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Census Study of Real-Life Near-Side Crashes with Modern Side Airbag-Equipped Vehicles in the United States

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Objective: This study aimed to investigate the crash characteristics, injury distribution, and injury mechanisms for Maximum Abbreviated Injury Score (MAIS) 2+ injured belted, near-side occupants in airbag-equipped modern vehicles. Furthermore, differences in injury distribution for senior occupants compared to non-senior occupants was investigated, as well as whether the near-side occupant injury risk to the head and thorax increases or decreases with a neighboring occupant.

Method: National Automotive Sampling System's Crashworthiness Data System (NASS-CDS) data from 2000 to 2012 were searched for all side impacts (GAD L&R, all principal direction of force) for belted occupants in modern vehicles (model year > 1999). Rollovers were excluded, and only front seat occupants over the age of 10 were included. Twelve thousand three hundred fifty-four MAIS 2+ injured occupants seated adjacent to the intruding structure (near-side) and protected by at least one deployed side airbag were studied. To evaluate the injury risk influenced by the neighboring occupant, odds ratio with an induced exposure approach was used.

Result: The most typical crash occurred either at an intersection or in a left turn where the striking vehicle impacted the target vehicle at a 60 to 70° angle, resulting in a moderate change of velocity (ΔV) and intrusion at the B-pillar. The head, thorax, and pelvis were the most frequent body regions with rib fracture the most frequent specific injury. A majority of the head injuries included brain injuries without skull fracture, and non-senior rather than senior occupants had a higher frequency of head injuries on the whole. In approximately 50% of the cases there was a neighboring occupant influencing injury outcome.

Conclusion: Compared to non-senior occupants, the senior occupants sustained a considerably higher rate of thoracic and pelvis injuries, which should be addressed by improved thorax side airbag protection. The influence on near-side occupant injury risk by the neighboring occupant should also be further evaluated. Furthermore, side airbag performance and injury assessments in intersection crashes, especially those involving senior occupants in lower severities, should be further investigated and side impact dummy biofidelity and injury criteria must be determined for these crash scenarios.

Keywords: side impact, senior occupants, in-depth study, injury mechanisms, occupant-to-occupant interaction

Introduction

Compared to frontal impacts, the risk for fatal injury in a side impact is greater, and the trend is increasing (Subit et al. 2010;). In side impacts, occupants are located close to the intruding structure; moreover, the introduction of rating procedures for side impacts occurred later than for frontal impacts. The first side airbag, protecting the thorax, was introduced in 1998 (compared to 1987 for frontal airbags). Since then, the fitment rate has increased, and variations of side airbags have been introduced. Today, the state of the art is to have one side airbag protecting the thorax and one protecting the head, but

variations with only thorax or head protection or combination bags are also common.

Based on U.S. and European data, previous studies have shown that injuries to the near-side occupant (adjacent to the intruding structure) are more frequent and severe than injuries sustained by the far-side occupant (opposite the intruding structure; Gabler et al. 2005; Sander and Boström 2010; Viano and Parenteau 2010a). Therefore, occupant side impact protection for the front seat is currently evaluated for the near-side driver in both legal and consumer rating test procedures representing car-to-car impacts and impacts with fixed objects. Occupant injury risk in side impacts is evaluated using the EuroSID2 (50th percentile male) or the SID2s (5th percentile female) dummy. In 2016, the European New Car Assessment Programme (EuroNCAP) will introduce the new, more biofidelic, side impact dummy Worldwide Side Impact Dummy (WorldSID, 50th percentile male). For these anthropometric test devices (ATDs), head injuries are addressed using head acceleration and the head injury criterion (HIC).

