 30). The front right of case vehicle struck the back left of the other vehicle in a minor impact. However, "the incident caused the subject to begin a left-right, over corrective steering maneuver that put the case vehicle into a clockwise yaw" as it traveled off of the right side of the interstate. The vehicle also overturned longitudinally once off the highway. The case vehicle, leading with its left side, struck down a chain-link fence and began to overturn. The case vehicle came to rest on its right side facing south.

The occupant was a 23-year-old, 165 cm tall, 67 kg female and was driving a 2005 Toyota Scion tC. She was wearing her seatbelt and had frontal airbags available, but they did not deploy during this crash. Her most serious injury was bilateral lung contusion (AIS 3) due to the belt restraint webbing/buckle. She also sustained an open and displaced radius fracture due to steering wheel

contact (AIS 2). The injuries most likely occurred in the impacts following the initial lane change event as the lane change event was noted to be minor.

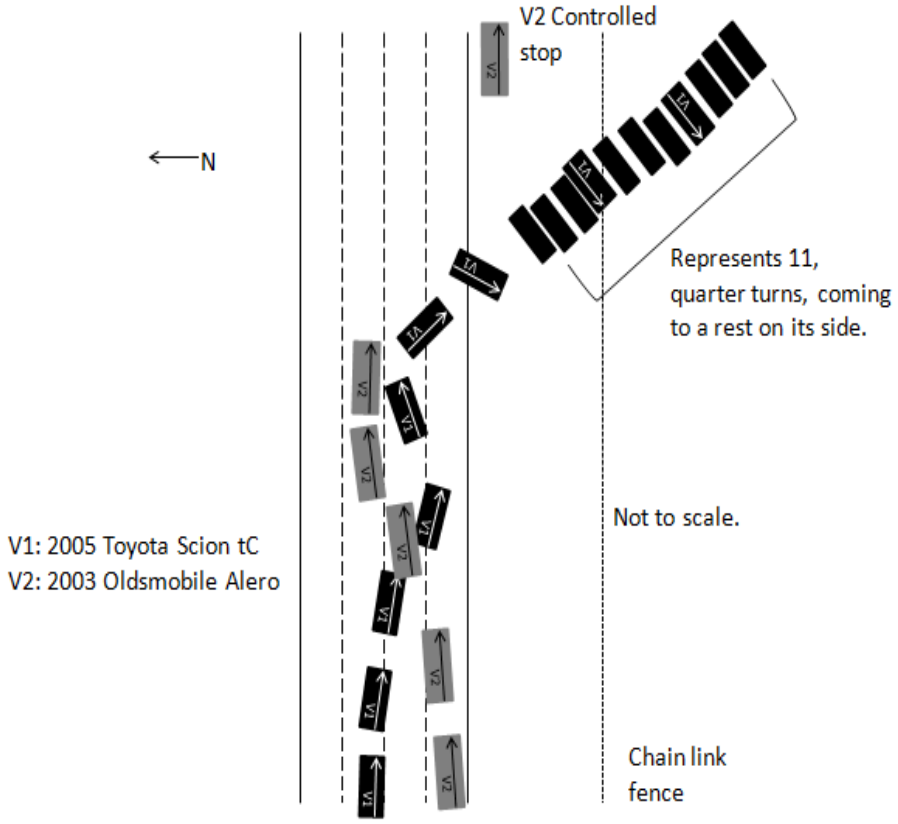

Figure 30 - *The initial impact for CIREN case 590123577 was minor, but the driver of the case vehicle initiated a left-right steering maneuver that led to a rollover crash. The deltaV of this crash was listed as unknown.*

CIREN Case 3 - 119946

The case vehicle entered an access ramp with greater than 2% grade that curved to the right as it merges with the freeway (Fig. 31). The driver of the case vehicle entered the right curve at too great a speed and the driver was unable to merge into the right lane in a controlled manner. The case vehicle therefore ran under the trailer of a 2006 Freightliner, tractor-trailer. No airbags deployed.

