Occupant-Restraint-Vehicle Interaction in Side Impact Evaluated Using a Human Body Model

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ABSTRACT

In North America, fatal injuries sustained by occupants in side impacts constitute almost 40% of road traffic deaths. While a decrease in fatalities was observed for frontal impact scenarios over the last decade, passive safety in side impacts remains a challenge. Side impact research with Anthropometric Test Devices has led to improvements in occupant protection. However, recent epidemiological data shows that side airbags are less effective than expected. Previous studies indicated that the effectiveness of restraint systems was sensitive to occupant pre-crash position. To further enhance occupant safety, understanding the occupant response and the potential for injury in side impact scenarios is necessary. To address these challenges, a finite element Human Body Model was used in a parametric study on the occupant response sensitivity to the occupant pre-crash position and side airbag configuration. The Finite Element Human Body Model with detailed thoracic section was integrated with a mid-sized sedan, seatbelts, and side airbag models, and subjected to a moving deformable barrier impact at 61 kph (38 mph). Two pre-crash occupant positions were considered, with arms in a vertical and horizontal configuration. Side airbag location and inflator mass flow rate was varied in a parametric study. It was observed that the predicted occupant response was most sensitive to the arm position, while the side airbag configuration had a less significant effect. With the arm in a vertical position, the chest deflection, Viscous Criterion, number of fractured ribs, and contused lung volume increased regardless of the side airbag configuration. The lowest values of the injury metrics were predicted for a horizontal arm position where no side airbag was present.

INTRODUCTION

Car accidents are one of the most common causes of injuries and fatalities in developing and developed countries, and the primary cause of death for ages 15-24 in the US (Schmitt, 2014). Globally, there are 1.24 million fatalities due to road accidents every year (WHO, 2013). In 2012, 21,795 occupants died in passenger car crashes in the US, and side impacts accounted for 38% of the fatalities. In Canada, 2,006 people died and 10,443 sustained serious injuries in passenger car accidents in 2011 (Transport Canada, 2011). In spite of introduction of advanced safety systems, the number of injured occupants remains significant (Schmitt, 2014). While the current vehicle structures and restraints address frontal impact scenarios quite well, side impact scenarios remain a challenge, due to limited space for the restraints systems and narrow structural crush zone. The epidemiology data indicates that the thorax and pelvis are the most likely body regions to be injured in near-side impacts (Samaha, 2003), and nearly 60% of severe to fatal injuries are associated with the thorax (Morris, 1994; Kahane, 2007). Thoracic injuries result from laterally intruding door and contact with the upper door panel (Morris, 1997; Tencer, 2005) (Figure 1).

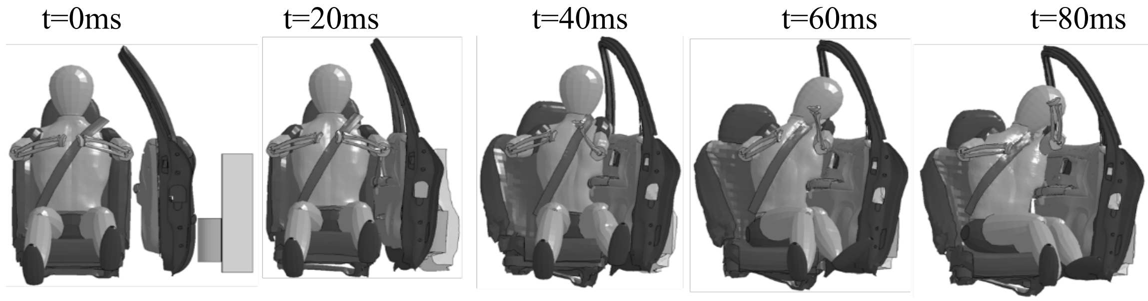


Figure 1: Door-occupant interaction in the vehicle side impact with a deformable barrier.

Interior properties on the occupant-door interface and interaction between the occupant and SABs remain an important consideration in side impacts. Tencer discovered that change of door trim material, increasing distance between the door and the occupant, and redesigning the seat would be more beneficial in reducing injuries than SABs (Tencer, 2005). Parametric study on door shape and compliance effect on the occupant response was performed by Campbell with use of a HBM. He observed that presence of deformable door compared to a rigid door could reduce the injury metrics, with VCmax reduction by 16% being the most significant (Campbell, 2014).

