Thoracic and Abdominal Injuries to Drivers in Between-rail Frontal Crashes

Rudolf Reichert, Richard M. Morgan, Chung-Kyu Park, Kennerly H. Digges, Cing-Dao (Steve) Kan

Abstract Recent efforts to understand frontal crashes have investigated the between-rails crash. The research question investigated in this study is as follows: What was (1) the type of thoracic/abdominal trauma; (2) what were the contacts associated with the thorax/abdomen trauma; and (3) how did the age of the driver affect the injury severity? The method was to review NASS-CDS cases where a driver suffered an AIS≥3 plus fatal torso injury in between-rail crashes. This study examines crash data from the NASS-CDS between the years 1997-2009. The raw data count for between-rail NASS-CDS cases was 784, corresponding to 227,305 weighted, tow-away crashes. A previous study suggested that, for between-rail crashes, approximately 20% of the AIS≥3 injuries and fatalities were to the chest. Roughly 5% of the AIS≥3 injuries were to the abdomen. The distribution of AIS≥3 injuries are presented by anatomical structure and organ for the chest and abdomen. The source of AIS≥3 injuries are presented by the interior contact. To assess the mechanical particulars of the injury mechanism, frontal crashes were analyzed with an integrated vehicle-occupant finite element model (FEM) of a small-size car and the THUMS FEM human model.

Keywords abdominal injury, center pole crash, finite element model, frontal impact, thoracic injury

I. INTRODUCTION

In 2009, Brumbelow and Zuby posed the question, "How might we upgrade future frontal crash tests to further improve occupant protection in real-world crashes?" [1]. They suggested that advancements made in past frontal crashworthiness and the solid arrival of active safety technologies has resulted in less attention on improving passive safety. Their perspective was that a large number of fatal and serious injuries continue in frontal crashes, and skillful enhancements in crashworthiness should still be sought. In their study of National Automotive Sampling System - Crashworthiness Data System (NASS-CDS) cases, Brumbelow and Zuby noted that center impact (major load path was between the two main longitudinal rails), small overlap and moderate overlap together comprised two-thirds of their study cases. In an earlier study, Arbelaez et al. analyzed real-world crash data and found that frontal collisions with narrow objects contribute significantly to occupant fatalities and injuries [2]. For future study of passive crashworthiness in the frontal direction, Arbelaez proposed that safety professionals for government regulation and consumer information include the frontal collision with narrow objects in their contemplation of significant real-world collisions.

Sullivan et al. developed a methodology for defining the post-crash damage profile of vehicles in a frontal impact collision, using both vehicle crush measurements and other elements of the NASS-CDS [3]. Sullivan identified the *between-rail* impact as having an especially high injury risk for all frontal crashes. Scullion et al. applied the Sullivan taxonomy to classify real-world frontal-impact crashes based on NASS-CDS [4]. Vehicles in frontal impacts were identified for 1985 – 2008 model year passenger vehicles. Using the Collision Deformation Classification (CDC)-based information in NASS and using the methodology identifying the location of the longitudinal rail, he successfully grouped together the frontal impact crashes with common damage patterns. The Scullion findings suggested that the *between-rail* crash—where the direct damage is between the two longitudinal rails—accounts for (1) 6.1% of all frontal crashes and (2) has a higher injury risk than any other frontal crash type studied, i.e., about 3.7% at the AIS≥3 + fatal level of trauma.

In Germany, Berg and Ahlgrimm noted that vehicle impacts into trees are still one of the most significant collisions with struck objects for roadway deaths [5]. Based on federal statistics for 2008 in Germany, out of the total of 4,117 crashes with fatalities, 838 crashes (38%) were vehicle-to-tree impacts (not specified as to percentage of frontal or side impact) alongside the roadway. For impact of a tree into the side of a vehicle, they pointed out that EuroNCAP does a 29 km/h test into a fixed rigid pole of 254 mm diameter. Similarly, USA NCAP, ANCAP, and KNCAP do a test of a rigid pole into the side of a vehicle. At present there is no consumer-

R. Morgan is a senior research scientist (tel: 571-435-3325, fax: 703-726-3530, email: rmorgan@ncac.gwu.edu); C-K. Park is a research scientist; K. H. Digges is professor of Engineering, George Washington University, USA. R. Reichert is a research consultant. C-D. Kan is professor of Physics, Astronomy, and Computational Sciences, George Mason University, USA.

information test for propelling a pole into the front of a vehicle [6]. In 2012, Lockhart and Cronin observed that frontal impacts with fixed roadside structures—such as poles—can lead to severe injuries and fatalities [7]. Based on the Fatality Analysis Reporting System (FARS), they reported 1,113 crashes (not specified as to percentage of frontal or side impact) involving poles in the US in 2009, which resulted in 1,759 fatalities.

In a series of papers from 2011 to 2013 and based on laboratory data and real-world crash data, Scullion, Morgan et al. investigated the *between-rail* crash, employing both macroscopic and microscopic approaches [8 - 11]. Based on the 50th percentile male Hybrid III dummy in the driver and right front passenger seats in laboratory tests, injury risks were calculated for five body regions: head, neck, thorax, knee-thigh-hip (KTH) and foot/ankle. For the five body regions, the average injury risk in the center-pole laboratory test was always higher than the average injury risk for the NCAP frontal test and the IIHS frontal test. Similarly, the driver compartment intrusion in the center pole test was larger than the intrusion in the NCAP frontal test and the IIHS frontal test.

