VEHICLE-TO-VEHICLE FRONT-TO-SIDE CRASH ANALYSIS USING A CAE BASED METHODOLOGY

Saeed Barbat, Xiaowei Li and Priya Prasad
Passive Safety Research and Advanced Engineering
Ford Motor Company
United States
Paper Number 07-0347

ABSTRACT

Fundamental physics and numerous field studies have clearly shown a higher fatality risk for occupants in smaller and lighter vehicles when colliding with the heavier one, especially when the struck vehicle is a passenger car and the striking vehicle is an LTV or an SUV. The consensus is that the significant parameters influencing compatibility in front-to-side crashes are geometric interaction, vehicle stiffness, and vehicle mass. The effect of each individual design parameter, however, is not clearly understood.

A finite element (FE) model-based design of experiments (DOE) methodology focused on evaluating the effects of a few striking vehicle design variables on dummy responses of the struck vehicle in front-to-side impact was developed. This study utilized a deterministic approach including optimally spaced Latin hypercube sampling which allowed analytical prediction equations for dummy responses to be generated from twenty-one simulation runs. Selected response variables were the dummy injury measures Thoracic Trauma Index (TTI) and pelvis acceleration.

Several multi-dimensional response surfaces were constructed based on the simulation results and found to be well correlated (R^2= 0.83 and R^2=0.94 for TTI and pelvis acceleration, respectively). Results indicate that lower front-end structures in vehicle-to-vehicle front-to-side collisions have the greatest effect on reducing (struck vehicle driver) TTI than other design variables. This was found to contrast the pelvic acceleration results, which tended to increase with lower front structure height of the striking vehicle. The stiffness and mass showed moderate significance on the TTI with less mass effect than stiffness. The mass showed no significant effect on the pelvis acceleration.

1. INTRODUCTION

Vehicle compatibility has been investigated in many studies using different approaches such as real-world crash statistics, crash testing, and computer modeling. NHTSA used U.S. crash statistics from the Fatality Analysis Reporting System (FARS) to determine the number of fatalities in vehicle-to-vehicle collisions [1]. Field data analysis shows that side impact can be severe, harm producing crashes, even though they occur less frequently than frontal impacts [2]. Inherent design differences between utility vehicles and pickups, on one hand, and passenger cars, on the other, may lead to a higher fatality risk for occupants in passenger cars when colliding with the utility or pickups. This is commonly attributed to differences in geometry, relative masses, and relative stiffnesses between these two vehicle segments.

The Insurance Institute of Highway Safety (IIHS) reported a series of crash tests to assess the influence of mass, stiffness, and vehicle ride height on occupant responses, but the results were somewhat inconclusive [3]. Separating the effects of the compatibility factors via experimentation would not only be costly and time consuming, but also susceptible to systemic errors due to test-to-test variability. Because of the limitations of statistical approaches and physical crash testing, math models in combination with design of experiments (DOE) methods were deemed necessary.

Past studies of compatibility by the authors have addressed front-to-front compatibility. Barbat, *et al.* [4, 5] investigated factors influencing compatibility in frontal SUV/LTV-to-car crashes. Their study proposed a robust and repeatable vehicle-to-vehicle test procedure to assess vehicle compatibility and to extract individual effect of the compatibility factors on the injury outcome of occupants. Their results indicated that the geometric compatibility was the dominant factor influencing injury outcome in frontal vehicle-to-vehicle crashes.

Finite element (FE) simulations have been used to study many aspects of vehicle crashworthiness. Carefully designed experiments (partially factorial) can characterize responses over a selected design space using a reduced number of simulations (as compared to full-factorial study). In this study, the authors used a very similar approach to that reported by Barbat et. al. [6], which reported on front-to-front compatibility. The application of this methodology was extended to investigate the effect of compatibility factors in front-to-side impact.

A FE model-based DOE methodology focused on evaluating the effects of a few design variables on dummy responses in front-to-side vehicle crash has been developed. The striking vehicle was selected to be an SUV while the struck vehicle was a mid size passenger car. The current study utilizes a deterministic approach that allowed analytical prediction equations for dummy responses to be generated. This study combined FE analysis, Latin Hyper Cube Sampling (LHS), and subset selection with sequential replacement to produce a powerful tool that may be used to investigate vehicle compatibility issues.