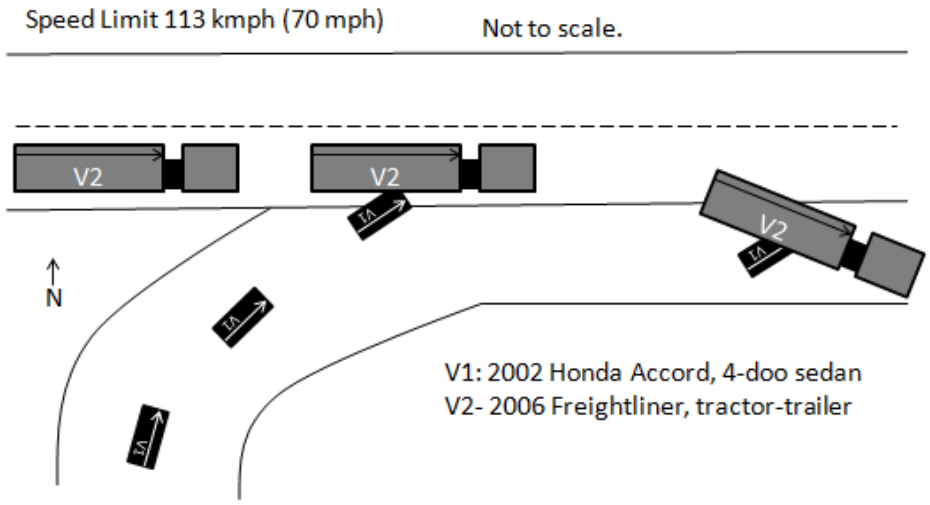

Figure 31 - *In CIREN case 119946, V1 drove under the tractor-trailer. The deltaV of this crash was listed as unknown [12].*

The 24 year old, 193 cm, 82 kg, male was belted and driving a 2002 Honda accord. On impact, he moved to the left, relative to the vehicle interior. He sustained a loss of consciousness (AIS 2), a comminuted basilar skull fracture (AIS 3), a left C1 inferior articular facet fracture (AIS 2), and a thoracic spine (T2) fracture (AIS 2) from contact with and loading by the left roof side rail at the grab handle (compression and lateral bending). He also sustained a left upper lobe pulmonary contusion (AIS 2) from contact with the left b-pillar. Multiple fractures to the lower extremity regions (AIS 3) were recorded. The crash was not fatal and all injuries were sustained as a result of the impact with the tractor-trailer.

Discussion

Crash preventive technology (e.g. lane change notifications) has the potential to reduce lane change crash outcomes. However, adaptation of this technology will not be universal for decades (IIHS, 2016). Semi-autonomous behaviors need to be able to mitigate crashes initiated by cars around the case vehicle. Although the literature and the NASS study showed a lesser degree of risk to the occupants in a lane change scenario, it may not have accounted for chaotic events such as secondary impacts. Such a scenario may be better explained using CIREN cases, which may be used to review injury mechanisms. This CIREN review showed that lane change crashes can quickly escalate if the vehicle is not controlled before, during and after the impact. Furthermore, this case review has shown how similar pre-crash scenarios may lead to diverse crash scenarios that result in a number of serious injuries and varying mechanisms of those injuries.

A unifying trend throughout the cases reveals that the drivers may not optimally respond to the pre-crash and/or crash scenario. This may be due to unsafe driving practices, misuse of information errors, and/or overcorrection that places the vehicle in a crash-imminent trajectory. This is supported by studies on distracted driving (Stauback, 2009). Additionally, drivers may become incapacitated or lose consciousness during a crash, which may render them unable to respond. It is important to realize that autonomous vehicle behaviors designed to mitigate crash

scenarios will need to be able to control the vehicle through every stage of a potential crash. These behaviors should optimally brake and steer to decrease driver-over correction or lack of reaction. Similar behaviors exist in stability control and lane-keeping semi-autonomous behaviors (NHTSA, 2017) (Pohl). These example behaviors sense instability (e.g. sliding and lane-deviation respectively) and aid the driver in maintaining control of the vehicle by sensing the environment.

Although many of the severe injuries were found to be thorax injuries due to safety technology contacts or intrusion of vehicle structures, whipping or bending motions caused by erratic vehicle motions also resulted in injuries. It is important to take into account that serious injuries are not always a result of contact with a structure. As shown in case 120380, some injuries were caused by non-contact motion (rotation) of the occupant. Additionally, steering/speed control could have been used to avoid the impact that caused the initial impact, which initiated many of the injuries. For case 590123577, the left-right overcorrective steering maneuver caused the occupant to encounter the roll over events that caused most of the severe injuries. If stability were maintained following the initial minor crash, the injuries may have been avoided. Finally, in case 119946, the entry speed of the case vehicle onto the merge ramp was cited as a factor in the crash with the trailer. An autonomous vehicle could potentially know that there is a trailer approaching and brake or veer to avoid driving under the trailer. Occupant-centric behaviors must take into account the complex nature of the human body in order to better protect occupants from harm during crashes. Additionally, these behaviors should be prepared to compensate for the reactions (or lack thereof) of the driver to crash imminent scenarios.

