# Coupled Human Body Side Impact Model to Predict Thoracic Injury

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## ABSTRACT

The goal of this study was to evaluate side impact crash conditions using a detailed human body model and side impact crash model to provide an improved understanding of side impact injury and the primary contributing factors. This study builds on an advanced numerical human body model, including a detailed thorax, which has been validated using available PMHS test data for pendulum and side sled impact tests. Crash conditions were investigated through use of a coupled side impact model, used to reproduce full scale crash tests. The model accounts for several important factors that contribute to occupant response as noted in the literature: the relative velocities between the seat and door, the occupant to door distance, the door shape and compliance. The coupled side impact model was validated using FMVSS 214 and IIHS side impact test data, comparing the thoracic response predicted by the model to that of the ES-2 dummy used in the crash tests. Importantly, the door and seat models were developed based on experimental data in the literature.

The side impact model was used to investigate the effects of door to occupant spacing, door velocity profile, restraint system, and seat foam properties. The current study was limited to the use of velocity profiles in the direction of impact and did not consider rotational effects or motion perpendicular to the impact direction. It was found that injury as predicted using the detailed human body model and the Viscous Criterion (VC) was controlled by the second velocity peak typically found in door velocity profiles.

## INTRODUCTION

Although there have been tremendous improvements in crash safety there has been an increasing trend in side impact fatalities, rising from 30% to 37% of total fatalities from 1975 to 2004 [1]. Between 1979 and 2004, 63% of AIS≥4 injuries in side impact resulted from thoracic trauma [1]. Lateral impact fatalities, although decreasing in absolute numbers, now comprise a larger percentage of total fatalities. Safety features are typically more effective in frontal collisions compared to side impact due to the reduced distance between the occupant and intruding vehicle in side impact collisions.

Automotive research is a challenging field due to the complexity and cost associated with full-scale vehicle testing. Recent efforts have focused on the development of advanced finite element models of vehicles and occupants capable of reproducing the response present in crash scenarios.

Forbes [2,3] developed a detailed numerical human thorax model with simplified models of the remaining body regions. The human body model developed by Forbes [2,3] was validated by correlating the response of pendulum and sled simulations to tests performed on PMHS. This study has integrated the human body model in crash scenarios representing FMVSS 214 side impact testing. This research is intended to provide a detailed understanding of thoracic response due to side impact using the numerical human body model previously developed [2-5]. The first goal of this study was to develop and validate a side impact model capable of reproducing the conditions present in full scale crash testing. The second goal of this study was to perform a parametric study varying conditions in the side impact model to provide an understanding of loading and its effect on thoracic trauma in side impact collisions.

## SIDE IMPACT MODEL DEVELOPMENT AND VALIDATION

The side impact model (Figure 1) was developed to reproduce the important conditions present in side impact crash scenarios. The model accounts for several factors that contribute to occupant response based on the literature [5-11] including: the relative velocities between the seat and door, the occupant to door distance, door shape, and door compliance.

Although some components were simplified in terms of geometry, they were based on geometries found in typical vehicles and material characteristics determined by experiment or found in the literature.

The side impact model consisted of several components modeled as rigid materials, including the seatbelt anchors, sled base, and outer door. The seat, seatbelts, and door were based on representative geometries and material properties determined by experimental testing and data from the literature [7,12-17].

The simplified door was based on a cross section of a Ford Taurus model door [18] for consistency with the side impact test data used in this study. The door was sectioned through the area that had the greatest armrest depth in order to produce a conservative door model geometry. The mechanical response of the simplified door model was set to produce the same force-deflection characteristics as found in the literature [13].

The seat pan, sled base, and door were given prescribed velocity profiles based on full-scale crash tests from the NHTSA database, applied for the duration of the simulation. The sled was constrained vertically and in the direction perpendicular to impact to prevent rotations. Although rotational velocities do exist in full scale crash testing, any significant rotation tends to occur long after the maximum thoracic response is observed and was not considered for this study.

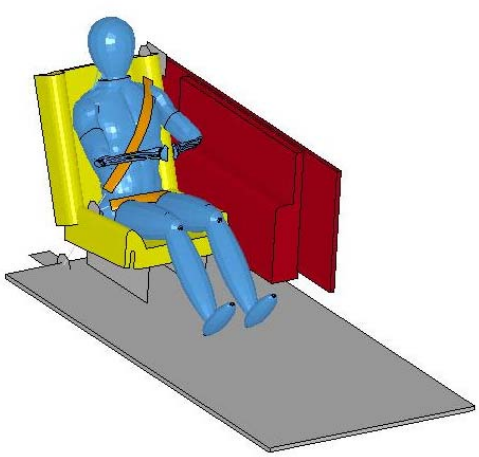

**Figure 1 Side Impact Model.**

The validation of the side impact model was done by comparing the thoracic response of the human body model to experimental results from an ES-2 for two side impact crash scenarios reported here. Velocity inputs from two specific cases were selected and the side impact model was modified to represent a FMVSS 214 test of a Ford Taurus and an IIHS test of a Nissan Maxima. For brevity, only the Ford Taurus data is presented in this paper. These two test cases were selected for several reasons. First, accurate velocity profiles for the vehicle CG, seat, and door were required to provide input conditions for the side impact model. However, door accelerometers are not regularly included in side impact test procedures, therefore narrowing the test cases to those tests that do include door accelerometers. Second, current and past research using the human body model has focused on VC response to predict injury. However, typical side impact test procedures use a Side Impact Dummy (SID) with TTI injury criteria based on accelerations. This further narrowed the available side impact tests to those that use the ES-2 since VC is used as the injury criteria. Finally, two test types (FMVSS 214 and IIHS) with different test procedures were selected to validate the side impact model under differing test conditions.

**Side Impact Model Input Profiles**

Based on information for similar sled tests in the literature [10,19,20], input velocities for the sled, seat, and door were determined by the integration of accelerations recorded by uniaxial accelerometers positioned at the vehicle CG, driver seat track, and inner door panel respectively. Full-scale crash data was obtained from a FMVSS 214 and an IIHS test [21,22]. These tests used a modified 50$^{th}$ percentile ES-2 dummy so comparison of the simulated occupant response to the ES-2 response was based on rib deformation compression, velocity, and the Viscous Criterion. Input pulses for the FMVSS 214 test are shown in Figure 2 and application to the side impact model in Figure 3.

