Analysis of Nearside Narrow Object Impacts with and without Shoulder Injuries in Real-World Crashes

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Abstract: This study was designed to investigate factors involved with shoulder injuries and their influence on injury patterns of other body regions in nearside narrow object impacts. CIREN cases from 2000-2011 were examined for nearside narrow object crashes involving passenger cars, light trucks and vans. Occupants with shoulder injuries were identified, and crash, vehicle, occupant and injury characteristics were evaluated. After controlling for delta-V, occupant stature, vehicle type and direct damage location, results of the matched-pair analysis showed that the primary direction of force can play a role in shoulder injuries, with anterior oblique force vectors increasing the incidence of this injury. Additionally, differences in injury patterns between the shoulder injury and non-injury groups suggest an increase in thoracic and abdominal injuries and a decrease in pelvic and lower extremity injuries when an occupant sustains a shoulder injury in this crash scenario. Further research is needed to better understand the load paths and crash factors involved in nearside narrow object impacts with and without shoulder injury. These findings are pertinent to dummy evaluations (biofidelity, injury criteria), as the pure lateral impact-based ES2-re and WorldSID have different seated heights and different torso and pelvis designs.

Keywords matched-pair analysis, CIREN, narrow object impact, nearside, shoulder injury.

I. INTRODUCTION

Nearside impacts, to the left side for left-sided occupants and to the right side for right sided occupants, are a particularly injurious crash configuration given the proximity of the occupant to the vehicle side structures. Injuries to these occupants have been a focus of study for almost five decades and initial research conducted in the 1970s by the United States Department of Transportation National Highway Traffic Safety Administration (NHTSA) led to the promulgation of side impact standards in 1990 [1]. Many laboratory and field studies have been advanced since this time wherein attention has been focused on delineating regional responses and establishing injury criteria, leading to the recent upgrade of this side impact standard. Since 1996, NHTSA has been conducting field-based studies to gather more medical information than the National Automotive Sampling System (NASS) by analyzing crash and medical data from real-world Motor Vehicle Crashes (MVCs) in a program called the Crash Injury Research and Engineering Network (CIREN). The CIREN includes a team of engineers and physicians that connect each injury in a MVC to its source (vehicle component or other cause [2]). The present study used these data to analyze specific types of side impacts.

From a side impact perspective, narrow object impacts with a pole or a tree often create occupant compartment intrusion due to their focal nature [3]. Because of the rigidity and the geometry of the narrow object, side impact injuries can be distributed to the ipsilateral region of the occupant. In other words, injuries might occur from the head to the torso and lower extremities due to impact and intrusion associated with these crashes. While many side impact studies have focused on the head and torso regions for protection, analysis of injuries associated with the shoulder have been limited [4]. Because the analysis of narrow object-induced crashes has been limited in literature, this study was designed to investigate factors involved with shoulder injuries and their influence on injury patterns of other body regions in nearside narrow object MVCs. This was accomplished by comparing the injury patterns and other crash characteristics of occupants with and without shoulder injury in nearsided narrow object impacts while controlling for belt use and seat position and with similar delta-Vs, vehicle types, occupant statures, and direct damage locations.

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II. METHODS

The CIREN database from 2000-2011 was examined to identify crashes involving passenger cars, light trucks and vans (vehicle model-years 2000-2011). Currently, there are approximately 4,000 cases in the CIREN with crash and injury data. In order to qualify for the CIREN database, an occupant must have Abbreviated Injury Scale (AIS) 3 or greater, with some exceptions [5, 6]. Other criteria for CIREN cases are that the case vehicle should be within six model years of the crash date and that no completely ejected occupants are enrolled. All included cases in this study were nearside narrow object crashes, which was defined by using the Collision Deformation Classification (CDC) for the highest severity impact (defined by NASS and CIREN as the most severe event in a crash sequence [7]). For cases where the third character of the CDC (general area of damage) was to the left, drivers were selected. If the general area of damage was to the right, passengers were selected only if they were in the right-front seat. Narrow object impacts were defined as a crash where the highest severity impact was with a fixed, non-breakaway pole or with a tree.

Only first-row occupants were considered, and all occupants were required to have at least one AIS 2+ injury. Rollovers and unbelted occupants were excluded from the data set. Crashes involving first-row occupants on the struck side in nearside impacts that were ranked as the highest severity event were then analyzed. Specific AIS codes were used to identify occupants with a shoulder injury. Shoulder injuries were defined for this study as clavicle, scapula, acromion and humerus fractures, as well as acromioclavicular joint and glenohumeral joint dislocations, at the AIS 2+ level, based on two AIS coding schemes [5, 6]. Both codes were used to identify shoulder injuries, since the AIS 2005 coding scheme was adopted by the CIREN starting in crash year 2008. In CIREN case histories, the only humerus fractures considered to be a shoulder injury were those involving the surgical neck or above. The humerus fracture location was determined by referring to the radiology images and accompanying radiology report. A list of AIS codes used to identify shoulder injury cases is provided in Table 1.