Many authors identified thoracic airbags to result in reduced injuries in side impacts, but to lower extent than expected from the ATD tests. While head protecting airbags were observed to reduce injury risk (37% reduction, Aldaghlas, 2010; McCartt, 2007), torso-only SABs did not present evidence of reduction of fatalities (Yoganandan, 2007; Welsh, 2007; Gaylor, 2015). Limitations of current test methods, namely one standard driving position, biofidelity and frangibility of the ATDs, and adequacy of the MDB test to represent changes in the vehicle fleet, compliance, and compatibility of the vehicles have been discussed (Tencer, 2005; Welsh, 2007, Yoganandan, 2007). Welsh recommended increasing bolstering and padding in the side door and evaluation of the out-of-position scenarios as an alternative for SABs. Shaw et al. suggested further study on occupant injury tolerance in side impacts with SAB deployment (Shaw, 2014).

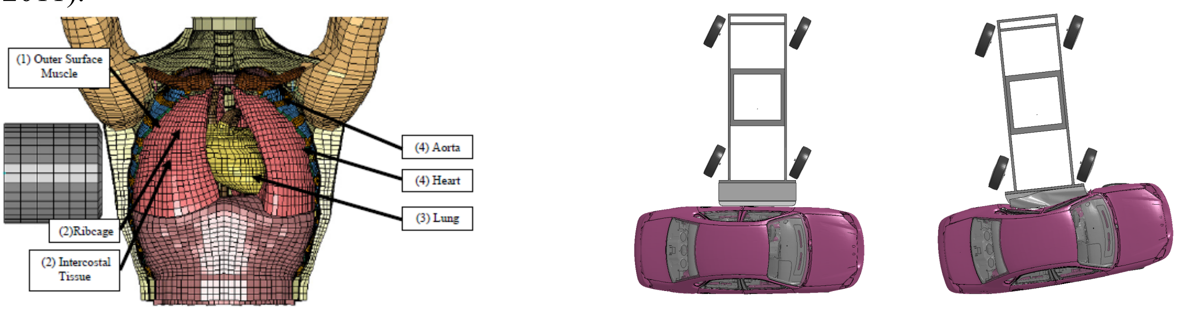
Different researchers studied the effect of arm position on predicted injury response in lateral impacts, often presenting conflicting results (Stalnaker, 1979; Cesari, 1981; Kemper, 2008). Low sensitivity of ATD response to pre-crash position was also reported (Baudrit, 1999; Trosseille, 2011; Gehre, 2013), suggesting further studies on ATD capability to capture effect of non-standard occupant position on the injury metrics. Previous studies with use of HBMs identified arm position as the main factor affecting thoracic response, and the extent to which response was affected depended on type of loading (Gierczycka, 2015). The velocity-pulse impacts, such as vehicle-MDB impact, were found to be the most sensitive to arm position.

Confounding factors, such as the occupant pre-crash position, anthropometric differences between the individuals, wide range of direction and severity of the real-world impacts, impede studies on the differences between laboratory results and real-world crash data. Continued data analysis and advanced methods, such as numerical modeling, can help to identify injury mechanisms in side impacts, and provide guidance on reduction of fatalities. Although HBMs can predict occupant response at a global level through measurement of accelerations, velocities, and displacements, a primary benefit is tissue-level injury prediction.

This study aims to identify the kinematic response and the potential for thorax injury in side impact using tissue level injury metrics in addition to standardized injury criteria, and to demonstrate the benefits of a HBM with detailed thoracic section in a crash environment.

