# INVESTIGATION OF STRUCTURAL FACTORS INFLUENCING COMPATIBILITY IN VEHICLE-TO-VEHICLE SIDE IMPACTS

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## ABSTRACT

The aim of this study is to identify how vehicle safety during side impacts may be enhanced by changes to the structures of bullet vehicles. Side impact tests being conducted around the world are focusing on the improvement of self-protection performance of target vehicles, based on existing vehicle fleets. However, the protection of occupants in the target vehicle is influenced both by the characteristics of the target vehicle and the characteristics of the bullet vehicle. Since test procedures for frontal impact compatibility are currently being planned, those that encourage homogeneity and good structural interaction among vehicles may also be beneficial for side impacts. Thus, it is necessary to investigate the design factors of the bullet vehicle in terms of side impact compatibility.

First, a study using FE simulation was carried out to develop an understanding of the major influencing factors relating to side impact compatibility. From this understanding, concept ideas for enhancing vehicle side impact compatibility were proposed. Second, FE simulation of a Full Width Deformable Barrier test was conducted with unmodified and modified vehicles to check that the test and assessment technique could correctly distinguish the improved performance of the modified vehicle. Finally, vehicle-to-vehicle tests using modified bullet vehicles were performed to demonstrate the principles identified in the FE simulation.

The results showed that the matching of geometry and stiffness in vehicle front-end structure contributes significantly to vehicle safety during side and frontal impacts.

## INTRODUCTION

In recent years, front-to-front impact compatibility has been discussed by a wide variety of governments, researcher organizations and automakers. In the United States, the Enhancing Vehicle-to-Vehicle Crash Compatibility Technical Working Group (EVC TWG) has developed performance criteria to further enhance occupant protection in both front-to-front and front-to-side crashes. In front-to-front TWG, Phase 1 commitment was announced on December 3, 2003 as a first step towards improving geometrical compatibility [1]. By production year 2006, approximately 75 % of applicable vehicle have been designed in accordance with the front-to-front criteria. In the recent Insurance Institute for Highway Safety (IIHS) study which measured the benefit from front-to-front compatibility as determined through the EVC Phase 1 Commitment, the simple geometric alignment prescribed in this Commitment has resulted in an impressive real world improvement in front-to-side compatibility[2].

Side impact tests being conducted around the world are focusing on improving the self-protection performance of target vehicles, based on existing vehicle fleets. However, the protection of occupants in the target vehicle is influenced both by the characteristics of the target vehicle and of the bullet vehicle. There appears to be few published literature on the reduction of bullet vehicle aggressivity as a factor in side impact. Side impact compatibility can be considered the next subject to examine, to further reduce harm in side impacts. The National Highway Traffic Safety Administration (NHTSA) reported the issue of aggressivity in sport utility vehicles (SUV) and light trucks and vans (LTV) in their U.S. fleet. In side impacts, the drivers of the struck vehicles are much more likely to be killed than those in frontal impacts. In the U.S., the emphasis is on LTV-to-car impact compatibility, whereas car-to-car impact appears to take on significance in Europe and Japan. According to the NHTSA report, the driver in the struck passenger car is 8.2 times more likely to be killed as the driver in the striking passenger car [3]. Since test procedures for frontal impact compatibility are currently being developed, not only in the U.S., but in Europe and Japan as well, procedures that encourage good structural interaction and homogeneity among vehicles may also provide an opportunity to enhance side impact compatibility. Thus, investigation into the design factors of the bullet vehicle would be beneficial for both side impact and frontal impact compatibility.

In general, three different factors are relevant to impact compatibility; namely mass, stiffness and geometry. According to Hobbs et al., increased striking vehicle mass had little effect on struck vehicle driver injuries and front structure homogeneity, rather than simple stiffness dominating the injury risk in side impacts [(4), (5)]. IIHS reported that that front-end geometry was the most consistent factor influencing vehicle aggressivity [(6)]. Regarding modification of vehicle front-end structures, several studies have been made on reducing the aggressivity of striking vehicles based on the basic understanding of relevant factors to side impact compatibility [(7), (8)]. Better understanding of these design factors may present opportunities to reduce side impact harm, by modifying side structure and restraint systems, and by modifying front-end structures.