Autonomous vehicle behaviors could seek to optimize the principal direction of the force to allow energy absorbing structures and vehicle safety features to reduce the energy transfer perceived by the occupant. Smart braking behaviors could also reduce impacts, by making sure the vehicle is clear of other traffic before applying the brakes to prevent secondary impacts. Autonomous technologies could also be applied to airbag deployment by utilizing input about the occupant's movement around the vehicle during a crash and data about events outside of the vehicle.

The results of this study only apply to severe crashes and are not based on a population-based sample. Additionally, the occupants chosen for the in-depth case studies were not elderly. These results of this study should guide further investigations, along with driver simulations, human body modeling, and autonomous vehicle behavior design.

This case review is limited to entries within CIREN. Because CIREN has a minimum requirement for severe injuries, the data presented only represents severe crash scenarios. We have therefore used literature studies focused on data from the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS), driver behavioral studies (e.g. driving simulation studies) and other data as a means for comparing our findings to those of other researchers.

Crashes that occur during lane changes or merging may take place at high speeds and on busy highways. This leads to complicated, often multi-impact, multi-vehicle crashes. Overly complicated, multi-vehicle crashes were excluded from this study and may not be largely present in CIREN based on the aforementioned inclusion criteria.

Conclusion

An analysis of lane change crashes utilizing the NASS showed a risk of AIS 2+ injury to many body regions. The analysis of CIREN showed that lane change accidents may escalate into more chaotic crashes with secondary impacts. Autonomous vehicles may be able to perceive and process their environment faster than their human driver. Autonomous control could therefore potentially mitigate driver over corrections and/or reduce secondary impacts, such as those shown here.

References

Abdel-Aty, M. and Abdelwahab H. Modeling rear-end collisions including the role of driver's visibility and light truck vehicles using a nested logit structure. *Accid. Anal. Prev.* Vol. 36, no. 3, pp 447-456, 2004.

Acierno S, Kaufman R, Rivara FP, Grossman DC, and Mock C. Vehicle mismatch: injury patterns and severity. Accident Analysis and Prevention. 2004; 36:761-772.

AIS 2005 Abbreviated Injury Scale 2005 Update 2008 Course Book – Association for the Advancement of Automotive Medicine

Augenstein J, Perdeck E, Bowen J, Stratton J, Singer M, Horton T, Rao A. Injuries in Near-Side Collisions. In 43rd, Annual Proceedings, Association for the Advancement of Automotive Medicine, Barclona, Spain., 1999.

Augenstein J. *et al*. "Characteristics of Crashes that Increase the Risk of Serious Injuries," Proc. AAAM, Lisbon, Portugal, 2003.

Bahouth J, Digges K. Characteristics of Multiple Impact Crashes that Produce Serious Injuries, Proceedings of the 19th International Technical Conference on the Enhanced Safety of Vehicles, Washington D.C., USA, 2005.

Bergh C, Retting R.A, Myers E. Continued reliance on traffic signals: the cost of missed opportunities to improve traffic flow and safety at urban intersections. *Insurance Institute for Highway Safety*. September 2005.

Brown J, Coxon K, Fong C, Clarke E, Keay L. (May 2013) Seat belt wearing characteristics of drivers aged 75 years and older. Proc. ESV, Seoul, Republic of Korea.

Brumbelow M.L., Mueller B.C., and Arbelaez R.A. "Occurrence of Serious Injury in Real-World Side Impacts of Vehicles with Good Side-Impact Protection Ratings," *Traffic Inj Prev.* Vol 16, pp S125-S132, 2015.

Crash Injury Research and Engineering Network (CIREN) Data Dictionary version 1.2, December 29, 2015.

Crash Injury Research and Engineering Network website: https://one.nhtsa.gov/Research/Crash-Injury-Research-(CIREN)/Data:

CIREN case 120380: http://www-nass.nhtsa.dot.gov/nass/ciren/CaseForm.aspx?xsl=main.xsl&CaseID=120380. Accessed [February 21, 2017].