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Thoracic injuries are assessed by measuring chest deflection and the deflection rate (viscous criterion). For pelvic injuries, pubic loading is measured and rated for the EuroSID2 and WorldSID, and combined loading to the acetabulum and iliac wing is rated for SID2s. FMVSS 214 and NCAP ratings use a moving deformable barrier to evaluate a lateral car-to-car crash and an oblique pole test to evaluate occupant protection for crashes with fixed objects. Lateral impact speed ranges from 45 to 55 km/h for the barrier tests and 30 km/h for the pole test. These impact speeds, depending on vehicle weight and structural behavior, result in a range of lateral change of velocity (ΔV) from 20 to 35 km/h. The Insurance Institute for Highway Safety (IIHS) procedure evaluates occupant performance for a lateral SUV impact to the vehicle resulting in a 25 to 35 km/h ΔV and 250–500 mm intrusion depending on the target vehicle (Arbelaez et al. 2005). The introduction of side impact, legal, and consumer rating test procedures have improved occupant protection and encouraged standard implementation of side airbags in cars (Kahane 2007; Teoh and Lund 2011).

Senior occupants are both frail and fragile and therefore overrepresented in regard to injuries sustained in both frontal and side impacts (Ridella et al. 2012). Head injuries along with rib fractures in particular are sustained at lower severities for senior compared to non-senior occupants (Augenstein et al. 2005; Kent et al. 2005; Mallory 2010). It has also been shown that the frailty of senior occupants results in a higher mortality rate even from less severe injuries (Kent et al. 2008).

Previous studies have shown that the side airbag designed for the protection of the head and chest reduced the risk of fatal injuries by approximately 30% (Kahane 2014; McCartt and Kyrychenko 2007). Evaluation of the 30% risk reduction by applying it to the incidence of fatal injuries in vehicles without a side airbag showed that in order to increase protection of senior occupants the airbag should reach a higher protection level for severities currently evaluated in legal and consumer test procedures. Furthermore, increased protection of non-senior occupants should be improved at higher severities (Sunnevang et al. 2009). These conclusions were also reached when analyzing Swedish fatal car-to-car intersection crashes involving modern vehicles. All were side impacts at rural intersections where a senior near-side occupant, in a majority of cases accompanied by a neighboring occupant, was fatally injured by combined injuries to the head, thorax, and pelvis (Sunnevang et al. 2011a). That the presence of a neighboring occupant influences occupant injury risk was also shown by Viano and Parenteau (2010b).

Few studies have described the injuries sustained in side impacts for side airbag-equipped vehicles. When comparing injury outcomes for near-side occupants injured in side airbag-equipped vehicles compared to vehicles without side airbags, Stigson and Kullgren (2011) found a 30% reduction of Maximum Abbreviated Injury Score (MAIS) 3+ injuries. A comparison of Crash Injury Research Engineering Network data showed that the MAIS level and total injury severity score were reduced when the occupant was protected by a deployed side airbag, and injuries to the head, face, cervical spine, and thorax were reduced in frequency as well as severity (Loftis et al. 2011). By investigating weighted National

Automotive Sampling System's Crashworthiness Data System (NASS-CDS) data, Yoganandan et al. (2007) concluded that MAIS 2 injuries to the head and chest were reduced by the side airbag. Griffin et al. (2012) concluded that although risk of serious head injury was reduced by head-protecting side airbags, there was no reduction of thoracic injury risk. Moreover, the study concluded that thoracic injury risk increased for senior occupants protected by a deployed side airbag.

To further develop side restraint systems using crash test dummies and finite element human body models, it is necessary to understand the crash characteristics of injurious side impacts, as well as occupant injuries and corresponding injury mechanisms. The aim of this study is 3-fold: Firstly, to investigate crash characteristics, injury distribution, and injury mechanisms for Abbreviated Injury Scale (AIS) 2+ injured belted, near-side occupants in airbag-equipped modern vehicles. Secondly, to investigate differences in injury distribution for senior occupants compared to non-senior occupants and, thirdly, to evaluate whether the near-side occupant injury risk to the head and thorax changes with a neighboring occupant.