This paper reports on a study that was conducted to examine side impact compatibility and the factors influencing occupant injuries in side impact. Computer simulation was utilized to understand the factors influencing side impact compatibility. In addition, physical crash testing was performed to demonstrate the effect of a modification, obtained from the computer simulation, for the bullet vehicle. This paper attempts to contribute to a better understanding of side impact compatibility by means of observations gained through computer simulation and physical crash testing.

## COMPARISON OF MDB-TO-CAR TEST AND CAR-TO-CAR TEST

New Car Assessment Program (NCAP) tests are currently being carried out to assess side impact occupant protection performance in various countries. In the NCAP testing, a Moving Deformable Barrier (MDB), which has an aluminum honeycomb component mimicking the front-end stiffness of vehicles, collides into the stationary target vehicle to assess dummy injury measures and target vehicle body deformation. However, the stiffness distribution of the MDB is generally more homogeneous than that of actual vehicles. Therefore, a MDB-to-Car test and a Car-to-Car test were carried out to identify the difference by comparing the body deformation and dummy injury measures. A small 5-door hatchback car, which performs well in ECE R95-type tests without side airbags, was selected as the target vehicle. A car with no side air bag was specified, as a side airbag is considered a supplemental restraint that could hinder improvement on what could be achieved with the structure of the bullet vehicle, likely complicating the interpretation of the research results.

Figure 1 shows the side impact test configuration in this study. The test configuration of the Euro-NCAP, where a bullet vehicle collides into the stationary target vehicle at a collision velocity of 50km/h, was chosen as the basis from which to compare the test results. In the MDB-to-Car test, the MDB, as specified by ECE -R95, collided into the small 5-door car, and in the Car-to-Car test, an identical small 5-door car was used as the bullet vehicle to compare to the MDB-to-Car test. The EuroSID-2 dummy was used to measure the injury criteria. Body deformation and the dummy injury measures of the target vehicle were compared between the MDB-to-Car and Car-to-Car tests.

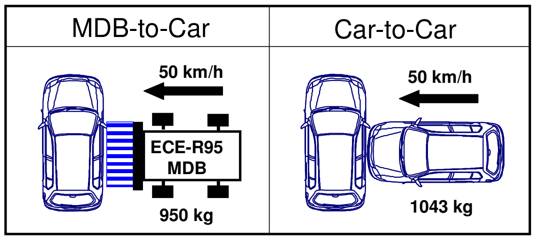
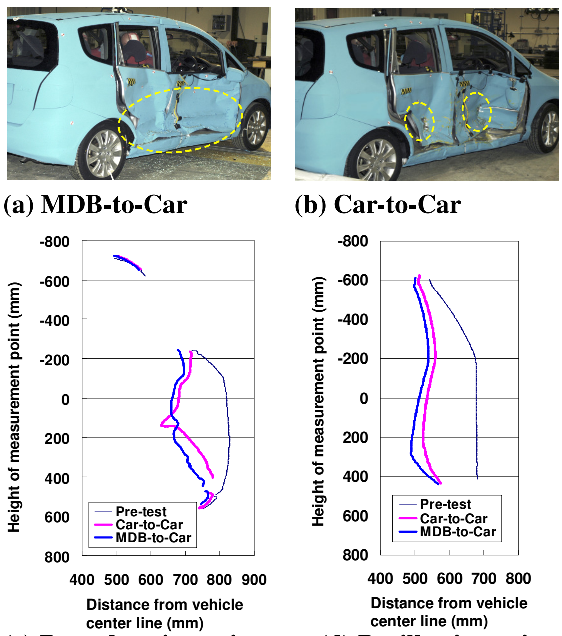



**Figure 1. Side impact test configuration**

### Body Deformation

Body deformation of the target vehicle in the MDB-to-Car test and in the Car-to-Car test is shown in Figure 2. The stiffness distribution in the front-end of the bullet vehicle actually affects the deformation mode of the target car. There was localized deformation on the target vehicle that was aligned with the position of the bullet car's front side member in the Car-to-Car test, whereas relatively flat deformation was seen in the MDB-to-Car test.




**(c) Rear door intrusion** **(d) B-pillar intrusion**

**Figure 2. Comparison of body deformation**

### Dummy Response

Injury measures were normalized by the injury values of the MDB-to-Car test, and shown in Figure 3. Comparison of the driver dummy results from the MDB-to-Car and Car-to-Car tests showed that the injury values on the upper torso were almost similar between the two tests, whereas significant differences were seen for the pubic symphysis force, the driver's right femur load and femur bending moment. The intrusion into the passenger compartment resulted in some higher driver dummy injury values, especially for the femur, which was aligned with the main bullet vehicle structure.

