INJURY ANALYSIS OF REAL-WORLD SMALL OVERLAP AND OBLIQUE FRONTAL CRASHES

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Paper Number 11-0384

ABSTRACT

Recent research has indicated poor injury outcomes for front row occupants of passenger vehicles equipped with frontal air bags when the longitudinal frame rail(s) are missed by the struck object. The objective of this research was to establish key factors for injury causation from a uniform manual analysis of real world crashes where very limited or no engagement of the longitudinal structures occurred. A multidisciplinary team of experts at the National Highway Traffic Safety Administration was assembled to review the available real-world cases matching this crash profile. The NHTSA team utilized a uniform process to review all cases to ensure the same data points were evaluated by each team member. Regular meetings were held by the team to discuss cases and to keep the reviews uniform. More than 380 cases were extracted from the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) and the Crash Injury Research and Engineering Network (CIREN) for analysis.

Injuries to the thorax and pelvis were the most prevalent, and oblique loading played a role in thoracic and head injury causation. The cases reviewed demonstrated possible issues with air bag coverage of contact points, intrusion contributing to injury, and occupant lower extremity kinematics associated with crash obliquity influencing pelvic fractures. The final result of the reviews was to initiate a vehicle crash research plan to test the feasibility of recreating the real-world crash and kinematic responses seen during the case reviews. The results of these case reviews indicate opportunities for improved anthropomorphic test device (ATD) response to duplicate the crash outcomes seen in this research.

INTRODUCTION

Recent studies of frontal crashes identified several factors that are thought to lead to fatalities of restrained occupants in newer vehicles [Brumbelow and Zuby, 2009; Rudd *et al.*, 2009]. The authors in both studies identified concentrated or limited engagement of frontal structures as one of the factors associated with increased risk to the occupants. These findings were consistent with those by Lindquist *et al.* [2004] who associated small overlap frontal crashes with a large percentage of fatalities in a Swedish study. As a result of the NHTSA study published by Bean *et al.* [2009], NHTSA stated its intent to further analyze low-offset and oblique frontal crashes in its Vehicle Safety Rulemaking & Research Priority Plan 2009-2011 published in November 2009 [NHTSA, 2009].

Prior studies of field data related to frontal crashes and the amount of overlap have yielded varying results. Pintar *et al.* [2008] examined NASS-CDS and CIREN crashes meeting frontal crash criteria, and focused heavily on the injury outcome in crashes with small overlap based on the Collision Deformation Classification (CDC) [SAE, 1980]. They found that the lower extremities, thorax and head were the most common AIS 3+ injuries in nearside small overlap crashes as determined by those with specific classifications in the CDC (they used FLEE and FREE crashes, which represent frontal plane damage near either the left or right corner with everything below the beltline sustaining damage). They noted that the average Injury Severity Score (ISS) was greater for mismatched vehicle crashes (based on size and geometry) compared to pole/tree impacts or matched vehicle crashes, suggesting that crash partner size and geometry play a role in small overlap crashes. Of particular interest

was their finding, among the CIREN cases, that occupant injury tended to differ based on the CDC extent zone such that occupants in crashes with extent zone 2-5 had more severe spine and chest trauma than those in crashes with extent zone 6-9. The thought was that vehicle kinematics differed during later phases of the crash, and the occupants did not engage the air bag as effectively due to vehicle rotation in the cases with extent zone between 2 and 5. Scullion *et al.* [2010] also examined the small overlap crash problem, but did so using a slightly different approach. Cases were selected from NASS-CDS, and they used an adaptation of the Frontal Impact Taxonomy (FIT) developed by Sullivan *et al.* [2008] to segregate the crashes in a way that accounted for longitudinal rail location. They found that the AIS 2+ and AIS 3+ injury risk in the small overlap crashes was not higher than that in moderate offset or offset crashes. Results from both of these studies suggest that further investigation of the problem is needed.

In order to establish a more comprehensive method to identify small overlap and oblique crashes, in which the longitudinal rails are not optimally engaged, the Medical College of Wisconsin (MCW) examined the nature of the crash problem and developed a crash filter that uses vehicle class-specific geometry along with crush measures and the CDC to identify these crashes in NASS-CDS and similar databases [Halloway *et al.*, 2011]. Their method identifies the small overlap and oblique crashes from crashes that are considered frontal based on the CDC damage plane, but also includes those to the left or right side as long as certain other criteria are met. This approach extracts a larger number of cases that meet the small overlap and oblique crash criteria.

