Published in final edited form as:

Accid Anal Prev. 2011 May ; 43(3): 829–839. doi:10.1016/j.aap.2010.11.002.

Door Velocity and Occupant Distance Affect Lateral Thoracic Injury Mitigation with Side Airbag

Jason J Hallman, Narayan Yoganandan, and Frank A Pintar

Department of Biomedical Engineering, Marquette University Department of Neurosurgery, Medical College of Wisconsin Zablocki VA Medical Center Milwaukee, Wisconsin

Abstract

The relationship between thoracic injury risk and parameters of door velocity and occupant distance was delineated in blunt lateral impact with side airbag deployment. A sled impact model was exercised with the validated MADYMO fiftieth percentile facet occupant model and a generalized finite element torso side airbag. Impact velocity was incremented from 4.0 to 9.0 m/s; occupant-airbag distance (at time of airbag activation) was incremented from 2.0 to 24.0 cm; simulations without airbag were also examined. Using compression, deflection rate, and the Viscous Criterion, airbag performance was characterized with respect to occupant injury risk at three points of interest: occupant distance of most protection, distance of greatest injury risk, and the newly defined critical distance. The occupant distance which demonstrated the most airbag protection, i.e., lowest injury risk, increased with increasing impact velocity. Greatest injury risk resulted when the occupant was nearest the airbag regardless of impact velocity. The critical distance was defined as the farthest distance at which airbag deployment exacerbated injury risk. This critical distance only varied considering chest compression, between 3 and 10 cm from the airbag, but did not vary when the Viscous Criterion were evaluated. At impact velocities less than or equal to 6 m/s, the most protective occupant location was within 2 cm of the critical distance at which the airbag became harmful. Therefore, injury mitigation with torso airbag may be more difficult to achieve at lower ΔV .

Keywords

biomechanics; thorax; trauma; side airbags; multi-body model

INTRODUCTION

Because over 50% of occupants injured in nearside motor vehicle crashes sustain injury to the thorax (Samaha and Elliott, 2003), thorax protection technologies are relevant to reducing injury risk in lateral impact. As the vehicle is struck laterally, the door structure is crushed inward, pushing the door interior into the occupant compartment where the nearside occupant torso is located (Lau et al., 1991). Door contact may occur before the struck vehicle has had sufficient time to accelerate or change trajectory in response to the impact. As a result, thoracic injury risk in lateral crashes has been correlated to the characteristics of

Send Correspondence to: Jason J Hallman Research Lab 151 5000 West National Avenue Milwaukee, Wisconsin 53295 USA Tel: 414.384.2000, x 41534 Fax: 414.384.3493 jhallman@mcw.edu .

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

intrusion such as door velocity profile and door compliance (Huang et al., 1994; Kent et al., 2001).

Many studies, experimental and computational, have examined different parameters to identify interior door conditions least harmful to the thorax. With full scale vehicle testing, decreased injury severity was observed when intrusion was prevented (Cesari et al., 1983). Analysis of a simplified thorax model demonstrated that protection offered by padding was dependent not just on stiffness but on complex dynamic padding behavior (Viano, 1987a; Viano, 1987b). Consequently, some types of padding have been observed to increase the magnitude of thoracic deformation in lateral impact experiments (Cavanaugh et al., 1993; Lau et al., 1991; Pintar et al., 1997). Further, door orientation has been shown to increase thoracic injury risk when deformation profiles are uneven in the coronal or transverse planes (Tencer et al., 2005; Yoganandan et al., 2008).

Torso side airbags were introduced to mitigate injury risk by altering lateral contact characteristics experienced by nearside occupants. While torso airbag efficacy has been studied using real-world motor vehicle crash data from multiple datasets, inconsistent results have been reported (Braver and Kyrychenko, 2004; Kirk and Morris, 2003; McCartt and Kyrychenko, 2007; McGwin et al., 2004; Weber et al., 2004; Yoganandan et al., 2007a; Yoganandan et al., 2007b). While this may be attributable to limited sample size, the complexity of side impact may also obscure results. Torso airbag performance is further complicated by occupant position with respect to the device, an elusive parameter in real-world crash data.

Experimental and computational studies have quantified injury risks to close-proximity occupants from deploying side airbags. These studies have focused on the prevention of the most adverse effects of airbag deployment (Duma et al., 2003a; Duma et al., 2003b; Happee et al., 2000; Pintar et al., 1999; Tylko and Dalmotas, 2000). Other studies have proposed airbag characteristics to minimize particular biomechanical responses (Deng et al., 1998; Haland and Pipkorn, 1996; Pipkorn and Haland, 1996). These have noted that different variations of cushion characteristics, e.g., depth, pressure, ventilation area, etc., are required to minimize different measurements of injury risk (Deng et al., 1998). Namely, the Viscous Criterion (Lau and Viano, 1986) and chest compression required different airbag designs for optimal injury mitigation. Yet, few studies have examined airbag performance over a range of impact severities or possible occupant distances with respect to the device. Although a preliminary computational study observed changes in the Viscous Criterion as great as 135% with changing occupant-airbag distance (Hallman et al., 2008), this relationship has not been delineated in the literature.

The objective of this study was to delineate the relationship between crash severity, injury mitigation, and occupant distance in blunt thoracic impact with side airbag using a computational model.

METHODS

The fiftieth percentile facet occupant model was utilized in MADYMO (R6.3, TNO-MADYMO, Livonia, MI) simulations. The model consisted of head, neck, thorax, abdomen, and upper and lower extremities (Fig. 1). Each body region was modeled with rigid bodies of proportional mass. Masses were enclosed by facet surfaces to reproduce the complex anthropomorphic geometries. Skeletal joint motions, including extremity and intervertebral motions, were modeled as rigid body joints with restraints applied to appropriate degrees of freedom. The facet model was selected over available dummy models because facet surfaces were fully enclosed, providing realistic interactions with airbag deployment.

The thorax, the region of interest to meet the objectives of the present study, consisted of four discrete deformable structures (contours). Progressing caudally, thoracic contours were located at lateral levels of the fourth, sixth, eighth, and tenth ribs (Fig. 2). The nodes of these elliptical contours collectively defined the circumference of the thorax surface. Deformation in response to lateral impact occurred in a medial direction (Fig. 3). The model biomechanical thoracic response was validated for side impact by comparison to cadaveric force-deflection and acceleration response in sled, pendulum, and drop tests at impact velocities between 3.3 and 9.9 m/s (de Lange et al., 2005; Hallman et al., 2010; Happee et al., 2000).

The model was exercised in a simplified side impact environment (Figs 1 and 2). This environment simulated a Heidelberg-type sled device (Pintar et al., 1997). A zero-friction bench seat and back rests supported the occupant, which was positioned such that the Frankfort plane was horizontal, legs stretched parallel to the mid-sagittal plane, and posture was forward upright with normal dorsal spinal curvature and alignment. A rigid structure was positioned to simulate an intruding door contacting the occupant left side during nearside impact. To isolate airbag effects, all impacts occurred at a predefined impact velocity (Δ) representing the relative velocity between the intruding door and the occupant at time of contact in a lateral motor vehicle crash. The lateral thorax was fully exposed to impact by orienting the arms anteriorly, and the loading surface did not engage the shoulder complex. A door-mounted torso side airbag was simulated by housing the bag in a module within the rigid structure.

A finite element airbag was constructed to approximate a generalized side airbag available in current automobiles. The airbag fabric consisted of two circular halves composed of 13,000 triangular membrane elements with 0.5 mm thickness. The resulting airbag geometry achieved an inflated depth of 18 cm and an inflated volume of 13 L. The airbag required 14 ms to inflate, and in a 60 L tank test, the prescribed inflator achieved 95 kPa maximum pressure and 5 kPa/ms maximum onset rate. The inflator gases approximated atmospheric mixture. Thermodynamic calculations assumed uniform pressure throughout the airbag volume. However, inflator nozzle gas flow was approximated by applying additional momentum to nodes within the nozzle outflow stream. Surface-to-surface contacts were defined between the airbag fabric, the rigid structure, and the facet surface skin of the occupant.