For real-world crash data of *between-rail* crashes, the chest had a greater percentage of injuries than the head (at the AIS≥3 level of trauma). The pelvis/thigh/knee/leg and foot/ankle accounted for a large percentage (48%) of the AIS≥2 injuries. Surprisingly, the struck object for 46% of the *between-rail* crashes (real-world crash data) was another vehicle. Thirty-nine percent of the other *between-rail* crashes were with a large tree or pole. For a vehicle-to-vehicle case study of a *between-rail* crash, it is suggested that the striking car had an angled impact with the struck vehicle. The front of the striking vehicle impacted such that the direct damage to the struck vehicle was located between the two rails of the struck vehicle. For *between-rail* crashes, approximately 15% of the AIS≥2 + fatal injuries were to the foot or ankle. The significance of this result is that the *between-rail* frontal crash inflicts high levels of disability on the driver.

In 2012, an overall breakdown of injuries was undertaken for frontal crashes in which the struck object went between the two longitudinal rails of the struck vehicle [10]. As shown in Figure 1 (from reference 10), the chest accounted for about 21% of all AIS≥3 + fatal level injuries and the abdomen accounted for an additional 5% of all AIS≥3 + fatal injuries.

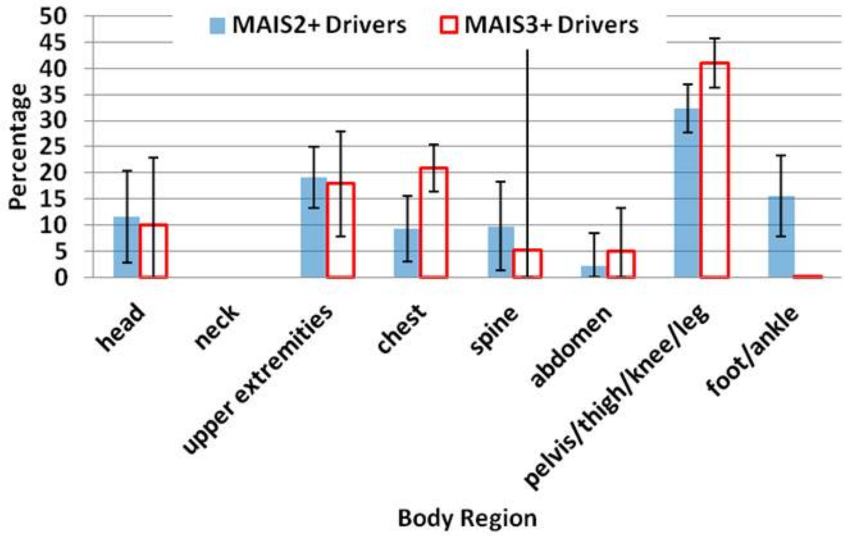

Figure 1 - Distribution of AIS≥2 injuries and AIS≥3 injuries by body region *for between-rail* frontal crashes (NASS weighted data) [10]

II. METHODS

Study of thoracic/abdominal trauma using NASS

The National Automotive Sampling System - Crashworthiness Data System (NASS-CDS) is a collection of data that typifies police-reported motor vehicle collisions that occur on roadways within the United States. In the crash, at least one vehicle was towed from the scene. Presently and yearly, NASS examiners handle roughly 3,500 detailed crash-case investigations.

Because NASS-CDS is a representative random sample of thousands of minor, serious and fatal crashes, every case is given a weighting factor (Ratio Inflation Factor). The weighting factor affords an estimation of the frequency that a comparable collision happens in the total population of police-reported tow-away crashes. The weighting factor is the inverse probability of a sampled collision being selected from the overall population of these real-world crashes.

This investigation utilized real-world crash data from NASS-CDS to investigate thoracic and abdominal trauma in between-rail frontal crashes. The between-rail dataset was gathered from the entire NASS-CDS data. The case selection criteria applied to the total NASS-CDS data were:

- NASS-CDS data years 1997-2009
- Passenger cars or Light Trucks and Vans
- Vehicle model years 1997+
- Vehicles with a General Area of Damage to the Front of the vehicle
- Vehicles with their direct damage between the two frontal rails (identified through Sullivan Taxonomy)
- Vehicles with a Direction of Force of 11, 12, or 1 o'clock
- Occupants were a belt-restrained driver 16 years of age or older
- Vehicles with a secondary impact where the extent of damage was greater than 2 were excluded.

Computational Modeling

The National Crash Analysis Center (NCAC) built (reverse engineered) a detailed, finite element model (FEM) of a small size sedan vehicle [12]. The model year 2010 sedan has front-wheel drive, a transverse-mounted engine, advanced airbag, and seat belt systems with pre-tensioner and belt force limiter. The structural FEM consists of 771 parts and 974,383 elements. The model was first validated against two laboratory crash tests with respect to structural performance: (1) NCAP full frontal rigid barrier test at 56 km/h and (2) IIHS 40% frontal offset deformable barrier test at 64 km/h. Based on the validated structural model, an integrated occupant-vehicle model with interior and generic restraint system components, such as driver airbag and seat belt, was created. Again available full scale crash data of (1) NCAP full frontal rigid barrier tests at 56 km/h and (2) IIHS 40% frontal offset deformable barrier test at 64 km/h were used to validate the integrated vehicle-occupant simulation model, using a Hybrid III 50th percentile dummy.

The Total Human Model for Safety (THUMS) was then used in the validated, integrated vehicle-occupant model [13]. THUMS is a finite element model of the entire human body developed by Toyota Motor Corporation. The version used for the studies presented in this paper is the academic version 4.0 of a 50th percentile Adult Male (AM50). The purpose of the THUMS model is to simulate the response of the human body undergoing impact loads. The model runs on LS-DYNA software. The NCAP frontal test, IIHS 40% offset test and the center-pole test were all simulated with the integrated THUMS-vehicle model.

Figure 2 shows the complete integrated FEM which consists of 2,274 parts and 3,253,427 elements. Using this model the approach was to study loadings to the thorax/abdomen of the THUMS in the *between-rail* test, and observe similarities and differences as compared to the thorax/abdomen loadings of the THUMS in the traditional NCAP full frontal and IIHS 40% offset frontal test.