Table 1: Description of AIS codes used to identify crashes with shoulder injuries

Injury description	**AIS Codes (1990)**	**AIS Codes (2005)**
Acromion Fracture	751600.2	N/A (Combined with scapula codes)
Clavicle Fracture	752200.2	750500.2/ 750501.2/ 750511.2/ 750512.2/ 750521.2/ 750522.2/ 750551.2/ 750552.2/ 750561.2/ 750562.2/ 750571.2/ 750572.2/ 750531.2/ 750532.2/ 750551.2/ 750552.2/ 750561.2/ 750562.2
Scapula Fracture	753000.2	750900.2/ 750901.2/ 750951.2/750952.2/ 750961.2/ 750962.2/750971.2/ 750972.2
Humerus Fracture	752600.2/ 752602.2/ 752604.3/752606.3	751111.2/ 751112.2/ 751151.2/ 751152.2/ 751161.2/ 751162.3/ 751171.2/ 751172.3
Acromioclavicular joint dislocation	750230.2/750240.2	770799.1/ 770789.1/ 770710.1/ 710720.1 /770730.2/ 730731.2
Glenohumeral joint dislocation	751030.2/ 751040.2/ 751050.3	771099.1/ 771089.1/ 771010.1/ 771020.1/ 771030.2/ 771031.2

The selected occupants within each dataset were then divided into two groups: those with and those without an AIS 2+ shoulder injury. Analyses were then performed to determine which other crash factors had an effect on the occurrence of a shoulder injury for an occupant in a near-sided crash. For this study, factors on the occupant, vehicle and crash level were all examined. The CIREN occupants with a shoulder injury were then examined in greater detail, and a case study was then performed for these occupants. Biomechanical information, radiology and vehicle damage were all considered in order to determine what factors and interior vehicle components contributed to the occupant's shoulder injury. The analysis of the CIREN database found 337 cases of accidents involving nearside occupants in the two front seat outboard seating positions. Of these, 55 cases involved nearside impact with a narrow object. 48 of these occupants did not have any shoulder injury as defined above, while seven occupants sustained a shoulder injury (SI) based on AIS codes.

Identifying the specific site of a humerus fracture is not possible in data using AIS 1990/98 codes. During the review of CIREN case histories, the determination of the humerus fracture location was made by referring to the radiology images and accompanying radiology report. Only humerus fractures involving the surgical neck or above were defined as a shoulder injury. One case that was identified as sustaining a shoulder injury was excluded because the nearside humerus fracture was distal, not occurring in the area in the surgical neck or above. This case was therefore moved to the non-SI group.

Shoulder injuries were required to occur on the near side (right shoulder injury for a left impact, left shoulder injury for a right impact) and were not considered as part of the SI group if they occurred on the far side. During the review of the CIREN case histories, two cases selected as nearside-impact shoulder injuries were reclassified as non-shoulder injury cases due to the fractures being on the inboard side of the body, with case notes attributing the injury to sources other than interior side structures. After identifying the three shoulder injuries that did not meet criteria, the final occupant count was 51 in nearside pole impacts without shoulder injury and 4 in nearside pole impacts with shoulder injury.

Table 2: Investigation frame of case selection methods

Description	Total Occupants	With Shoulder Injury	Without Shoulder Injury
Restrained, first row outboard nearsided occupants	**337**	**61**	**276**
Impact with narrow object (tree or pole)	**55**	**4**	**51**
Passenger cars, delta-V 21-41 kmph (13-25 mph), direct damage within 41 cm of wheelbase, occupant stature 152-173 cm (5'0"-5'8")	**9**	**4**	**5**

III. RESULTS

Of the four occupants identified with shoulder injury, three sustained a clavicle fracture and one sustained a humerus fracture. The delta-V, calculated as the barrier equivalent speed by the NHTSA-developed software WinSMASH and based on stiffness coefficients and vehicle crush, ranged from 21-41 kmph. The barrier equivalent speed was used because WinSMASH's algorithm only allows for delta-V to be calculated in vehicle-to-vehicle impacts, not in vehicle-to-object impacts. The barrier equivalent speed is defined as the "speed with which a vehicle would have to collide with a fixed barrier in order to absorb the same amount of energy or produce same amount of crush to the vehicle as in the crash" and is WinSMASH's indicator of speed change in vehicle to object impacts [8]. The average amount of maximum crush for the four cases was 42 cm. Two of the impacts occurred with impacts to trees, while two occurred during impacts with utility poles. The ages ranged from 18-46 years and there was an oblique primary direction of force in three of the four crashes. All of the occupants were in passenger cars (not SUVs, pickup trucks or vans), and the center of the direct damage was within 41 cm of the center of the undamaged wheelbase in all of the crashes. All of the shoulder injured occupants ranged in height from 152-173 cm. Additionally, side impact airbags (defined as curtain and/or seat mounted airbags) deployed in two of the four shoulder injury crashes. Table 2 illustrates some of the crash characteristics of the SI group.