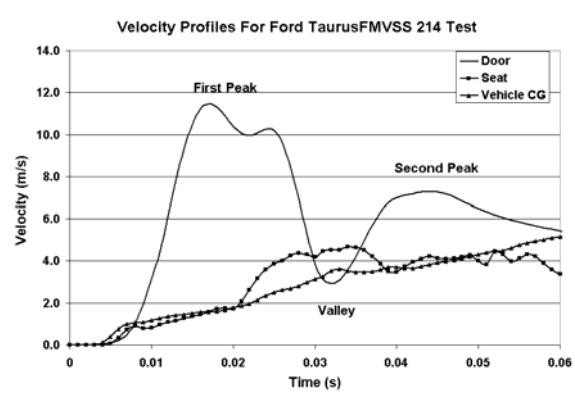


**Figure 2 Input Velocity Profiles [22].**

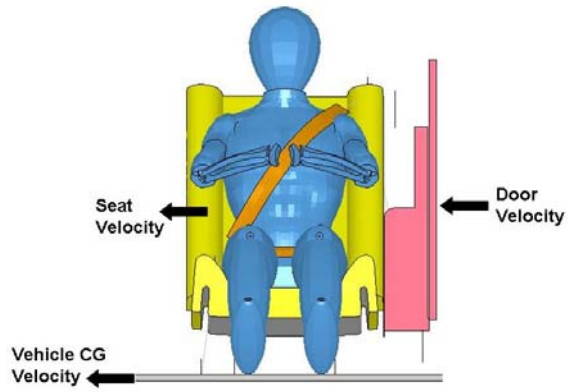


**Figure 3 Side Impact Model with Input Velocities**

It should be noted that vehicles were equipped with several accelerometers; however, the exact location often varies from vehicle to vehicle. Also, because the door was directly impacted by the intruding moving deformable barrier (MDB), sensors may rotate during the collision. This can result in inaccurate results, as acceleration will not be measured with respect to the expected coordinate system. However, for the purposes of this study, it was assumed that the accelerometer data was accurate and rotation occurred after injury was predicted, approximately 50 msec after the initial impact.

**Measuring Thoracic Response**

The ES-2 records numerous acceleration, displacement, and force responses throughout the duration of a crash event. However, for this study, only the lower, middle, and upper rib responses were evaluated for comparison with the human body model. For purposes of comparison, three levels have been selected on the human body model, representing anatomically equivalent areas to the lower, middle, and upper ribs of the ES-2 (Figure 4).

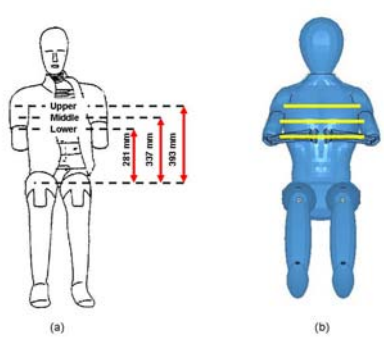


**Figure 4 Response Locations (a) ES-2 Rib Location (b) Model Chest Levels.**

The ES-2 measures deflection based on the half thorax dimension, by measuring the deflection of the ribs on the struck side. To ensure comparable results, the response of the human body model was also predicted using the half thoracic deflection as defined by Samaha et al. [23].

The degree of injury was measured using the Viscous Criterion developed by Lau & Viano [24]. Lau & Viano defined the viscous response (VC) as the product of deformation velocity, V(t), and the instantaneous normalized compression, C(t).

$$VC(t) = V(t) x C(t) \qquad (1).$$

Where $C(t) = \dfrac{D(t)}{D_o}$ and $V(t) = \dfrac{d[D(t)]}{dt}$

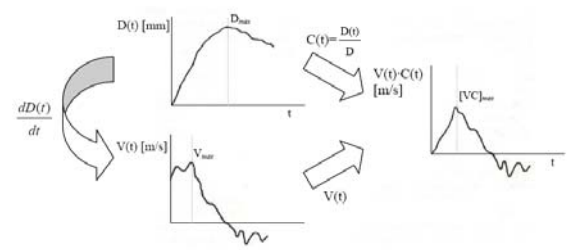


**Figure 5 The Viscous Criterion [24].**

**Validation with FMVSS 214 Crash Test**

The human body side impact simulation response during an impact with velocity profiles (Figure 2) and Arm to Door (AD) distance as determined by the FMVSS 214 side impact testing of a Ford Taurus is shown in Figure 6.

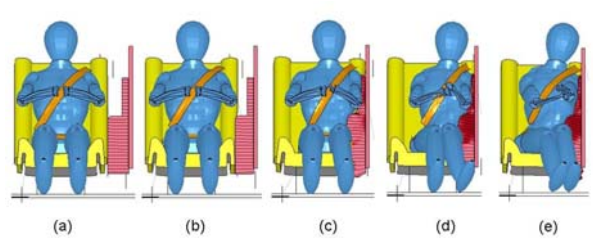


**Figure 6 Impact Sequence of Ford Taurus Side Impact Simulation (a) t=0 ms (b) t=15ms (c) t=30ms (d) t=45ms (e) t=60ms.**

The simulated compression, velocity, and VC response for the upper chest band described in Figure 4 is compared to the ES-2 response obtained from a full-scale FMVSS 214 crash test in the figures below (Figure 7, 8 and 9). Additional data and comparisons can be found in Campbell [12].