2. FINITE ELEMENT MODELING

Reliable finite element models of the vehicles are required to enable reasonable predictions of structural performance. In this study, a baseline front-to-side vehicle-to-vehicle FE model was constructed and correlated to a physical vehicle-to-vehicle front-to-side crash test. As in the physical test, the simulated passenger vehicle was stationary and the simulated SUV was given an initial velocity of 48kph (See Figure 1).

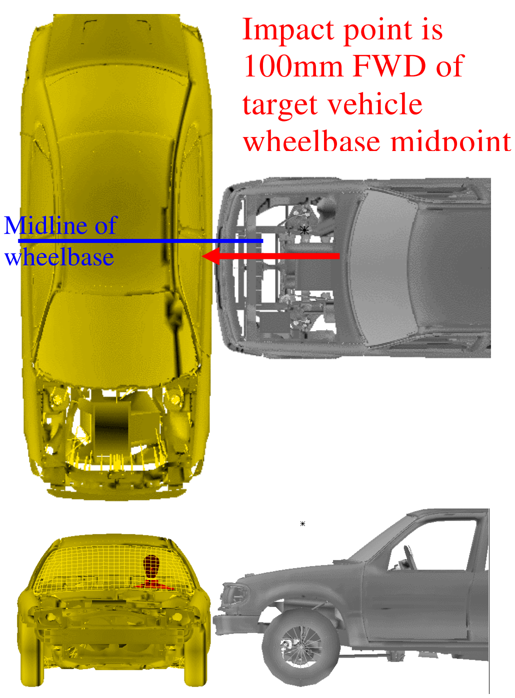

Figure 1. Impact configuration of an SUV-to-Car in front-to-side simulation.

Front-to-side SUV-to-passenger car simulations involve many complex and non-linear interactions. The nonlinear, explicit FE crash code, RADIOSS [7], was used for all of the simulations. The simulated structural deformation and side intrusion of the struck vehicle in a front-to-side SUV-to-passenger car impact were well correlated with test observations, as shown in Figures 2 and 3.

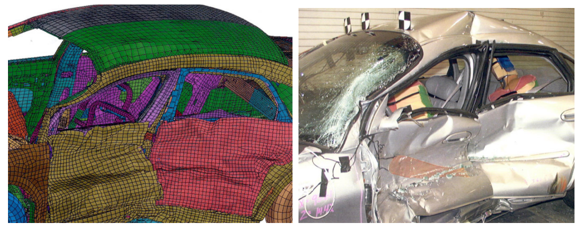

Figure 2. Validation of the deformation of struck vehicle in SUV-to-Car side impact.

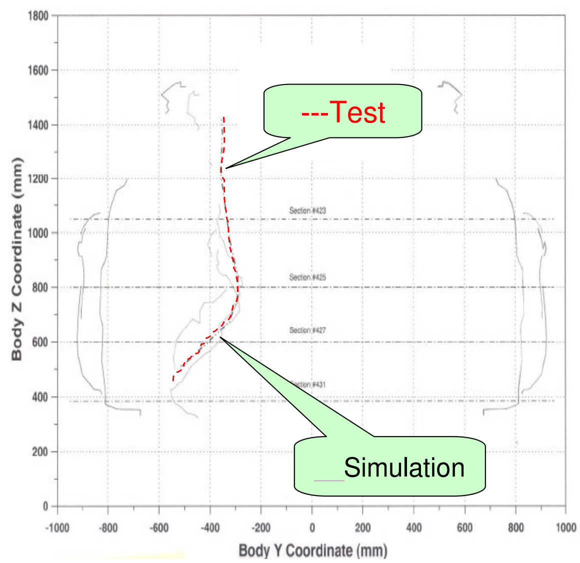

Figure 3. Intrusion comparison of struck vehicle in SUV-to-Car side impact.

3. DESIGN VARIABLE SELECTION

The appropriate selection of the striking vehicle design variables and the pertinent system responses are basic requirements. It is generally accepted that the determining factors of vehicle compatibility in frontal or side vehicle-to-vehicle impacts are relative geometry, relative stiffness, and relative mass. In this study, factors affecting the size and stiffness of the interaction zone were also considered. The following factors were considered as design variables for the striking vehicle (average SUV): front rail height, front rail thickness, vehicle mass, and bumper beam geometry (width and thickness).