CIREN case 590123577: http://www-nass.nhtsa.dot.gov/nass/ciren/CaseForm.aspx?xsl=main.xsl&CaseID=590123577. Accessed [February 21, 2017].

CIREN case 119946: http://www-nass.nhtsa.dot.gov/nass/ciren/CaseForm.aspx?xsl=main.xsl&CaseID=119946. Accessed [February 21, 2017].

CIREN case 537106994: https://www-nass.nhtsa.dot.gov/nass/ciren/CaseForm.aspx?xsl=main.xsl&CaseID=537106994 Accessed [February 21, 2017].

CIREN case 338117581: https://www-nass.nhtsa.dot.gov/nass/ciren/CaseForm.aspx?xsl=main.xsl&CaseID=338117581. Accessed [February 21, 2017].

CIREN case 904429225: https://www-nass.nhtsa.dot.gov/nass/ciren/CaseForm.aspx?xsl=main.xsl&CaseID=904429225. Accessed [February 21, 2017].

CIREN case 842003316: https://www-nass.nhtsa.dot.gov/nass/ciren/CaseForm.aspx?xsl=main.xsl&CaseID=842003316. Accessed [February 21, 2017].

CIREN case 842005510: https://www-nass.nhtsa.dot.gov/nass/ciren/CaseForm.aspx?xsl=main.xsl&CaseID=842005510. Accessed [February 21, 2017].

CIREN case 591153089: https://www-nass.nhtsa.dot.gov/nass/ciren/CaseForm.aspx?xsl=main.xsl&CaseID=591153089. Accessed [February 21, 2017].

Daly B, Abboud S, Zabiullah A, Sliker C, and Fowler D. Comparison of whole-body post mortem 3D CT and autopsy evaluation in accidental blunt force traumatic death using the abbreviated injury scale classification. *Forensic Science International*, 2013; 225: 20-26.

Digges K, and Bahouth G. "Frequency of Injuries in Multiple Impact Crashes," Proc. AAAM, Lisbon, Portugal, 2003.

Dineen M.D., Wetter L.A., and Orr N.M. "Traumatic indirect inguinal hernia: a seatbelt injury," *Injury: the British Journal of Accident Surgery.* vol. 20, no. 3. 1989.

Elliott MR, Resler A, Flannagan CA, Rupp JD. Appropriate analysis of CIREN data: Using NASS-CDS to reduce bias in estimation of injury risk factors in passenger vehicle crashes. *Accident analysis and Prevention*, 2010; 42: 530-539.

Ekambaram K, Frampton R, Bartlett L. Improving the Chest Protection of Elderly Occupants in Frontal Crash Load Limiters. Traffic Inj. Prev. vol 16, pp. S2:S77-86, 2015.

Gabler H. and Hollowell W. The crash compatibility of cars and light trucks. *J. Crash Prev. Inj. Control.* Vol. 2, no. 1, pp 19-31, 2000.

Griffin R, Huisingh C, McGwin G, Reiff D, "Association between side impactairbag deployment and risk of injury: A matched cohort study using the CIREN and the NASS-CDS," *J Trauma and Acute Care Surgery,* vol. 4, 2012.

Hendey G, Votey S. "Injuries in Restrained Motor Vehicle Accidents." *Annals of Emergency Medicine*, 1994; 24(1): 77-84.

IIHS website [http://www.iihs.org/iihs/topics/t/roundabouts/topicoverview]

Huelke D. et. Al, (September, 1994) Upper Extremity Injuries Related to Air Bag Deployments. Proc. AAAM-IRCOGI Special Seccion, Lyon, France. [Presented].

Insurance Institute for Highway Safety, Status Report Vol. 51, No 8. Special Issue: Autonomous Vehicles November 10, 2016

Kahane C.J. Fatality reduction by safety belts for front-seat occupants of cars and light trucks: updated and expanded estimates based on 1986-99 FARS data. Washington, DC: US Department of Transportation, National Highway Traffic Safety Administration; 2000. Publication no. DOT-HS-809-199.

Kildare S, and Digges K. (May 2013) Characteristics of Crashes with Multiple Frontal Impacts. Proc. ESV. Seoul, Republic of Korea, Paper number 13-0061.

Kulowski J, and Rost W. "Intra-abdominal injury from safety belt in Auto Accident," *JAMA Surgery, case report,* vol. 73, no. 6, pp. 970-971, Dec. 1956.