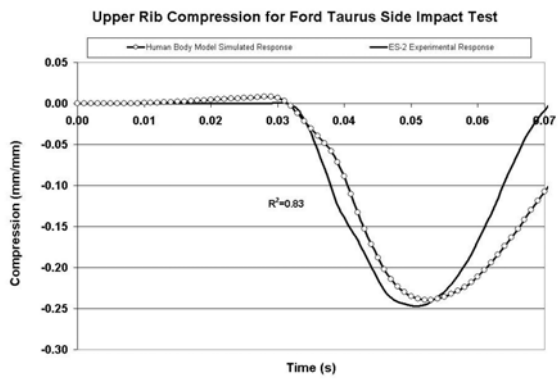


**Figure 7 Upper Rib Compression Response for the Side Impact Model with Ford Taurus Inputs.**

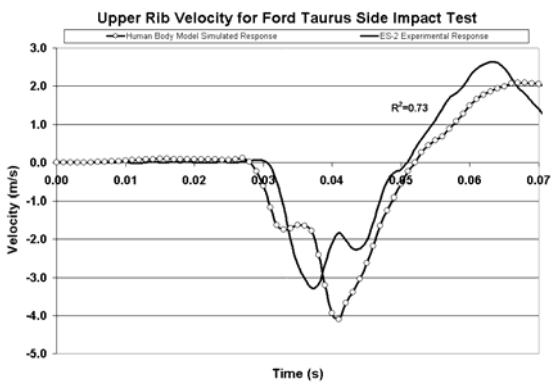


**Figure 8 Upper Rib Velocity Response for the Side Impact Model with Ford Taurus Inputs.**

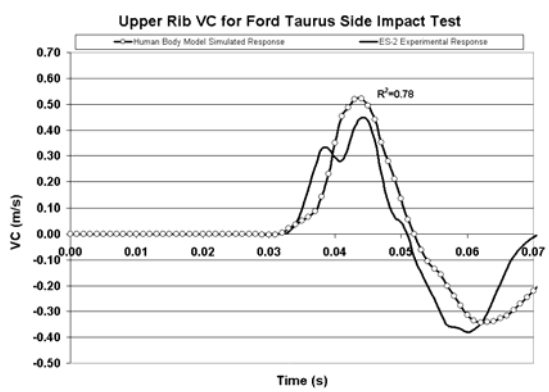


**Figure 9 Upper Rib VC Response for the Side Impact Model with Ford Taurus Inputs.**

Model assessment was undertaken following the methods used by Forbes. The predicted thoracic response was compared to ES-2 based on data for loading, peak, unloading, and overall r-squared for the curves. The following qualitative measures as applied in previous validation of the human body model [2,3] have been used to compare the simulated response to the experimental response (Table 1):

- Good — Falling close to the experimental response at the discretion of the author
- Reasonable — Falling reasonably close to the experimental response at the discretion of the author
- Poor — Falling significantly far from the experimental response at the discretion of the author

**Table 1 Side Impact Simulation vs Ford Taurus v3522 Injury Response Correlation**

| CHEST BAND | IMPACT PHASE | CORRELATION | | |
|---|---|---|---|---|
| | | Compression (mm/mm) | Velocity (m/s) | VC (m/s) |
| Upper Rib | Loading | Good | Reasonable | Good |
| | Peak | Good | Reasonable | Reasonable |
| | Unloading | Reasonable | Good | Good |
| | $R^2$ | 0.83 | 0.73 | 0.78 |
| Middle Rib | Loading | Good | Good | Good |
| | Peak | Good | Good | Good |
| | Unloading | Reasonable | Reasonable | Reasonable |
| | $R^2$ | 0.67 | 0.56 | 0.58 |
| Bottom Rib | Loading | Reasonable | Reasonable | Poor |
| | Peak | Reasonable | Poor | Poor |
| | Unloading | Reasonable | Reasonable | Reasonable |
| | $R^2$ | 0.53 | 0.51 | 0.40 |

The information presented in Table 1 shows that the side impact model closely reproduced the timing and injury response as measured in the FMVSS 214 test, producing *good* to *reasonable* response overall. Discrepancies are attributed to minor differences in occupant positioning, door positioning and compliance, and geometric differences between the ES-2 and human body model at the specified chest band locations.

## SIDE IMPACT SIMULATION - PARAMETRIC STUDY RESULTS

The side impact and human body models were used to undertake a parametric study to evaluate the different factors that contribute to injury response.

For this aspect of the study, injury was evaluated based on full thorax deformation (as opposed to half thorax for the ES-2 comparison) using the same chest band locations implemented by Forbes [2,3] to ensure consistency with prior human body model usage and PMHS testing in the literature [2,3,25].

Thoracic response was measured using upper, middle, and lower chest bands located at the lateral level of the 4$^{th}$ rib, level of the xiphoid process, and the level of the 10$^{th}$ rib respectively (Figure 11). Also, it was found that the half thoracic deflection was lower than the full thoracic deflection, in agreement with the literature [26]. This indicates that a considerable amount of deformation occurs on the non-struck side, which is unaccounted for when using the half thoracic response. Maltese et al. [26] clearly show that the half thoracic deflection is often approximately 60% of the full thoracic deflection. Similar differences between full and half thoracic deflection were found for the human body model as seen in Figure 10.

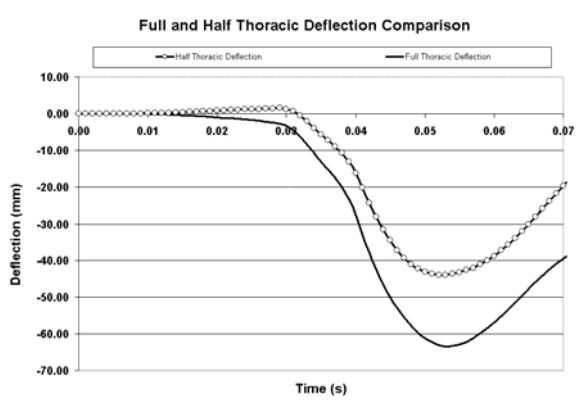


**Figure 10 Human Body Model Full and Half Thoracic Deflection Comparison.**

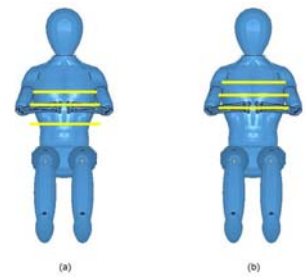


**Figure 11 Chest band location: (a) Parametric Study Location (b) Validation Case Location.**

### Side Impact Model Baseline Conditions

The velocity profiles, door compliance, and occupant position for the validation case above were used as the baseline for the parametric study (Figure 2).

Full-scale side impact tests typically produce door intrusion velocity profiles that consist of three common characteristics; first peak, valley, and second peak [10]. The first peak occurs immediately after the barrier contacts the door causing the door velocity to rapidly increase to its initial peak. The door velocity then decreases to its valley as the vehicle side structure transfers load to the main structure of the vehicle [11]. The second peak in door velocity is caused by stiffening of the barrier prior to slowing to its final velocity. It has been found that the overall kinematics of the door is essentially unaltered by the interaction with the occupant [27].