Geometric difference between the SUV and the passenger vehicle was defined as the relative vertical alignment between the fore-most structural members (rails) and the struck vehicle's rocker. The SUV front-end stiffness was characterized through the front rail thickness. The bumper beam size and stiffness were also varied in front-to-side impacts. For each design variable, only the SUV portions of the FE models were allowed to vary within their respective ranges. A brief description of how the variables were introduced into the FE models and the levels selected for the design variables follows.

3.1 Geometry

In the baseline simulation both the SUV and the passenger car have the same ground reference plane The vertical alignment of energy-absorbing structures (rail) relative to the side of the passenger car was varied to four different levels by changing the ground reference plane of the SUV, as shown in Figure 4.

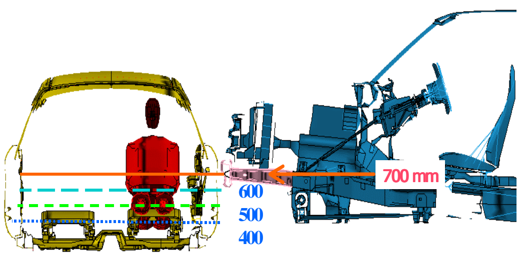

Figure 4. Levels of geometrical alignments of the SUV relative to the passenger car.

3.2 Stiffness

In general, thicknesses, cross section, and material strength, among other design parameters, determine the stiffness and the load carrying capacity of the front rail/frame of a vehicle. In this particular study, the cross section and material strength were kept as those of the baseline and thickness of the SUV rail was selected to be the stiffness-related deign variable. The thickness was studied at four distinct levels as indicated in Figure 5.

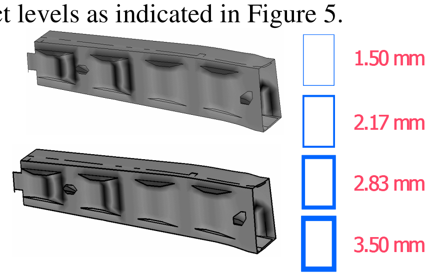

Figure 5. SUV rail and section thickness levels.

3.3 Mass Ratio

In order to vary the mass ratio of the impacted vehicles, the mass of the SUV was varied between baseline value less 13.5% to baseline value plus 24% in 227 kg increments. The SUV mass was adjusted by distributing small masses throughout the model such that the center of gravity location remained equivalent to that of the baseline model. This range approximately spans vehicle segments from small-size SUV to Mid-size SUV. Thus, the effect of the mass ratios was evaluated at four discrete levels (see Table 1).

Table 1. Passenger Vehicle and SUV Mass Levels

Struck Vehicle Mass (Kg)	Striking Vehicle Mass (Kg)	Striking/Struck Mass Ratio
1724	1680	0.97
1724	1906	1.11
1724	2133	1.24
1724	2360	1.37

3.4 Bumper Thickness and Width

Bumper size (expressed by its width in the vertical direction) and bumper metal thickness were considered as design parameters in this study. Three bumper width levels and four bumper metal thickness levels were selected to be evaluated for their effect on the struck vehicle occupant's TTI and Pelvis responses, as shown in Figure 6.

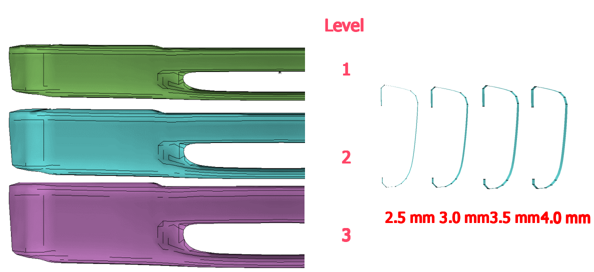

Figure 6. Bumper width and thickness levels.

Table 2 contains a summary of the design variables and their corresponding levels used in this study. The levels have been associated with an integer representation (coded) for simplicity.

Table 2: Coded Design Variables/Levels Summary

Rail Height
1=Ground to Rail Height 400 mm
2=Ground to Rail Height 500 mm
3=Ground to Rail Height 600 mm
4=Ground to Rail Height 700 mm
Mass
1=1680 kg
2=1906 Kg
3=2133 Kg
4=2360 Kg
Rail Thickness
1=1.5 mm
2=2.17 mm
3=2.83 mm
4=3.5 mm
Bumper Thickness
1=2.5 mm
2=3.0 mm
3=3.5 mm
4=4.0 mm
Bumper Height
1=1
2=2
3=3

4. SYSTEM RESPONSES

The struck passenger vehicle was stationary and contained the US side impact dummy (SID) in the driver seat, seated according to FMVSS 214. The striking SUV was given an initial velocity of 48 kph in the perpendicular direction to that of the side of the passenger vehicle. The SID dummy responses that were monitored in this study as system reponses were the Thoracic Trauma Index (TTI) and Pelvis acceleration.