METHODS

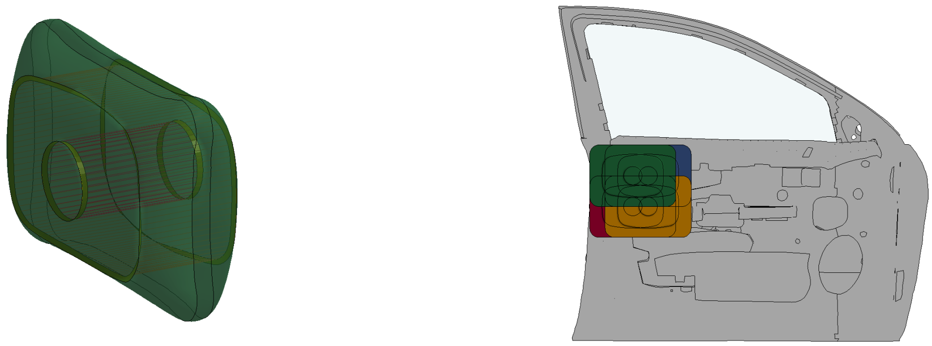
A FE HBM with detailed thoracic section (Figure 2a) (Forbes, 2005) was integrated with a vehicle model representing a mid-sized sedan and Moving Deformable Barrier (MDB) lateral impact (Figure 2b). The HBM has been verified and validated using omni-directional pendulum impacts and side sled impact tests (Forbes, 2005; Campbell, 2009; Yuen, 2009), and in vehicle side impact scenarios (Campbell, 2014). The vehicle and MDB models have been validated using available side impact data for NCAP and FMVSS 214 MDB tests (NHTSA, 2006; NHTSA, 2012), with and without an ATD model (ES-2re and SID) (Opiela, 2008; Watson, 2011).



a) b)

Figure 2: a) detailed thoracic section of the HBM in a lateral pendulum validation test scenario (Forbes, 2005); b) MDB lateral impact setup.

A seatbelt and a configurable side airbag (SAB) were added to the vehicle model. The seatbelt implementation and material properties were validated in studies preceding this research (Campbell, 2014). The SAB model was designed specifically for the purpose of parametric studies, with simplified rectangular shape and approximate volume of 7 liters (Figure 3a). Inflator characteristics were based on available NCAC data (Opiela, 2008), and scaled down to accommodate smaller airbag volume, and obtain maximum airbag pressure of 40 or 20 kPa (Pipkorn, 1996). Four locations of the SAB were considered (Figure 3b), and simulations were run with and without SAB. In all cases, the occupant was belted since previous studies reported negligible effect of the three-point seatbelt on the occupant response in side impact (Campbell, 2014; Watson, 2009).



a) b)

Figure 3: a) inflated SAB; b) four considered SAB locations.

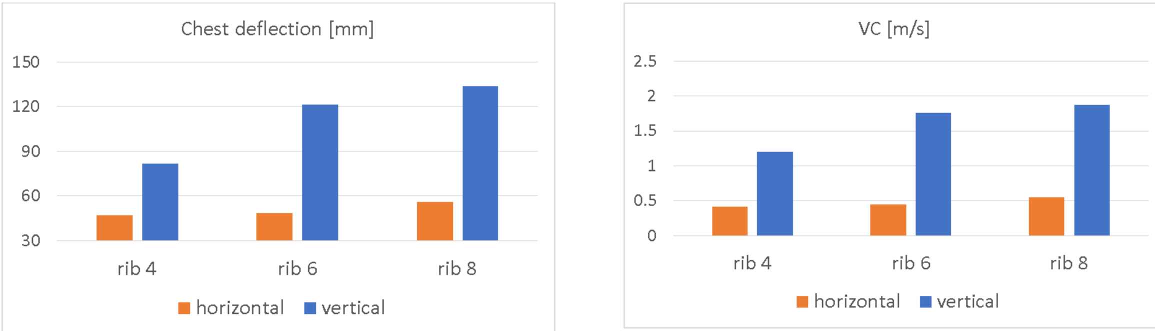
The HBM pre-crash position was varying between horizontal arm (Figure 4a), and vertical arm position (Figure 4b). The injury response was assessed using chest deflection (Viano, 1989), and Viscous Criterion (VC) (Lau, 1986), evaluated at three chest band levels. The injury threshold for chest deflection is 44mm, according to the US standards (NHTSA, 2006), and VCmax value of 1.0 (FMVSS 214) indicates 50% probability of serious injury (Viano, 19890). Global injury response was supported with evaluation of tissue level response, namely number of rib fractures, and through analysis of potential for pulmonary contusion (Yuen, 2008; 2009).

a) b)

Figure 4: HBM with varying arm positions: a) horizontal; b) vertical.

