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Occupant thorax response variations due to arm position and restraint systems in side impact crash scenarios

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ABSTRACT

Recent epidemiological studies have identified that thoracic side airbags may vary in efficacy to reduce injury severity in side impact crash scenarios, while previous experimental and epidemiological studies have presented contrasting results. This study aimed to quantify the variations in occupant response in side impact conditions using a human body computational model integrated with a full vehicle model. The model was analyzed for a Moving Deformable Barrier side impact at 61 km/h to assess two pre-crash arm positions, the incorporation of a seatbelt, and a thorax air bag on thorax response. The occupant response was evaluated using chest compression, the viscous criterion and thoracic spinal curvature. The arm position accounted for largest changes in the thorax response (106%) compared to the presence of the airbag and seatbelt systems (75%). It was also noted that the results were dependant on the method and location of thorax response measurement and this should be investigated further. Assessment using lateral displacement of the thoracic spine correlated positively with chest compression and Viscous Criterion, with the benefit of evaluating whole thorax response and provides a useful metric to compare occupant response for different side impact safety systems. The thoracic side airbag was found to increase the chest compression for the driving arm position (+70%), and reduced the injury metrics for the vertical arm position (−17%). This study demonstrated the importance of occupant arm position on variability in thoracic response, and provides insight for future design and optimization of side impact safety systems.

1. Introduction and background

In 2015, there were 22,441 passenger vehicle occupant fatalities, and 2,181,000 injuries reported in the USA (Fatal Accident Reporting System, FARS, 2016). Although a significant decrease in fatalities has been achieved in frontal impact crash scenarios, attributed to advanced active and passive safety systems, side impact motor vehicle crashes remain a challenge as evidenced by high fatality and severe injury rates. In 2015, side impacts fatalities constituted 29% of fatalities in passenger cars (IIHS, 2016). It was also found that 58% of the AIS 4+ injuries of front seat occupants in near-side impacts were associated with the thorax (Kahane, 2007). The odds ratio of sustaining a fatal injury in a side impact was estimated to be 2.26 times higher for near-side impact compared to frontal impact, based on the FARS database over 1975–1998 (Bédard et al., 2002). A study on pulmonary contusion (PC), which is a serious injury (AIS 3+) resulting from blunt trauma to the thorax, reported PC sustained by 26.9% of occupants in near-side impacts (O'Connor et al., 2009). This was almost twice the frequency of PC for occupants injured in frontal impacts (15%). For the same impact severity, measured as delta-V, the odds of pulmonary contusion were 1.8 times higher in lateral impacts (35%) compared to frontal impacts (19%) (O'Connor et al., 2009; NHTSA, 2006).

The most commonly identified source of thoracic injuries is contact with the door (Tencer et al., 2005), which remains a challenge due to the limited crush zone and space available. Injuries to thorax include pneumothorax, hemothorax, rib fractures, pulmonary contusion, contusion and laceration of the internal organs, and aortic rupture (Thomas and Frampton, 1999). Strother et al. (1984) demonstrated that the severity of injuries in side impact was predominantly affected by a difference in velocity between the occupant and contacted surface rather than by the vehicle intrusion itself. Recommendations for effective countermeasures included solutions that reduce the relative velocity and distribute the impact (padding, airbags), rather than increasing vehicle structural strength to reduce intrusion (Strother et al., 1984).

Laboratory experiments and numerical simulations have demonstrated that certain configurations of side airbags (SABs), such as head-and-torso airbags have been effective in reducing response and thoracic injury metrics in Anthropometric Test Devices (ATDs) (Schneider et al., 2005; Luzon-Narro et al., 2014). Over the past decade, some researchers have identified reductions in maximum occupant injury

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Table 1
Summary of studies on tSAB effectiveness.

	tSAB effect	Reference
Experimental PMHS tests	Rib fractures occurred when a large volume tSAB was deployed, despite low chest deflection values.	Shaw et al. (2014), rigid sled 4.4 m/s impacts, 3 PMHS
	Presence of the tSAB affected the load distribution, and therefore deformation profile and fracture pattern of the ribs.	Trosseille et al. (2008), static deployment, 3 PMHS
Experimental ATD tests	tSAB reduced HIC and head acceleration, but increased the chest deflection (+22%, SD 5%) and pelvic acceleration (+16%, SD 4%), bringing the chest deflection response above the IARV range.	Viano and Parenteau (2016), FMVSS 214 matched-pair tests with SID IIs in 2003–2007 MY vehicles
	Large volume tSAB reduced peak rib deflection by 40% compared to a representative tSAB in common use.	Luzon-Narro et al. (2014). 50 km/h MDB test with ES2
Epidemiological studies	tSABs did not contribute to AIS 2+ injuries, and were not observed to cause AIS 3+ chest injuries.	Yoganandan et al. (2007), NASS 1997–2004
	Occupants with tSAB deployed had a risk of injury similar to that of occupants without a deployed tSAB (RR 0.99; 95% CI: 0.79-1.24), risk increased for occupants 50 years and older (RR 1.27; 95% CI: 0.84-1.93).	Griffin et al. (2012), 2000–2009 NASS and CIREN data
	Increase in injury risk, including fatal injury, when tSAB fitted in the vehicle (+5.2%), not statistically significant.	D'Elia et al. (2013), Police reported crash data 2001–2010, Transport Accident Commission data
	tSABs reduced fatalities by 7.8% (confidence bounds 0.4% to 14.7%).	Kahane (2014); Fatality Analysis Reporting System (FARS) 1994–2011
	tSABs reduced vehicle driver fatality risk in driver-side crashes by 26% for passenger cars, and by 30% for SUVs.	McCartt and Kyrychenko (2007), Fatality Analysis Reporting System (FARS) 1997–2004
	No net reduction of injury severity with a deployed tSAB.	Gaylor and Junge (2015), German In-Depth Accident Study (GIDAS) 1997–2012.

severity for side impact crashes in vehicles equipped with side airbags, relative to older vehicles without side airbags (McCartt and Kyrychenko, 2007; Yoganandan et al., 2007). This benefit was not identified in subsequent studies.