Areas with high potential loads in thorax and abdomen areas were identified by analyzing simulation animations. Measurements were taken at injury-specific thorax and abdomen locations in order to quantify and compare the results. Effective plastic strain values were analyzed for the rib cage and internal organs of the THUMS model, and potential injury risks and causes were compared to the NASS data analysis.

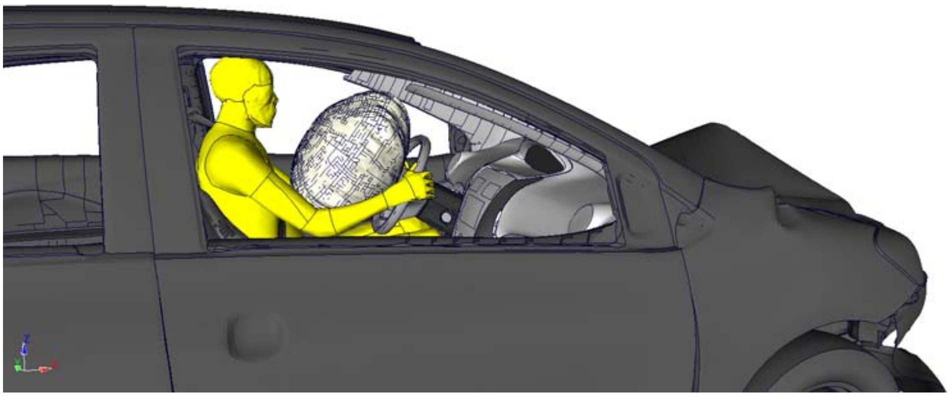

Figure 2 – Side view of integrated occupant-vehicle model with THUMS

III. RESULTS

Study of thoracic/abdominal trauma using NASS

AIS≥3 Chest Injury

Figure 3 shows the distribution of AIS≥3 plus fatal chest injuries by anatomic structure in *between-rail* crashes. The rib cage and lung were most often traumatized at the serious or greater level, their aggregate count was just over 78% of all serious or greater injuries. The aorta accounted for 10.6% of these injuries.

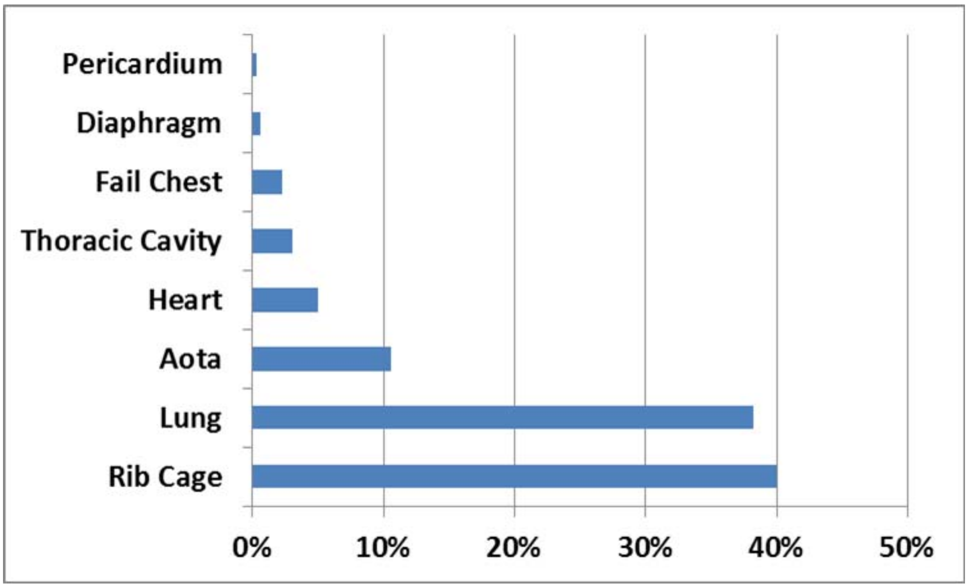

Figure 3 – Distribution of AIS≥3 chest injuries by anatomic structure (weighted NASS/CDS 1997 – 2009)

The sources of these chest injuries are shown in Figure 4. Contact with the steering wheel rim or belt accounted for 81.1% of the serious or greater trauma. In many crashes, rib cage, lung and aorta trauma were correlated to interaction with the belt or with the steering wheel rim. Later in this paper, the documented high percentage of steering wheel contact as source of chest injuries in the NASS data will be examined using the computational model. Airbag performance, adequate seat belt usage, impact configuration, and impact severity are issues used in determining how injuries were caused. Viewing the crushed vehicles after the collision, the NASS investigators assess these issues when drawing conclusions about the source of the injury.

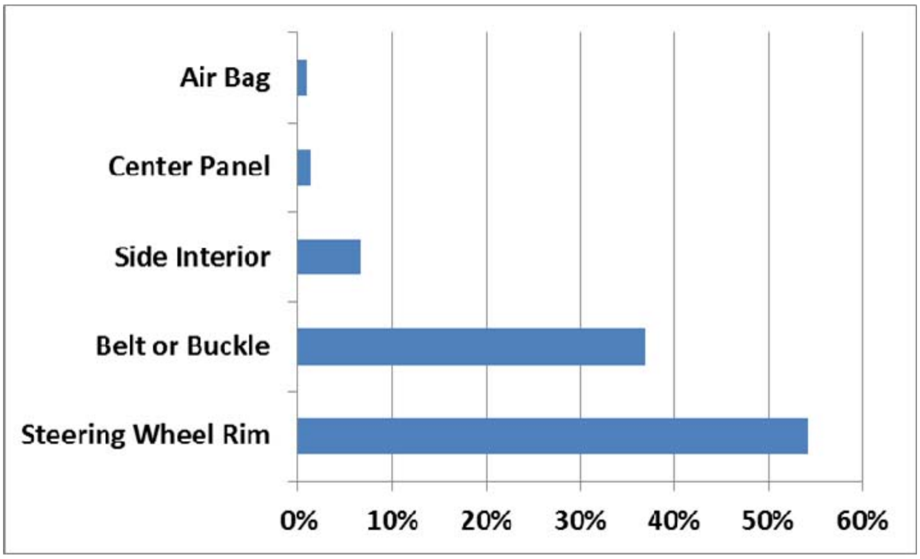

Figure 4 – Source of AIS≥3 plus fatal chest injuries to occupants in *between-rail* crashes (weighted NASS/CDS 1997 – 2009)