For this parametric study, the occupant model was subjected to six door velocities and thirteen side airbag deployment conditions. Door velocity was incremented from $\Delta V = 4.0$ to 9.0 m/s in 1.0 m/s intervals. At each velocity, the side airbag was activated at the instant the occupant came within a predetermined distance from the airbag and rigid boundary. This occupant distance was incremented from 2.0 to 24.0 cm in steps of 2.0 cm. Each ΔV was also repeated without airbag deployment. Including all scenarios, a total of 78 simulations were completed.

Thoracic injury risk was quantified using thoracic biomechanical response measured at the aforementioned four thoracic contours (Figs. 2 and 3). At each contour full-chest compression (C), deflection rate, and the Viscous Criterion (Viano et al., 1989b) were calculated. The Viscous Criterion (VC) is the instantaneous product of compression and deflection rate. Compression and the Viscous Criterion have been correlated with injury risk to the thorax in blunt lateral impact (Pintar et al., 1997; Viano et al., 1989b). All responses were computed in time domain for 100 ms following airbag activation for each scenario. Response peak were identified and compared between occupant distances and between door contact velocities. These were also compared to unprotected impacts, i.e., rigid contact without airbag interaction.

RESULTS

Shown in Figures 4-7 are exemplar time histories for $\Delta V = 7.0$ m/s calculated for each contour level; similar trends were apparent at other ΔV . Scenarios shown unprotected impact (Fig. 4) and airbag activation at occupant distances corresponding to greatest injury risk (Fig. 5), minimized compression (Fig. 6), and minimized VC (Fig. 7). For each plot, $t = 0$ indicates simulation time at which first thorax contact occurred; for simulations without airbag $t = 0$ represents contact with rigid structure. For the unprotected impacts, overall peak compression, deflection rate, and VC were consistently observed at R4 level, immediately inferior to the shoulder complex (Fig. 2). This was contrasted by airbag impacts in which greatest biomechanical responses were observed at the R8 level for all ΔV (Fig. 5). This level corresponded to the center of the airbag module. With increasing occupant distance, the exhaustion of airbag gases following impact permitted rigid structure interaction from behind the airbag fabric and elevated biomechanical response observed at the R4 and R6 levels (Figs. 6 and 7). As occupant distance grew farther from the airbag, biomechanical responses at R8 and R10 decreased due to decreased airbag inflation loads. Yet, farther distances increased biomechanical response at R4 and R6 levels as rigid interaction became more pronounced without sufficient airbag cushion pressure.

These biomechanical response time traces demonstrated a “dual impact” scenario of protected lateral impact: (i) thorax-airbag contact followed by (ii) thorax-rigid contact. The thorax initially deformed due to airbag contact only; after airbag gases were exhausted thoracic deformation increased due to rigid interaction from behind airbag fabric. Tables 1-6 contain airbag injury mitigation results as quantified by changes to peak compression, peak deflection rate, and peak VC (compared to unprotected impact). Negative values indicate reduced biomechanical response (and therefore injury risk) compared to rigid contact; positive values indicate increased biomechanical response. Time of peak response is also listed; negative values for time indicate peaks occurring earlier in deformation history compared to rigid contact; positive values indicate peaks occurring later in deformation history. When occupant was 2 cm from the airbag, biomechanical response (and therefore thoracic injury risk) was greater with the airbag than unprotected impact. Peaks were also attained earlier than with unprotected impact. When occupant distance was sufficiently far from the device, airbag deployment cushioned the impact but prolonged the impact duration, resulting in delayed peak attainment time.

Trends in peak responses were plotted as a function of occupant distance at the instant of airbag activation (Fig. 8). For clarity, only metric trends for $\Delta V = 4.0$ m/s and 9.0 m/s are shown; trends for intermediate ΔV were within these boundaries. Trend lines were punctuated by three points of interest. Square markers indicate the points at which greatest biomechanical response, i.e., greatest injury risk, were observed. For each ΔV , this point corresponded to the nearest occupant distance examined with side airbag, and response to airbag exceeded response to unprotected impact. Triangular markers denote the locations at which injury risk with airbag was equivalent to unprotected rigid contact; this is hereafter referred to as the critical distance. This distance, quantified using linear interpolation of adjacent points, varied with ΔV and between the different biomechanical responses, i.e., compression or VC. Diamond markers indicate occupant distance of greatest airbag protection, denoted by minimum biomechanical response obtained at each ΔV . This distance was also dependent upon ΔV and the response of interest.

Shown in Figure 9 are the aforementioned defining points for compression and for VC. Examining compression metrics (Fig. 9a), the airbag was most protective when occupant distance was between 14 and 18 cm. At these distances, chest compression with airbag was approximately 30% lower than during unprotected impact. The critical distance deviated

toward the airbag with increasing ΔV from 10.1 to 3.2 cm. Peak compression, i.e., most injury risk, for each ΔV was observed when the occupant was nearest the airbag at deployment. At this distance, compression was increased between 3% and 68% compared to unprotected impact. Shown in Figure 9b, trends in VC response were quantitatively different from trends in compression response. Most airbag protection was attained when occupant distance was between 16 and 24 cm. At these distances, airbag presence reduced VC to between 49% and 64% of response during unprotected impact. Unlike with compression, the critical distance as determined by VC varied by less than 0.5 cm with increasing ΔV . Peak VC was observed when the occupant was nearest the airbag at deployment, which increased VC between 40% and >300% compared to unprotected impact.

Biomechanical sensitivity to airbag deployment also varied with ΔV . Sensitivity was defined as the slope of the biomechanical trends (Fig. 8) evaluated at the critical occupant distance. Thus, sensitivity represented the change in response prompted by an increase in occupant distance of 1 cm. Resulting values are shown in Table 7. Additionally, relative values are shown, representing both compression and VC sensitivities normalized to values $\Delta V = 4$ m/s. Sensitivity of compression decreased with increasing ΔV by approximately one-third. VC sensitivity increased with ΔV by nearly twofold.

DISCUSSION

The purpose of this study was to assess the dependency of injury mitigation on occupant distance and door velocity with torso side airbag using biomechanical injury criteria. Thoracic response was used to identify three locations of interest: the critical distance, the most protective distance, and the distance of greatest injury risk.

In this study, lateral impact was simplified using a controlled constant door velocity. In contrast, lateral motor vehicle crashes exhibit complex door velocity time-traces with variable door crush profiles (Kent et al., 2001; Lau et al., 1991; Tencer et al., 2005). Yet, controlled door velocities have been utilized in Heidelberg-type sled devices to simulate lateral motor vehicle crashes (Maltese et al., 2002; Pintar et al., 1997; Yoganandan and Pintar, 2005). Such simulations demonstrated door velocity to correlate with crash ΔV (Dargaud and Bourdillon, 1986; Pintar et al., 1997; Watson et al., 2009), a measure of impact severity. Although the scenario in this study neglects variable door velocity and geometry, this methodology isolated side airbag effects. Because door velocity and therefore impact severity remained unchanged with variable occupant distance, only changes in airbag characteristics affected biomechanical response. From this perspective the present results represent a component analysis necessary to delineate occupant position effects on side impact injury mitigation.

Thoracic interaction with airbag demonstrated a “dual impact” pattern in which thoracic response to airbag and door contact could be independently identified in time traces. Studies of padded lateral impact have described similar behavior (Morris et al., 1999; Viano, 1987a; Viano, 1987b). Viano (1987a and 1987b) described the effects of two different padding materials using a simple thorax model. Thoracic compression and VC were minimized when padding properties led to two equal biomechanical responses: padding interaction following by door interaction. Observations in this study are in agreement with this finding. With increased occupant distance, greater time lapsed between airbag activation and thorax contact. This greater duration allowed airbag pressure losses to venting and softened the airbag cushion. This softened cushion reduced the influence of the airbag contact on the total biomechanical response.