5. EXPERIMENTAL DESIGN

The number of factors and levels included in this study describe a sizable design space. Numerous techniques exist for constructing experimental designs that specify a minimal number of samples throughout the design space required to characterize the responses [8, 9]. Latin Hypercube Sampling was utilized to select the levels for the design variable in the FE analyses. Since no noise factors were introduced into this study, total of 21 simulations were used to construct reasonably accurate response surfaces. The outcome of the sampling process is shown in Table 3. One additional run was included in the matrix to represent the baseline simulation that was correlated to a physical test for model validation. The corresponding matrix plot for all the five design variables used is shown in Figure 7.

Table 3. Design of Experiment Matrix

	Rail Height (mm)	Mass (kg)	Rail Thickness (mm)	Bumper Thickness (mm)	Bumper Width (Level)
Baseline	560	1906	3	3	2
1	400	1680	2.17	3	1
2	500	1680	1.5	3	3
3	600	1680	3.5	3	3
4	700	1680	2.17	3	1
5	400	1680	2.83	4	2
6	500	1906	3.5	4	1
7	600	1906	2.17	4	3
8	700	1906	1.5	2.5	2
9	400	1906	2.83	3.5	1
10	500	1906	3.5	2.5	3
11	600	2133	2.17	3.5	1
12	700	2133	1.5	3.5	2
13	400	2133	2.83	3	2
14	500	2133	3.5	4	2
15	600	2133	2.17	2.5	1
16	700	2360	1.5	2.5	3
17	400	2360	2.83	3.5	3
18	500	2360	3.5	2.5	1
19	600	2360	2.17	4	2
20	700	2360	1.5	3.5	2

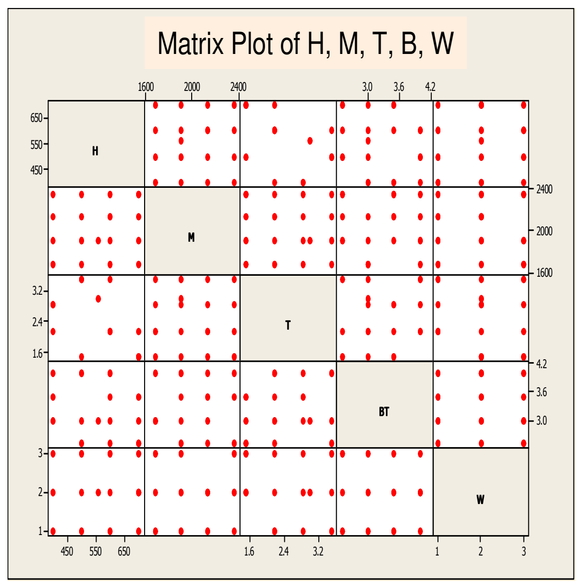

Figure 7. The DOE matrix plot.

6. FINITE ELEMENT SIMULATION RESULTS

Table 4 contains the dummy responses from all the 21 FE simulations. All dummy responses such as ribs and pelvis accelerations were normalized by their corresponding values obtained from the side impact baseline simulation. Values exceeding those obtained from baseline simulation are highlighted in yellow in Table 4. The TTI "Thoracic Trauma Index (TTI)" was calculated as the average of T12 and the maximum of the upper (U) or lower (L) rib accelerations.

7. RESPONSE SURFACE GENERATION AND PREDICTION EQUATIONS

The sample SID dummy responses of the TTI and pelvis acceleration obtained from the FE simulations (Table 4) were fitted with quadratic polynomials using a regression based upon subset selection by sequential replacement. These data were used to generate the response surfaces. The polynomial basis of the equations allows the response surface dependency on the design variables to be interpreted by observation. The response surfaces and R^2 values for the fitted polynomials are listed below. In the response surface expressions, *H* is the SUV rail height, T is the SUV rail thickness, *M* is the mass ratio, *B* is the bumper metal thickness, W is the bumper width in the vertical direction and a_1-a_6 and b_1-b_6 are the best fit coefficients