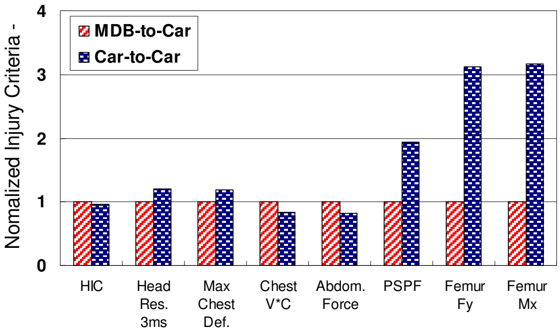



**Figure 3. Comparison of injury measures**

The overall levels of deformation indicated that the bullet vehicle's front structure was stiffer, relative to the target vehicle's side structure. The lack of deformation of the bullet vehicle's frontal structure showed that little energy was absorbed by the bullet vehicle in the impact, resulting in high levels of deformation of the target vehicle, as shown in Figure 4.

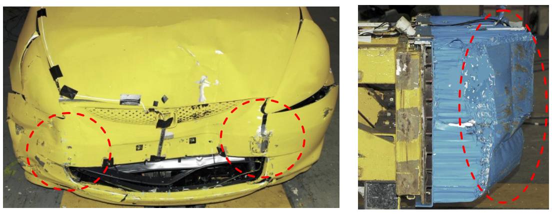


**Figure 4. Comparison of bullet vehicle and MDB deformation**

## COMPUTER SIMULATION

The capability of improvements to side impact compatibility was investigated using an FE model. A parametric study was carried out using full-car finite element models that corresponded to the Car-to-Car test. The aim of this work was to aid our understanding of the effects of the bullet vehicle's structural characteristics that will enhance compatibility. To enhance side impact compatibility, the front-end of the bullet vehicle should effectively absorb impact energy to reduce the intrusion into the target vehicle. In this study, main energy-absorbing structures, e.g., front side members, bumper crossbeams, and sub-frames etc., were modified to enhance the side impact compatibility of the bullet vehicle. Originally, the baseline model, which is the same vehicle as that used in the Car-to-Car tests, did not have a sub-frame. In this study, a simple sub-frame extended to the vehicle front-end for the purpose of creating good structural interaction between the side sill of the target vehicle and front-end structure of the bullet vehicle has been designed for the FE analysis. The FE model of the small 5-door car and EuroSID-2 dummy model used for this study are shown in Figure 5. The models were validated for a European side impact test and shown to give reasonable agreement (Figure 6).

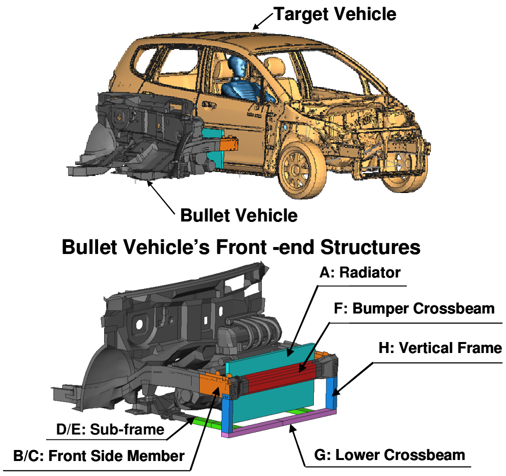



**Figure 5. Full vehicle FE simulation model**

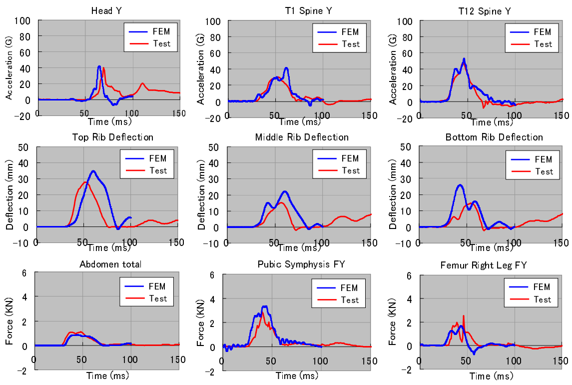



**Figure 6. Comparison of FE simulation and crash test injury values**

## SIMULATION RESULTS

Orthogonal arrays were utilized for the matrix experiments in the design of experiments (DOE). Since there were five design variables and three levels, $L_{18}$ $(2^1 \times 3^7)$ standard orthogonal arrays were selected for the frontal structures (Table 1).