The objective of this effort was to identify injury causation in small overlap and oblique frontal crashes, and to support the development of a research program to investigate these types of crashes. Prior studies have evaluated prevalence and injury distribution [Pintar *et al.*, 2008; Scullion *et al.*, 2010], but a more in-depth review of injury causation and crash configuration was required. While case-by-case analysis is labor-intensive, a thorough assessment of the problem cannot be developed based on coded data alone. This paper represents the findings from an in-depth review of applicable small overlap and oblique frontal crashes.

METHODS

Cases for review were selected from NASS-CDS and CIREN. The following parameters were required for inclusion into the dataset:

- Passenger vehicles model year 1998 and newer
- General area of damage of most significant event (GAD1) is frontal (F) or left side (L) with frontal directions of force (PDOF1 between 320 and 0 degrees)
- Belt-restrained drivers only
- AIS 3+ injuries to the head, chest and knee/thigh/hip (KTH) of lower extremity; fatalities were excluded since they were reviewed in the study by Rudd *et al.* (2009) and are generally more severe
- Cases with over- or underride were removed

A preliminary filter was applied to the crashes to determine whether they were left offset or left small overlap type crashes. The filter was developed by MCW [Halloway *et al.*, 2011], and bases the crash type on the CDC code and the crush measurements. The distinction between an offset and small overlap impact (SOI) is based on whether the left longitudinal or frame rail was engaged in the crash based on generalized geometric measures.

The cases were divided among a multi-disciplinary team of engineers and crash investigators, and were reviewed, in-depth, to extract pertinent observations about the crash and injury causation beyond what is available in the coded data. A case review tool, similar to that described by NHTSA [2009b], was used by the reviewers to display case information and record reviewer feedback in a consistent, structured manner. The reviewers relied on coded variables, photographic, graphic, and supplementary data sources available within the NASS-CDS and CIREN data systems to reach the conclusions drawn for each case. The case review tool compiled the case-based and reviewer-entered data for analysis, and guided the reviewer through the case starting with the crash elements, then focusing on the occupant and injury causation, and ending with a narrative. Examples of

reviewer-coded variables include assessment of the obliquity of the crash, amount of offset, whether occupant anthropometry played a role in the injury causation, the advanced restraint features available on the vehicle, as well as an evaluation of the injury sourcing for the major head, chest and KTH injuries. The pelvic injuries were investigated further using the available radiology or mannequin diagrams, when possible, to determine the specific type of pelvic fracture(s) sustained by the occupant.

Given the case-review nature of this work, the NASS-CDS and CIREN cases have been combined for analysis and presentation purposes. No statistical analyses have been performed on the combined data, and no assessment of injury risk can be conducted since case weights were not used. Some cases were removed from the dataset by the reviewers if the nature of the crash was felt to be outside the area of interest.

RESULTS

A total of 387 cases were selected from the NASS and CIREN databases for inclusion in this study based on the inclusion criteria presented above. After removing the cases rejected by the reviewers, 276 remained. Cases were typically rejected due to the crash involving multiple impacts or catastrophic severity. Table 1 shows some summary information for the final dataset. There were 124 left small overlap cases and 152 left offset cases. Although the CIREN and NASS-CDS cases are separated in this table, they have been combined for the remainder of the analysis. Though the average ISS was slightly higher for CIREN for both crash types, the difference was not large enough to raise question about the similarity of the two sets of data in the context of this study. One larger difference in the data was that the CIREN left offset crashes consisted of a higher proportion of vehicle-to-vehicle crashes than NASS, with 82% compared to 70% for NASS.

Table 1.
Summary of case data

	CIREN	**NASS**	**CIREN**	**NASS**	**Total**
	Left Offset	*Left Offset*	*Small Overlap*	*Small Overlap*	
Case count	89	63	70	54	276
% male	53.9	47.6	48.6	53.7	51.1
Min age	17	15	16	17	15
Max age	83	79	83	80	83
Mean age	45	41	44	41	43
Min ISS	9	9	9	9	9
Max ISS	43	50	50	50	50
Mean ISS	19.7	18.2	19.9	18.2	19.1
% vehicle to vehicle	82	70	66	67	72
% oblique[1]	39	40	31	50	39
1. Reviewer-determined classification					

Figure 1 shows the percentage of cases for each crash type (SOI and offset) in which the occupant sustained AIS 3+ injuries to the indicated body regions (AIS 2+ for leg/foot) by crash type. The percentage of injuries for each body region was similar for both crash types, and Figure 1 shows that the knee-thigh-hip (KTH, which includes pelvis) body region was the most-injured for both crash conditions. AIS 2+ below-knee injuries occurred with nearly the same frequency as AIS 3+ chest injuries in both crash types.