Method

NASS-CDS data between 2000 and 2012 were searched for all side impacts (GAD L&R, all principal direction of force) with belted occupants in modern vehicles (model year > 1999). Rollovers were excluded, and only front seat occupants above 10 years of age were included. Occupants from this sample, seated adjacent to the intruding structure (near-side) and protected by at least one deployed side airbag, were studied case by case.

To set the context of the small sample in a greater perspective, all data for side impacts with occupants of modern cars were collected. Data were then stratified into far-side (with the occupant seated opposite the intruding structure) and near-side (occupant adjacent to the intruding structure) impacts, as well as into senior occupants (60 or older) and non-senior occupants (10–59). Whether the driver was alone or accompanied by a passenger was also investigated (presence of a neighboring occupant). All crashes where the near-side occupant was protected by at least one side airbag and sustaining at least one AIS 2+ or fatal injury were selected for a case-by-case study.

A total of 7,727 (3,085,656 weighted) occupants in side impacts with a modern target vehicle (model year > 1999) and a front seat occupant older than 10 (known age) were found in NASS-CDS. Of these occupants, 82% were non-senior, 50% were single drivers (no neighboring occupant), and 46% were male. In 46% of the crashes the occupant was seated far-side, and in the remaining 54% the occupant was seated near-side (adjacent to the intruding structure). Of all side impacts, approximately 1,628 (180,493 weighted) occupants sustained at least one AIS 2+ or fatal injury and 1,125 (129,462 weighted) of these were near-side occupants. In 240 (27,649 weighted) of these cases the target car was equipped with at least one side airbag.

Some of the 240 cases had very high weight factors, which, if included, dominated the total sample. These cases were

considered outliers. Removing 5% of the highest weight factors reduced the sample size to 228 cases that, as weighted to U.S. national representative data, represented 12,354 occupants equipped with at least one side airbag and where at least one side airbag was deployed.

Case-by-Case Study

The case-by-case study was performed to verify side airbag deployment and gain a more detailed understanding of occupant injuries in terms of frequency and associations between injuries. For the case-by-case study a preliminary study with a limited sample of cases was performed by all authors to select relevant injuries to the most frequently injured body regions for subsequent notation. As a result, 23 injured body parts were identified as recurring in the trial cases and therefore selected for further analysis in all 228 cases. The selected injuries analyzed in the case-by-case study are shown in Table A1 (see online supplement). All 228 cases were analyzed by 2 traffic safety researchers, and the most severe injury according to the AIS (1998) related to the body parts chosen was noted (Association for the Advancement of Automotive Medicine 1990). When all cases were completed, a third researcher performed random controls to ascertain that the same injuries had been analyzed. Airbag deployment was noted based on photos from the impacted vehicle. Cases from 2010 were, in addition to AIS 1998, coded according to the 2008 version of AIS, and this new scaling include an expanded list of injuries and reflects advances in medical interventions (Barnes et al. 2009). However, because MAIS 2+ injuries are included in this study, the modifications are not believed to affect the results.

To evaluate crash characteristics, precrash conditions in terms of accident type, light, and road conditions as well as alcohol and drug involvement were noted for each case. In cases of intersection- or left turn-related crashes, precrash records for both drivers were checked for blood alcohol content levels and drug test results.

To evaluate the distribution of impact directions, the angles of the principal direction of force were used. To establish crash severity, intrusion and delta- V are commonly used. Depending on vehicle weight and side structure, the same delta- V can result in very different intrusions. For almost 50% of the cases in this study, either delta- V or information regarding intrusion was missing from the NASS-CDS files, making the relationship between injury and crash severity difficult to evaluate. In addition, the accuracy of the estimated NASS-CDS delta- V depends on vehicle type (e.g., passenger car vs. LTV/MPV), structural engagement/overlap, and the level of reconstruction. Because of these different factors, delta- V might be underestimated by 5 to 15% (Hampton and Gabler 2010). To have as large a sample size as possible to study injury distribution, all side crashes were included regardless of vehicle and crash type, making delta- V less reliable as a severity measurement, even when noted. To evaluate injuries related to intrusion, deformation close to the occupant is most important (Farmer et al. 1997). To maintain a consistent measurement, B-pillar intrusion for cases with noted crush profiles was calculated by using deformation measurements available in the NASS-CDS