The biomechanical responses evaluated in this study are generally correlated to specific injury patterns in vehicle occupants. Specifically, chest compression is considered most predictive of rib fracture in cadaveric specimens (Cavanaugh et al., 1990; Chung et al., 1999; Pintar et al., 1997). VC, being a rate-sensitive injury criterion, is generally associated with visceral injury, e.g., liver laceration, spleen rupture, etc. (Lau and Viano, 1986; Viano et al., 1989a). Therefore, contrasting results between chest compression and VC may indicate contrasting injury patterns between occupants subjected to unprotected and airbag deployment impacts.

Because of transient airbag characteristics, the most protective distance was found to vary with ΔV , shifting up to 10 cm further away from the airbag module with increased ΔV . Depicted in Figure 10 are positions of most protection for both compression and VC; linear fit lines are also present. As shown, the distance minimizing compression was consistently 2 cm closer to the airbag than the distance minimizing VC. Further, injury metrics were not reduced equivalently at all ΔV . Peak compression was reduced by approximately 30% compared to values without airbag, regardless of ΔV . In contrast, peak VC was reduced by 35% at the least ΔV and by 50% at the greatest ΔV . This finding is in agreement with other studies of thoracic injury mitigation, where padding was more mitigative of VC than of compression (Deng, 1989; Deng and Tzeng, 1996). These results indicate that side airbags may better mitigate visceral trauma than rib fracture, particularly at high impact velocities.

Although a previous study found excessively stiff padding to be equivalent to rigid contact (Viano, 1987a), the thoracic response of an occupant too close to airbag deployment was more complex than stiff padding. Early stages of airbag deployment resulted in high cushion pressures as well as airbag deployment energy. Thus, unlike padded contact with constant material properties, the net energy imparted to the thorax by the airbag contact may be greater than unprotected rigid contact (Haland and Pipkorn, 1996; Smith et al., 2003; Yoganandan et al., 2007a; Yoganandan et al., 2007b). Studies of close-proximity airbag deployment have demonstrated high forces imparted to test subjects (Horsch et al., 1990; Lau et al., 1993). Yet, parametric analyses tuning airbag parameters to meet deflection-, viscous-, and acceleration-based thoracic injury criteria have neglected the role of the inflation phase in airbag-occupant interaction (Haland and Pipkorn, 1996; Pipkorn and Haland, 1996). In this study, the distance of greatest thoracic injury risk was consistently two centimeters from the airbag module, the closest position evaluated in this study. At this distance, airbag effects on biomechanical response were proportionally greater at lower ΔV compared to higher ΔV . While few studies have addressed the role of impact velocity in close-proximity side airbag deployments (Schroeder et al., 1998; Sieveka et al., 1998), an extension of the present analysis suggested that stationary close-proximity testing may not capture all scenarios in which a torso airbag may cause injury (Hallman et al., 2010).

The critical distance was the occupant position at which the airbag ceased to be mitigative, i.e., biomechanical responses with and without airbag deployment were equivalent. From this threshold, a closer occupant sustained increased injury risk and a further occupant sustained reduced injury risk. Critical distances for both compression and VC are depicted on the same axes in Figure 10 for all ΔV . Considering VC, the critical distance was independent of ΔV , approximately 13 cm. Critical distances for compression metrics varied approximately 7.0 cm closer to the airbag as ΔV increased. These results suggest that a minimum distance from the airbag was required to avoid exacerbated visceral injury risk, regardless of impact severity. In contrast, the suggested distance at which airbag deployment exacerbated rib fracture risk decreased with increased impact severity. In other words, the occupant could be closer to the device and still benefit from deployment. This observation regarding compression also is supported by sensitivity values (Table 7). With increasing ΔV , compression response demonstrated less sensitivity to occupant distance while VC

demonstrated a two-fold greater sensitivity. VC sensitivity suggests that injury resulting from real-world side impacts with torso airbag may be more likely soft tissue trauma. Preliminary real-world observations have found this to be the case (Hallman et al., 2009; Kirk and Morris, 2003), noting evidence of visceral injury following seemingly low-severity impacts and torso airbag deployment.

The distances examined in this study are relevant to real-world impacts involving torso side airbags. Pretest occupant positioning is in the mid-seat position for side impact crashworthiness tests according to the United States (NCAP) and European (EuroNCAP) specifications (EuroNCAP, 2004; NHTSA, 2008). This positioning is also true for IIHS tests (IIHS, 2008). An analysis of US NCAP tests indicates that the mid-seat positioned dummy distance from the door ranges from 11 to 22 cm. Further, occupants may deviate from the centerline position during normal roadway maneuvers, greater than 18 cm toward the door in some cases (Dinas and Fildes, 2002). Because of occupant position dependency, reasonable lateral variations in posture may greatly affect thoracic injury mitigation with a torso airbag: At lower impact severities in this study, the critical distance for VC was only 2 cm from the most protective distance for chest compression. Arm position represents another postural change which may affect these results. While not considered in this study, prior work has demonstrated arm interaction to be protective of thoracic injury (Cesari et al., 1981). Therefore it is likely that arm interaction would isolate the thorax from detrimental airbag effects.

The generalized side airbag incorporated in this parametric analysis remains a limitation of this study. No independently validated side airbag model was available to the authors, as these are generally proprietary. Therefore an airbag was developed such that the inflator maximum tank test pressure was realistic for a torso-interacting side airbag. Airbag aggressivity was conservative as measured by the inflator maximum tank pressure onset rate; onset rates 300% greater than specified in this study have been reported (Pintar et al., 1999). Likewise, the airbag volume was reasonable: side airbags of 12L have been reported (Haland and Pipkorn, 1996). It is also important to note that this side airbag was employed in the less popular door-mounted configuration, but this ensured that the airbag deployment direction was along the primary direction of model response (Fig. 3). In light of results presented here, future work should incorporate vehicle-specific airbag designs. Other occupant orientations may also be relevant and were not examined in this study. For example, prior examinations of unprotected lateral impact have demonstrated that other occupant postural changes in the longitudinal direction, i.e., forward/back, influence thoracic biomechanical response and therefore injury risk (Allan-Stubbs, 1998). Lastly, because impactor velocities in vehicle crashworthiness tests such as EuroNCAP are greater than those examined in this study, the impact velocity range should be expanded.

Research Highlights

1. Using a generalized torso side airbag in dynamic impact, occupant distance of most protection, distance of greatest injury risk, and the newly defined critical distance were characterized.
2. Distance providing most protection increased with impact velocity.
3. Distance of greatest injury risk was nearest the airbag and independent of impact velocity.
4. At low impact velocities, distance at which airbag deployment became harmful was within 2 cm of distance at which airbag deployment was most protective.

Acknowledgments

This research was supported in part by NIH Grant (R01AG024443), the NSF Graduate Research Fellowship Program, and Veterans Affairs Medical Research.