Table 3: Crash characteristics of the shoulder injury cases in CIREN

CIRENID	Age	Sex	Height (cm)	Weight (kg)	Seat Position	Class	Object	Delta-V (kmph)	Maximum Crush (cm)	PDOF (Degrees)	Direct Damage Location	Side Airbag Deploy
160157102	18	Male	173	63	Driver	Intermediate	Tree	30	29	290	-20	Yes
160158143	22	Female	152	49	Driver	Compact	Tree	41	71	290	-19	Yes
407068584	27	Female	163	79	RF Seat	Intermediate	Pole	21	36	80	13	No
857088552	46	Female	168	102	RF Seat	Intermediate	Pole	21	33	70	-41	No

Of the 51 nearside occupants involved in crashes with narrow objects without shoulder injuries, the delta-V ranged from 11-72 kmph. Occupant heights ranged from 147-196 cm. All vehicle classes were included in this data set, including passenger cars, SUVs, pickups and light trucks. Direction of force (DOF) included pure lateral impacts, (defined as 3 and 9 o'clock), oblique lateral impacts (defined as 2, 4, 8 and 10 o'clock), as well as other impacts (1, 11, 5 and 7 o'clock). Figure 2 illustrates some of the crash characteristics of the 51 non-shoulder injury cases.

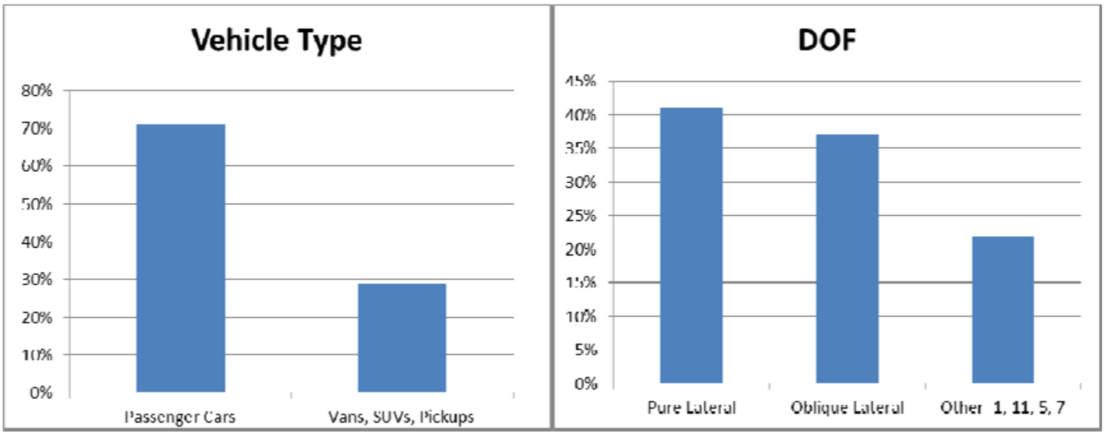

Fig. 1. Crash characteristics of the non-shoulder injury cases in the CIREN (N=51)

Occupant injury to other body regions was also examined for both the groups. Three of the four shoulder injuries were an AIS 2, although this is a function of AIS coding, which assigns an AIS 2 code to all clavicle fractures but can assign an AIS 3 to certain humerus fractures. Three of the four shoulder injury cases sustained a head injury, with two receiving a brain injury and one a skull fracture. All four shoulder injury cases also had an AIS 3+ thoracic injury, with all of them sustaining thoracic organ injuries and 3 also receiving rib fractures. Additionally, three of the four occupants sustained abdominal injuries, two sustained pelvic injuries, while no shoulder injury cases had an accompanying lower extremity (not including pelvic) injury. Table 4 illustrates some of the injury characteristics of this group.

Table 4: Injury characteristics of the shoulder injury cases in CIREN

CIRENID	Shoulder Injury	Shoulder AIS	MAIS	ISS	Head MAIS	Head Bone MAIS	Head Organ MAIS	Thorax MAIS	Thorax Bone MAIS	Thorax Organ MAIS	Abdomen MAIS	Pelvis MAIS	Lower Extremity MAIS
160157102	Clavicle Fx	2	3	17	2	0	2	3	0	3	0	0	0
160158143	Clavicle Fx	2	4	34	3	3	0	4	4	4	3	0	0
407068584	Clavicle Fx	2	3	17	2	0	2	3	3	3	2	2	0
857088552	Humerus FX	3	4	34	0	0	0	4	4	4	3	3	0

The 51 nearside occupants without shoulder injury were also examined based on where they sustained injuries. AIS 2+ head injuries were the most prevalent for this group, occurring in 65% of the occupants, while skull fractures occurred in 25% of this group. Fifty-seven percent of this group sustained a thorax injury of AIS 2 or greater, while 39% had rib and/or sternal fractures. Additionally, 24% sustained AIS 2+ abdominal injuries, 53% sustained AIS 2+ pelvic injuries and 35% sustained AIS 2+ lower extremity (femur and below) injuries. Figure 3 illustrates the distribution of AIS 2+ injuries for the non-shoulder injury group.