file and by making some assumptions. To calculate deformation at the vehicle centerline, an algorithm using the NASS parameters of DVL (length of crush profile), DVD (distance between the center of the vehicle and the center of direct damage), and DVC1-6, which are 6 deformation measurements evenly distributed over deformation length DVL, was created. The B-pillar was then assumed as positioned at the center of the vehicle, and this deformation was used as a severity measurement (providing that all information was included in the NASS file) for the crash (NHTSA 2012).

Influence of Neighboring Occupant

A statistical analysis was carried out using odds ratio calculations with an induced exposure approach to investigate the influence of a neighboring occupant to the near-side occupant injury outcome. When true exposure is unavailable, an analysis using induced exposure can be substituted (Evans 1998; Lie et al. 2006; Strandroth et al. 2012). The key is to identify at least one crash or injury type in which the countermeasure under analysis can be reasonably assumed (or known) to be ineffective or less effective. In the present study, injuries to the near-side occupant with or without a neighboring occupant during a side collision were compared. By assuming that femur fractures in terms of injury risk are unaffected/less affected if there are one or 2 occupants in the front seat, the relationship between femur fractures with other injuries to the upper body could be considered as the true exposure relationship. Any deviation from the relationship between nonsensitive injuries is considered to be a result of occupant-to-occupant consequences. The risk of injury for a near-side occupant with a neighboring occupant is equal to the injury risk for a single near-side occupant if R in Eq. (1) is equal to 1. The analysis was performed using nonweighted data, and odds ratio and P values were calculated for the comparisons.

$$R = \frac{A_{1occupant}}{N_{1occupant}} \div \frac{A_{2occupants}}{N_{2occupants}}$$

where $A_{1occupant}$ is the number of injuries sensitive to occupant interaction in side collisions with one occupant; $A_{2occupants}$ is the number of injuries sensitive to occupant interaction in side collisions with 2 occupants; $N_{1occupant}$ is the number of injuries nonsensitive to occupant interaction in side collisions with one occupant; and $N_{2occupants}$ is the number of injuries nonsensitive to occupant interaction in side collisions with 2 occupants.

Results

Of the 12,354 occupants with at least one AIS 2+ injury, 5874 occupants were traveling in a vehicle equipped with side airbags protecting the head and thorax as either one combined side airbag or as 2 separate airbags, where one protected the thorax and one the head. Of the total sample, 5,258 occupants were protected by a deployed side airbag only covering

Table 1. Accident type for the weighted sample ($N_{\text{wgt}} = 12354$)

	Loss of control	Intersection or Left turn	Other
Total sample ($N_{\text{wgt}}=12354$)	21% (N = 2632)	71% (N = 8793)	8% (N = 929)
Non-senior occupants ($N_{\text{wgt}}=9384$)	24% (N = 2275)	66% (N = 6197)	10% (N = 912)
Senior occupants ($N_{\text{wgt}}=2970$)	12% (N = 357)	87% (N = 2596)	1% (N = 17)

the thorax, and 1,224 occupants were protected by head side airbag only.

For precrash conditions, 71% of crashes occurred at intersections or when a driver intended to turn left. Twenty-one percent occurred due to loss of control, and the remaining 8% occurred at entry/exit areas, driveways, or with vehicles traveling in the same direction. At least one driver was under the influence of drugs or alcohol in approximately 15% of the intersection- or left turn-related crashes. Corresponding numbers for the crashes related to loss of control were 25%. Senior occupants were more often involved in crashes at intersections or left turns and were involved in fewer crashes due to loss of control compared to the non-senior group. A comparison of crash types is presented in Table 1. Positive blood alcohol content tests were found in 2% of the cases for the senior occupants compared to 24% for the non-senior group.