Reviewers were tasked with identifying the crash angle as either co-linear or oblique, which affects occupant kinematics and interaction with the restraints and interior components. Figure 2 shows the percentage of cases in each crash category in which the occupant sustained AIS 3+ injuries to the indicated body regions (AIS 2+ for leg/foot) in co-linear or oblique left SOI crashes. The percentage of injuries for each body region was generally similar for both crash angles, and Figure 2 shows that the

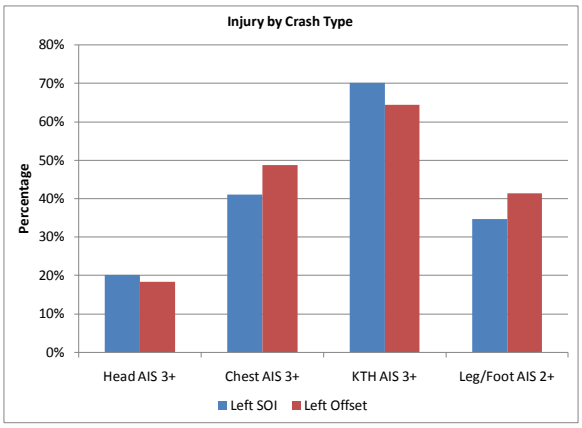

Figure 1. Percentage of cases sustaining injury to specified body regions for left small overlap and left offset crashes

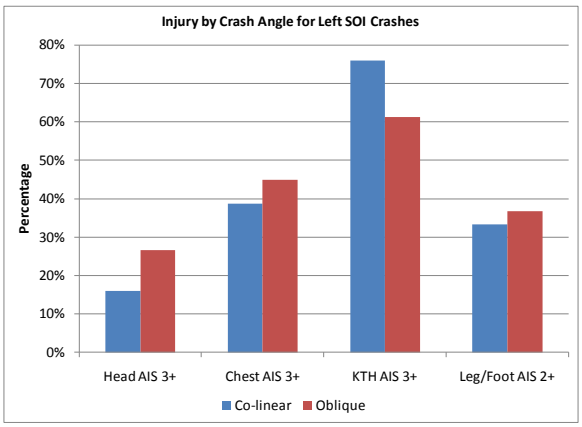

Figure 2. Percentage of cases sustaining injury to specified body regions for left SOI crashes by co-linear and oblique crash angle

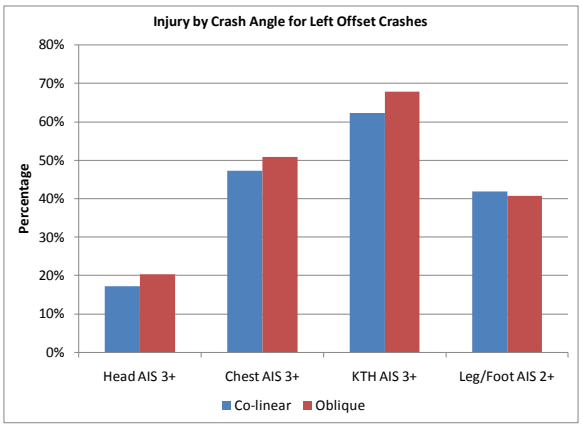

Figure 3. Percentage of cases sustaining injury to specified body regions for left offset crashes by co-linear and oblique crash angle

KTH body region showed the most difference between co-linear and oblique. Oblique crashes also showed a higher percentage of cases with AIS 3+ head injury. Figure 3 shows that crash angle has a relatively minor effect in the left offset crashes, with the various body regions seeing similar injury prevalence regardless of obliquity.

Figure 4 shows the assigned source for the most severe head injury for both left SOI and left offset crashes. For left SOI, the A-pillar and the steering wheel (SW) stand out as the most prominent injury sources for head injuries. For left offset crashes, the steering wheel and air bag were the most prominent, though the "other" category was cited frequently as well. Notable differences between the two crash types are seen with the air bag, A-pillar and instrument panel (IP), with the IP and A-pillar being more common in the small overlap crashes. Figure 5 shows the assigned source for the most severe chest injury for both left SOI and left offset crashes. There was a large difference in the number of chest injuries sourced to the door when comparing SOI to offset, which was offset by belt- and steering wheel-induced injuries. The KTH sources are shown in Figure 6, where it is evident that the instrument panel is the most frequent source in both SOI and offset crashes. There are more door-related KTH injuries in SOI crashes, but the proportion is small compared to the IP.