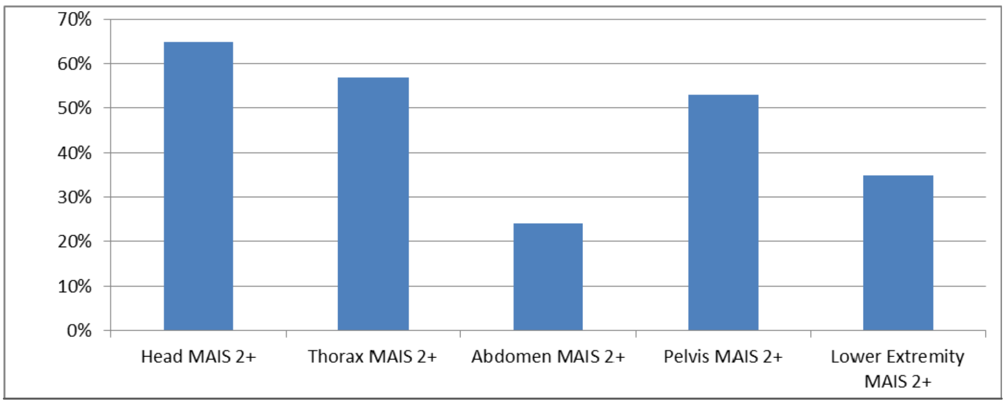

Fig. 2. Injury characteristics of the non-shoulder injury occupants (N=51).

Matched-pair analysis

For the non-shoulder injury group, further selection criteria were then enacted in order to create a matched-pair analysis with the four shoulder injury occupants. Four crash variables; delta-V, occupant stature, vehicle type and direct damage location were all chosen and matched between the non-shoulder injury and shoulder injury groups. Delta-V, one of the best indicators of crash severity, had to be between 21 and 41 kmph to be included. Occupant stature was between 152 and 173 cm. Only passenger cars were considered for the analysis; vans, pickup trucks and utility vehicle were excluded. Finally, the direct damage location was normalized by including only cases in which the center of the direct damage from the narrow object was within 41 cm of the center of the vehicle's undamaged wheelbase. This direct damage range ensured that there would be direct interaction between the nearside occupant and the vehicle damage resulting from the narrow object impact.

The Delta-V ranged from 26-39 kmph in the five non-shoulder injury crashes. The average amount of maximum crush for the four cases was 46 cm. Two of the impacts occurred with impacts to trees, while the other three occurred during impacts with poles. The ages ranged from 16-44 years and there was an oblique primary direction of force in one of the five crashes, the other four being pure lateral. All of these occupants ranged in height from 160-173 cm. Additionally, side impact airbags (defined as curtain and/or seat mounted airbags) deployed in three of the five crashes. Table 4 illustrates crash characteristics of these cases.

Table 5: Characteristics of non-shoulder injury cases with same delta-V, stature, direct damage & vehicle range

CIREN ID	Age	Sex	Height (cm)	Weight (kg)	Seat Position	Class	Object	Delta-V (kmph)	Maximum Crush (cm)	PDOF (Degrees)	Direct Damage Location	Side Airbag Deploy
117404	16	Female	165	60	RF Seat	Compact	Tree	39	43	80	-15	No
286038494	17	Male	173	72	Driver	Compact	Pole	30	44	280	-5	Yes
338055651	26	Female	163	67	Driver	Intermediate	Tree	29	46	270	13	Yes
338090847	44	Female	160	100	Driver	Intermediate	Pole	26	44	260	-38	Yes
857076265	16	Female	163	59	Driver	Compact	Pole	29	52	310	31	No

Three of the five non-shoulder injury occupants sustained a head injury, with three receiving a brain injury and two receiving a skull fracture. Two of the non-shoulder injury cases had an AIS 3+ thoracic injury, with both sustaining thoracic organ injuries and rib fractures. None of the five non-shoulder injury occupants sustained AIS 2+ abdominal injury but all five sustained pelvic injuries, ranging from AIS 2 to AIS4. Finally, two of the five non-shoulder injury occupants sustained a lower extremity (not including pelvic) injury. Table 5 illustrates some of the injury characteristics of these occupants.

Table 6: Injury characteristics of the non-shoulder injury cases with the same delta-V, stature, direct damage and vehicle range

CIREN ID	MAIS	ISS	Head MAIS	Head Bone MAIS	Head Organ MAIS	Thorax MAIS	Thorax Bone MAIS	Thorax Organ MAIS	Abdomen MAIS	Pelvis MAIS	Lower Extremity MAIS
117404	5	50	5	3	5	4	4	4	0	3	0
286038494	3	19	3	3	2	0	0	0	0	3	0
338055651	3	14	0	0	0	0	0	0	0	2	3
338090847	4	29	0	0	0	3	3	2	0	4	0
857076265	5	34	5	0	5	0	0	0	0	2	3

The four shoulder injury cases and the five matched pair non-shoulder injury cases were then examined in detail. The purpose of this matched-pair analysis was to determine what crash and injury factors are related to shoulder injuries in nearside crashes with narrow objects.