RESULTS

For cases without the SAB and for all the considered SAB configurations, the arm position had the highest impact on the predicted injury response in terms of chest deflection, VC, number of rib fractures and predicted contused area. When no SAB was present, the increase in chest deflection due to vertical arm position was as high as 160%, and the increase in VC exceeded 400% (Figure 5).



a) b)

Figure 5: HBM response at three chest band levels: a) chest deflection; b) VC.

After introduction of the SAB, its performance was highly dependent on the arm position. While for the vertical arm position it was possible to find a combination of SAB location and pressure that did not increase or that reduced both chest deflection and VC, for the horizontal arm position any combination of SAB position and pressure resulted in an increase or a very significant increase of the injury metrics (200% increase of the maximum chest deflection, and 340% increase of VCmax).

For the horizontal arm position (denoted as 'H' in the graphs, Figure 6), the reference scenario without a SAB ('H no SAB') was compared to the SAB location that resulted in the lowest maximum chest deflection and VCmax ('H with SAB (best)'), and to the SAB location that resulted in the highest maximum chest deflection and VCmax values ('H with SAB (worst)') in the parametric study. In case of the horizontal arm position, most SAB combinations increased the chest deflection and VC values at all chest band levels, compared to the reference ('H no SAB') scenario.

Chest deflection [mm] VC [m/s]

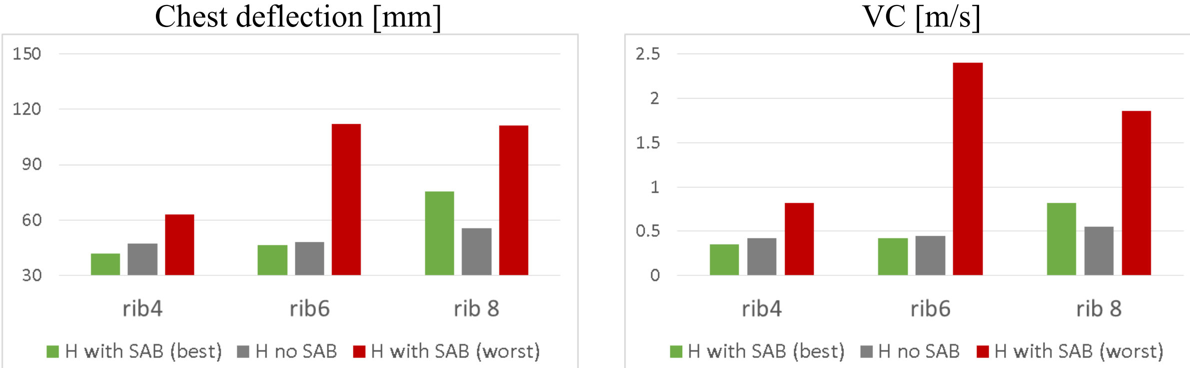


Figure 6: Chest deflection (left) and VC (right) responses at three chest band levels for a scenario without the SAB (gray), with reduction of the injury metrics due to SAB at the level of rib 4 and rib 6 (green), and with increase of the injury metrics due to SAB (red).

For the vertical arm position (denoted as 'V' in the graphs, Figure 7), the reference scenario without a SAB ('V no SAB') was compared to the SAB location that resulted in the lowest maximum chest deflection and VCmax ('V with SAB (best)'), and to the SAB location that resulted in the highest maximum chest deflection and VCmax values ('V with SAB (worst)') in the parametric study. Differences between the reference case (no SAB) and the case with the highest maximum chest deflection and VCmax were less pronounced than in case of the horizontal arm position.