**Table 1.**
**Orthogonal arrays of $L_{18}$**

| | Discription | | Levels | | | Simulation Run Number & Levels 1 | 2 | 3 | ~ | 18 |
|---|---|---|---|---|---|---|---|---|---|---|
| A | Radiator | Strength | 0.34 MPa | 1.71 Mpa | | 1 | 1 | 1 | | 2 |
| | | | 1 | 2 | | | | | | |
| B | Front Side Member | Thickness | 2.0 mm | 1.5 mm | 1.0 mm | 1 | 1 | 1 | | 3 |
| | | | 1 | 2 | 3 | | | | | |
| C | | Height | Baseline | +75 mm | +150 mm | 1 | 2 | 3 | | 3 |
| | | | 1 | 2 | 3 | | | | | |
| D | Sub-frame | Thickness | 1.2 mm | 0.8 mm | 1.6 mm | 1 | 2 | 3 | | 2 |
| | | | 1 | 2 | 3 | | | | | |
| E | | Height | Baseline | +75 mm | -75 mm | 1 | 2 | 3 | ~ | 1 |
| | | | 1 | 2 | 3 | | | | | |
| F | Bumper C/Beam | Thickness | 1.0 mm | 1.5 mm | 2.0 mm | 1 | 2 | 3 | | 2 |
| | | | 1 | 2 | 3 | | | | | |
| G | Lower C/Beam | Thickness | 1.2 mm | 0.8 mm | 1.6 mm | 1 | 2 | 3 | | 3 |
| | | | 1 | 2 | 3 | | | | | |
| H | Vertical Frame | Thickness | 1.2 mm | 0.8 mm | 1.6 mm | 1 | 2 | 3 | | 1 |
| | | | 1 | 2 | 3 | | | | | |

**Table 2.**
**FE simulation results**

| | | | Rib_Top | Rib_Mid | Rib_Bot | Abdomen | Pubic | Backplate | T12 | Femur | T12 | Femur | HIC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Compression | | | Fy | | | | | Mx | | |
| Radiator | Stronger | A | | | | | | ↗ | | | | | |
| Front Side Member | Stronger | B | ↗ | ↗ | | ↗ | ↗ | | | ↗ | | ↗ | ↗ |
| | Heigher | C | ↗ | ↗ | ↗ | ↗ | ↗ | ↗ | | ↗ | ↘ | ↗ | ↗ |
| Sub-frame | Stronger | D | ↘ | ↘ | ↘ | ↘ | | | | ↘ | | | |
| | Heigher | E | | | | | | | | | ↗ | | ↗ |
| Bumper Cross Beam | Stronger | F | | | ↗ | | | ↗ | | | | ↘ | |
| Lower Cross Beam | Stronger | G | | | | | | | | | | | |
| Verical Frame | Stronger | H | | | | | | | | | | | |

After the row experiments were performed, design parameters were analyzed using analysis of variance (ANOVA) techniques. Effective design factors for the characteristic values, obtained from the ANOVA analysis, are summarized in Table 2. The significance level was set at 5 %, although lower levels are sometimes specified. Red arrows show significant factors, while also indicating a dummy injury response. The upward direction of the arrow means that the dummy injury value increases when the magnitude of each design factor enlarges, and vice versa. It was found from ANOVA that the radiator strength, side member thickness and height, sub-frame thickness and height, and bumper crossbeam thickness were dominant for each characteristic value, as shown in Table 2. It is seen that stiffening and raising the height of the front side member increases almost all of the injury parameters and stiffening the bumper crossbeam causes an even larger increase in the chest injury values. In contrast, stiffening the sub-frame reduces the injury value. These results can be explained by the load share between the load path into the door and the path into the floor. Stiffening the front side member directly increases the load through the door into the occupant and hence increases injury. In contrast, stiffening the sub-frame increases the load into the floor and decreases the load through the door into the occupant. Thus, it is reasonable to suppose that reducing the direct load into the occupant resulted in reducing the injury value. Hence, the load share between the two major load paths should be considered so as to enhance side impact compatibility.