CIREN Shoulder Injury Case Studies

Case 160157102: This case involved an 18-year-old belted male driver who lost control, departed a roadway and struck two trees. The first impact was to the right side with a small tree, causing the vehicle to rotate clockwise before it struck a larger tree with its left side. This second impact to the left side with the larger tree was coded in the CIREN as the most severe event. The left-side impact had a primary direction of force of 290 degrees, and caused 29 cm of maximum crush to the vehicle exterior and 18 cm of intrusion to the left front door. The center of the vehicle damage for the left-side impact was 20 cm behind the center of the vehicle's undamaged wheelbase. Additionally, the near-side impact had a non-horizontal element, as there was more crush to the vehicle's rocker panel (floor sill) than to its door sill or roof rail. The driver's frontal, left seat-mounted thorax and left curtain airbags all deployed during the second event. The driver sustained a small left apical pneumothorax, a clinically diagnosed mild concussion without loss of consciousness and a left mid to distal clavicle fracture with minimal inferior angulation of the distal fracture fragment. In this case, the CIREN sourced the clavicle fracture and the pneumothorax to the occupant's shoulder loading the left door through the side impact airbags during the second impact.

Fig. 3. CIREN Case 160167102 Radiology and Vehicle Exterior and Interior

Case 160158143: This case involved a 22-year-old belted female driver who departed a roadway, began to yaw clockwise, and struck a large tree on the left side plane. The primary direction of force was 290 degrees, and the impact caused 71 cm of maximum crush to the vehicle exterior as well as 51 cm of intrusion to the left door. The center of the vehicle damage was 19 cm behind the center of the vehicle's undamaged wheelbase. Additionally, the near-side impact had a non-horizontal element, as there was more crush to the vehicle's roof side rail and there was direct damage to the outboard edge of the vehicle's sunroof. The left sided seat-mounted thorax and left curtain airbags both deployed during impact. The driver sustained a basilar skull fracture, grade III spleen laceration, a left T1 transverse process fracture, right 1st rib and left 1-4 and 6-11 rib fractures, as well as a left lung laceration and bilateral pneumothoraxes. Additionally, she sustained a left midshaft clavicle fracture. Each of the occupant's thoracic and shoulder injuries were sourced by the CIREN to the left door, through the side impact airbags.

Fig. 4. CIREN Case 160158143 Radiology and Vehicle Exterior and Interior

Case 407068584: This case involved a 27-year-old belted female in the right front passenger seat of a vehicle that departed a roadway, entered a counterclockwise yaw, and struck a utility pole with its right side. The primary direction of force was 80 degrees, and the impact caused 36 cm of maximum crush to the vehicle's exterior as well as 22 cm of intrusion to the right front door. The center of the vehicle damage was 13 cm in front of the center of the vehicle's undamaged wheelbase. Additionally, the near-side impact had a non-horizontal element, as there was more crush to the vehicle's rocker panel (floor sill) than to its door sill or roof rail. No airbags deployed in the occupant's seating position. This passenger sustained a clinically diagnosed concussion with a loss of consciousness under one hour, a liver contusion, bilateral inferior/superior pubic rami fractures, and a right sacral fracture. In addition, she sustained a right 5th rib fracture, a right pneumothorax, a right pulmonary contusion and a right comminuted, displaced distal clavicle fracture. The CIREN sourced all of this occupant's thoracic and shoulder injuries to the right front door.

Fig. 5. CIREN Case 407068584 Radiology and Vehicle Exterior and Interior

Case 857088552: This CIREN case involved a 46-year-old belted female in the right front passenger seat of a vehicle that departed a roadway, began to yaw counterclockwise and then struck a utility pole on its right door. The primary direction of force was 70 degrees, and the impact caused 33 cm of maximum crush to the vehicle's exterior as well as 26 cm of intrusion to the right front door. The center of the vehicle damage was 41 cm behind the center of the vehicle's undamaged wheelbase. This impact with a pole was completely planar based on vehicle damage. No airbags deployed in the occupant's seating position. This passenger sustained a right kidney contusion, a left (inboard) clavicle fracture, a grade III liver laceration, transverse process fractures from L3-L5, bilateral pubic rami, and right sacrum and acetabulum fractures. Additionally, the occupant sustained left rib fractures from 4-6, right rib fractures of the 6th and 8-11 ribs, a right-sided pneumothorax and a comminuted and open fracture of the anterolateral right humeral head and neck. The rib fractures, pneumothorax and humerus fractures were all sourced by the CIREN to the right front door. This occupant's left-sided clavicle fracture (far-sided relative to the impact) was postulated by the CIREN to be caused by contact with the vehicle's driver.