### The Effect of Varying Door to Occupant Distance

This study investigates the effect of the door to occupant distance by using two door types; a rigid plate and a representative door with armrest (Figure 12). The AD spacing used in this study was selected to cover a range as determined by the maximum and minimum values found in FMVSS 214 test reports [28].

One would expect that increasing the spacing between the occupant and the intruding door would reduce occupant injury. The amount of space between the occupant and the door has a direct effect on the contact velocity as well as the contact timing with respect to the velocity profile [10]. The effect of the occupant to door spacing was investigated by varying the spacing of an intruding rigid door and

armrest in the side impact model. As discussed in the previous section, the velocity profiles applied to the side impact model were controlled by the crushing of the vehicle structure and were independent of occupant positioning. Therefore, the velocity profiles for the baseline case were applied for each AD distance in this study.

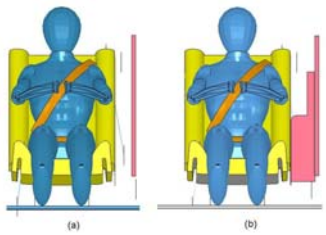


**Figure 12 Door Type (a) Rigid Door (b) Armrest.**

Two cases were used to investigate the effects of door to occupant spacing. First, a rigid door as seen in Figure 12 was used to investigate the effect of varied AD distance excluding effects caused by armrest geometry and compliance. Second, the same AD study was performed to investigate differences in thoracic response caused by the presence of an armrest in comparison to a flat rigid door.

**Rigid Door Simulation** - The upper band VC response for varying door to occupant distances for an intruding rigid door is shown in Figure 13.

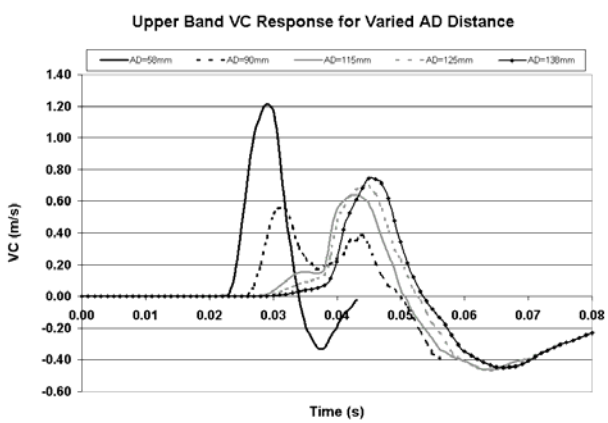


**Figure 13 Upper Band VC Response for Varied AD Distance of an Intruding Rigid Door.**

Investigating the VC response shown in Figure 13 can provide some insight into the timing of injury and the role of the occupant to door distance. Two curves (58mm & 90mm) had their peak injury response occurring just after the first peak in the door intrusion velocity profile (Figure 14). The remaining three scenarios (115mm, 125mm, and 138mm) had their maximum injury response closely coinciding in time with the second peak of the door velocity profile. Further insight may be provided by examining the contact timings of the door to chest as determined by the upper band velocity response shown in Figure 14.

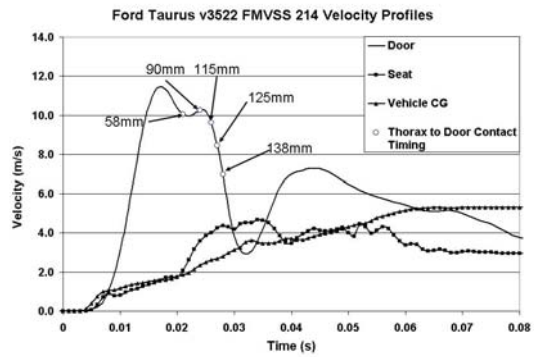


**Figure 14 Contact Timing for Varying Door to Occupant Spacing.**

The contact timings for the five AD spacings discussed occur within 7 ms of each other, but have a significant influence on occupant injury despite the minor differences in contact timing. The variance in injury responses may be explained by examining the occupant motion relative to the sled base by tracking the velocity of the center of the occupant chest relative to the sled floor (Figure 15).

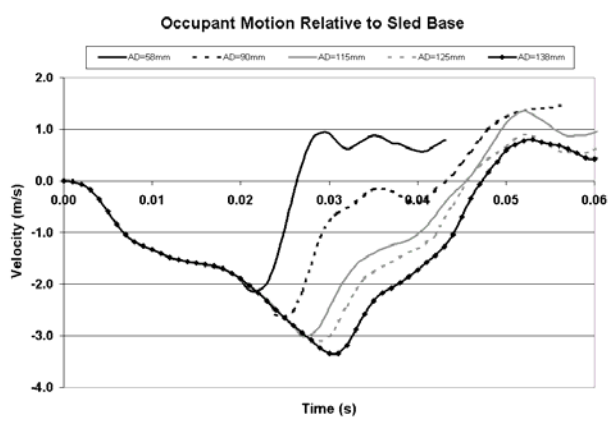


**Figure 15 Occupant Motion Relative to Sled Base for Varied Door to Occupant Spacing.**

The occupant response relative to the sled base in Figure 15 essentially consists of a decrease in occupant velocity relative to the sled floor prior to

door contact followed by an increase in occupant velocity after contact. Therefore, the decreasing relative velocity actually represents the sled floor moving while the occupant remains relatively stationary due to its inertia. When contact with the door occurs the occupant velocity begins to catch-up to and surpass the velocity of the sled.

One would expect that thoracic response would inversely correlate to AD distance, such that an increase in AD distance would cause a decrease in injury. This inverse correlation does occur to some extent in the scenario presented and would likely occur for all AD distances if not for the second peak in the door velocity profile.

For a door to occupant distance of 58mm, the VC response is controlled by the first peak and VCmax occurs just before the door velocity profile valley. The thoracic compression present at the onset of the second peak in door velocity was 20.9% and was the maximum compression observed in the study [12]. The velocity of chest compression at the onset of the second peak is near zero, confirming that the chest has in fact reached the maximum compression at this point. The occupant motion relative to the sled base prior to the second peak suggests that the occupant has surpassed the velocity of the sled floor due to the aggressive impact with the intruding door.