## Observation of Body Deformation

### <u>Influence on Front Side Member Strength and Height</u>

Figure 7 shows the deformation modes of the side of the target vehicle and the front end structure of the bullet vehicle. In the stiffer side member model, little front side member deformation was identified. However, the weaker side member was more deformed and absorbed more impact energy, along with a reduction in the localized intrusion of the door.

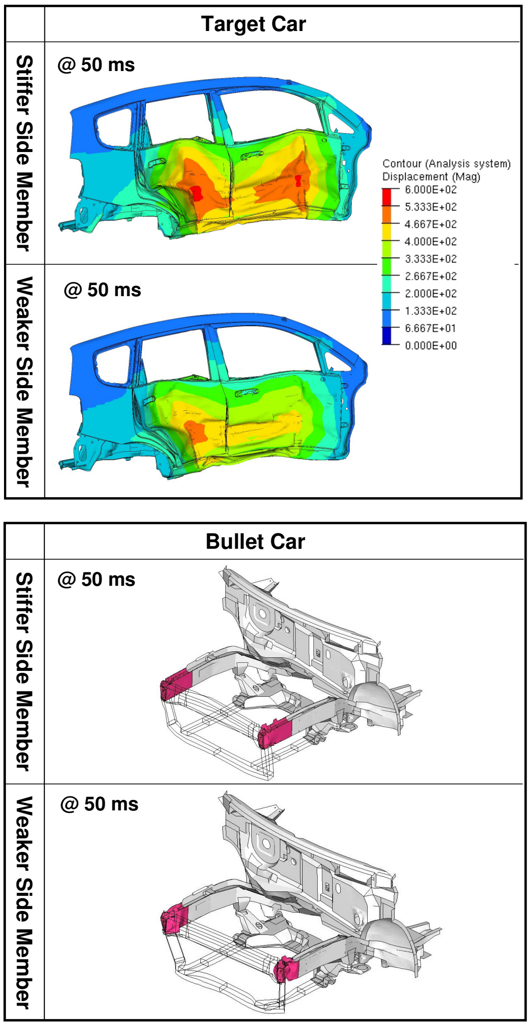



**Figure 7. Deformation of side panel and front-end structure**

### <u>Influence on Bumper Crossbeam Strength</u>

In Car-to-Car frontal impact, stiff front structures, such as front side members, are more likely to penetrate into the weak structures of the struck vehicle (fork effect). It is said that the homogeneity of a crash force is an important factor in preventing the fork effect. The same thing may be said of side impact. Therefore, the horizontal homogeneity of front-end structures was investigated by changing the stiffness of the bumper crossbeam of the vehicle equipped with a weaker bumper crossbeam (less homogeneous), which was then compared to the vehicle with a stiffer bumper crossbeam (more homogeneous).

Figure 8 shows the deformation modes of the side of the target vehicle and the front-end structure of the bullet vehicle. In the model equipped with the weaker bumper crossbeam, since the bumper crossbeam deformed greatly and pulled the front side member, a bending load was applied to the front-end of the front side member in addition to the compression load from the side structure of the target vehicle. Therefore, the front side member deformed inward. In the model equipped with the stiffer bumper crossbeam, the deformation of the bumper crossbeam was smaller than that of a weaker crossbeam. In such case, the load input from the B-pillar is transmitted to the front side member of the target vehicle as a compression load. The front side member crushed axially in response to the compression load.