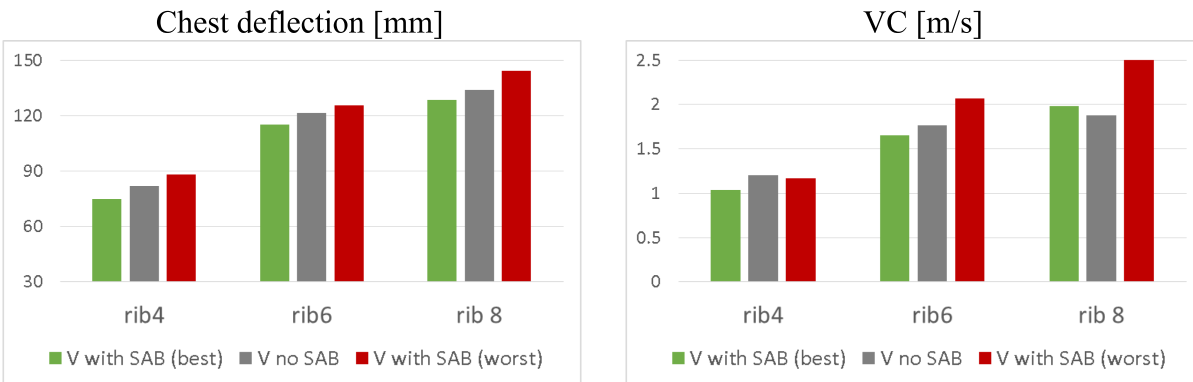


Figure 7: Chest deflection (left) and VC (right) responses at three chest band levels for a scenario without the SAB (gray), with some reduction of the injury metrics due to SAB (green), and with increase of the injury metrics due to SAB (red).

Effect of the SAB pressure on the predicted occupant response was much lower than the effect of arm position. With higher SAB pressure, maximum chest deflection increased by approximately 9%, and the VCmax by 15% for the considered SAB locations and occupant pre-crash positions.

Arm position was observed to have the most significant effect on the number of rib fractures. Regardless of the SAB location, load cases with arm in the vertical position had approximately 60% more rib fractures than load cases with arm in the horizontal position (average for the horizontal arm position: 11 fractures, range 7-12, for the vertical arm position: 17 fractures, range 17-18 fractures).

Analysis of lung contusion pattern demonstrated that the volume of contused lungs was the most sensitive to arm position. With arm in the vertical position, contused volume of the right lung increased by as much as 90% (from 13-18% to nearly 30%). With the SAB located in the shoulder and upper thoracic region, contused lung volume increased by 30% compared to SAB location in the lower thoracic and abdominal region. Due to aggressive nature of the impact, total volume of contused lungs remained above 40% for all load cases, indicating risk of pulmonary contusion regardless of the SAB configuration.

DISCUSSION

The pre-crash position was observed to have an effect on the HBM response with the arm position being the most significant. Positioning the arm in the load path, namely the vertical arm position, increased the injury metrics in terms of maximum chest deflection, VCmax, number of predicted rib fractures and predicted contused volume of the lungs. When no SAB was present, maximum chest deflection was more than two times higher, and VCmax almost five times higher than for the horizontal arm position. The predicted contused lung volume pattern was in agreement with the chest deflection and VC metrics, demonstrating more contused lung volume when the arm was located in the load path (i.e. vertical position).

Slight reduction of the injury metrics was observed for the bottom SAB locations, where it could provide coverage for the lower torso and move the arm away from the load path. The least desired SAB position for both the horizontal and vertical arm positions was in the shoulder and upper torso area, where the deploying SAB would rotate and push the arm towards the torso.

With the dominating effect of the occupant pre-crash position, for the considered set of SAB positions and parameters, variations of the SAB peak inflator pressure had a negligible effect on the predicted injury response.

The MDB-to-vehicle impact was a simplified representation of the vehicle-to-vehicle lateral impact. Results and conclusions of this study were related to this specific scenario and should not be extrapolated to passenger vehicle fleet at this stage of the research. Optimization of the side impact restraints, namely SABs, was beyond the scope of this study. Further steps will include studies on sensitivity of the occupant response to impact location, direction and sensitivity, interaction between the SAB and door padding, and evaluation of SAB location, orientation, mass flow rate, venting, and chamber shape in attempt to reduce occupant injury metrics.

CONCLUSIONS

The aim of this study was to demonstrate significance of the pre-crash position (namely the arm position) and restraint settings (namely the airbag position and inflation parameters) on the predicted response and potential for injury. It was demonstrated that a SAB can reduce or enhance the potential for injury, and for the considered set of parameters and boundary conditions, the pre-crash position of the occupant was the predominant factor. Both the chest deflection and VC response were more sensitive to the arm position than to SAB location and pressure. This study presented factors that could contribute to understanding the ability to improve side impact protection to be applied to future optimization studies.

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