The 90mm door to occupant scenario can be described in much the same way as the 58mm case. However, the 115mm case differs as it was controlled by the second peak in the door velocity profile. The first peak did produce minor thoracic response as observed in the VC response shown in Figure 13, but was superseded by the injury produced by the second peak. This response can be largely explained by the time of contact and occupant response prior to the second peak. As seen in Figure 14, the contact timing for an AD of 115mm occurs as the door was decelerating to its valley, which decreased the time for the door to compress the chest and accelerate the occupant. In this case, the chest compression is only 5% prior to the second peak [12]. Also, the occupant velocity relative to the sled base suggests that the occupant was beginning to accelerate due to contact with the intruding door, but was still moving considerably slower than the sled floor. These factors significantly increase the effect of the second peak because the occupant was not accelerated enough to minimize the impact of the second peak.

The same reasoning can be applied to the final two cases (125mm and 138mm). Injury in both cases was highly influenced by the second peak due to the time of contact with the intruding door. As intuition would suggest, the first peak response continually decreases as AD distance increases, but this decrease in first peak response causes an increase in the effects of the second peak, thus creating the observed VC response. The later contact time reduces the ability of the first peak to accelerate the occupant, thereby causing the second peak to be far more injurious than observed in scenarios with smaller AD distances.

**Padded Armrest Simulation** - The VCmax of an occupant for varied AD spacing of a simplified door including an armrest is compared to that of a rigid flat door in the following bar chart (Figure 16). Trend lines are included to track VCmax for varying AD spacings.

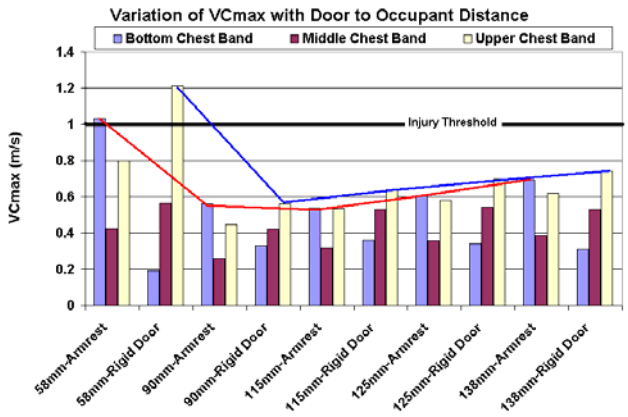


**Figure 16 Variation of VCmax with Door to Occupant Distance.**

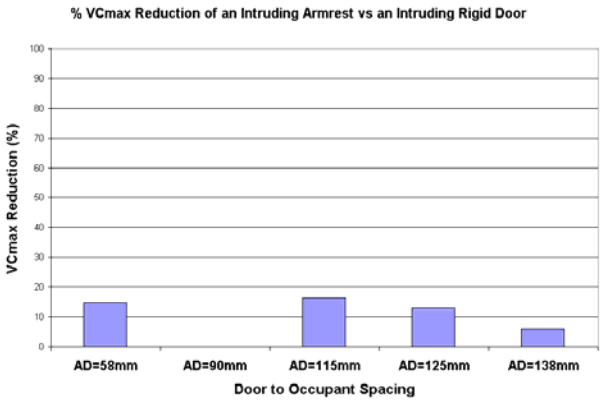


**Figure 17 VCmax Reduction of an Intruding Deformable Door vs an Intruding Rigid Door.**

As one would expect, the presence of an armrest tends to increase the injury response at the level of the lower chest band in comparison to the rigid door. This response can be attributed to an earlier time of contact with the thorax due to the geometry of the armrest effectively reducing the door to occupant spacing. Also, the armrest caused the localized deformation of the thorax, therefore resulting in higher levels of compression and VC response. Although the peak VC response observed does not change drastically, the maximum injury was found at the level of the lower chest band when an armrest was present. However, the presence of an armrest tended to reduce the VCmax observed by a maximum of 16% compared to the VC response caused by an intruding rigid door (Figure 17). This shows that door compliance and shape plays a significant role in thoracic response. The VC response of the upper chest band is presented in Figure 18.

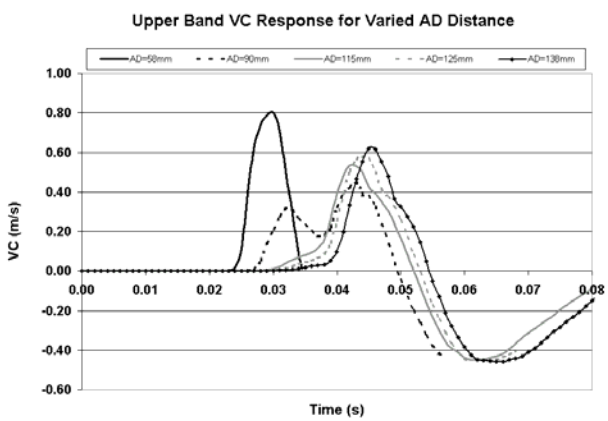


**Figure 18 Upper Band VC Response for Varied AD Distance, Deformable Door.**

The effect of door to occupant spacing on the thoracic response of an occupant due to an intruding armrest can be explained in a similar fashion to the case of a rigid intruding door previously discussed.

### The Effect of Varying Door Intrusion Velocity

Based on information from the literature and the arm to door distance investigation, it is clear that the door interaction with the occupant is an important factor in occupant injury. The occupant to door distance study above showed that the distance was an important factor in determining thoracic response, but the relationship between VCmax and AD distance was not linear. This is largely due to the effects of the velocity profile and variation in contact timing. The following study examines the effect of the velocity profile by varying the first and second peak of the velocity profile by +/- 15% as shown in Figure 19. This velocity profile study was based on the research performed by Morris et al. [10]. As in the previous case study, it was assumed that the velocity profiles applied to the side impact model were independent of occupant positioning.

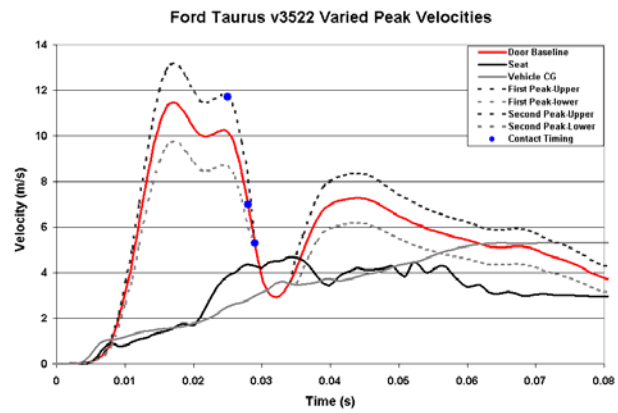


**Figure 19 Varied Door Intrusion Velocity Profile & Contact Times.**

Figure 20 shows the relationship between injury and velocity profile for variations in first and second peak velocity.