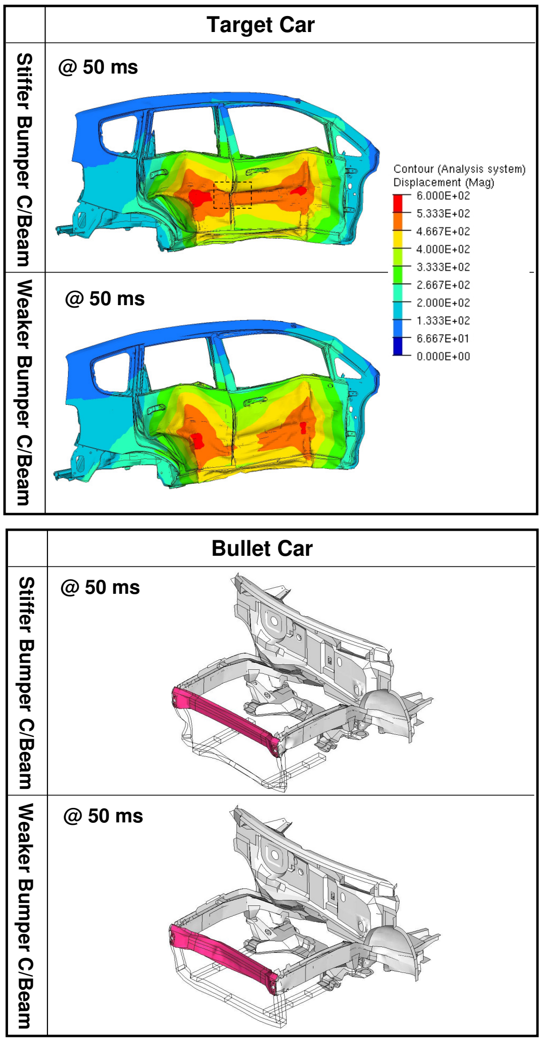



**Figure 8. Deformation of side panel and front-end structure**

The critical issue was that the deformation of the B-pillar increased as the stiffness of the bumper crossbeam became higher. Namely, although the deformation mode of the target car's body side structure became uniform and prevented localized intrusion by the increased stiffness of the bumper crossbeam, the average deformation of the target vehicle increased due to a larger intrusion into the B-pillar of the target vehicle. Generally speaking, vehicles with a more homogeneous frontal stiffness will appear to avoid concentrated loading. A vehicle with a stiff homogeneous front may bridge the gap between the door and pillars. If the stiffness is lower, the bridging effect is lowered and loading through the door to the occupant increases. However, a stiffer bumper crossbeam would likely overload the B-pillar. Therefore, stiffness matching, in addition to structural interaction, is important in side impact compatibility.

## Influence on Sub-frame Strength and Height

It is appropriate to consider the two load paths for side impact compatibility, which are the load path through the door into the occupant and through the vehicle's side sill. A sub-frame achieves this by giving better structural engagement with the sill. When structural interaction between the side sill of the target vehicle and sub-frame of the bullet vehicle is possible, impact energy is absorbed further by these structures, which would thus enhance side impact compatibility.

Figure 9 shows the deformation of the body side structure of the target vehicle and of the front-end structure of the bullet vehicle. The weaker sub-frame was able to decrease the localized door intrusion because the crash force was directly transmitted from a sub-frame to a side sill with the side sill absorbing the impact energy. Equipping the model with a stiffer sub-frame further reduced dummy injury values. However, the larger intrusion into the bottom of the B-pillar was seen in the case of the stiffer sub-frame, which produced little deformation; deformation of the front side member was also minimal, compared to the weaker sub-frame. That is, less energy was absorbed by the target vehicle than by the model equipped with the weaker sub-frame. Since a stiffer sub-frame would likely overload to the side sill, which was the same effect produced in the stiffer bumper cross beam simulation, stiffness matching is an important factor in both side impact compatibility and structural interaction.