The data presented in Figure 3 are for AIS ≥ 3 plus fatal injury to the chest. An individual driver—especially in the more severe collisions—can have multiple AIS ≥ 3 plus fatal injuries. Approximately 46% of the thoracic injuries were to a driver with a single thoracic injury. Twenty-two percent of the injuries were to a driver with two thoracic injuries. Thirty-two percent of the injuries were to a driver with more than two thoracic injuries. Figure 5 shows all injuries divided into these three driver groups versus extend of damage [14] of the between-rail collision. Drivers with a single AIS ≥ 3 plus fatal injury to the chest are generally in lower severity collisions. Similarly, drivers with more than two thoracic injuries are in the higher severity crashes.

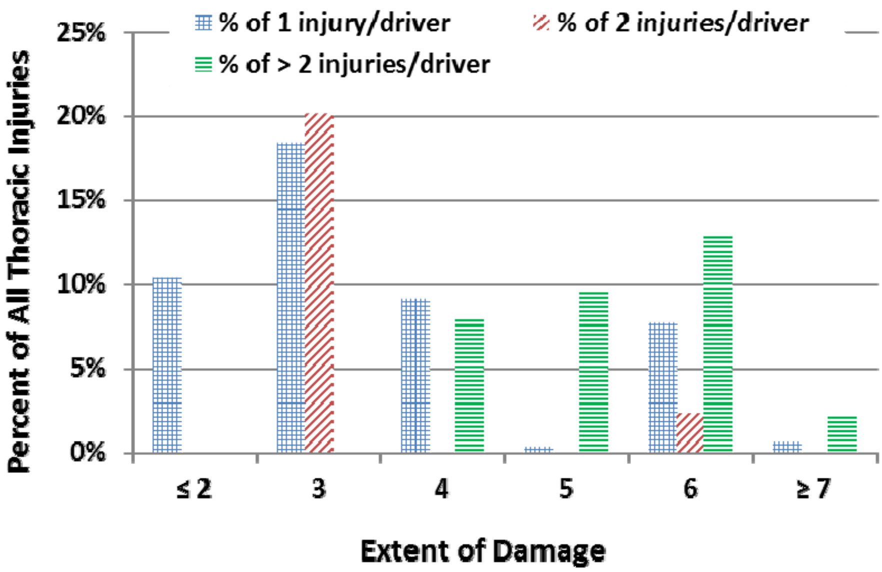

Figure 5 – Distribution of single thoracic injury, double injury, and more than two injuries to a driver (weighted NASS/CDS 1997 – 2009)

Figure 6 shows the breakdown by age of the overall driver distribution and the chest trauma inflicted upon the drivers in *between-rail* crashes. Some previous studies have suggested a tendency for occupants older than 70 years to sustain more severe trauma [15]. These data show an increase of chest injury with age. The data point for chest-injured drivers in the 41 – 50 year old range is lower than the other age ranges for chest-injured drivers. The authors were not able to explain this seemingly low percentage.

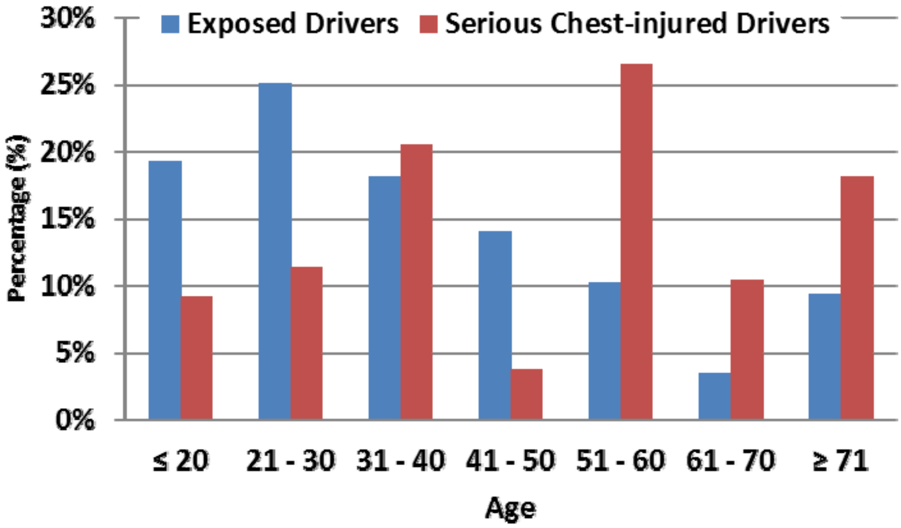

Figure 6 – Distribution of driver age for all drivers and for those enduring an AIS≥3 plus fatal chest injury (weighted NASS/CDS 1997 – 2009)

For the weighted, NASS analysis of the *between-rail* collisions, the male drivers had about 40% of the chest injuries (AIS≥3 plus fatal injury). The female drivers accounted for the greater percentage (60%) of the serious chest trauma. For all drivers (both injured and non-injured drivers in a between-rail collision), 55% of the drivers were male and 45% were female. This dataset suggests that female drivers were more susceptible to chest injury than male drivers.