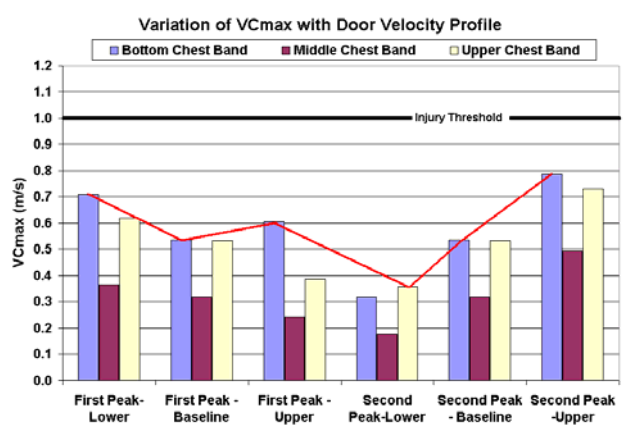


**Figure 20 Variation of VCmax with Door Velocity Profile.**

The VC responses for the upper chest band are shown below. As expected, the variation in velocity profile has a significant effect on occupant response.

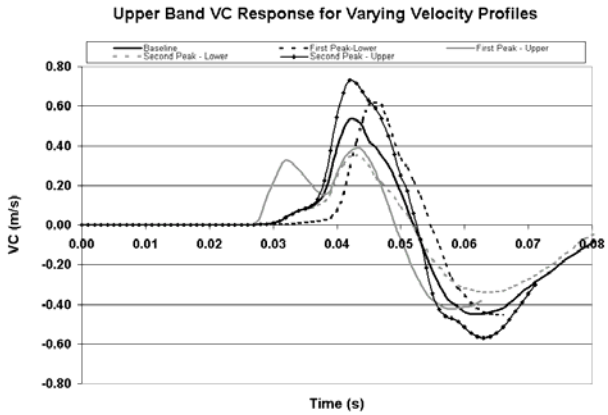


**Figure 21 Upper Band VC Response for Varying Velocity Profiles.**

Figure 21 shows that the peak VC response in each scenario corresponds in time with the second peak of the door velocity profile. However, varying the first peak had a significant impact on the magnitude of VC response produced by the second peak. This can be explained by investigating the occupant motion relative to the sled base (Figure 22). As it has been shown that VC response was largely dependant on the second peak in velocity profile, increasing the velocity of the second peak would clearly increase thoracic response and a decrease in peak velocity would result in a decreased VC response.

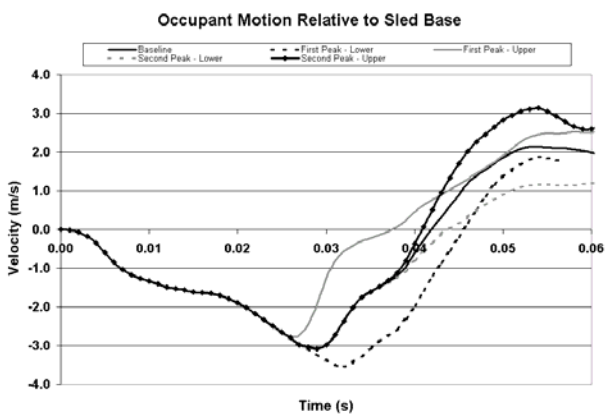


**Figure 22 Occupant Motion Relative to Sled Base for Varied Door Intrusion Velocity Profile.**

Similar to the previous study on varied AD distance, variation in velocity profile had a somewhat counter-intuitive effect on occupant injury. Although VC response in the current scenario corresponds in time with the second velocity peak for all cases, the first peak directly contributes to the degree at which the second peak influenced VC.

For the baseline case and therefore the cases varying the second peak velocity, the effect of the first peak was the same in terms of chest compression, velocity of compression, VC, and occupant motion relative to the sled base. Since the conditions prior to the second peak were known and constant for the baseline, upper second peak, and lower second peak it was possible to understand the effect of the second peak velocity irrespective of the effects of the first peak. It is clear that the second peak of the door intrusion velocity profile follows conventional expectations, such that an increase in velocity would cause an increase in injury and a decrease in velocity would cause a subsequent decrease in injury.

However, the first peak acts as a means to accelerate the occupant following contact with the door, thereby increasing the occupant velocity and minimizing the impact of the second peak. An increase in first peak velocity would reduce the effect of the second peak, while a decrease in the first peak would increase the influence of the second peak. This effect can be observed by comparing the occupant motion relative to the sled base (Figure 22) and VC response (Figure 21) for the baseline, upper first peak, and lower first peak.

Figure 23 shows that increasing the first peak velocity by 15% can reduce the Upper Band VCmax by 27% and decreasing the first peak velocity by 15% can increase the Upper Band VCmax by 16%. However, increasing the second peak velocity by 15% increases the Upper Band VCmax by 37% and decreasing the second peak velocity by 15% caused a 33% reduction of the Upper Band VCmax.

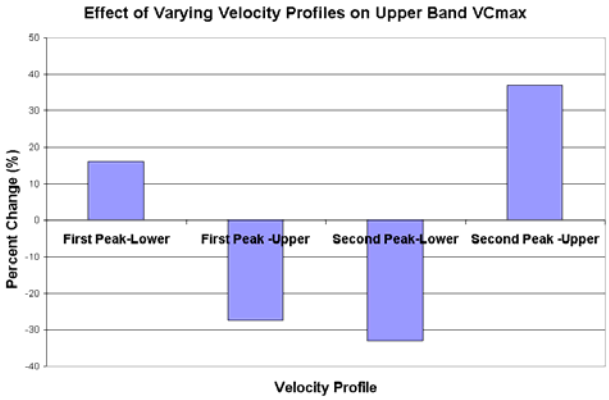


**Figure 23 The Effect of Varying Velocity Profiles on Upper Band VCmax.**

The middle chest band follows the same tendencies as the upper band in response to varied velocity profiles. However, the response of the lower chest band did not follow the same trend as the middle and upper band for the case of an increase in first peak velocity (Figure 20). This discrepancy was due to the high contact velocity at the lower chest band caused by the reduced door to occupant distance due to the armrest geometry.