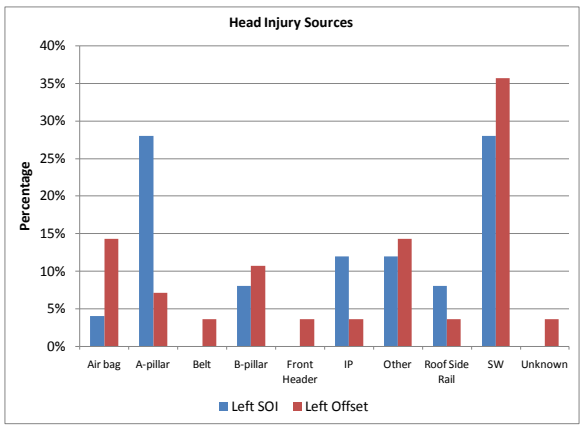

Figure 4. Injury source for most severe AIS 3+ head injuries for left SOI and left offset crashes

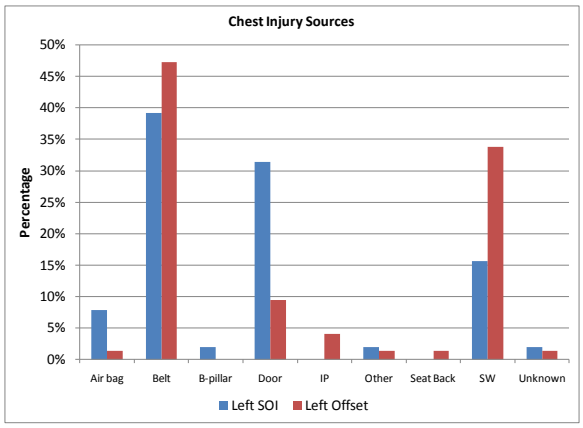

Figure 5. Injury source for most severe AIS 3+ chest injuries for left SOI and left offset crashes

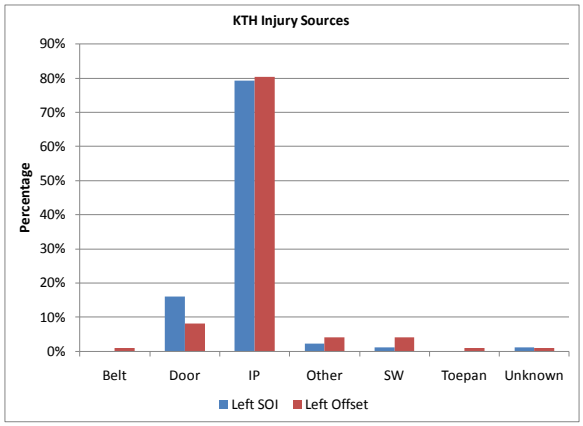

Figure 6. Injury source for most severe AIS 3+ KTH injuries for left SOI and left offset crashes

The next part of the analysis was to determine if crash angle has an effect on injury sources to the head, chest and KTH. Due to the number of cases for each crash type, the left SOI and left offset crashes were combined for this analysis so that the groups would not be too small. Figure 7 shows the head injury sources broken down by the reviewer-assessed obliqueness category. The most noticeable differences, other than for the "other" category, were the larger number of head injuries caused by the A- and B-pillars in oblique crashes. For the chest injury sources, only door showed a large difference for co-linear and oblique crashes (Figure 8). The belt was the most common source of chest injury, regardless of crash angle. The KTH sources are shown in Figure 9 for co-linear and oblique, but the differences are minor with only a slight increase in KTH injuries attributed to the door in the oblique crashes. Contact with the instrument panel is, by far, the most common cause of the KTH injuries.

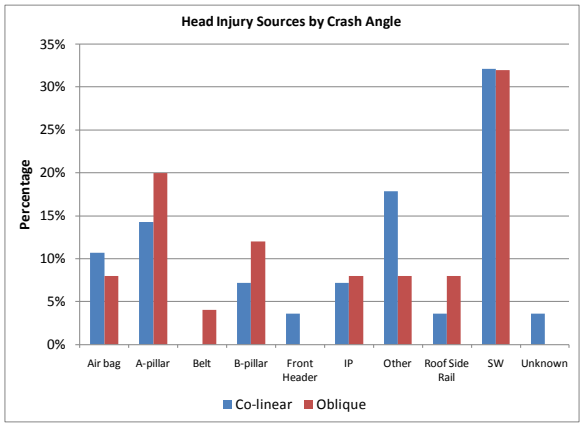

Figure 7. Injury source for most severe AIS 3+ head injuries for co-linear and oblique crashes