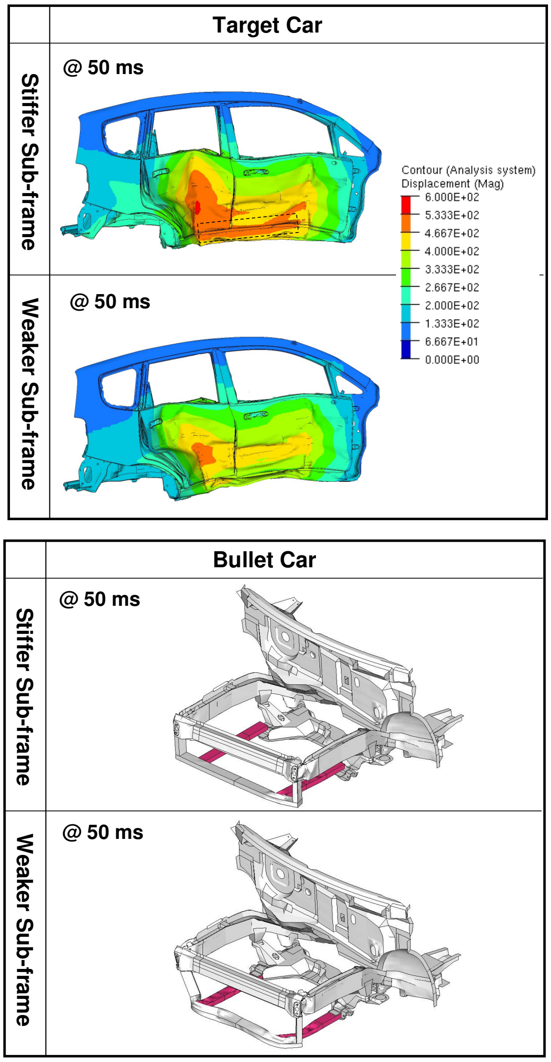



**Figure 9. Deformation of side panel and front-end structure**

From these simulation results, it is thought that in a Car-to-Car side impact, the structural interaction between vehicles has a big effect on the reduction of the body deformation. However, it is possible that if the stiffness of the sub-frame is greater than that of the floor of the target vehicle, the floor of the target vehicle deforms to a large extent and subsequently, the sub-frame may not effectively help protect the occupants. That is, the stiffness of the side sill and of the floor of the target vehicle should match with the stiffness of the sub-frame of the bullet vehicle for side impact compatibility.

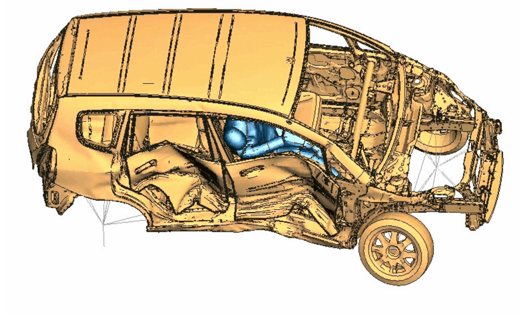
## OPTIMIZATION OF THE FRONT-END STRUCTURES

This study involves; modeling the Car-to-Car side impact using the finite element method and validating the modeling results with a Euro-SID2 dummy model, identifying influential parametric effects using DOE and ANOVA analysis and optimizing the identified influential parameters to achieve better vehicle side impact compatibility performance. An optimized vehicle frontal structure was created by choosing the dominant factors of vehicle design obtained from ANOVA as is shown in Table 3.

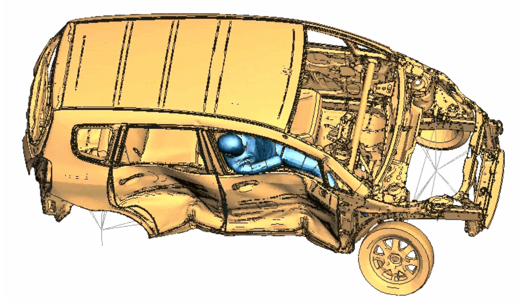
**Table 3.**
**Comparison of baseline model and optimal model**

| Discription | | Baseline | Optimal |
|---|---|---|---|
| Radiator | Strength | 0.34 Mpa | 0.34 Mpa |
| Front Side Member | Thickness | 2.0mm | 1.0mm |
| | Height | Baseline | Baseline |
| Sub-frame | Thickness | Without Sub-frame | 1.6mm |
| | Height | | -75mm |
| Bumper Crossbeam | Thickness | 1.0mm | 1.0mm |
| Lower Crossbeam | Thickness | Without Crossbeam | 1.2mm |
| Vertcal Frame | Thickness | Without V-Frame | 1.2mm |

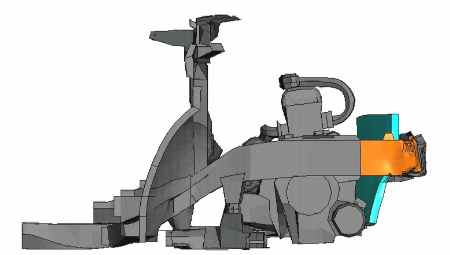
Figure 10 shows the deformation mode of the side of the target vehicle and front-end structure of the bullet vehicle. The Optimal Model was equipped with the stiffer sub-frame that was positioned -75 mm lower than that on the Baseline Model. Therefore, the Vertical Frame impacted the side sill, enabling the localized deformation in the sill to be identified. In this study, this sub-frame gave the better dummy injury values compared to the Baseline Model. However, generally the height of the sub-frame in alignment with the sill would provide better performance in terms of energy absorption