Of the 12,354 MAIS 2+ injured occupants, 76% were non-senior, 55% were single drivers, and 40% were male. The median age of the total sample was 45, and the median impact angle was $\pm 70^\circ$ (0° representing the center line from the front to rear of the car) for driver and passenger, respectively. Eighty-five percent of occupants were traveling in a passenger car, and 70% of the crashes involved a high vehicle (SUV/LTV/HGV/VAN) or fixed object (see Table 2). Median intrusion at the B-pillar was 210 mm and median delta- V (total) was 30 km/h (Table 3).

For non-senior occupants the median impact angle was $\pm 70^\circ$, delta- V was 31 km/h, and median deformation at the B-pillar was 250 mm. For the senior group, the median impact angle was $\pm 60^\circ$, delta- V was 28 km/h, and deformation at the B-pillar was 190 mm. For both groups the greatest proportion of collision partners was a utility vehicle (54 and 59%, respectively), and the second most frequent collision partner was another passenger car. Fixed objects (pole/post/tree) were hit in 17% of the non-senior crashes, compared to 3% for senior occupants. Overall, non-senior occupants had a greater proportion of high collision partners and a higher proportion of high delta- V /intrusion crashes than senior occupants. Crash

characteristics for the total sample as well as the different age groups are shown in Table 3.

Injury distribution with respect to body region for the weighted NASS/CDS sample is presented in Figure A1 (see online supplement). For each occupant the highest AIS score per body region was included, and the total sum for the distribution for each age group exceeded 100% because multiple injuries per occupant were included. Stratification by age showed that for non-senior MAIS 2+ injured occupants the head and lower extremities were the most frequently injured body regions, followed by the thorax. For the senior group the thorax was the most frequently injured body region followed by the lower extremities and head. Comparing injury distribution per body level for males and females, as well as injury distributions for occupants involved in intersection and left-turn crashes compared to loss of control, showed similar injury distributions for the entire sample. Even if upper extremities were more frequently injured in loss-of-control crashes and the total number of injuries was slightly higher than for crashes in intersections and left turns, the most frequent injuries were to the head, thorax, and lower extremities.

Case-by-Case Study

Focusing on specific injuries, the distribution is presented in Figure 1. Again, distribution is the highest ranked injury for each injured body part and hence the total sum exceeds 100%. The most frequent injury to both age groups was rib fractures, followed by pelvic fractures, brain injuries, and lung injuries. The frequency of fractures for the senior group was higher than for the non-senior group. For non-senior occupants, concussion and spleen lacerations were more frequent compared to the senior occupants.

Skull fractures were associated with severe (AIS 3+) brain injuries for 3% of the injuries, and most head injuries occurred without fracture. The most frequent injury types for both age groups were concussion (AIS 2) and cerebrum or subarachnoid hemorrhage (AIS 3–5). For the most severe injuries, brain stem lacerations or compressions (AIS 5–6) were the most frequent. A higher frequency of head injuries was found when the collision partner was higher than a standard passenger car (high collision partner) and at a higher median delta- V and B-pillar intrusion. In comparison to thorax side airbag only, the presence of a head protecting airbag reduced the number of concussions and brain injuries.

The most common thoracic injury was rib fracture followed by lung injury, where lung contusions with and without pneumo-/hemothorax were most frequent. For senior occupants, the majority of lung injuries were associated with multiple rib fractures. The relationship between lung injury and rib fractures was not as pronounced for non-senior occupants. For outboard clavicle fractures approximately 50% were associated with at least one AIS 2+ injury to the lungs and ribs, and the other 50% occurred without thoracic injuries. All scapula fractures ($N_{\text{wgt}} = 394$) were associated with an AIS 3 or AIS 4 injury to the ribs.

The most common pelvic injuries were pelvic fractures coded as either none—further specified and as open or closed.