Kusano K, and H. Gabler H. "Potential Occupant Injury Reduction in Pre-Crash System Equipped Vehicles in the Striking Vehicle of Rear-end Crashes." *Ann. Adv. Automotive Med.*, vol. 54, pp. 20-3214, 2010.

Lee E.L., Craig M., and Scarboro M. "Real-World Rib Fracture Patterns in Frontal Crashes in Different Restraint Conditions," *Traffic Inj. Prev.* vol 16, pp.S115-S123, 2015.

Lenard J.A., and Frampton R.J. "Two-impact crashes- implications for occupant protection technologies". Loughborough University, UK Paper 512.

Mandavilli, Srinivas; Retting, Richard A.; McCartt, Anne T. Crash patterns and potential engineering countermeasures at Maryland roundabouts. *Traffic Injury Prevention.* February 2009.

Melocchi, A., Van Horn, M., Faust, D., Fowler, G. et al., U of Michigan CIREN Side Impact Field Crashes and Injury Patterns. SAE Technical Paper 2010-01-1157, 2010, doi:10.4271/2010-01-1157.

Mohamed A., and Benerjee A. "Patterns of injury associated with automobile airbag use," *Postgrad Medical J*, vol 74, pp 455-458, 1998.

National Automotive Sampling System – Crashworthiness Database System. https://one.nhtsa.gov/Data/National-Automotive-Sampling-System-(NASS) [Feb, 21, 2017].

Najm WG, Smith JD, Yanagisawa M. Pre-crash scenario typology for crash avoidance research. National Highway Transportation Safety Administration, DOT-HS-810, 767., 2007.

Newgard CD, Lewis RJ, Kraus JF. "Steering Wheel Deformity and Serious Thoracic or Abdominal Injury Among Drivers and Passengers Involved in Motor Vehicle Crashes." *Annals of Emergency Medicine*, 2005; 45(1)

Newgard CD, Lewis RJ, Kraus JF, McConnell KJ. "Seat position and the risk of serious thoracoabdominal injury in lateral motor vehicle crashes." *Accident Analysis and Prevention*, 2005; 37(4): 668-674 25.

Nirula R., and Pintar F.A., "Identification of vehicle components associated with severe thoracic injury in motor vehicle crashes: A CIREN and NASS analysis," *Accident Anal. Prev*, vol. 40, pp 137-141, 2008.

National Highway Traffic Safety Administration. Third report to Congress: effectiveness of occupant protection systems and their use. Washington, DC: US Department of Transportation, National Highway Traffic Safety Administration; 1996. Available at http://www.nhtsa.gov/people/injury/airbags/208con2e.htm

National Highway Traffic Safety. The Impact of Driver Inattention on Near-Crash/Crash Risk: An Analysis using the 100-Car Naturalistic Driving Study Data. DOT HS 810 594, 2006.

National Highway Transportation Safety Association (NHTSA) Injury Coding Manual using AIS 2005/ update '08. Gennarelli T.A. and Elaine Wodzin. Association for the Advancement of Automotive Medicine, Barrington, IL, 60011-4172. 2008.

National Highway Transportation Safety Association (NHTSA) Injury Coding Manual using AIS 2005/ update '08. Gennarelli T.A. and Elaine Wodzin. Association for the Advancement of Automotive Medicine, Barrington, IL, 60011-4172. 2008.

National Highway Transportation Safety Association. "Crash Injury Research and Engineering Network." Internet: https://one.nhtsa.gov/Research/Crash- Injury-Research-Engineering Network (CIREN)/Data: [Feb. 21, 2017].

National Highway Traffic Safety Administration. Lives saved in 2014 by restraint use and minimum-drinking-age laws. Washington, DC: US Department of Transportation, National Highway Traffic Safety Administration; 2015. Publication no. DOT-HS-812-218. Available at http://www-nrd.nhtsa.dot.gov/Pubs/812218.pdf.

NHTSA. "Crash Injury Research and Engineering Network." Internet: https://one.nhtsa.gov/Research/Crash- Injury-Research-Engineering Network (CIREN)/Data:. [Feb. 21, 2017].

Ossiander, E.M., Koepsell, T.D., McKnight, B. Crash fatality and vehicle incompatibility in collisions between cars and light trucks or vans. *Inj. Prev*. vol. 20, no. 6, 2014.