Fig. 6. CIREN Case 857088552 Radiology and Vehicle Exterior and Interior

CIREN Without SI Case Studies- Same Vehicle, Delta-V, Direct Damage Location and Occupant Stature

Case 117404: This CIREN case involved a 16-year-old belted female in the right front passenger seat of a vehicle that departed the roadway, began to yaw counterclockwise and struck a large tree on its right door. The primary direction of force was 80 degrees, and the impact caused 43 cm of maximum crush to the vehicle's exterior as well as 40 cm of intrusion to the right front door. The center of the vehicle damage was 15 cm behind the center of the vehicle's undamaged wheelbase. The near-side impact had a non-horizontal element, as the vehicle was on a down slope and probably struck the tree at an angle. No airbags deployed in the occupant's seating position. This occupant died from her injuries 22 days post-crash. This passenger sustained head injuries, including diffuse axonal injury (DAI), cerebrum contusions, epidural and subarachnoid hemorrhages, pneumocephalus, and basilar, vault, orbital and mandible fractures. In addition, she sustained bilateral lung contusions, a right pneumothorax and right rib fractures 1-4 and a left 1st rib fracture. She also sustained an L5 spinous process fracture and right pubic rami, sacral and pubic symphysis fractures. Her head injuries were sourced by the CIREN to the struck tree, while her thoracic and pelvis injuries were sourced to the right front door.

Fig. 7. CIREN Case 117404 Radiology and Vehicle Exterior and Interior

Case 286038494: This case involved a 17-year-old belted female driver who departed a roadway, entered a clockwise yaw, and struck a utility pole on its left door. The primary direction of force was 280 degrees, and the impact caused 44 cm of maximum crush to the vehicle's exterior as well as 30 cm of intrusion to the driver's door. This vehicle was equipped with an Event Data Recorder (EDR), which recorded a longitudinal delta-V of 4 kmph and a lateral delta-V of 39 kmph. The center of the vehicle damage was 5 cm behind the center of the vehicle's undamaged wheelbase. This impact with a pole was completely planar based on vehicle damage. The curtain airbag deployed in the driver's position, but no other airbags deployed. The driver sustained a basilar skull fracture and a brief loss of consciousness, as well as left sacrum, iliac and bilateral superior pubic rami fractures. The CIREN sourced the pelvic fractures to contact with the driver door and the head injuries to contact with the right front passenger in the vehicle.

Fig. 8. CIREN Case 286038494 Radiology and Vehicle Exterior and Interior

Case 338055651: This case involved a 26-year-old belted female driver who departed a roadway in a clockwise yaw and struck a tree with the vehicle's left door. The primary direction of force was 270 degrees, and the impact caused 46 cm of maximum crush to the vehicle's exterior as well as 40 cm of intrusion to the driver's door. The center of the vehicle damage was 13 cm in front of the center of the vehicle's undamaged wheelbase. Additionally, the near-side impact had a non-horizontal element, as there was more crush to the vehicle's rocker panel (floor sill) than to its door sill or roof rail. The curtain airbag and the seat-mounted thorax airbag both deployed during the impact. The driver sustained a midshaft displaced left femur fracture, a left radial head fracture, a left L5 transverse process fracture and fractures to the left sacral ala and superior pubic rami. All of the occupant's injuries were sourced by the CIREN to the left door except the pelvic injuries, which were postulated to be caused by the pelvis contacting the left door while the vehicle's center console acted as a boundary condition on the occupant's pelvis.

Fig. 9. CIREN Case 338055651 Radiology and Vehicle Exterior and Interior

CIREN Case 338090847: This case involved a 44-year-old female driver who entered a clockwise rotation, departed a roadway and struck a large utility pole with the vehicle's left side. The primary direction of force was 260 degrees, and the impact caused 44 cm of maximum crush to the vehicle's exterior as well as 21 cm of intrusion to the driver's door. The center of the vehicle damage was 38 cm behind the center of the vehicle's undamaged wheelbase. This impact with a tree was completely planar based on vehicle damage. The seat-mounted head and thorax airbag deployed during this impact. The driver sustained rib fractures 2-4 and the 6th on the left and a left lung contusion. In addition, she sustained a right sacrum, left pubic rami, left radial shaft and right transverse processes L2, L4 and L5 fractures. The CIREN sourced all of these injuries to the left door except for the pelvic injuries, which were postulated to be caused by the pelvis contacting the left door while the vehicle's center console acted as a boundary condition on the occupant's pelvis.