REFERENCES

- Allan-Stubbs B. The effect of changes in seating position and door velocity time history on side impact dummy response. *SAE Trans.* 1998;980911.
- Braver ER, Kyrychenko SY. Efficacy of side air bags in reducing driver deaths in driver-side collisions. *Am J Epidemiol.* 2004; 159(6):556–564. [PubMed: 15003959]
- Cavanaugh, JM.; Walilko, TJ.; Malhotra, A.; Zhu, Y.; King, AI. Biomechanical response and injury tolerance of the thorax in twelve sled side impacts. 34th Stapp Car Crash Conference; Orlando, FL. 1990. p. 23-38.
- Cavanaugh, JM.; Zhu, Y.; Huang, Y.; King, AI. Injury and response of the thorax in side impact cadaveric tests. 37th Stapp Car Crash Conference; San Antonio, TX. 1993. p. 199-221.
- Cesari, D.; Ramet, M.; Bloch, J. Influence of arm position on thoracic injuries in side impact. 25th Stapp Car Crash Conference; San Francisco, CA. 1981. p. 271-297.
- Cesari, D.; Zac, R.; Johnson, A. Evaluation of side impact protection in barrier to car tests. 27th Stapp Car Crash Conference; San Diego, CA. 1983. p. 399-406.
- Chung, J.; Cavanaugh, JM.; King, AI.; Koh, S.-.; Deng, YC. Thoracic injury mechanisms and biomechanical responses in lateral velocity pulse impacts. 43rd Stapp Car Crash Conference; San Diego, CA. 1999.
- Dargaud R, Bourdillon T. Simulation of lateral impact with mobile deformable barrier. *SAE* 860051. 1986;41–50.
- de Lange R, van Rooij L, Mooi H, Wismans J. Objective biofidelity rating of a numerical human occupant model in frontal to lateral impact. *Stapp Car Crash J.* 2005; 49:457–479. [PubMed: 17096285]
- Deng, YC. The importance of the test method in determining the effects of door padding in side impact. 33rd Stapp Car Crash Conference; Washington, DC. 1989. p. 79-85.
- Deng YC, Tzeng B. Side impact countermeasure study using a hybrid modeling technique. *SAE Trans.* 962413. 1996;43–50.
- Deng YC, Wang JT, Peng JH, Kulkarni S. An analytical study of side airbag designs for TTI reduction in a large size car. *SAE Trans.* 982322. 1998
- Dinas A, Fildes BN. Observations of seating position of front seat occupants relative to the side of the vehicle. *Annu Proc Assoc Adv Automot Med.* 2002; 46:27–43. [PubMed: 12361498]
- Duma SM, Boggess BM, Crandall JR, Hurwitz SR, Seki K, Aoki T. Upper extremity interaction with a deploying side airbag: a characterization of elbow joint loading. *Accid Anal Prev.* 2003a; 35(3): 417–425. [PubMed: 12643959]
- Duma SM, Crandall JR, Rudd RW, Kent RW. Small female head and neck interaction with a deploying side airbag. *Accid Anal Prev.* 2003b; 35(5):811–816. [PubMed: 12850083]
- EuroNCAP. Side Impact Testing Protocol. 2004.
- Haland Y, Pipkorn B. A parametric study of a side airbag system to meet deflection based criteria. *J Biomech Eng.* 1996; 118(3):412–419. [PubMed: 8872265]
- Hallman JJ, Brasel KJ, Yoganandan N, Pintar FA. Splenic trauma as an adverse effect of torso-protecting side airbags: Biomechanical and case evidence. *Ann Adv Automot Med.* 2009; 53:13–24. [PubMed: 20184829]
- Hallman JJ, Yoganandan N, Pintar FA. Thoracic injury metrics with side airbag: Stationary and dynamic occupants. *Traffic Inj Prev.* 2010; 11(4):433–442. doi: 10.1080/15389581003753017. [PubMed: 20730691]
- Hallman JJ, Yoganandan N, Pintar FA. Torso side airbag out-of-position evaluation using stationary and dynamic occupants. *Biomed Sci Instrum.* 2008; 44:123–128. [PubMed: 19096733]
- Happee, R.; Ridella, S.; Nayef, A.; Morsink, P.; de Lange, R.; Bours, R.; van Hoof, J. Mathematical human body models representing a mid size male and a small female for frontal, lateral, and

- rearward impact loading. 2000 International IRCOBI Conference; Montpellier, France. 2000. p. 67-89.
- Horsch, JD.; Lau, IV.; Andrzejak, DV.; Viano, DC.; Melvin, JW.; Pearson, J.; Cok, D.; Miller, G. Assessment of air bag deployment loads. 34th Stapp Car Crash Conference; Orlando, Florida. 1990. p. 267-288.
- Huang Y, King AI, Cavanaugh JM. A MADYMO model of near-side human occupants in side impacts. *J Biomech Eng*. 1994; 116(2):228–235. [PubMed: 8078331]
- IIHS. Side impact crashworthiness evaluation: Crash test protocol. 2008.
- Kent R, Crandall J, Butcher J, Morris R. Sled system requirements for the analysis of side impact thoracic injury criteria and occupant protection. *SAE Trans*. 2001-0-0721. 2001
- Kirk, A.; Morris, A. Side airbag deployments in the UK - Initial case reviews. 18th International Technical Conference on the Enhanced Safety of Vehicles; Nagoya, Japan. 2003.
- Lau, IV.; Capp, JP.; Obermeyer, JA. A comparison of frontal and side impact: crash dynamics, countermeasures, and subsystem tests. 35th Stapp Car Crash Conference; San Diego, California. 1991. p. 109-124.
- Lau IV, Horsch JD, Viano DC, Andrzejak DV. Mechanism of injury from air bag deployment loads. *Accid Anal Prev*. 1993; 25(1):29–45. [PubMed: 8420532]
- Lau, IV.; Viano, DC. The viscous criterion - bases and applications of an injury severity index for soft tissues. 30th Stapp Car Crash Conference; San Diego, CA. 1986. p. 123-142.
- Maltese MR, Eppinger RH, Rhule HH, Donnelly BR, Pintar FA, Yoganandan N. Response corridors of human surrogates in lateral impacts. *Stapp Car Crash J*. 2002; 46:321–351. [PubMed: 17096232]
- McCart AT, Kyrychenko SY. Efficacy of side airbags in reducing driver deaths in driver-side car and SUV collisions. *Traffic Inj Prev*. 2007; 8(2):162–170. doi: 10.1080/15389580601173875. [PubMed: 17497520]
- McGwin G Jr, Metzger J, Rue LW 3rd. The influence of side airbags on the risk of head and thoracic injury after motor vehicle collisions. *J Trauma*. 2004; 56(3):512–516. [PubMed: 15128120]
- Morris RA, Crandall JR, Pilkey WD. Multibody modelling of a side impact test apparatus. *IJCrash*. 1999; 4(1):17–29.
- NHTSA. Laboratory test procedure for new car assessment program side impact moving deformable barrier testing. 2008.
- Pintar, FA.; Yoganandan, N.; Hines, MH.; Maltese, MR.; McFadden, J.; Saul, R.; Eppinger, RH.; Khaewpong, N.; Kleinberger, M. Chestband analysis of human tolerance to side impact. 41st Stapp Car Crash Conference; Lake Buena Vista, FL. 1997. p. 63-74.
- Pintar, FA.; Yoganandan, N.; Maltese, MR.; Samaha, RR.; Eppinger, RH. Three-year-old child out-of-position side airbag studies. 43rd Stapp Car Crash Conference; San Diego, CA. 1999. p. 25-38.
- Pipkorn B, Haland Y. A side airbag system to meet chest injury measures: evaluation by mathematical simulations. *IJCrash*. 1996; 1(2):145–161.
- Samaha, RR.; Elliott, DS. NHTSA side impact research: motivation for upgraded test procedures. 18th International Technical Conference on the Enhanced Safety of Vehicles; Nagoya, Japan. 2003.
- Schroeder, G.; Kallieris, D.; Tschaeschke, U.; Scheunert, D.; Schuetz, J.; Zobel, R. Are side airbags dangerous in certain seating positions?. 1998 International IRCOBI Conference; Goeteborg, Sweden. 1998. p. 447-483.
- Sieveka, E.; Crandall, JR.; Duma, SM.; Pilkey, W. Development and application of a side airbag computer model using the CVS/ATB multi-body dynamics program. 16th International Technical Conference on the Enhanced Safety of Vehicles; Windsor, Ontario, Canada. 1998. p. 1925-1935.
- Smith MJ, Kaleto HA, Nowak TJ, Gotwals DG. Advancements in equipment and testing methodologies for airbag systems in response to changes to Federal Safety Requirements. *SAE Trans*. 2003-01-0497. 2003
- Tencer AF, Kaufman R, Huber P, Mock C. The role of door orientation on occupant injury in a nearside impact: a CIREN, MADYMO modeling and experimental study. *Traffic Inj Prev*. 2005; 6(4):372–378. doi: 10.1080/15389580500256813. [PubMed: 16266946]