Table 4. Normalized Simulated Responses

	T12	U Rib	L Rib	TTI	Pelvis
base	1.00	1.00	1.00	1.00	1.00
1	1.08	0.65	0.84	0.94	1.89
2	0.87	0.86	0.79	0.82	1.01
3	1.12	1.38	1.06	1.11	1.04
4	0.99	1.25	1.15	1.08	0.63
5	0.88	0.73	0.70	0.78	1.67
6	1.05	1.01	0.95	0.99	1.23
7	1.11	1.25	0.98	1.05	1.05
8	0.95	1.23	0.90	0.97	0.66
9	0.95	0.70	0.63	0.77	1.51
10	0.96	0.93	0.80	0.87	1.19
11	1.00	1.10	1.00	1.00	0.88
12	0.96	1.58	1.06	1.13	0.58
13	0.89	0.73	0.69	0.78	1.70
14	0.88	0.80	0.75	0.81	1.05
15	1.03	1.11	1.00	1.01	0.71
16	0.95	1.49	1.10	1.09	0.59
17	0.88	0.79	0.78	0.82	1.66
18	0.95	0.83	0.97	0.96	1.16
19	0.97	1.10	1.31	1.17	1.01
20	1.00	1.30	0.97	1.02	0.51

$$TTI = a_1 - a_2.T^2 + a_3.M - a_4.M.T + a_5 H.T - a_6 H \quad \text{Eq.1}$$

$(R^2 = 0.83)$

$$Pelvis\_Accel. = b_1 + b_2.H.T + b_3.B - b_4.T + b_5 H^2 + b_6 H \quad \text{Eq.2}$$

$(R^2 = 0.93)$

The coefficient of determination, referred to symbolically as R^2, is a measure of the model's ability to fit the specified regression curve and was used to quantify the quality of fit of the polynomial regression equation in a least squares sense. These coefficient of determination values (0.83 and 0.94) for the TTI and pelvis acceleration respectively indicate that the response surfaces are capable of representing the sampled FE results.

8. DISCUSSION OF RESULTS

Figures 8 and 9 show comparisons between FE simulation and predicted responses for normalized TTI and pelvis acceleration respectively. The comparison shows a good correlation between the simulated and predicted responses. Therefore, the response surfaces can be used with some confidence to predict occupant responses for other designs contained within the original design space of the design variables.

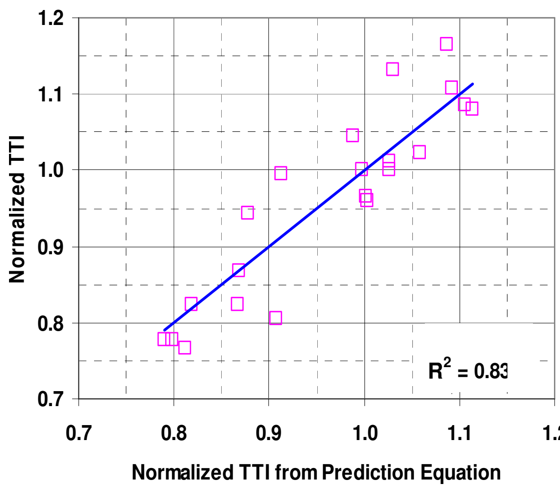

Figure 8. Normalized TTI from FE simulation versus that of prediction equation.

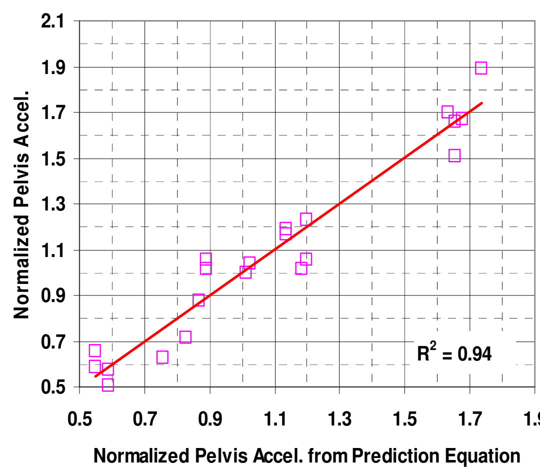

Figure 9. Normalized pelvis acceleration from FE simulation versus that of prediction equation.