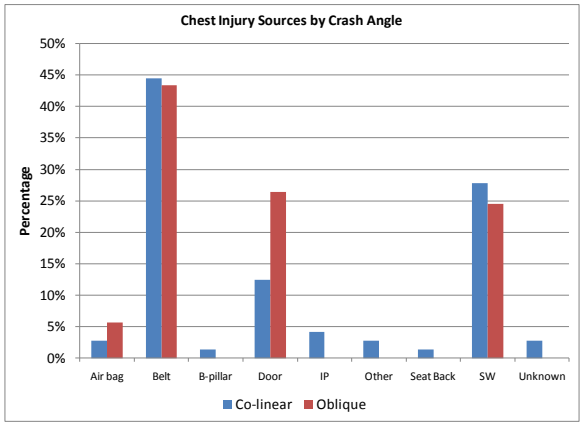

Figure 8. Injury source for most severe AIS 3+ chest injuries for co-linear and oblique crashes

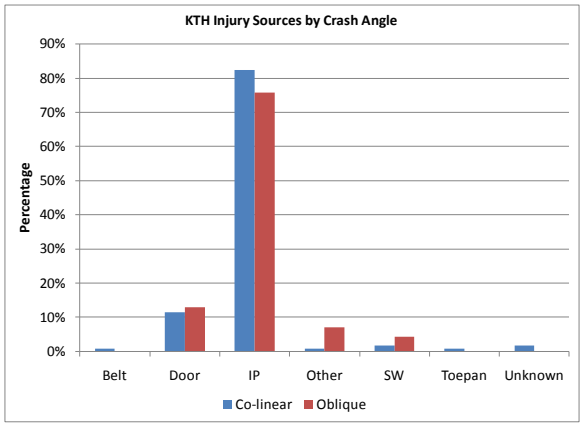

Figure 9. Injury source for most severe AIS 3+ KTH injuries for co-linear and oblique crashes

Since loading and intrusion of the footwell area is influenced by the motion of the left front wheel,

reviewers were asked to identify whether the wheel and tire assembly had engaged the rear portion of the wheel well and front door hinge pillar. Figure 10 and Figure 11 show the engagement of the tire for left SOI and left offset crashes. Tire engagement seemed to affect head injury most in the small overlap crashes. It can be seen from Figure 11 that left offset cases, in which the tire had engaged the structure near the occupant compartment, had a higher frequency of KTH injuries. There was less noticeable of a difference for the head and chest.

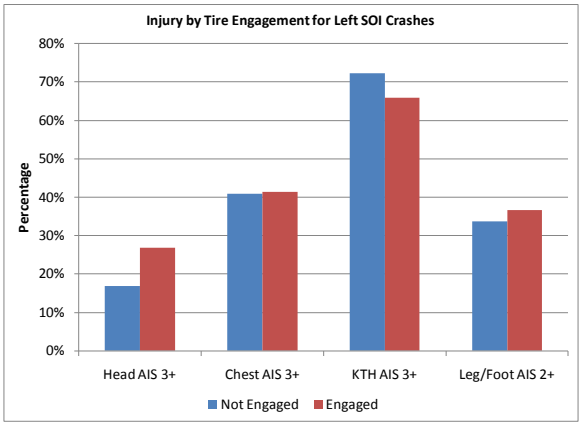

Figure 10. Injury prevalence per body region for wheel/tire engagement in left SOI crashes

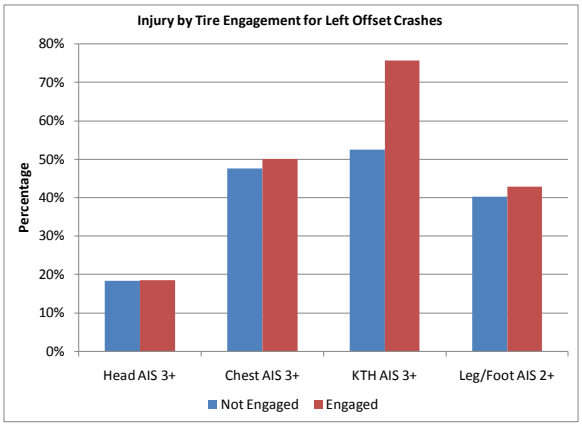

Figure 11. Injury prevalence per body region for wheel/tire engagement in left offset crashes

Since the KTH region stood out as the most injured body region, a more detailed analysis was conducted. Although there was a large number of thigh injuries (femur shaft, subtrochanteric and/or supracondylar fractures) captured in the KTH grouping, there was an interest in looking into the detail of the pelvic and hip injuries in the KTH group due to the clinical significance of these injuries. The types of fractures associated with thigh injuries do receive an AIS level 3 severity score indicating a serious threat to life, however, when treated promptly and appropriately these injuries, as a single-system insult, typically have shorter hospital stays and good outcomes. In contrast, injuries to the hip (especially injuries involving the articular surface of a joint) are well documented to be more complex to treat and have less optimal outcomes when compared to non-articular fractures of the KTH. Due to the non-specificity of the AIS coding system as it relates to hip injuries and the identification of articular involvement, it was necessary to review each case to document the level of pelvic and hip injury in greater detail. Since AIS severity coding is based on threat to life it was determined that hip and pelvic injuries at the AIS 2 level would be included in this analysis as well, since these codes include injuries to articular and weight-bearing structures. Along with capturing anatomical detail, the determination of loading conditions for injury causation was also pursued.