- Tylko, S.; Dalmotas, D. Assessment of injury risk to children from side airbags. 44th Stapp Car Crash Conference; Atlanta, GA. 2000.
- Viano, DC. Evaluation of the benefit of energy-absorbing material in side impact protection: Part I. 31st Stapp Car Crash Conference; New Orleans. 1987a. p. 185-203.
- Viano, DC. Evaluation of the benefit of energy-absorbing material in side impact protection: Part II. 31st Stapp Car Crash Conference; New Orleans. 1987b. p. 205-224.
- Viano DC, Lau IV, Andrzejak DV, Asbury C. Biomechanics of injury in lateral impacts. *Accid Anal Prev.* 1989a; 21(6):535–551. [PubMed: 2629762]
- Viano DC, Lau IV, Asbury C, King AI, Begeman P. Biomechanics of the human chest, abdomen, and pelvis in lateral impact. *Accid Anal Prev.* 1989b; 21(6):553–574. [PubMed: 2629763]
- Watson, B.; Cronin, DS.; Campbell, B. Study of vehicle dynamics and occupant response in side impact crash tests. 21st International Technical Conference on the Enhanced Safety of Vehicles; Stuttgart, Germany. 2009.
- Weber PR, Cassatta SJ, Sochor MR, Faust DP, Fakry S, Watts D, Mock C, Wang SC. Lateral air bag performance in CIREN field studies. *SAE Trans.* 2004-01-0331. 2004
- Yoganandan N, Pintar FA. Deflection, acceleration, and force corridors for small females in side impacts. *Traffic Inj Prev.* 2005; 6(4):379–386. doi: 10.1080/15389580500256888. [PubMed: 16266947]
- Yoganandan N, Pintar FA, Gennarelli TA, Martin PG, Ridella SA. Chest deflections and injuries in oblique lateral impacts. *Traffic Inj Prev.* 2008; 9(2):162–167. doi: 10.1080/15389580701775942. [PubMed: 18398780]
- Yoganandan N, Pintar FA, Stemper BD, Gennarelli TA, Weigelt JA. Biomechanics of side impact: injury criteria, aging occupants, and airbag technology. *J Biomech.* 2007a; 40(2):227–243. doi: 10.1016/j.jbiomech.2006.01.002. [PubMed: 16527285]
- Yoganandan N, Pintar FA, Zhang J, Gennarelli TA. Lateral impact injuries with side airbag deployments--a descriptive study. *Accid Anal Prev.* 2007b; 39(1):22–27. doi: 10.1016/j.aap.2006.05.014. [PubMed: 16911812]

Figure 1.
Perspective view of occupant model in sitting posture following airbag deployment.

Figure 2. Facet occupant model in sitting posture, viewed from anterior, with contours of deformation measurement indicated. NOTE: Upper extremities were positioned anteriorly as shown in Figure 1.

Figure 3. Predefined thoracic deformation pattern for injury metric evaluation with facet occupant model. Nodes corresponding to spine and sternum are indicated.

Figure 4. Time-domain response to $\Delta V = 7.0$ m/s for (a) compression, (b) deflection rate, and (c) viscous metrics without airbag.

Figure 5.
Time-domain response to $\Delta V = 7.0$ m /s for (a) compression, (b) deflection rate, and (c) viscous metrics at distance of greatest metrics (2.0 cm).

Figure 6.
Time-domain response to $\Delta V = 7.0$ m /s for (a) compression, (b) deflection rate, and (c) viscous metrics at distance of least compression metrics.

Figure 7. Time-domain response to $\Delta V = 7.0$ m/s for (a) compression, (b) deflection rate, and (c) viscous metrics at distance of least viscous metrics.

Figure 8.

Trends in peak injury metrics of (a) chest compression and (b) viscous criterion for $\Delta V = 4.0$ m/s and 9.0 m/s. Dash-dotted lines indicate peak metric for rigid contact boundary condition (i.e., without airbag). Square denotes maximum metric for ΔV , diamond denotes minimum metric for ΔV , and triangle denotes critical position.

Figure 9.

Defining points of airbag interaction trends for each impact velocity as denoted by (a) chest compression and (b) the viscous criterion. Maximum injury metrics are indicated by squares, minimum metrics by diamonds, and critical location by triangles. Trend lines are drawn for clarity.

Figure 10. Comparative plot of critical distance (triangles) and most protective distance (diamonds) defined by peak compression (filled) and VC (hollow) metrics. Most protective points are shown with linear fit curves.

Table 1

Deviations from Rigid Contact in Peak Metrics and Time of Attainment for $\Delta V = 4.0$ m /s

Distance (cm)	Change in time of peak (ms)				Change in peak compression			
	R10	R8	R6	R4	R10	R8	R6	R4
2	-15.2	-16.3	-15.6	-12.3	0.137	0.132	0.079	0.040
4	-14.8	-15.9	-15.1	-13.8	0.117	0.110	0.064	0.033
6	-14.3	-15.6	-15.2	-13.3	0.092	0.084	0.044	0.018
8	-12.8	-14.7	-14.4	-12.2	0.067	0.053	0.021	-0.001
10	-11.9	-13.0	-12.7	-12.1	0.043	0.022	-0.007	-0.026
12	-10.5	-10.7	-10.3	-9.4	0.018	-0.007	-0.031	-0.047
14	-8.5	-8.4	-7.8	57.7	-0.006	-0.032	-0.053	-0.049
16	-6.8	-4.5	56.1	62.5	-0.028	-0.055	-0.067	-0.027
18	43.5	42.3	36.8	53.8	-0.036	-0.070	-0.060	-0.016
20	44.0	41.9	43.1	47.8	-0.024	-0.062	-0.046	-0.011
22	31.7	30.1	34.0	35.6	-0.008	-0.050	-0.031	-0.005
24	28.8	27.9	29.4	32.5	0.000	-0.041	-0.019	0.000

Distance (cm)	Change in time of peak (ms)				Change in peak rate (m/s)			
	R10	R8	R6	R4	R10	R8	R6	R4
2	-5.3	-5.5	-5.3	-5.0	4.96	7.11	4.57	2.49
4	-5.5	-5.8	-5.5	-5.1	4.01	6.41	3.55	1.82
6	-6.1	-6.3	-6.2	-5.6	4.61	5.81	3.76	1.39
8	-6.1	-6.4	-6.1	2.4	2.79	5.01	2.18	0.89
10	-6.4	-6.6	-6.4	2.4	1.93	3.72	1.52	0.27
12	-6.5	-6.7	-6.5	4.4	0.80	2.00	0.45	-0.33
14	5.8	-7.0	5.9	5.9	-0.65	0.16	-0.85	-0.68
16	6.3	-7.1	6.4	53.8	-1.43	-0.87	-1.53	-0.96
18	6.7	10.6	55.3	50.8	-1.83	-1.82	-1.64	-0.72
20	48.4	50.1	50.3	46.9	-0.91	-1.69	-0.76	-0.48
22	35.7	37.4	37.8	34.1	-0.01	-1.21	-0.34	-0.24

Distance (cm)	Change in time of peak (ms)				Change in peak rate (m/s)			
	R10	R8	R6	R4	R10	R8	R6	R4
24	32.6	35.4	35.5	30.3	-0.01	-1.15	-0.33	0.00

Distance (cm)	Change in time of peak (ms)				Change in peak rate (m/s)			
	R10	R8	R6	R4	R10	R8	R6	R4
2	-5.3	-5.5	-5.3	-5.0	4.96	7.11	4.57	2.49
4	-5.5	-5.8	-5.5	-5.1	4.01	6.41	3.55	1.82
6	-6.1	-6.3	-6.2	-5.6	4.61	5.81	3.76	1.39
8	-6.1	-6.4	-6.1	2.4	2.79	5.01	2.18	0.89
10	-6.4	-6.6	-6.4	2.4	1.93	3.72	1.52	0.27
12	-6.5	-6.7	-6.5	4.4	0.80	2.00	0.45	-0.33
14	5.8	-7.0	5.9	5.9	-0.65	0.16	-0.85	-0.68
16	6.3	-7.1	6.4	53.8	-1.43	-0.87	-1.53	-0.96
18	6.7	10.6	55.3	50.8	-1.83	-1.82	-1.64	-0.72
20	48.4	50.1	50.3	46.9	-0.91	-1.69	-0.76	-0.48
22	35.7	37.4	37.8	34.1	-0.01	-1.21	-0.34	-0.24
24	32.6	35.4	35.5	30.3	-0.01	-1.15	-0.33	0.00

R10, Rib 10; R8, Rib 8; R6, Rib 6; R4, Rib 4.