Fig. 10. CIREN Case 338090847 Radiology and Vehicle Exterior and Interior

CIREN Case 857076265: This case involved a 16-year-old female driver who entered a clockwise yaw, departed a roadway and struck a non-breakaway traffic signal pole with its left door. The primary direction of force was 310 degrees, and the impact caused 52 cm of maximum crush to the vehicle's exterior as well as 23 cm of intrusion to the driver's door. The center of the vehicle damage was 31 cm in front of the center of the vehicle's undamaged wheelbase. This impact with a pole was planar based on vehicle damage, but there were two impacts with a barrier curb prior to the pole impact that could have induced a non-horizontal element to the crash. Both of the vehicle's frontal airbags deployed during this impact. The driver sustained bilateral superior pubic rami and right inferior pubic rami fractures in this impact. In addition, she also sustained a diffuse axonal injury and concussion, along with a left femoral shaft fracture. The CIREN sourced all of this occupant's injuries to the left door, although it was noted that the head could have also contacted the pole or the vehicle's left A-pillar.

Fig. 11. CIREN Case 857076265 Radiology and Vehicle Exterior and Interior

IV. DISCUSSION

As stated in the introduction, although field-based studies exist on nearside crashes, analyses of recent crash data delineating the role of shoulder loading and injuries to other body regions are limited, especially in narrow object impacts. The aim of this study was to better understand this role by performing matched-pair analyses of injuries using similar crashes. This was accomplished by analyzing crash and injury characteristics of occupants involved in crashes of this configuration in the CIREN database for those occupants with and without a shoulder injury.

Statistical analysis was not possible because the CIREN database is not population-based and data are not weighted. Because of the small sample size, a matched-pair analysis was performed between occupants with and without shoulder injury with similar crash characteristics. The strength of this methodology is that a detailed review can be performed on a case-by-case basis, and subtle factors often not coded and extrapolated from photographic and medical documentation can be examined in more detail than the analysis from a larger ensemble. From this perspective, this is a unique strength of the present analysis.

A limitation is that no CIREN case presented with a shoulder injury as the sole occupant injury, because many shoulder injuries are only AIS 2 and the CIREN inclusion criteria require at least one AIS 3 injury (with few exceptions). While the NASS database can be used to investigate this aspect, it was not considered because of its inability to identify humerus fracture location (only proximal humerus fractures were considered shoulder injuries in this study) using AIS 1998 codes and radiologic images are not available in the NASS. Analysis of NASS cases with radiological images is needed to enhance the sample size and examine the robustness of the conclusions drawn from this paper. Additionally, the delta-V in the present study was computed using the WinSMASH software, which calculates the delta-V at the vehicle's center of gravity. The actual delta-V experienced at the shoulder and vehicle components in close proximity to the shoulder is not identical to the delta-V computed at the center of gravity. Consequently, for an improved understanding of the biomechanics of shoulder injuries, it may be important to further investigate this discrepancy and this is considered an area for further research.

After identifying the shoulder injury case occupants, four important factors were considered to conduct the matched-pair analysis: delta-V, stature, vehicle type and location of the direct damage. Delta-V was selected because it is widely used as a hallmark in crashworthiness studies, international regulations and New Car Assessment Programs in Europe and the United States [9-12]. Furthermore, the parameter has been used in the development, validation and biofidelity assessment of dummies, ES-2re in the United States, ES-2 in Europe and the recent dummy WorldSID for pure lateral and oblique side impacts [13-16]. The range of delta-V for the matched-pair cases is approximately in line with the motor vehicle safety standards [9]. The second parameter, the stature of the occupant, like the delta-V is also in-line with the mid-size occupant demographics used in crashworthiness studies [10]. The third variable, passenger cars contribute to a major proportion of vehicles although other types of vehicles also constitute the fleet. It should also be noted that the combination of occupant stature and vehicle type dictates where the occupant's shoulder is aligned in the vehicle in relation to the beltline and door and, from this perspective, the use of these two variables are pertinent to the objectives of the study. Such type of combination has not been attempted to the best knowledge of the current authors in analyzing the effects of the presence or absence of shoulder injury in CIREN or other similar databases. The fourth parameter, the location of direct damage, was selected because the proximity from the center of the direct damage to the center of the undamaged wheelbase is a good indicator of the front seat occupant's location in relation to the narrow object and it projects that crush and intrusion would be at the occupant's position.

The shoulder is hypothesized as a load path to other body regions in lateral impacts [17, 18]. As a first step in the present study, injuries to different body regions were examined and compared between shoulder injured and non- shoulder injured groups to determine the potential effects of shoulder injuries on other body regions (Figure 13). Thoracic and abdominal injuries were more frequent with the presence of a shoulder injury, while pelvic and lower extremity injuries occurred at lower frequency. Although from a limited sample size and confined to a non-population based data collection study, this finding from the matched-pair analysis suggest that shoulder engagement is not protective of the thorax and abdomen during a nearside narrow object impact. The load path that occurs during a shoulder injury appears to also engage the thoracic and abdominal body regions, directly or indirectly, at a higher severity than in non- shoulder injury occupants. It is possible that when the shoulder region is fractured in this crash scenario, it exposes the thorax and abdomen to the vehicle's interior side components, resulting in more injuries to these body regions. Perhaps, shoulder injury weakens or exposes other regions of the torso in such cases. This conclusion from a small ensemble should be viewed with caution and further field studies are needed to reinforce these observations. Laboratory studies with PMHS are also needed to clearly delineate the effects of shoulder injury and its potential load-path in side impacts.