AIS≥ 3 Abdomen Injury

Figure 1 (from a previous study) shows the extent of abdominal injuries to drivers in *between-rail* crashes. About 5% of the AIS≥3 + fatal trauma were found in and about the abdomen. Figure 7 shows the distribution of abdominal lesions to the drivers in *between-rail* collisions. The spleen and liver trauma accounts for roughly 64% of all abdominal injuries at the AIS≥3 + fatal level. The most-traumatized organs next in order were the kidney, colon and bladder.

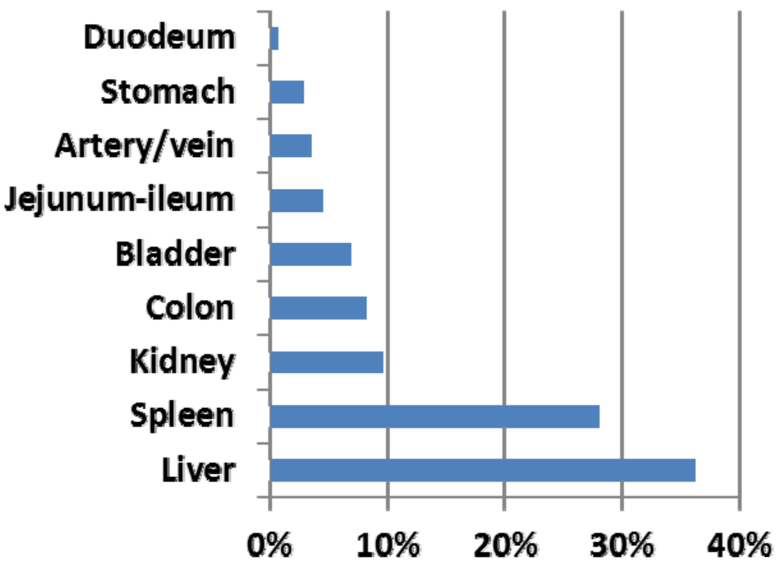

Figure 7 - Distribution of AIS≥3 plus fatal abdominal injuries by anatomic structure (weighted NASS/CDS 1997 – 2009)

Figure 8 displays the source of these grave abdominal injuries. Just as for the thoracic trauma, both the steering wheel rim and belt or buckle together are major sources of contact during the impact, accounting for approximately 96% of recorded contact to an abdominal organ.

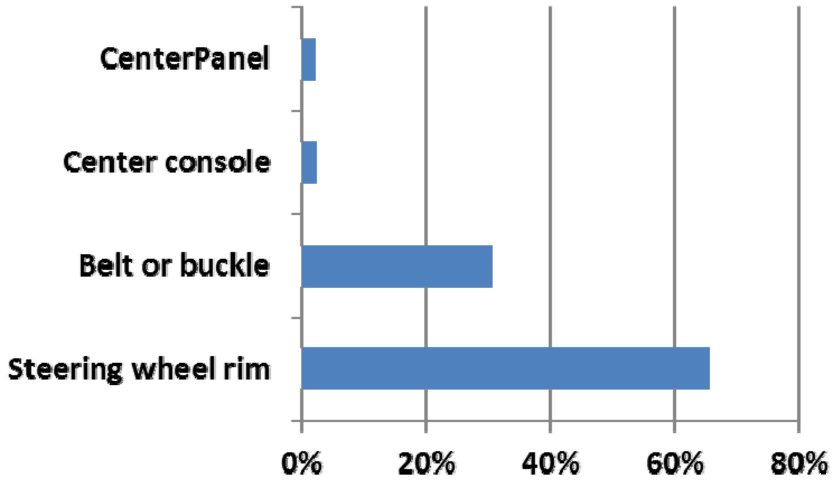

Figure 8 – Source of AIS≥3 plus fatal abdominal injuries to occupants in *between-rail* crashes (weighted NASS/CDS 1997 – 2009)

Study of thoracic/abdominal trauma using Computational Modeling

Figure 9 shows the comparison of a full-scale laboratory test and the corresponding LS-DYNA3D simulation with a 50th percentile Hybrid III dummy (HIII) in the driver seat of the small size sedan vehicle in a 56 km/h full-overlap NCAP frontal impact. The maximum head acceleration in the simulation is 4% higher than in the test. The maximum chest acceleration in the simulation is 6% higher than in the test. The maximum chest deflection in the simulation matches the value seen in the full scale crash test. These data suggest the simulation is close to the responses in the full-scale NCAP laboratory test.

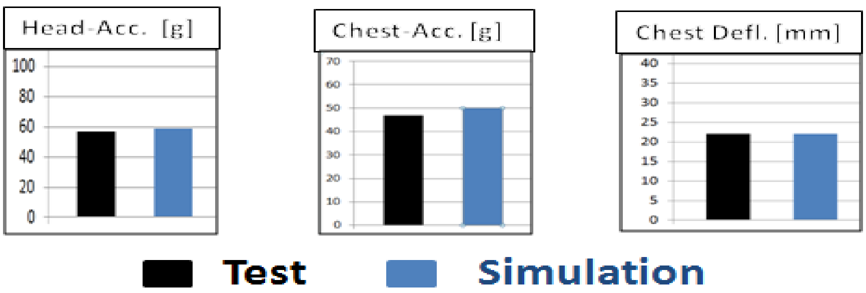

Figure 9 – Comparison of HIII dummy test and simulation in NCAP frontal test configuration

For the small-size sedan vehicle in a 64 km/h, 40% offset IIHS frontal impact, Figure 10 shows the comparison of a laboratory full scale crash test and the corresponding simulation, with a 50th percentile Hybrid III dummy in the driver seat. The maximum head acceleration and the maximum chest acceleration in the simulation are both 9% higher than the respective values in the test. The maximum chest deflection in the simulation is 10% higher than in the full scale crash test. These data suggest that the simulation is close to the responses in the full-scale IIHS laboratory test.