More recent investigations have categorized SABs by location and engaged body regions. Curtain airbags were defined as airbags covering the side window, A and B pillars, and engaging the head. Head-and-thorax or head-and-torso airbags engaged both the head and torso, while thoracic airbags were defined as those engaging only the thorax (tSABs) (Table 1) (Griffin et al., 2012 D'Elia et al., 2013; Viano and Parenteau, 2016).

The curtain and head-and-thorax SABs were found to be very effective in reducing fatalities in side impacts and also positively contributed to occupant protection in other accident scenarios (D'Elia et al., 2013; Kahane, 2014). For the near-side impacts, the estimate of fatality reduction due to a combination of curtain and tSAB was 32.8%, for the curtain only it was 16.8%. For the tSAB only, the reduction of driver fatalities was 10.4%. Kahane's study (2014) demonstrated that tSAB effectiveness in far-side impacts was lower than in near-side impacts. The tSAB was estimated to have no effect or increase odds of fatal injuries for the right-front passenger in the near-side (−0.4%), and for both driver and right-front passenger in far-side (−4.9%) impacts. Sources of these differences included a wide range of potential impact forces and directions for the far-side impacts (Kahane, 2014), and potentially the occupant pre-crash position.

Studies based on the National Automotive Sampling System – Crashworthiness Data System (NASS-CDS) (Aldaghlas et al., 2010) and German In-Depth Accident Study (GIDAS) (Gaylor and Junge, 2015) crash databases did not identify a statistically significant reduction of injuries attributed to tSABs, comparing similar model year vehicles with and without tSABs. Interestingly, the results obtained in matched-pair full vehicle side impacts with ATDs (Viano and Parenteau, 2016) revealed that tSABs reduced the probability of head injury only, and did not provide a benefit for the thorax (Table 1). In general, older studies and those with ATDs (Luzon-Narro et al., 2014; Viano and Parenteau, 2016) suggest a benefit of reduced injury metrics using tSAB, while more recent epidemiological studies have identified neutral effects, or increases in injury rates (Griffin et al., 2012 D'Elia et al., 2013; Gaylor and Junge, 2015) for side impacts.

Different approaches have been undertaken to investigate the sources of variation in side impact restraint effectiveness. Human occupant surrogates including ATDs and Post Mortem Human Surrogates (PMHS) have been subjected to lateral sled and pendulum impacts with and without tSABs in controlled laboratory tests. In experimental tests, PMHS were tested with a small volume airbag (frontal airbag sewn to reduce the diameter of deflated airbag to 500 mm) (Trosseille et al., 2008), and with a large volume airbag (42 l) (Shaw et al., 2014; Luzon-Narro et al., 2014). Trosseille et al. (2008) found that a tSAB in a rigid wall sled impact distributed the impact load evenly over the ribs when the PMHS was seated with arms positioned above the head, and that the chest deformation was distinguishably different in terms of pattern and magnitude from a concentrated impact (e.g. pendulum impact). For the large volume tSAB tested with a PMHS in a rigid sled configuration (Shaw et al., 2014), numerous rib fractures were identified despite low chest compression values. Shaw et al. could not identify the reason for the unexpected fractures. The PMHS studies have presented valuable information on occupant response in side impact; however, the applicability of the PMHS in parametric studies has been limited due to variability between the test subjects in terms of anthropometrics, mechanical properties, and response to impact.

Limitations of experimental studies using ATDs include response biofidelity and one seating posture in standard tests (Wismans et al., 2005; Kemper 2013; Park et al., 2016). Kim et al. (2016) highlighted differences between the ES-2re ATD and PMHS response for a lateral impact with a large volume tSAB, and identified challenges related to biofidelity of the ATD arm, lower back, and connection to the pelvis. Unphysical behaviour of those body regions resulted in the load transmission path being different between the ATD and the PMHS (Kim et al., 2016). Trosseille et al. (2010) reported a low sensitivity of the ES-2re ATD to test configuration, comparing rib deflection for experimental tests in rigid sled and padded sled impact (Trosseille and Petitjean, 2010). A computational study by Gierczycka et al. (2015) confirmed Trosseille and Petitjean's (2010) findings, reporting negligible sensitivity of an ES-2re ATD computational model to changing door trim material properties in a full-vehicle lateral impact (Gierczycka et al., 2015). In a computational study including a SID-IIs ATD, Uduma et al. (2005) reported that while the ATD chest deflection was not sensitive to augmenting the door padding, increased lateral clearance in side impact crash reduced chest deflection effectively (Uduma et al., 2005). Supporting this finding, a computational study by Kaneko et al. (2007) including an ES-2 ATD model demonstrated that chest deflection values decreased with the early onset of spine