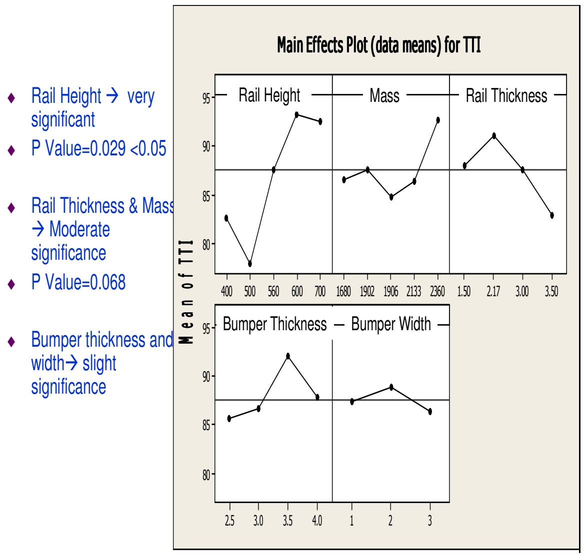

Figure 10. Main effect plot of design variables on TTI.

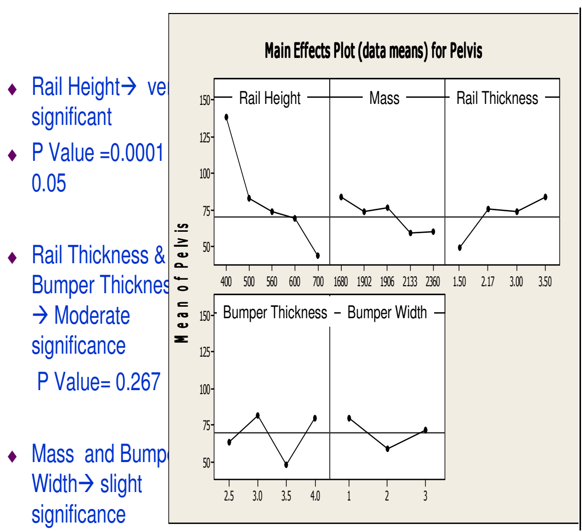

Figure 11. Main effect plot of design variables on pelvis acceleration.

Figures 10 and 11 show the main effects of the five design variables on dummy responses expressed by TTI and pelvis acceleration. The main effect plots indicate that both bumper width and bumper metal thickness have no significant effect on TTI and pelvis acceleration. This is also observed in the prediction equations (1) and (2) for TTI and pelvis acceleration respectively. The Plots also indicate that the rail/frame height from the ground reference has the most significant effect on the occupant's TTI and pelvis acceleration responses. The mass and stiffness have moderate significance.

9. PAIR-WISE COMPARISON OF DESIGN VARIABLE EFFECTS ON DUMMY RESPONSES

Pair-wise comparisons of the predicted effects of the design variables show the relative importance of each factor. For all comparisons described, the omitted variables were set to their baseline levels. Figure 12 shows the normalized TTI's response surface variation with rail height and rail thickness while the other design variables such as the mass, bumper width and bumper metal thickness were set to their baseline values. Similarly, Figure 13 shows the Normalized TTI's response surface variation with the rail thickness and striking vehicle mass while setting other design variable such as rail height, bumper width and bumper metal thickness to their baseline values. These figures show the dominant effect of the rail height on normalized TTI.

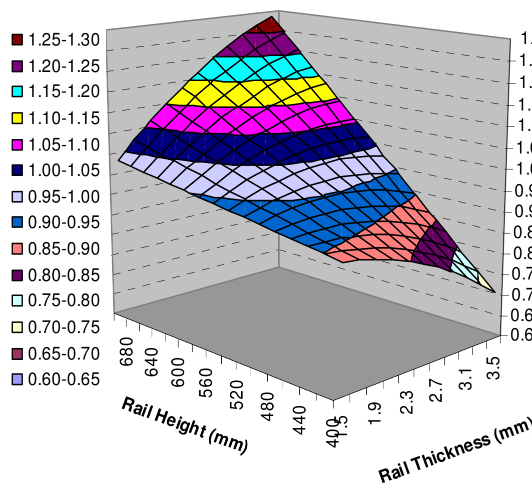

Figure 12. Normalized TTI response surface variation with rail height and rail thickness.