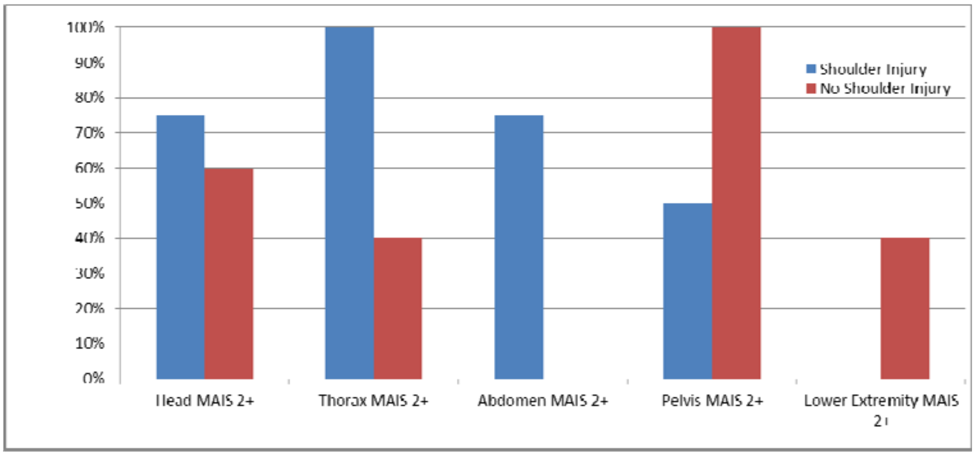

Fig. 12. Body regions with AIS 2+ injuries from matched-pair analysis

Three out of four shoulder injury crashes had an anterior-oblique primary direction of force (50-70 degrees for right front occupants, 290-310 degrees for drivers), while only one out of five non-shoulder injured occupants was involved in an anterior oblique impact. Similarly, only one of the four shoulder injury crashes involved a pure lateral PDOF (80-100 degrees for a right front occupant, 260-280 degrees for a driver), while four out of five non- shoulder injury crashes were of this configuration (Figure 14). Oblique lateral impacts thus appear to be involved in shoulder fractures with more frequency than pure lateral impacts, suggesting that obliquity could be a factor in shoulder trauma. It can therefore be postulated that angulation of the force vectors relative to the occupant, especially in narrow object impacts where the direct damage is proximal to the vehicle occupants, dictates how the door intrudes into the occupant space and influences injury patterns. While oblique studies in laboratory sled tests have been conducted, this aspect has not been examined and the present results underscore the need to pursue this line of research in order to fully understand the role of the shoulder in side impact load-paths and injuries to the torso and pelvic regions [19]. Such studies based on these results are pertinent to dummy evaluations (biofidelity, injury criteria) as the lateral impact-based ES2/Es2-re and WorldSID have different torso and pelvis designs as well as different seated heights.

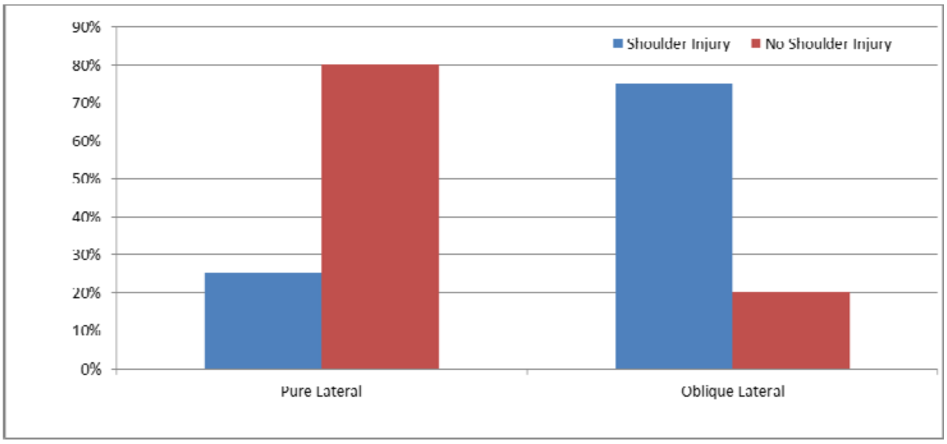

Fig. 13. Primary direction of force distribution for matched-pair analysis

V. CONCLUSIONS

After controlling for delta-V, occupant stature, vehicle type and direct damage location, the results of the matched-pair analysis showed that the primary direction of force in this crash scenario can play a role in shoulder injuries, with anterior oblique force vectors increasing the incidence of this injury. Additionally, differences in injury patterns between the shoulder injury and non-injury groups suggest an increase in accompanying injuries to the thorax and abdomen and a decrease in injuries to the pelvis and lower extremity when an occupant sustains a shoulder injury in this crash scenario. Further research is warranted to better understand load paths and crash factors involved in nearside narrow object impacts with and without shoulder injury.

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