Table 2. Collision opponent stratified by age

Bullet vehicle	Non-senior occupants	Senior occupants
Car	22%	27%
SUV/LTV/Van	46%	49%
HGV	8%	10%
Pole/Post/Tree	17%	3%
Wall/Barrier/Bridge	2%	0%
Other	5%	10%

Fig. 1. MAIS2+ injury distribution for the weighted sample (IB = In-Board; OB = Out-Board).

The majority of the coded fractures were to the pelvic ring. Multiple fractures were coded for approximately 20% of cases.

For head injuries the most frequently listed injury source was the A-pillar or B-pillar and side interior, followed by other objects such as hood edge, pole or tree, noncontact injury source, and another occupant. Side interior, armrest, or B-pillar was the most frequent injury source listed for thorax injuries. For one occupant (an 83-year-old male) the airbag was listed as the injury source. For pelvic fractures the side interior was also listed as the injury source in the majority of cases.

Influence of Neighboring Occupant

The relative risk of injury, using odds ratio calculation, for cases where a side airbag protecting the head deployed showed a 17% risk reduction for head injuries for the near-side occupant when accompanied by a neighboring occupant (see Table A2, online supplement). On the other hand, comparing cases when the side airbag protecting the thorax was deployed, the risk of thoracic injury was approximately 24% higher for the near-side occupant with a neighboring occupant present (see Table A3, online supplement).

Injury distribution for a single non-senior driver, compared to a near-side occupant with neighboring occupant present, showed an increase in lung injuries (27 vs. 14%), cervical spine injuries (15 vs. 8%), and pelvic fractures (30 vs. 25%) when a neighbor was present. For senior near-side occupants with a neighboring occupant ($N_{\text{wgt}} = 2,343$), the frequency of in-board rib fractures (29 vs. 7%) as well as outboard rib fractures (70 vs. 64%) and pelvic fractures (53 vs. 15%) increased compared to injuries sustained by single near-side senior drivers. The distributions are shown in Figures A2 and A3 (see online supplement).

Discussion

Because a majority of cases lacked severity information, it is difficult to draw conclusions based on crash severity, but the

Table 3. Crash characteristics stratified by age

	Median impact angle LH/RH	High/Low collision partner	Median B-pillar intrusion	Median Delta-V (total)
Total sample ($N_{\text{wgt}} = 12354$)	+/- 70 deg	76% / 24%	210 mm	30 km/h
Non-senior occupants ($N_{\text{wgt}} = 9384$)	+/- 70 deg	71% / 29%	250 mm	33 km/h
Senior occupants ($N_{\text{wgt}} = 2970$)	+/- 60 deg	63% / 34%	190 mm	28 km/h

indication is that on an MAIS 2+ injury level, the severity range in terms of B-pillar intrusion and total delta- V (presented in Table 3) was within the range currently evaluated in side impact legal and consumer rating tests. The results of this study showed that protecting the head and thorax was most important for mitigating injuries to occupants exposed to near-side impacts, but attention should also be given to pelvic fractures. As shown in Figure 1, rib fractures and pelvis fractures are more frequent for senior occupants compared to non-seniors, indicating that improved thorax side airbag protection would be necessary. Using injury risk functions derived for senior occupants could increase protection levels of future side airbags to better address the observed injuries.

Using active safety systems to reduce high-speed crashes due to loss of control and introducing emergency braking to prevent intersection crashes will most likely prevent many future high-speed side crashes. Furthermore, considering that more than 20% of non-senior occupants were injured in a crash where drivers were influenced by drugs or alcohol, such sensors might also be effective in mitigating or preventing side crashes. Avoiding crashes due to loss of control would reduce approximately 20% of the cases in this study (Table 1). However, crashes at intersections where vehicle trajectories intersect will remain and hence increase the accident data. Senior occupants, as a growing group, are already being injured at lower severities than non-senior occupants (Table 3) and to a greater extent injured in intersection crashes (Table 1). Therefore, even lower crash severities than are currently addressed

in consumer rating tests could become important for addressing senior occupant injuries. To evaluate the injury risk in lower severities than those currently tested, the biofidelity of anthropometric test devices, such as WorldSID, needs further evaluation (Sunnevang et al. 2011b).