Table 2

Deviations from Rigid Contact in Peak Metrics and Time of Attainment for $\Delta V = 5.0$ m/s

Distance (cm)	Change in time of peak (ms)					Change in peak compression				
	R10	R8	R6	R4	R10	R8	R6	R4	R10	R8
2	-13.9	-14.8	-14.3	-12.6	0.130	0.121	0.061	0.014	0.061	0.043
4	-13.4	-14.4	-13.7	-10.9	0.112	0.096	0.043	0.005	0.043	0.032
6	-12.6	-13.8	-13.1	-12.0	0.093	0.080	0.032	-0.001	0.032	0.014
8	-11.6	-12.9	-12.7	-9.8	0.071	0.055	0.014	-0.015	0.014	0.006
10	-10.2	-11.2	-10.5	-9.5	0.049	0.030	-0.006	-0.032	0.030	0.002
12	-9.2	-9.6	-9.1	-7.9	0.026	0.002	-0.029	-0.052	0.002	-0.050
14	-7.6	-7.1	-6.8	69.8	0.005	-0.022	-0.050	-0.068	-0.022	-0.070
16	-5.7	-5.3	-5.0	57.1	-0.016	-0.045	-0.070	-0.042	-0.045	-0.064
18	-4.1	-3.4	47.4	52.9	-0.037	-0.064	-0.078	-0.036	-0.037	-0.067
20	30.8	28.5	30.1	43.4	-0.046	-0.083	-0.067	-0.026	-0.046	-0.075
22	25.5	19.9	27.0	33.2	-0.032	-0.075	-0.052	-0.008	-0.032	-0.065
24	28.0	27.1	27.9	33.8	-0.011	-0.065	-0.034	0.016	-0.011	-0.034

Distance (cm)	Change in time of peak (ms)					Change in peak rate (m/s)				
	R10	R8	R6	R4	R10	R8	R6	R4	R10	R8
2	-4.3	-4.5	-4.4	-4.0	4.68	6.81	4.15	1.88	4.68	5.87
4	-4.6	-5.0	-4.7	-4.2	3.55	5.87	3.05	1.29	3.55	5.74
6	-4.8	-5.2	-4.9	3.6	3.04	5.74	2.42	0.97	3.04	4.58
8	-5.1	-5.4	-5.2	3.6	2.27	4.58	1.68	0.66	2.27	3.24
10	-5.4	-5.6	-5.4	3.3	1.30	3.24	0.96	0.33	1.30	1.73
12	-5.5	-5.7	-5.5	4.6	0.37	1.73	0.01	-0.23	0.37	-0.10
14	6.5	-5.9	6.3	5.8	-0.61	-0.10	-0.78	-0.70	-0.61	-1.09
16	7.0	7.0	7.1	7.1	-1.05	-1.09	-1.22	-1.10	-1.05	-1.90
18	11.0	11.0	11.2	46.9	-2.02	-1.90	-1.83	-1.54	-2.02	-2.32
20	1.9	15.0	46.8	43.0	-2.13	-2.32	-2.01	-0.76	-2.13	-2.39
22	33.9	35.1	35.7	32.6	-1.48	-2.39	-1.30	-0.19	-1.48	-2.39

Distance (cm)	Change in time of peak (ms)				Change in peak rate (m/s)			
	R10	R8	R6	R4	R10	R8	R6	R4
24	33.5	34.3	34.8	31.7	-0.39	-1.61	-0.61	0.30

Distance (cm)	Change in time of peak (ms)				Change in peak VC (m/s)			
	R10	R8	R6	R4	R10	R8	R6	R4
2	-4.6	-8.4	-4.7	-4.0	0.95	1.00	0.73	0.65
4	-4.1	-4.4	-4.0	-3.1	0.70	0.61	0.36	0.26
6	-3.7	-4.2	-3.8	-2.6	0.58	0.56	0.34	0.24
8	-3.1	-3.8	-3.3	-2.9	0.41	0.39	0.24	0.18
10	-1.6	-3.5	-3.4	-3.4	0.25	0.21	0.10	0.05
12	-1.2	-2.4	-1.8	-1.3	0.14	0.07	-0.01	-0.04
14	-0.9	-1.4	-0.7	-0.5	0.03	-0.03	-0.10	-0.13
16	2.0	2.6	2.6	41.3	-0.06	-0.11	-0.17	-0.18
18	5.4	6.2	6.3	38.6	-0.12	-0.16	-0.21	-0.15
20	38.8	9.7	38.5	35.1	-0.15	-0.21	-0.18	-0.11
22	26.1	27.2	28.2	37.9	-0.10	-0.19	-0.13	-0.05
24	28.0	27.9	29.5	35.0	-0.04	-0.16	-0.09	0.00

R10, Rib 10; R8, Rib 8; R6, Rib 6; R4, Rib 4.

Table 3

Deviations from Rigid Contact in Peak Metrics and Time of Attainment for $\Delta V = 6.0$ m/s

Distance (cm)	Change in time of peak (ms)				Change in peak compression			
	R10	R8	R6	R4	R10	R8	R6	R4
2	-13.3	-14.2	-13.8	-12.1	0.124	0.114	0.045	-0.013
4	-12.6	-13.7	-12.9	-10.1	0.112	0.091	0.030	-0.016
6	-11.8	-13.2	-12.2	-9.8	0.094	0.073	0.018	-0.023
8	-10.6	-11.8	-11.3	-9.1	0.074	0.054	0.005	-0.031
10	-9.4	-10.7	-10.0	-9.1	0.054	0.032	-0.012	-0.044
12	-8.5	-9.3	-8.7	-8.0	0.032	0.008	-0.030	-0.061
14	-7.2	-7.8	-6.7	-6.1	0.014	-0.012	-0.048	-0.076
16	-5.2	-5.6	-5.4	52.0	-0.004	-0.031	-0.064	-0.065
18	-3.7	-4.3	-4.0	45.0	-0.025	-0.055	-0.085	-0.047
20	2.2	-2.8	35.7	45.8	-0.044	-0.075	-0.083	-0.043
22	16.2	14.0	18.6	30.2	-0.049	-0.093	-0.071	-0.034
24	14.2	12.0	21.5	25.6	-0.037	-0.084	-0.057	-0.015