As shown in Figure 24, the Lower Band VCmax occurred at the first peak in the response. Although the first peak did not control injury for the middle and upper chest bands in this study, a greater increase in first peak velocity would result in injury being dominated by the first peak, similar to the response of the lower chest band.

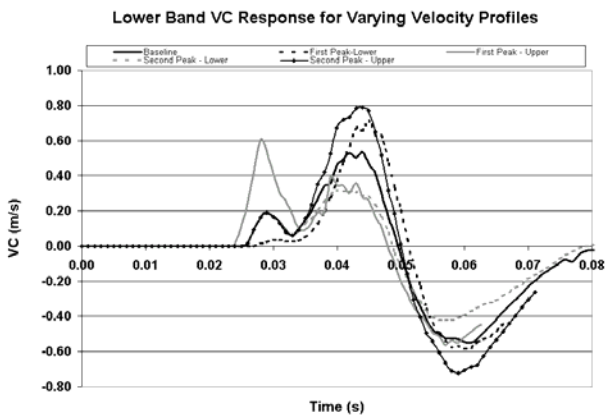


**Figure 24 Lower Band VC Response for Varying Velocity Profiles.**

### The Effect of Varying Seat Foam on Thoracic Trauma

The seat acts as a primary point of interaction between the occupant and the vehicle, although seat foam is predominately used as a means of improving occupant comfort. While the mechanical properties of common seat foams fall within a relatively small range, their impact on occupant injury can be significant despite being largely developed for comfort rather than safety. This study presents the relevance of seat foam in side impact by comparing the occupant response in a seat modeled using a high stiffness (Foam 2) and a low stiffness (Foam 4) foam characterized for varying rates of strain [7,12]. The results are summarized in the bar chart presented in Figure 25.

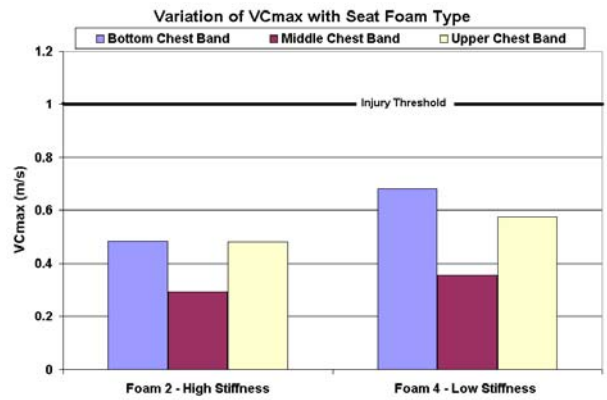


**Figure 25 Variation of VCmax with Seat Foam Type.**

Despite modest differences in mechanical properties, seat foam clearly plays a significant role in side impact occupant safety. Figure 26 shows that using the low stiffness foam instead of the high stiffness foam caused a 41% increase in the observed VCmax value.

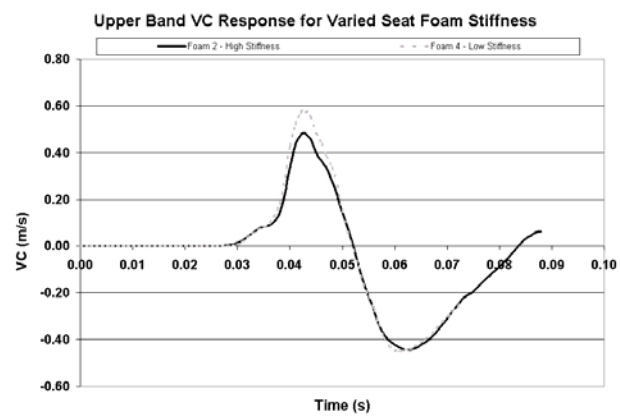


**Figure 26 Upper Band VC Response for Varied Seat Foam Stiffness.**

The response of the three chest bands were comparable in terms of their shape and timing, however the peak response observed when using Foam 4 was elevated for the compression, velocity, and VC [12]. This variation in response may be explained by comparing the occupant motion relative to the sled for each foam (Figure 27).

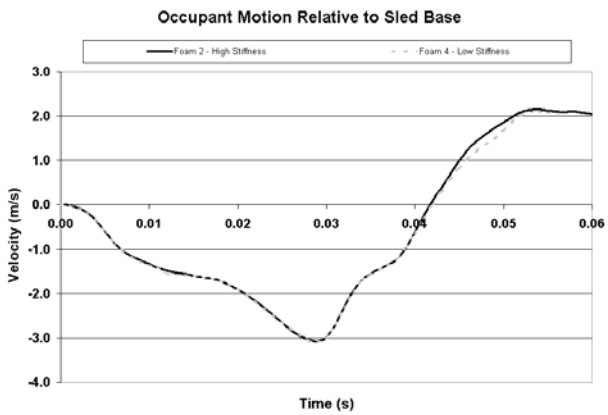


**Figure 27 Occupant Motion Relative to Sled Base for Varied Foam Stiffness.**

It can be seen that seat foam had minimal effect on occupant motion relative to the sled; however, the minor differences observed translated to considerable differences in thoracic response. A stiffer foam, such as Foam 2 in this case, was more capable of applying a load to the occupant, thus increasing the occupant velocity and reducing the effect of the intruding door.

Although the differences in mechanical properties between the seat foams compared in this study were relatively small the effect on thoracic trauma was noteworthy. Stiffer seat foams and more encompassing side bolsters may have the potential to significantly reduce injury.

### The Effect of Restraint Systems on Thoracic Trauma

The effect of restraints on the reduction of occupant trauma in frontal collisions is well-known. However, the effect of restraints in side impact is not as clear. According to a study performed by NHTSA [1], the reduction of fatalities in near-side impacts as a result of restraint systems was a mere 5 percent. In comparison, the fatality reduction as a result of seat belt usage was 39 percent in farside impacts, 50 percent in frontals, and 74 percent in rollovers.

However, because of large variation in crash scenarios it is difficult to quantify the effect of restraints in side impact. The study performed in this section compares the thoracic response of a belted and un-belted occupant under identical crash conditions to determine the effect of restraints. A summary of the results is presented in the bar chart in Figure 28.