Head injuries without associated skull fractures dominated the sample, and concussions were more frequent for non-senior occupants than senior occupants (Figure 2). Different injury mechanisms can result in brain injuries. Concussion can be caused by a sudden shift of momentum as well as the stretching of blood vessels in the brain. Diffuse axon injuries can also be caused by rotational forces where the brain lags behind the skull tearing nerves or brain tissue. AIS 1 concussions have been found to cause long-term impairment and are therefore important to consider in efforts toward prevention (Malm et al. 2008). In current legal and rating test procedures, head injuries are assessed using the HIC developed as a way of predicting the risk for skull fracture. Because the majority of head injuries were brain injuries without fracture, there is a need for an updated injury criteria. One example is the brain rotational injury criterion taking rotation into consideration (Takhounts et al. 2013). Combining HIC and brain rotational injury criterion when evaluating risk of head injury in side crashes could further reduce brain injuries. The fact that brain injuries increased with age and that head injuries for senior occupants occurred at lower delta- V s was shown by Mallory in 2010. The number of senior occupants sustaining this type of injury in this study were few ($N_{\text{wgt}} = 678$), but comparing the accident types (intersection versus loss of control) and the overall delta- V and intrusion comparison for the non-senior and senior groups supports this finding.

A neighboring occupant was listed as an injury source in some cases for head injuries but not for thoracic injuries. It might be true that an injury can occur due to heads colliding in a case with 2 front seat occupants, but the odds ratio calculation performed in this study showed a trend that for near-side occupants head injury risk was reduced by approximately 20% when a neighboring occupant was present. One possible explanation for this could be that a proportion of head injuries to a single occupant can be due to a secondary impact with the vehicle's interior. Having a neighboring occupant restraining the near-side occupant's thorax might reduce the possibility of secondary head impacts to interior structures.

Despite side airbag thorax protection, rib fractures to the outboard side were the most frequent injury, especially for senior occupants. It might be that the AIS severity of thoracic injuries was reduced by airbags (as found by Loftis et al. 2011) or that senior occupants did not benefit as much as non-senior occupants from the thorax side airbag. The side airbag could even be a potential injury source for senior occupants (Griffin et al. 2012). In either case, to further improve occupant protection in side crashes the number of fractures should be reduced. If rib fractures, mainly caused by thorax compression, could be prevented to a greater extent, a significant number of associated lung injuries could be reduced (Thor and Gabler 2008). However, lung injuries can also be the result of compression rates, difficult to establish in this sample, but could potentially be evaluated using the viscous criterion for side crash ATDs. For crashes with 2 front seat occupants inboard rib fractures

increased for the senior near-side occupants (see Figure A3), which was not the case for the non-senior group.

Investigating the influence of occupant-to-occupant interaction by calculating relative risk of injury using odds ratio calculation showed that the near-side occupant thoracic injury risk increased by approximately 25% with the presence of a neighboring occupant (Table A3). The difference in risk was not statistically significant but showed a trend requiring further evaluation when a larger sample of crashes becomes available. Impactor tests to postmortem human subjects have shown that fractures to the opposite side of a loaded thorax can occur during impact. This may have been the case in this study for both lone near-side occupants and when a neighboring occupant was present and should hence not influence the results. The trend of increased risk could be explained by the neighboring occupant, seated far-side, slipping out of the shoulder portion of the 3-point belt and reaching the inboard side of the near-side occupant at a relatively low crash severity (Douglas et al. 2007). The occupant-to-occupant interaction can result in a sequential bilateral loading where the near-side occupant rebounds from the intruding structure and interacts with the neighboring occupant, a loading condition not evaluated in any known biomechanical study. Injuries to both near- and far-side occupants due to occupant-to-occupant interaction can be mitigated by an inboard side airbag protecting the thorax (Boström et al. 2008; Newland et al. 2008). To evaluate thoracic injuries due to the sequential bilateral loading of the near-side occupant, in laboratory tests, an additional ATD could be added to the passenger seat in current side impact test procedures. Using the new side impact dummy WorldSID 50th percentile male with bilateral deflection measurement on the near side and another on the far side would address injuries caused by the intruding structure and occupant-to-occupant interaction for both occupants.