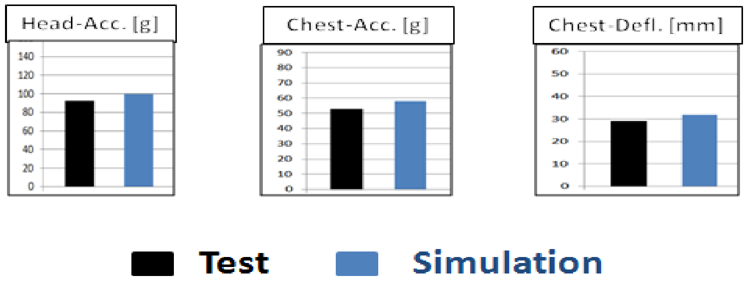

Figure 10 – Comparison of HIII dummy test and simulation in IIHS frontal test configuration

The integrated simulation model—that was validated for 56km/h NCAP full-overlap and 64 km/h IIHS 40% offset impact with the HIII dummy—was then used to evaluate occupant responses of the Total HUman Model for Safety (THUMS). The integrated occupant vehicle model with THUMS as seen in figure 2 was used to simulate a 64 km/h center pole (diameter 254 mm) impact in addition to the traditional NCAP full overlap and IIHS offset crash configurations.

Figure 11 shows the full integrated occupant-vehicle model for the three load cases. The center pole load case can be seen in green, the IIHS load case is shown in blue, and the NCAP load case is shown in coral. The corresponding vehicle pulses are depicted in the graph on the right.

Figure 11 – Integrated occupant vehicle model with THUMS (left) and vehicle pulses (right) in Center Pole (green), IIHS (blue) and NCAP (coral) load case

Figure 12 shows a side view of the kinematics throughout the impact event relative to the vehicle interior in the center-pole load case. The first picture on the left shows a state before the airbag is being inflated. The second picture from the left shows a state where the airbag is fully deployed and the occupant is already in a forward motion just before "coupling" with the airbag. The third picture from the left shows a state where the THUMS model is in full contact with the airbag from the chest to the face. In the most right picture the occupant has reached its most forward position relative to the vehicle just before the rebound phase. While the occupant moves forward and the airbag uses all of the available space between the THUMS and the steering wheel, no major contact between the chest and the steering wheel rim that would cause serious injuries could be observed in the model.

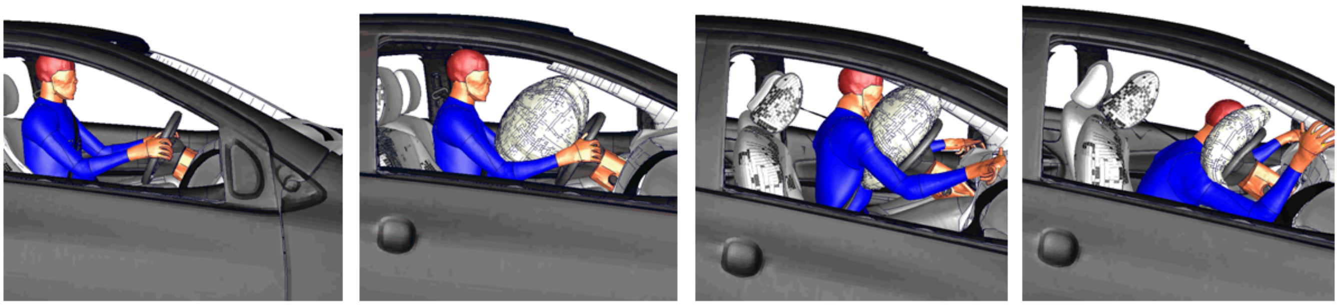

Figure 12 – Side view of THUMS kinematics throughout the center-pole impact simulation

Figure 13 shows vertical (left) and horizontal (right) cross section plots of the THUMS model. The first picture shows the location of the cross section, marked with V-V for vertical and H-H for horizontal. The second picture shows the cross section plot at the respective location in the initial state of the simulation. The third picture shows the cross section plot at a deformed state of the simulation. In addition two circles mark the location with high deformation to the chest and abdomen area as analyzed by simulation animations. One is located at the anterior costochondral junction of the 8th rib of the right chest and one is located in the center of the abdomen area. The abdominal penetration in the third picture in figure 13 above the pelvis is caused by the occupant models interaction with the belt.

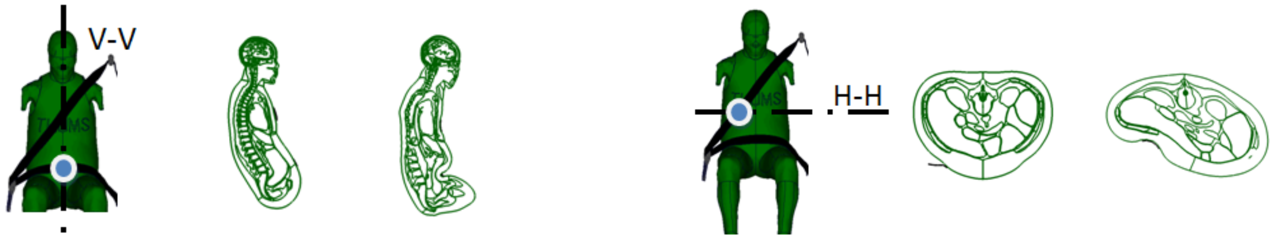

Figure 13 – Vertical (left) and horizontal (right) cross section plots of THUMS

In order to quantify loads experienced by the THUMS model, deflections were measured at the identified points at the chest relative to the back of the rib cage and at the abdomen relative to the spine. Figure 14 shows the maximum chest deflection and the maximum abdomen deflection at the identified locations at the THUMS model for the three different load cases. The maximum chest deflection at the specified point at the THUMS chest location in the simulation model was 20% lower in the IIHS load case and 14% lower in the NCAP load case when compared to the results seen in the center pole configuration. The maximum abdomen deflection at the specified point at the THUMS abdomen location was 28% lower in the IIHS load case and 2% lower in the NCAP load case when compared to the results seen in the center pole configuration.