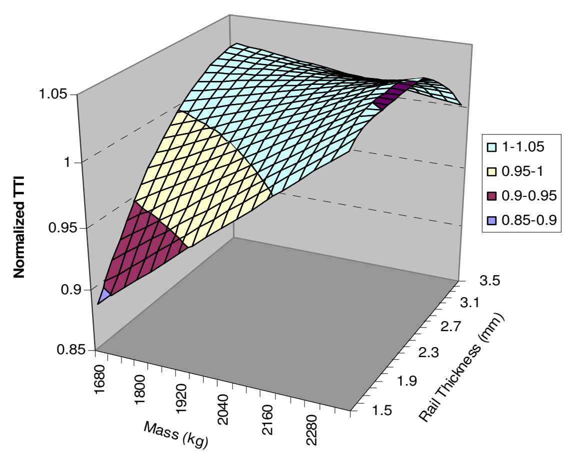

Figure 13. Normalized TTI response surface variation with mass and rail thickness.

In Figure 13 each color in the contours indicates a 5% change in effect. The normalized TTI can be reduced by 20% - 25% if rail height is reduced to the lowest level of 400 mm while keeping all the other four design variables the same as their baseline values. The response surface also shows an optimal design where the TTI can be reduced by 30% can be achieved by setting the rail height to the lowest of 400mm while increasing the rail thickness from the baseline by approximately 16% (baseline thickness of 3mm increase to 3.5 mm). This makes sense because slightly stiffer rail contacting the struck passenger car's area near stiff rocker dissipates more of the impact energy of the striking SUV through near rocker and rocker deformation.

The result achieved in this CAE based study appears to be very consistent with field data and real world performance as indicated in recent IIHS study on crash compatibility between cars and light trucks, Baker et. al. [10]. Their study focused on real world benefit achieved by lowering front-end energy-absorbing structure (rails) in SUV's and pickups. In their study only recent SUVs and pickup trucks of model years 2000 through 2003 were included for both front-to-front and front-to-side collisions (where the front end of a light truck strikes the driver side of a passenger car). In front-to-side impacts, a 30% risk reduction for SUVs and a 10% risk reduction for pickups are observed with SUVs complying vehicles with the Phase I Front-to-Front Compatibility Alliance Voluntary Standard [11].

Figure 13 shows that the optimum design can only lead to approximately 11% reduction in TTI even the striking SUV mass and rail thickness are set to their minimum values of 1680 Kg and 1.5 mm respectively. This also emphasize the fact that the most significant design variable effect on the TTI is the rail height.

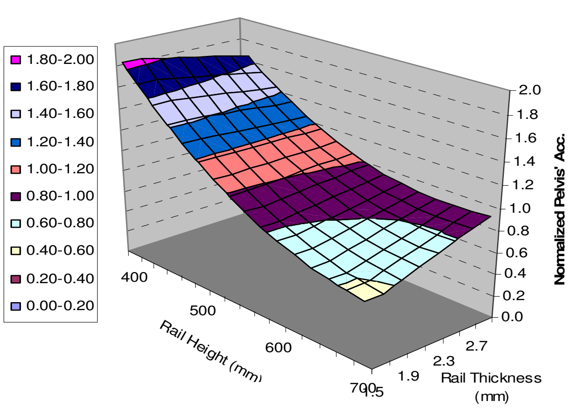

Figure 14. Normalized pelvis response surface variation with rail height and rail thickness.

Figure 14 shows the normalized pelvis acceleration's response surface variation with the rail height and rail thickness. Other design variables such as the mass, bumper width and bumper metal thickness were set to their baseline values. Each color in the contours indicates a 20% change in effect. The rail height shows its dominant effect on reducing pelvis acceleration when it is set to its highest level but it has an adverse effect on increasing the TTI. In other words, reducing the rail height to 400mm to achieve approximately 30% reduction in TTI will increase pelvis acceleration by approximately 60% (see color contours in Figure 14). However, the baseline run resulted in a very low pelvis acceleration value of approximately 44% below the IARV (Injury Assessment Reference Value). This points to a tradeoff between the TTI and pelvis acceleration when considering rail height changes.

As it is shown in Eq. (2), the mass effect did not appear in the prediction equation for pelvis acceleration, which means it has no significant effect on pelvis acceleration. These results are also consistent with conclusions found in other studies by Nolan et. al. [3] in laboratory testing. In their test series, it was shown that a 15% increase in the mass of the striking SUV has no significant effect on pelvis acceleration of the driver occupant of the struck passenger car.