Pelvic fractures occurred at high intrusions and might be due to outboard intrusion as well as the center console, as previously found by Tencer et al. (2005). Pelvic loading can take place through the pubic bone or anterior part of the pelvis (Salzar et al. 2009). In current side impact procedures public loading is evaluated using the 50th percentile male ATDs, and only the IIHS measures total pelvic loading (acetabulum and iliac wing) in the SID2s dummy. To improve pelvic protection and reduce the number of injuries, improved injury criteria with corresponding risk functions are needed for the 50th percentile male dummies.

Limitations

Delta- V comparisons are based on cases where delta- V was calculated, but a large number of crashes lacked this information. Previous comparisons between Event Data Recorder (EDR) data and the NASS-CDS delta- V calculated by WinSmash have also shown that delta- V might be underestimated, in particular for crashes with striking passenger cars, which can result in questionable conclusions for a mixed (with respect to collision partner) sample. In this study, the calculated B-pillar intrusion was used as a complementary crash severity

measurement, although less reliable due to the few records of intrusion in the sample.

Due to the lack of data, it was not possible to crash severity for each collision type (e.g., intersection or loss of control) and, hence, the odds ratio calculation was made without full control of crash severity. Because the femur is located in the possible deformation zone, it was believed that the femur fractures would indicate whether crashes occurred at different severities for the 2 groups. To have as large a sample size as possible, the ratio was calculated to the total unweighted sample. In the odds ratio calculation, femur fractures were assumed to be nonsensitive (or at least less sensitive than other injuries) and independent of one or 2 front seat occupants in side collisions. It was also assumed that senior occupants are at greater risk for femur fractures due to fragility; thus, the comparison has a built-in adjustment for the age factor. It is unclear whether the above assumptions are valid. However, the magnitude of calculated effects of injuries for one compared to 2 front seat occupants provides conservative results and thus will not lead to overestimation. If femur fractures differed depending on the number of front seat occupants, the results will be underestimated and lower the calculated difference in risk. By the comparison shown in Figure A3, the difference in injury frequency for lower legs is shown, but this difference is the result of few cases in which one case has a large weight factor.

To avoid overrepresentation by a low number of cases with extremely high weight factors, 5% of the cases with the highest factors were removed from this study ($n = 12$). Still, a small sample is sensitive to weight factors, and in some cases a single injury to an occupant in a highly weighted case significantly affected results. However, because potential outliers were already removed, it was assumed that the remaining weighted sample was to be considered valid and nationally representative of the United States.

The influence of drugs and alcohol could be underrepresented in this study due to occupants not always having been tested. However, a large proportion of drivers in this study had a record of positive alcohol or drug tests and hence this should be considered an important precrash condition.

Compared to non-senior occupants, the senior occupants sustained a considerably higher rate of thoracic and pelvis injuries, which should be addressed by improved thorax side airbag protection. With increased active safety systems better preventing high-severity crashes in the future, side airbag performance in intersection crashes, especially for senior occupants, will gain importance. To further reduce the injury risk to senior occupants, dummy biofidelity and injury criteria matching future crash modes must be ascertained.

The odds ratio calculation showed a trend of reduced risk of head injury and an increased risk of thoracic injury for the near-side occupant with a neighboring occupant present. Possible explanations for these trends is the sequential bilateral loading where the near-side occupant is rebounding from the intruding structure and interacts with the neighboring occupant, preventing the head from secondary impacts but increasing loading to the thorax, causing a higher number of rib fractures and lung injuries.

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Supplemental Material

Supplemental data for this article can be accessed on publisher's website

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