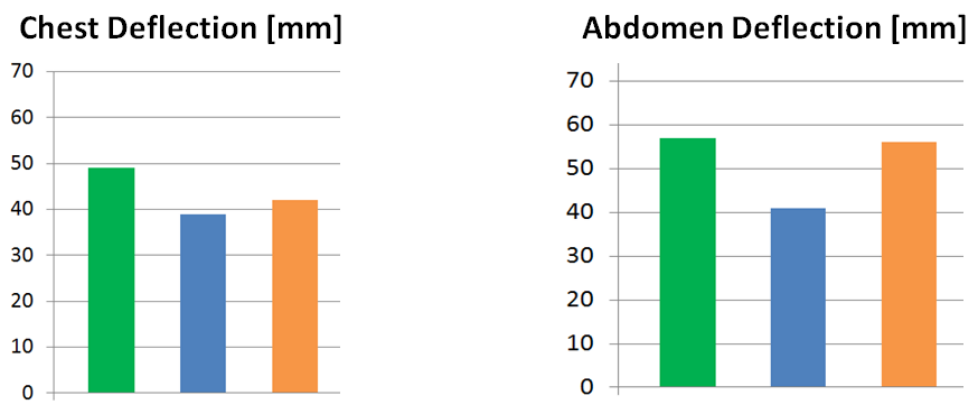

Figure 14 – Comparison of THUMS chest (left) and abdomen (right) deflections for center pole (green), IIHS (blue) and NCAP (coral) configurations

Besides analyzing simulation animations and deflection values for chest and abdomen and in order to identify potential injury risks, rib cage and internal organs of the THUMS model were evaluated using effective plastic strain fringe plots. Figure 15 shows the rib cage and internal organs of the THUMS model in the center-pole load case. The left picture showing the rib cage uses a scale where areas with effective plastic strain values below 1% are colored in blue and areas with values above 3% are colored in red. The right picture showing the heart, liver, and spleen uses a scale where areas with effective plastic strain values below 10% are colored in blue, and areas above 30% are colored in red.

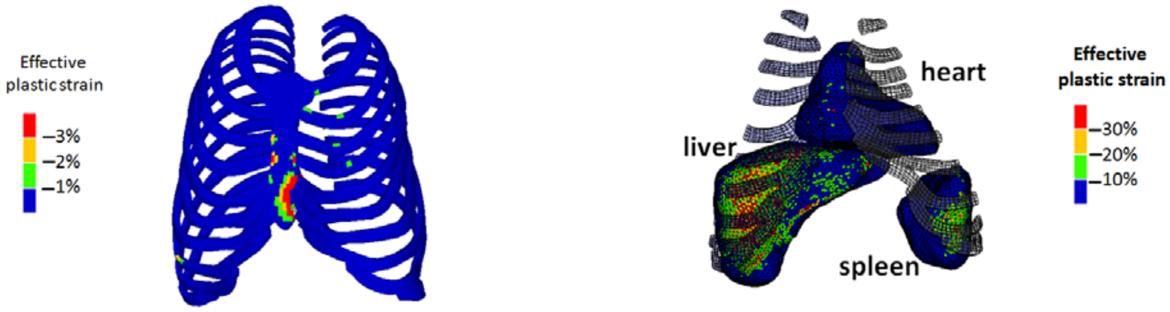

Figure 15 – Fringe plots showing effective plastic strain for the ribcage (left) and the internal organs heart, liver, and spleen (right)

IV. DISCUSSION

The results from both, the conducted NASS data analysis as well as the integrated THUMS occupant vehicle computational simulations are being discussed regarding observed injuries and potential injury sources.

Injuries to thorax/abdomen in between-rail crashes

Using NASS data of between-rail frontal crashes, a significant percentage of injuries to the chest and abdomen were identified. Using a validated integrated vehicle occupant simulation model of a small size sedan car with the THUMS model, higher chest and abdomen deflection values were observed for the center-pole load case when compared to a full overlap and a frontal offset impact, indicating the relevance of studying the between-rail configuration. This finding is in agreement with a series of full scale crash tests with a 50th percentile HIII dummy that showed higher injury risks for all body regions for the center-pole test, when compared to a full overlap and a frontal offset impact configuration [9].

When analyzing the simulation model in the center pole load case, areas with effective plastic strain values above 3% could be observed in the rib cage, suggesting a potential risk for rib fractures. The threshold of 3% was reported in injury-strain studies by Burstein (1976) and McCalden (1993) [13]. This potential for rib fracture is in agreement with the analyzed NASS data. The NASS data analysis also indicates a high percentage of injuries to the liver and spleen, and a rather low percentage of injuries to the heart. When analyzing the THUMS model in the center pole simulation, similar trends can be observed. While areas with effective plastic strain values above 30% can clearly be detected in the liver and to some extent in the spleen, no such high strains occur in the heart. The threshold of 30% as a reference criteria for potential injuries to these organs were reported by Melvin (1973) and Yamada (1970) [13]. The evaluation of potential injury risks to the ribs, liver, and spleen in the simulation model is in agreement with the NASS data analysis.