10. SUMMARY

- Validated finite element models of an "average" SUV and an "average" passenger vehicle were used to explore the effects of geometry, stiffness and mass in front-to-side impact simulations.
- A design of experiments methodology involving Latin Hypercube sampling was employed to select the appropriate number of simulations and the design levels of each of the design variables that should be incorporated in each simulation.
- Five design variables, the SUV rail height, rail thickness, mass, bumper width and bumper metal thickness were chosen.
- Thoracic Trauma Index (TTI) and pelvis acceleration of the SID dummy responses were selected for the system responses. These responses were normalized by their baseline corresponding values.
- The main effect plots were generated to identify the significance of individual design variable. The responses were characterized by quadratic polynomial surfaces.
- Pair-wise comparisons of the effects of the design variables were used to assess their

individual influence on TTI and pelvis acceleration. The pair-wise comparisons were based on the response surfaces generated from the 21 FE simulations. When a pair of design variables was compared, the remaining design variables were set to their BASELINE levels.

11. CONCLUSIONS

- A good correlation of the normalized dummy responses, TTI and Pelvis acceleration, between the values obtained from the FE simulations and those obtained from the prediction equations were achieved.
- The Main Effect Plots indicated that in front-to-side impacts of an SUV to a passenger car the geometrical effect, characterized by rail/frame height from the ground reference, on the normalized TTI and pelvis acceleration is most significant.
- The stiffness and mass effects on the normalized TTI response were identified to be of some significance, however, the geometry or the rail/frame height effect dominated the outcome. It should be emphasized that changing the rail thickness of the striking vehicle will affect its frontal crashworthiness. This effect has not been investigated in this study.
- The significant effect of geometry obtained through this CAE based study is consistent with field data and real world performance as indicated in recent IIHS study on crash compatibility between cars and light trucks [10]
- The main effect plots indicated that bumper width and bumper metal thickness have no significant effect on neither the normalized TTI nor the normalized pelvis acceleration.
- The normalized TTI response was seen to increase with striking vehicle rail height, mass and stiffness, but the response of normalized dummy pelvis was seem to be only sensitive to the striking vehicle's rail height. The mass has no significant effect on the normalized pelvis acceleration. This finding is also consistent with laboratory findings from crash testing conducted by IIHS [3]

12. REFERENCES

[1] Hollowell, W.T. and Gabler, H.C. 1996. “NHTSA’s Vehicle Aggressivity and Compatibility Research Program.” 15th ESV, Paper No 96-S4-O-01, Melbourne, Australia.

[2] Lugt, D.V., Connoly, T., and Bhalsod, D. 1999. "Vehicle Compatibility – Analysis of the Factors Influencing Side Impact Occupant Injury" SAE 1999-01-0067.

[3] Nolan, J., Powell, M., Preuss, A., and Lund, A. 1999." Factors Contributing to Front-Side Compatibility: A Comparison of Crash Test Results." 1999, Stapp Conference, 99SC02.

[4] Barbat, S., Li, X., and Prasad, P. 2001. "A Comparative Analysis of Vehicle-to-Vehicle and Vehicle-to-Rigid Fixed Barrier Frontal Impact." 17th ESV, Paper No. 01-S7-O-01, Amsterdam, Netherlands.

[5] Barbat, S., Li, X., and Prasad, P. 2001. "Evaluation of Vehicle Compatibility in Various Frontal Impact Configurations ." 17th ESV, Paper No. 01-S7-O-09, Amsterdam, Netherlands.

[6] Barbat, S., Li, X., Przybylo, P., and Prasad, P. 2003. "Vehicle-to-Vehicle Full Frontal Crash Optimization Using a CAE-Based Methodology." 18th ESV, Paper No. 05-S7-O-145, Nagoya, Japan.

[7] RADIOSS Crash Guidelines, Mecalog SARL, 1997.

[8] Yang, R.J., Akkerman, A., Anderson, D., Faruque, O., and Gu, L. 2000. "Robustness Optimization for Vehicular Crash Simulations." Computing in Science and Engineering.

[9] Gu, L. 2001. "A Comparison of Polynomial-based Regression Models in Vehicle Safety Analysis." ASME 2001 DETC, Paper No. DAC-21063, Pittsburgh.

[10] Baker, B,. Nolan, J., O’Neill, B., Genetos, A. 2007. “Crash Compatibility between Cars and Light Trucks: Benefits of Lowering Front-End Energy-Absorbing Structure in SUV’s and Pickups.” Insurance Institute for Highway Safety, Arlington, VA.

[11] Auto Alliance, December, 2003. “Enhanced Vehicle-to-Vehicle Crash Compatibility: Commitment for Continued Progress by Leading Automakers".