Distance (cm)	Change in time of peak (ms)				Change in peak rate (m/s)			
	R10	R8	R6	R4	R10	R8	R6	R4
2	-3.8	-4.0	-3.9	1.4	4.51	6.50	3.83	1.85
4	-4.0	-4.4	-4.1	-3.6	3.12	5.38	2.61	0.75
6	-4.3	-4.7	-4.4	4.0	2.46	5.16	1.86	0.60
8	-4.5	-4.9	-4.6	3.9	1.85	4.35	1.20	0.36
10	-4.8	-5.1	-4.8	4.0	0.92	2.94	0.47	0.24
12	-5.1	-5.3	-5.1	4.4	0.12	1.74	-0.27	-0.23
14	6.3	-5.5	5.9	5.3	-0.66	-0.34	-0.87	-0.71
16	7.3	7.1	7.0	6.4	-0.88	-0.93	-1.07	-1.09
18	7.6	7.5	7.6	7.7	-1.46	-1.40	-1.58	-1.49
20	11.3	11.0	11.0	40.3	-1.95	-1.80	-1.99	-1.77
22	6.2	6.6	6.6	29.8	-2.47	-2.25	-2.29	-1.05

Distance (cm)	Change in time of peak (ms)				Change in peak rate (m/s)			
	R10	R8	R6	R4	R10	R8	R6	R4
24	27.9	6.7	28.0	25.1	-2.32	-2.82	-1.58	-0.47

Distance (cm)	Change in time of peak (ms)				Change in peak VC (m/s)			
	R10	R8	R6	R4	R10	R8	R6	R4
2	-5.8	-5.3	-6.7	-4.0	0.86	0.83	0.64	0.55
4	-3.7	-4.0	-3.8	-2.9	0.80	0.67	0.35	0.20
6	-3.3	-3.7	-3.3	-2.2	0.70	0.60	0.33	0.19
8	-2.7	-3.5	-2.8	-1.7	0.51	0.45	0.23	0.12
10	-1.7	-3.1	-2.7	-2.2	0.34	0.31	0.13	0.03
12	-0.7	-2.2	-1.3	-0.8	0.22	0.14	0.01	-0.09
14	-0.3	-0.8	-0.3	-0.3	0.09	0.02	-0.09	-0.16
16	1.3	0.8	1.1	0.8	-0.01	-0.09	-0.18	-0.25
18	3.9	4.4	4.4	34.8	-0.10	-0.16	-0.24	-0.26
20	5.6	6.7	6.8	32.1	-0.16	-0.20	-0.28	-0.21
22	-0.4	0.7	25.5	23.7	-0.22	-0.26	-0.24	-0.17
24	19.7	20.0	20.0	29.7	-0.15	-0.26	-0.18	-0.13

R10, Rib 10; R8, Rib 8; R6, Rib 6; R4, Rib 4.

Table 4

Deviations from Rigid Contact in Peak Metrics and Time of Attainment for $\Delta V = 7.0$ m/s

Distance (cm)	Change in time of peak (ms)				Change in peak compression			
	R10	R8	R6	R4	R10	R8	R6	R4
2	-11.5	-12.3	-11.9	-9.8	0.120	0.108	0.028	-0.043
4	-10.3	-11.3	-10.6	-8.0	0.110	0.084	0.011	-0.040
6	-9.2	-10.3	-9.4	-7.1	0.097	0.065	-0.001	-0.046
8	-8.5	-9.7	-9.0	-7.1	0.077	0.048	-0.012	-0.052
10	-7.3	-8.6	-7.7	-6.5	0.060	0.031	-0.024	-0.061
12	-6.1	-7.5	-7.0	-5.2	0.040	0.009	-0.040	-0.074
14	-4.5	-6.0	-5.4	36.4	0.022	-0.011	-0.055	-0.083
16	-2.3	-4.4	-3.7	39.2	0.007	-0.027	-0.070	-0.077
18	-0.3	-1.9	-1.7	41.2	-0.009	-0.045	-0.085	-0.067
20	1.8	-0.2	24.3	39.6	-0.027	-0.066	-0.099	-0.060
22	2.7	2.5	24.4	39.4	-0.045	-0.085	-0.088	-0.050
24	13.9	11.4	17.5	32.3	-0.052	-0.098	-0.075	-0.038

Distance (cm)	Change in time of peak (ms)				Change in peak rate (m/s)			
	R10	R8	R6	R4	R10	R8	R6	R4
2	-3.3	-3.5	-3.5	1.6	4.43	6.26	3.37	1.26
4	-3.5	-3.9	-3.6	1.5	2.73	4.93	2.20	0.23
6	-3.8	-4.1	-3.8	4.4	1.96	4.55	1.36	0.00
8	-4.1	-4.4	-4.1	4.1	1.36	3.96	0.68	0.09
10	-4.2	-4.5	-4.3	4.5	0.47	2.62	-0.07	-0.05
12	5.3	-4.7	5.0	4.8	-0.03	1.11	-0.43	-0.33
14	5.9	-4.9	5.5	5.3	-0.48	-0.40	-0.77	-0.62
16	7.2	6.8	6.6	5.9	-0.86	-0.94	-1.20	-1.28
18	7.8	7.7	7.7	7.5	-1.29	-1.14	-1.29	-1.41
20	8.4	10.7	10.4	9.4	-1.95	-1.83	-1.85	-1.73
22	10.0	10.8	9.6	32.8	-2.47	-2.20	-2.23	-1.91

Distance (cm)	Change in time of peak (ms)				Change in peak rate (m/s)			
	R10	R8	R6	R4	R10	R8	R6	R4
24	5.4	6.1	6.2	25.5	-2.56	-2.29	-2.46	-1.24

Distance (cm)	Change in time of peak (ms)				Change in peak VC (m/s)			
	R10	R8	R6	R4	R10	R8	R6	R4
2	-3.2	-3.1	-2.9	-2.5	1.01	0.83	0.64	0.55
4	-2.6	-2.7	-2.5	-1.9	0.84	0.72	0.30	0.12
6	-2.0	-2.2	-1.9	-0.9	0.78	0.61	0.24	0.09
8	-1.4	-2.0	-1.3	-0.7	0.63	0.50	0.20	0.07
10	-1.0	-1.7	-1.2	0.3	0.44	0.39	0.10	-0.03
12	0.2	-1.0	0.3	0.7	0.30	0.23	0.00	-0.09
14	1.2	0.5	1.0	1.2	0.16	0.07	-0.10	-0.20
16	2.0	1.5	1.5	1.3	0.03	-0.04	-0.20	-0.31
18	4.5	4.1	4.8	4.7	-0.07	-0.15	-0.28	-0.38
20	5.4	5.8	5.6	29.2	-0.16	-0.21	-0.34	-0.31
22	5.3	5.5	6.0	25.6	-0.23	-0.28	-0.39	-0.26
24	0.5	0.8	22.5	20.7	-0.28	-0.33	-0.34	-0.21

R10, Rib 10; R8, Rib 8; R6, Rib 6; R4, Rib 4.

Table 5

Deviations from Rigid Contact in Peak Metrics and Time of Attainment for $\Delta V = 8.0$ m/s

Distance (cm)	Change in time of peak (ms)				Change in peak compression			
	R10	R8	R6	R4	R10	R8	R6	R4
2	-9.8	-10.1	-9.6	-6.9	0.113	0.099	0.010	-0.075
4	-8.6	-9.7	-9.1	-6.2	0.102	0.077	-0.004	-0.064
6	-8.1	-8.7	-8.2	-6.0	0.093	0.056	-0.019	-0.073
8	-7.1	-8.1	-7.2	-5.8	0.080	0.043	-0.026	-0.074
10	-6.1	-7.3	-6.2	-5.2	0.064	0.027	-0.037	-0.082
12	-4.9	-6.1	-5.1	-4.3	0.046	0.008	-0.051	-0.093
14	-3.5	-5.0	-4.4	-2.8	0.031	-0.009	-0.065	-0.097
16	-2.0	-3.5	-3.2	-1.8	0.015	-0.026	-0.077	-0.090
18	-0.5	-1.5	-1.5	-0.5	-0.001	-0.042	-0.090	-0.088
20	0.9	0.2	1.6	3.2	-0.016	-0.057	-0.101	-0.079
22	2.7	2.0	22.5	34.7	-0.028	-0.070	-0.097	-0.072
24	0.1	4.8	18.4	29.9	-0.046	-0.089	-0.085	-0.051