Figure 12 shows the breakdown of the locations of all coded KTH injuries with a severity of AIS 2 or higher among the 184 occupants who sustained AIS 3 and higher injury to the KTH region. There are a total of 384 AIS 2+ injuries coded for this group of occupants. The combination of pelvis and hip injuries makes up 44% of all AIS 2+ KTH injuries, while thigh injuries make up 37% of the injuries, and knee injuries account for the remaining 19%. There were 96 cases (52%) out of the 184 KTH cases where there was either a pelvic and/or hip injury.

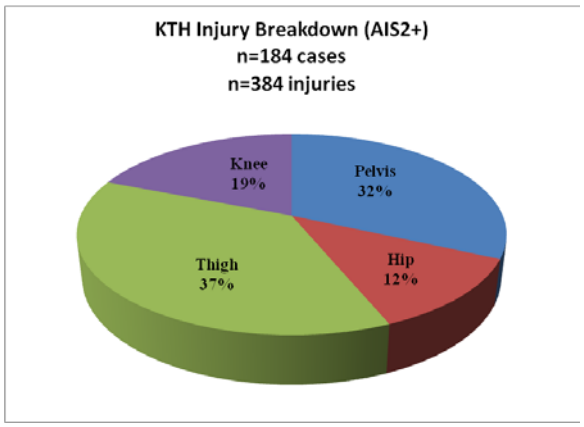

Figure 12. KTH injury breakdown for all injuries AIS 2 and higher

The breakdown of anatomical injury in the 96 cases where either a pelvic or hip injury was sustained, along with crash mode analysis, is displayed in Figure 13. Isolated acetabular fractures, pelvic ring fractures (sacrum, sacro-iliac joint(s), ilium or pubic rami) and proximal femur fractures are the highest frequency injuries. Acetabular fracture is present in 50% of all the cases, compared with only 36% of the cases having a pelvic ring fracture. The proximal femur (including fractures of the femoral head, neck, trochanter and hip dislocations) sustained injury in 32% of the pelvic/hip cases. The crash modes indicate minimal differences in the occurrence of acetabular fractures. Left offset crashes had the highest rate at 51% with the SOI crashes indicating 49%. The co-linear crashes had a rate of 52% with the oblique crashes demonstrating acetabular fractures 47% of the time.