Otte D., Suren E., Appel H, and Nehmzow J, (1984) Vehicle Parts Causing Injuries to Front-Seat Car Passengers in Lateral Impact. Proc of the 28th Stapp Car Crash Conference, pg. 13-26, SAE 841651.

Patel V., Griffin R, Eberhardt A, McGwin G. The Association between knee airbag deployment and knee-thigh-hip injury risk in motor vehicle collisions: A matched cohort study. *Accid. Anl. Prev.* vol. 50, pp 964-967, 2013.

Pohl J, Ekmark J. A Lane Keeping Assist System for Passenger Cars- Design Aspects of the User Inteface. Volvo Car Corporation. Gothenburg Sweden. Paper No. 529.

Retting, Richard A.; Persaud, Bhagwant N.; Garder, Per E.; Lord, Dominique
Crash and injury reduction following installation of roundabouts in the United States. *American Journal of Public Health.* April 2001.

Richtter M, Krettek C, Otte D, Wiese B, Stalp M, Ernst S, Pape H. Correlation between Crash Severity, Injury Severity, and Clinical Course in Car Occupants with Thoracic Trauma: A Technical and Medical Study. *The Journal of Trauma Injury, Infection and Critical Care*, 2001: 50(1): 10-16.

Safecar.gov [https://www.safercar.gov/Vehicle-Shoppers/Rollover/Electronic-Stability-Control]

SAS software. 9.3 PROC SURVEYLOGISTIC. SAS Institute Inc, North Carolina, USA.

Scarboro M. Rudd R, Sochor M. Nearside Occupants in Low Delta-V Side Impact Crashes: Analysis of Injury and Vehicle Damage Patterns. Enhanced Safety Vehicles 07-0225, Lyon, France. National Highway Traffic Safety Administration, 2007.

Schneider LW, Rupp JD, Scarboro, M, Pintar F, Arbogast K, Rudd R. et al. BioTab – A New Method for Analyzing and Documenting Injury Causation in Motor-Vehicle Crashes. *Traffic Injury Prevention.* 2011; 12: 256-265.

Sen B, Smith JD and Najm Wassim. Analysis of Lane Change Crashes. NHTSA DOT HS 809 571, 2003.

Society of Automotive Engineers International Standard J3016_201609, 2014.

Staubach M. "Factors correlated with traffic accidents as a basis for evaluating advanced driver assistance systems." *Accident Analysis and Prevention*, 2009; 41(5): 1025-1033

Stadter G, *et al.* "Injury and Side Impact Air Bag Deployment in Near and Far Side Motor Vehicle Crashes, United States, 2000-2005," *J of Trauma Injury, Infection, and Critical Care,* vol. 65, no. 6, pp 1333-1339, 2008.

Tencer A.F., Kaufman R., Mack, C. Mock, C, "Factors affecting pelvic and thoracic forces in near-side impact crashes: a study of US-NCAP, NASS and CIREN data," *Accident Anal Prev*, vol. 37, no. 2, pp 287-293, 2005.

Treat et al. Tri-Level Study of the Causes of Traffic Accidents Executive Summary. Institute for Research in Public Safety, Indiana University. DOT HS-034-3-535, 1979.

US Census Website https://www.census.gov/ [Feb. 21, 2017]

Wang J-S and Knipling RR. Lane Change/Merge Crashes Problem Size Assessment and Statistical Description. NHTSA DOT HS 808 075, 1994.

Wang J.S., Knipling R.R., Goodman M.J. "The Role of Driver Inattention in Crashes; New Statistics from the 1995 Crashworthiness Data System," Proc. AAAM, Vancouver, BC, 1996.

Weaver, K. Loftis, J. Stitzel. Investigation of the Safety Effects of Knee Bolter Air Bag Deployment in Similar Real-World Crash Comparisons. *Traffic Inj. Prev.* vol. 14, pp 168-180, 2013.

Young K, Salmon P, and Cornelissen M. "Distraction-induced driving error: An on-road examination of the errors made by distracted and undistracted drivers," *Accident Anal Prev*, vol. 58, pp. 218-225, 2013.

Yoganandan N, Pinar F, Zhang J, Gennarelli T. "Lateral Impact Injuries with Side Airbag Deployments-A descriptive study." *Accident Analysis and Prevention*, 2007; 39(1): 22-27.