Distance (cm)	Change in time of peak (ms)				Change in peak rate (m/s)			
	R10	R8	R6	R4	R10	R8	R6	R4
2	-3.0	-3.2	-3.2	1.6	4.33	6.05	2.98	0.96
4	-3.2	-3.6	-3.3	1.5	2.41	4.63	1.88	0.38
6	-3.6	-3.9	-3.6	4.3	1.40	3.88	0.81	-0.29
8	4.5	-4.1	-3.9	4.4	0.95	3.61	0.21	-0.15
10	5.1	-4.4	4.7	4.4	0.63	2.22	-0.47	-0.41
12	5.6	-4.5	5.3	5.0	-0.01	1.00	-0.73	-0.70
14	5.7	5.4	5.3	5.2	-0.34	-0.49	-0.81	-0.81
16	6.1	5.7	5.7	5.5	-0.85	-0.86	-1.09	-1.06
18	7.8	7.2	7.3	8.1	-1.17	-1.07	-1.31	-1.46
20	8.1	7.8	7.9	8.6	-1.71	-1.40	-1.49	-1.55
22	9.2	10.2	10.4	9.1	-1.96	-1.75	-2.14	2.33

Distance (cm)	Change in time of peak (ms)				Change in peak rate (m/s)			
	R10	R8	R6	R4	R10	R8	R6	R4
24	7.1	7.4	7.0	25.7	-2.89	-2.41	-2.35	-2.00

Distance (cm)	Change in time of peak (ms)				Change in peak VC (m/s)			
	R10	R8	R6	R4	R10	R8	R6	R4
2	-5.0	-5.0	-7.3	-7.0	0.98	0.83	0.64	0.55
4	-4.5	-4.6	-4.6	-4.3	0.85	0.74	0.18	-0.08
6	-4.0	-4.3	-4.0	-3.1	0.89	0.64	0.13	-0.10
8	-3.3	-3.8	-3.1	-2.6	0.75	0.52	0.11	-0.08
10	-2.7	-3.6	-2.8	-2.0	0.57	0.38	0.00	-0.18
12	-1.5	-3.0	-2.6	-1.0	0.42	0.24	-0.10	-0.26
14	-1.0	-1.8	-0.9	-0.7	0.27	0.11	-0.17	-0.32
16	-0.1	-0.5	-0.4	-0.5	0.10	-0.03	-0.27	-0.42
18	0.9	0.5	0.1	2.4	-0.03	-0.14	-0.38	-0.52
20	3.1	2.9	3.1	24.0	-0.14	-0.25	-0.45	-0.50
22	3.8	3.7	3.8	23.3	-0.20	-0.29	-0.51	-0.46
24	0.8	0.5	0.7	16.7	-0.31	-0.39	-0.58	-0.37

R10, Rib 10; R8, Rib 8; R6, Rib 6; R4, Rib 4.

Table 6

Deviations from Rigid Contact in Peak Metrics and Time of Attainment for $\Delta V = 9.0$ m/s

Distance (cm)	Change in time of peak (ms)				Change in peak compression			
	R10	R8	R6	R4	R10	R8	R6	R4
2	-8.7	-9.2	-8.7	-6.6	0.101	0.085	-0.007	-0.103
4	-7.7	-8.6	-6.5	-3.9	0.095	0.069	-0.012	-0.075
6	-7.2	-8.0	-7.1	-1.6	0.087	0.048	-0.033	-0.088
8	-6.1	-6.9	-5.8	-4.6	0.078	0.034	-0.040	-0.096
10	-5.4	-6.1	-5.1	-4.2	0.067	0.023	-0.046	-0.099
12	-4.3	-5.1	-4.0	-3.4	0.052	0.008	-0.058	-0.107
14	-3.3	-4.1	-3.4	17.7	0.035	-0.010	-0.072	-0.111
16	-2.1	-2.7	-2.1	20.0	0.021	-0.026	-0.084	-0.111
18	-0.8	-1.2	10.7	22.6	0.005	-0.042	-0.097	-0.099
20	0.7	0.4	13.7	25.1	-0.003	-0.050	-0.100	-0.098
22	2.2	2.0	16.8	28.5	-0.018	-0.065	-0.100	-0.085
24	-3.1	-3.4	12.3	25.2	-0.034	-0.080	-0.094	-0.069

Distance (cm)	Change in time of peak (ms)				Change in peak rate (m/s)			
	R10	R8	R6	R4	R10	R8	R6	R4
2	-2.8	-3.0	-3.0	1.9	4.18	5.80	2.62	0.65
4	-2.9	-3.3	-3.0	-0.7	2.16	4.32	1.51	1.01
6	1.9	-3.6	-3.2	4.6	0.98	3.37	0.36	-0.68
8	4.6	-3.9	-3.6	4.6	0.81	3.23	-0.23	-0.67
10	5.2	-4.0	4.9	4.6	0.80	2.07	-0.73	-0.73
12	5.6	-4.2	5.1	4.7	0.38	0.53	-0.90	-0.94
14	6.2	5.6	5.5	5.0	-0.29	-0.62	-1.13	-1.18
16	6.3	6.1	5.9	5.7	-0.62	-0.72	-1.12	-1.26
18	7.2	6.4	6.3	6.1	-1.26	-1.17	-1.39	-1.45
20	8.4	7.7	7.7	8.6	-1.65	-1.31	-1.53	-1.78

Distance (cm)	Change in time of peak (ms)				Change in peak rate (m/s)			
	R10	R8	R6	R4	R10	R8	R6	R4
22	8.7	8.3	8.6	8.7	-1.99	-1.61	-1.77	-1.90
24	3.0	3.3	3.4	2.6	-2.16	-1.82	-2.32	-2.63

Distance (cm)	Change in time of peak (ms)				Change in peak VC (m/s)			
	R10	R8	R6	R4	R10	R8	R6	R4
2	-3.6	-3.7	-4.0	-4.7	0.89	0.83	0.64	0.55
4	-3.7	-3.8	-3.9	-4.0	0.82	0.72	0.09	-0.28
6	-2.8	-3.0	-2.7	-1.8	0.88	0.60	0.02	-0.27
8	-2.3	-2.7	-2.0	-1.4	0.77	0.45	-0.05	-0.30
10	-1.6	-2.1	-1.5	-1.2	0.68	0.37	-0.08	-0.33
12	-0.5	-1.8	-1.0	-0.2	0.51	0.22	-0.18	-0.41
14	0.1	-1.0	-0.4	0.5	0.34	0.07	-0.29	-0.50
16	0.8	0.3	0.7	1.0	0.18	-0.04	-0.35	-0.55
18	1.7	1.3	1.3	1.2	-0.01	-0.17	-0.44	-0.66
20	4.1	2.2	4.0	4.5	-0.12	-0.29	-0.54	-0.72
22	4.9	4.3	4.4	21.6	-0.23	-0.38	-0.61	-0.64
24	1.1	-2.1	-1.7	14.2	-0.30	-0.44	-0.69	-0.55

R10, Rib 10; R8, Rib 8; R6, Rib 6; R4, Rib 4.

Table 7Metric sensitivity to occupant distance, normalized to valued at $\Delta V = 4$ m/s

ΔV (m/s)	C (1/cm)	NormC (1/cm)	VC(m/s/cm)	NormVC (1/cm)
4	-0.013	1.00	-0.046	1.00
5	-0.011	0.91	-0.051	1.10
6	-0.010	0.81	-0.064	1.39
7	-0.010	0.76	-0.070	1.51
8	-0.006	0.48	-0.074	1.59
9	-0.008	0.64	-0.086	1.86

C: Chest compression sensitivity

NormC: Chest compression sensitivity normalized to $\Delta V = 4$ m/s

VC: Viscous criterion sensitivity

NormVC: Viscous criterion sensitivity normalized to $\Delta V = 4$ m/s