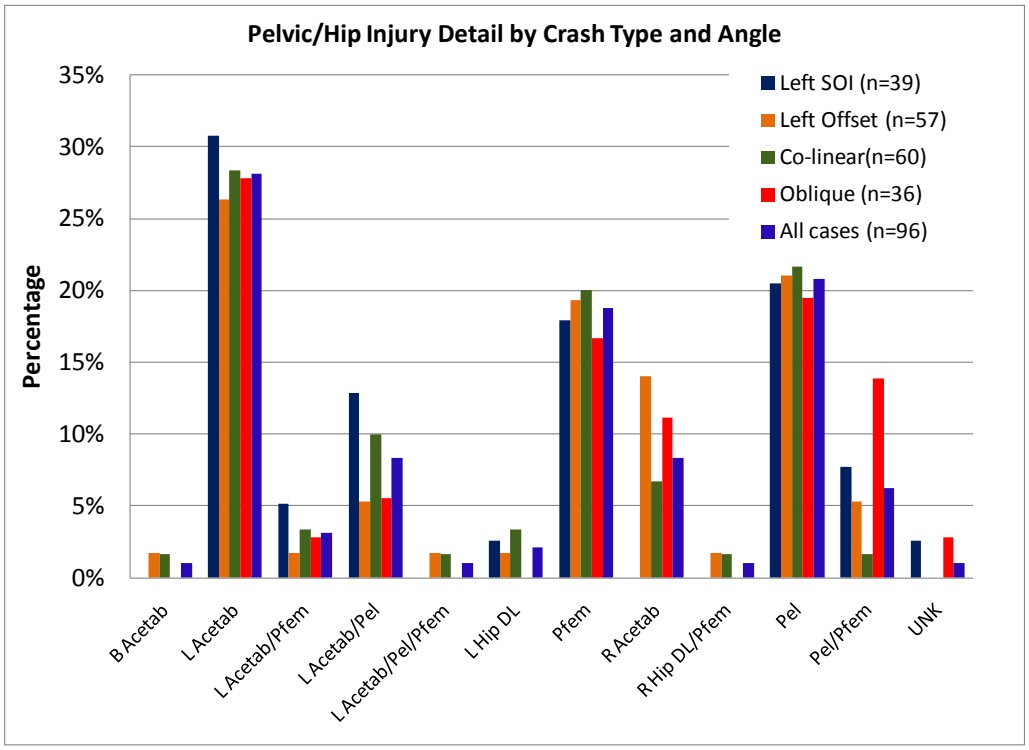

Figure 13. Anatomical detail of pelvic and hip injury for all study crash modes (B=bilateral, L=left, R=right, Pfem=proximal femur, Pel=pelvis, DL=dislocation)

In these two frontal crash modes, the femur shaft fractured less than 50% of the time, on average. However, the occupants in this group who sustained a pelvic and/or hip injury did so with the majority experiencing axial loading via the thigh. Figure 14 displays the incidence of femur shaft fracture in the subset of occupants sustaining pelvic and/or hip injury. Oblique crashes are the highest with a 50% incidence of femur shaft fracture concurrent with pelvic and/or hip injury. Left SOI and left offset both indicate the occurrence of femur shaft fracture with pelvic and/or hip injury slightly more than 40% of the time. Only 35% of the co-linear crashes resulting in pelvic and/or hip injury also sustained a femur shaft fracture.

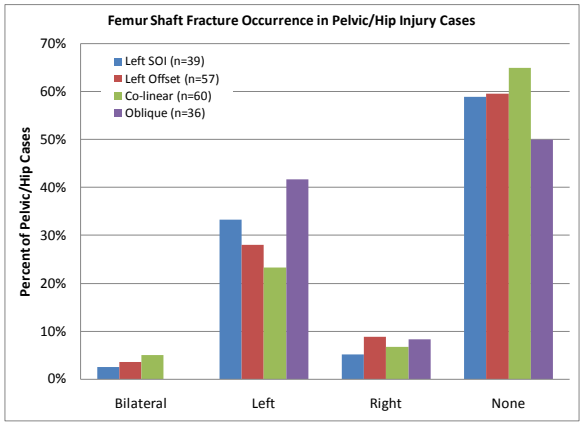

Figure 14. Pelvic/hip injury cases with associated femur shaft fractures

DISCUSSION

The differences in the incidence of injuries to the different body regions based on crash type and angle were not as large as was expected at the onset of this study. Regardless, in this subset of crashes, the results did show that the knee-thigh-hip was the body region sustaining the most AIS 3+ injuries. Overall, for the proportion of injury in the body regions, it seemed that crash angle had a greater influence than did crash type, especially when considering only left small overlap crashes (Figure 2). The oblique small overlap crashes saw a greater percentage of AIS 3+ head injury and a reduction in KTH injury compared to the co-linear crashes. For the head, as the crash angle deviates from co-linear, the kinematics of the occupant towards the left door results in less effective restraint by the air bag. A small increase in chest injury was also seen for the small overlap oblique crashes as well. It would be expected that the angle of the crash would play a role for left offset crashes as well, but there were only minor increases in injury prevalence compared to the co-linear crashes shown in Figure 3. In general, the findings of little distinction in injury between small overlap and offset are consistent with findings reported by Scullion *et al.* [2010] that injury risk was not higher in small overlap crashes.

Considering the source of the AIS 3+ head injuries, the steering wheel was the most common regardless of crash type or angle, though there were some differences worth noting. The A-pillar was more commonly cited in the small overlap than in the offset crashes, and it was responsible for a similar number of the AIS 3+ head injuries as the steering wheel in the small overlap group (Figure 4). There were also more head injuries associated with instrument panel contact in small overlap crashes, suggesting that the head was missing the air bag and steering wheel and moving slightly towards the side. This finding is corroborated by an increase in roof side rail contact and a decrease in air bag contact for the small overlap head injuries.

The changes in the chest injury source for small overlap crashes compared to left offset showed a similar trend of outboard movement, with SOI crashes having a larger percentage of AIS 3+ chest injuries associated with door contact and fewer with steering wheel contact (Figure 5). The proportion of chest injuries associated with belt contact were fairly similar for both crash types, and the belt was the most common source overall. Eighty percent of the knee-thigh-hip region injuries were associated with the lower instrument panel in both crash types, though there were slightly more KTH injuries associated with the door in the small overlap crashes (Figure 6). The overall tendency for more outboard injury sources in the small overlap crashes was expected due to the interaction of the struck and striking vehicle in these types of crashes, in which the striking object moves down the left side of the vehicle during the impact event. Figure 15 shows the crush of a vehicle in a co-linear small overlap crash, and Figure 16 shows the front left door of that vehicle, which is crushed due to continued interaction of the striking vehicle moving along the side. The vehicle position at, and after, impact is shown by the scene diagram in Figure 17, where it is evident that the case vehicle underwent rotation during the event. The rotation that occurred induced some lateral motion of the occupant towards the door, which was intruded by the crush caused by the striking vehicle moving along the side of the car. These factors lead to what appears to be a co-linear crash having injury sources that are more associated with an oblique crash. The driver in this case vehicle sustained chest injuries associated with contact to the interior door panel.