Sources of thoracic/abdominal injuries in between-rail crashes

According to the NASS data analysis, rib cage, lungs, liver, and spleen were the body regions with the highest percentage of AIS$\geq$3 plus fatal injuries. As a source for these injuries, mainly the steering wheel rim and the seat belt were documented. In the vehicle-THUMS simulation, the interaction with the belt was identified as the major source of the observed occupant loads, rather than the steering wheel rim. While only NASS cases with belt restrained occupants were considered, uncertainties exist regarding proper seat belt usage, how well airbag deployment was initiated in time by the vehicles sensor systems, and how well the seat belt and airbag restraint systems performed during each accident. In addition, impact configurations and severities varied from case to case. Looking at the steering wheel rim as the most frequent injury cause, the authors believe that caution needs to be used when interpreting these data. For example, analyzing direct steering wheel contact of a dummy in a full-scale crash test using high speed cameras involves some challenges; deciding whether such a contact was the source of a chest injury after a real-world crash seems even more challenging. Unless a clear failure/bending of a vehicle component can be directly connected to a related lesion in the driver, the determination of a source is difficult to establish. An alternate view of the steering wheel as the source in injury was suggested by Chen and Gabler [16]. In frontal crashes, they found only 4% of belted drivers were associated with measurable deformation of the steering wheel. However, these 4% of cases were over represented in 29% of MAIS3+ injured drivers. The same caution needs to be applied to the analysis of the airbag as a potential injury source.

Similarly, how can the NASS investigator be sure that the airbag was or was not the cause of an existing injury, e.g., when the vehicle can only be evaluated long after the actual crash event? This uncertainty is a moot point as the percentage of airbag-induced injuries in the evaluated NASS dataset was very small.

When discussing the computational results, it is important to be aware that the simulation model concentrates on a specific center-pole load case with a 50th percentile male occupant, standard seating position, proper seat belt usage, and a well performing airbag system. Other conditions of simulation—such as higher impact severity, less effective seat belt or airbag performance—could well lead to results where steering wheel rim contact would be observed in the simulation model as well. It is the strength and advantage of using the computational model to be able to analyze the source of an observed injury, whether it is the seat belt, the airbag, the steering wheel rim, other components interacting with the occupant, or a combination of multiple components in the considered load case and vehicle environment. Other than in the accident research analysis, where investigators rely on available information, such as police reports, medical reports, witness reports, and possibly analysis of the post crash vehicle, parts of the simulation model can be removed, parameter studies can be conducted, and cross section plots can be used to analyze kinematics and interactions regarding potential injury sources.

Using NASS data analysis, the question remains if it is possible to distinguish for example for a flail chest injury, whether the source is the airbag, the seat belt or the steering wheel rim or a combination of the above. When using the detailed and validated computational model, the injury causes can be distinguished much better using the diverse available post processing capabilities of simulation results.

While NASS data and simulation results complement each other regarding the steering wheel rim contact as an injury source, agreement exists between NASS data and simulation evaluations regarding the seat belt as a potential source for the observed occupant loads.

It should also be noted that the used small-size sedan vehicle was likely optimized to perform well in the two standard tests, full overlap and frontal offset impact. Therefore caution is needed when generalizing across the real world population of drivers, crash severities and vehicle types. Being aware of these limitations, the results are promising and clearly encourage the authors to conduct further research using available and additional state of the art simulation models, tools, and methodologies, in order to investigate occupant kinematics, injury patterns and potential improvements regarding vehicle safety in different impact configurations.

V. CONCLUSIONS

This study examined the scope of thoracic and abdominal trauma in *between-rail* frontal crashes, i.e., crashes where the major loading to the struck vehicle was between the two longitudinal rails. Chest and abdominal injuries together accounted for about 26% of all AIS≥3 + fatal injuries in *between-rail* frontal crashes. The rib cage or the lungs were the anatomical site for about 78% of all thoracic injury at the AIS≥3 + fatal level. The aorta was the anatomical site for another 10.6% of these thoracic injuries.

Impact of the torso with the steering wheel rim or with the belt accounted for 81.1% of the serious or greater thoracic trauma. In many crashes, rib cage, lung and aorta trauma were correlated to interaction with the belt or with the steering wheel rim. This data set suggests a correlation (increase) of serious or greater chest injury with age of the driver. It also suggests that female drivers were more susceptible to chest injury than male drivers.

Similarly, impact of the abdomen with the steering wheel rim or with the belt accounted for 96% of the serious or greater abdominal trauma. In many crashes, liver and spleen trauma were correlated to interaction with the belt or with the steering wheel rim.

The findings using the NASS analysis were complemented using computational modeling. The National Crash Analysis Center (NCAC) built a detailed model of a small-size sedan vehicle with relevant interior restraint system components. First integrated occupant-vehicle simulations were conducted with a 50th percentile Hybrid III dummy and compared to full scale crash test data in a 56 km/h NCAP full overlap and a 64 km/h IIHS 40% offset frontal impact. Comparison of test and simulation showed that injury criteria for head and chest correlate within 10% for the two traditional crash configurations.

The integrated occupant-vehicle model was then used with the Total Human Model for Safety (THUMS) in the driver seat. Thoracic and abdominal occupant loads were analyzed in a 64 km/h center-pole configuration and compared to loads seen in a NCAP full overlap and a IIHS 40% offset frontal impact. Higher chest and abdomen deflections were observed at specified points of measurement in the center-pole configuration, suggesting that the between-rail test configuration is important. Interaction with the belt was found to be the main cause of the observed occupant loads in the chest and abdomen area.

Injuries and injury sources in between-rail impacts were analyzed using both NASS data as well as detailed integrated occupant-vehicle simulation. Injury risks were mainly to the rib cage, liver, and spleen. These risks were observed in the NASS-CDS cases and in the simulation results with the THUMS. NASS data and computational analysis complement each other regarding the evaluation of the main potential injury sources steering wheel rim and seat belt.

Applying both methodologies—real-world crash data analysis and vehicle-occupant simulations—in tandem was found to be a promising approach in evaluating different load cases, occupant injuries, and their potential sources.

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