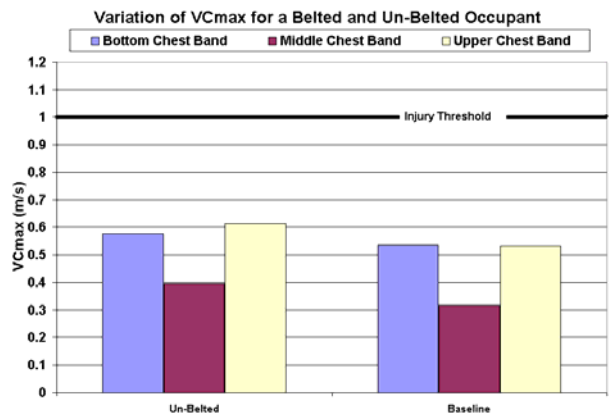


**Figure 28 Variation of VCmax for a Belted and Un-Belted Occupant.**

The small spacing between the occupant and the intruding door makes energy dissipation difficult and contact inevitable. However, it is clear that the presence of restraints reduces the thoracic response at each chest band level and can reduce VCmax by up to 13% compared to an un-belted occupant.

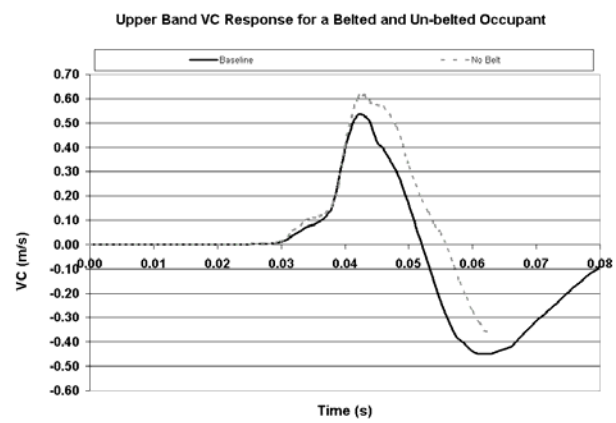


**Figure 29 Upper Band VC Response for a Belted and Un-Belted Occupant.**

As seen in Figure 28 and Figure 29 the VC response for the un-belted occupant was slightly elevated in comparison to the belted occupant. The modest difference in thoracic response may be explained by investigating the occupant motion relative to the sled base (Figure 30).

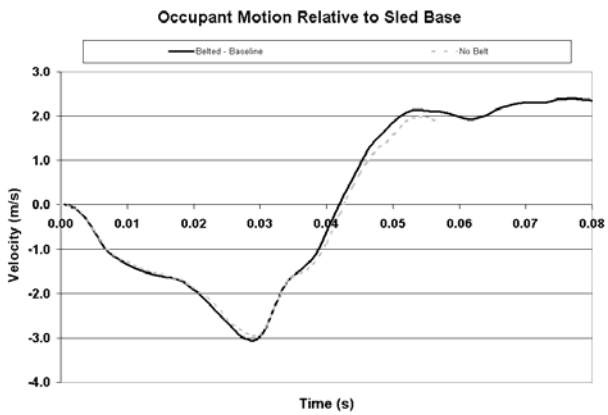


**Figure 30 Occupant Motion Relative to Sled Base for a Belted and Un-Belted Occupant.**

The presence of a seatbelt accelerates the occupant slightly more than in the case of the un-belted occupant, thereby moderately reducing the impact of the intruding door. It is likely that the increase in occupant velocity relative to the sled base was due to an increased interaction with the seat, facilitated by the restraint system. This displays the modest improvements to thoracic response in side impact collisions as a result of restraint systems.

## CONCLUSIONS AND RECOMMENDATIONS

A numerical side impact model has been developed to investigate factors and crash conditions present in full scale crash tests. The model was developed to account for several important factors that contribute to occupant response including the relative velocities between the seat and door, the occupant to door distance, as well as door shape and compliance.

Validation of the side sled model was undertaken by reproducing the crash conditions present in FMVSS 214 and IIHS side impact tests and comparing the thoracic response determined by the model to the response of the ES-2 dummy used in the crash tests. The side impact model was shown to produce *good* to *reasonable* injury response with respect to the full-scale FMVSS 214 side impact test of a Ford Taurus, as well as the IIHS side impact test of a Nissan Maxima.

The side impact model was then used to investigate the effects of door to occupant spacing, door velocity profile, seat foam stiffness, and the use of a restraint system. It was found that injury as predicted by the Viscous Criterion was controlled by both the first and second peaks typically found in door velocity profiles, but the influence of each varied depending on the situation.

The parametric study presented in this paper has provided valuable insight into the factors influencing thoracic trauma in side impact collisions. Clearly, occupant protection in side impact scenarios is a difficult task due to the limited door to occupant spacing associated with lateral collisions. The study performed has shown that thoracic injury was largely dependant on relatively small changes in a number of factors such as AD distance, door intrusion velocity, and seat foam properties.

It has been shown that the presence of a deformable door compared to a rigid door can reduce VCmax by up to 16%, showing that door geometry and compliance plays a roll in safety. Also, it was shown that the shape of the door intrusion velocity profile highly influences thoracic response. Therefore, altering the structural properties of the vehicle to minimize door intrusion or idealize the door intrusion velocity profile may significantly reduce VCmax.

The seat foam study performed has shown that using the low stiffness foam instead of the high stiffness foam can cause a 41% increase in the observed VCmax value. This was based on the investigation of seat foams falling in a relatively limited range of material properties. Clearly, seat foam plays an important role in crash safety and improving side bolsters and increasing foam stiffness may contribute to better side impact safety.

Although the effect of pre-tensioning restraint systems are limited in side impact crash, this study has shown that this can reduce VCmax by improving the contact between the occupant and the seat. The improved occupant to seat contact minimizes the impact of the intruding door by accelerating the occupant with the seat, thereby reducing the relative velocity between the occupant and intruding door. Thus causing a 13% decrease in VCmax in this study.

It should be noted that the current study was limited to velocity profiles obtained from a specific FMVSS 214 test and therefore results and observations are restricted to the confines of the input conditions used. Also, although based on vehicle geometries, the side impact model has been developed using simplified geometries for the seat, armrest, and restraints and may not fully encompass all vehicle designs. However, the side impact model developed is a useful tool for evaluating factors influencing side

impact and can be used to determine occupant response in any side impact crash scenario when the appropriate input conditions are provided.

**ACKNOWLEDGMENTS**

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