Figure 15. Front crush of vehicle in small overlap, co-linear crash

Figure 16. Crush of left front door of vehicle shown in Figure 15

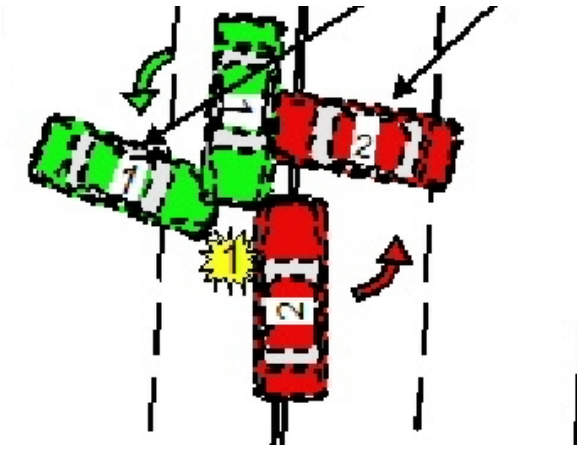

Figure 17. Vehicle rotation during crash indicated by position at impact and at rest (case vehicle, Vehicle 1, shown in green)

The injury source analysis was also conducted based on the reviewer-determined crash obliquity. As expected, the oblique crashes resulted in more A-pillar and roof side rail head injuries (Figure 7) and the chest had more of its AIS 3+ injuries sourced to the door than in the co-linear crashes (Figure 8). Chest injuries associated with the belt and steering wheel were about the same regardless of crash angle, which would be expected since these are all frontal crashes with a significant longitudinal loading vector. As with the crash type analysis, there wasn't much difference for the KTH injury source since most were attributed to contact with the lower instrument panel.

The knee-thigh-hip, which was the most frequently injured body region overall, was most often injured due to contact with the instrument panel in all crash types and angles. Because of the relatively small number of injuries associated with side components, it was not possible to discern any differences in causation based on crash type or angle. The detailed review of the pelvic and hip injuries indicates a large number of acetabular fractures within that group of injuries. Acetabular fractures typically involve disruption of the articular surface of the hip joint. This disruption often requires surgical repair, long-term recovery and can lead to artificial hip replacement, making this injury more life-altering than life-threatening. The pelvic and hip injury analysis also revealed over half of these injuries occurred in the absence of a femur shaft fracture, which suggests that more emphasis be placed on the evaluation of hip and pelvis loading in these types of crashes.

CONCLUSIONS

The detailed review of left offset and left small overlap frontal crashes in this study was conducted in order to identify distinct injury causation characteristics in each crash mode. The findings revealed that the crash angle influenced injury causation more than crash type, with oblique crashes demonstrating differences in head and chest injury sources. Small overlap crashes frequently produce oblique kinematics, and the interaction along the side of the struck vehicle increases chances for injuries from outboard components such as the door and A-pillar. A detailed review of the knee-thigh-hip injuries shows that hip and pelvis injuries frequently occur in the absence of femur fractures, especially in oblique crashes.

The findings of this work suggest that a test program to study occupant response in small overlap and oblique frontal crashes will need to be sensitive to the differences in occupant loading and injury causation that have been found in these cases. The ATD used in the testing should possess the biofidelity to replicate the real-world kinematics, and should be capable of measuring loads relevant to the dominant injuries. Appropriate biofidelity and injury measurement in the KTH complex is highly desirable due to the high number of injuries seen in this study.

Additional research is required to investigate the interaction and possible benefits of new safety technologies in these types of crashes. Technologies like side curtain air bags may be able to offer head

protection from A-pillar contact, striking vehicle contact or possibly upper door contact. Other improvements, such as chassis design, may minimize intrusion of components that frequently cause injury in crashes with small amounts of overlap.

ACKNOWLEDGEMENT

The authors would like to acknowledge the team members who assisted in the review of the NASS and CIREN cases and thank them for their contributions to this work: Matthew Craig, Mark Mynatt, Dan Parent, Michael Parsons, Jeff Suway and Chris Wiacek.

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