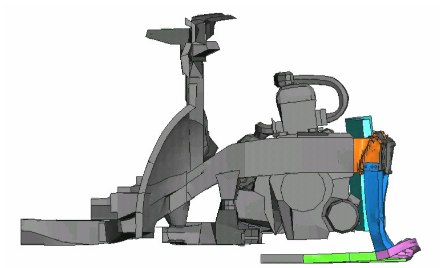
**(a) Baseline target car**



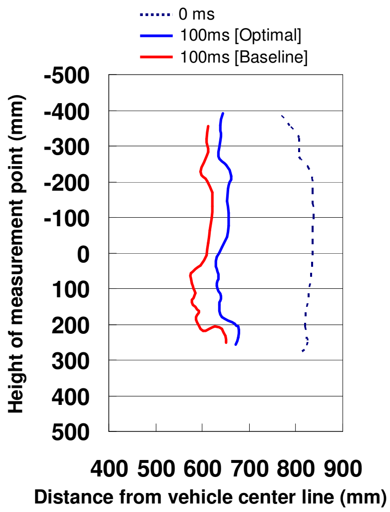
**(b) Optimal target car**



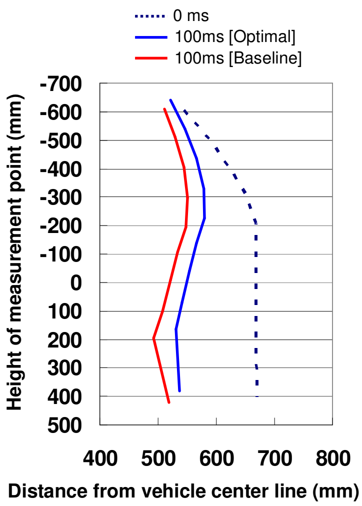
(c) Baseline bullet car



(d)Optimal bullet car




(e) Front door intrusion




(f) B-pillar intrusion

**Figure 10. Comparison of modified Car-to-Car test and Baseline Car-to-Car test in FE simulation**

Figure 11 compares injury values between the optimized and original target car. The modification of the front-end depicted in Fig. 10 was meant to improve the structural interaction and as such reduce intrusions. The results indicate that almost all of the injury values were reduced significantly. The reduction of intrusion can be clearly seen in Fig. 10, which shows deformed configurations for the target vehicle.

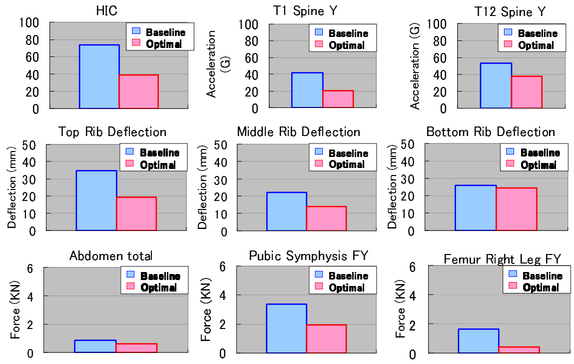
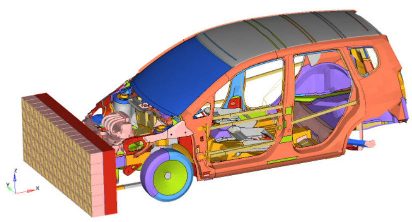



**Figure 11. Comparison of injury values**

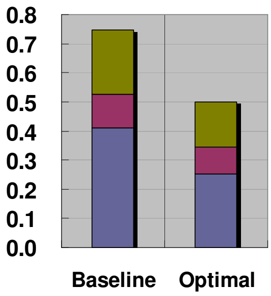
## OPTIMIZED STRUCTURE IN FRONTAL IMPACT

### FE Analysis

The effect of optimized structure in FE analysis, which was found to enhance compatibility in side impact, was studied in terms of frontal impact compatibility. The Full Width Deformable Barrier (FWDB) test, proposed by Transport Research Laboratory (TRL), was used to compare the compatibility metric in frontal impact at an impact velocity of 56 km/h. The compatibility metrics used for FWDB test simulation were Relative Homogeneity Criteria (RHC) and Average Height of Force (AHOF), which are calculated from load cell wall data [9], [10]. RHC and AHOF were compared between the Optimized Model and Baseline Model (Figure 12). The RHC for the Optimized Model indicated a lower RHC value than that of the Baseline Model, which means that the Optimized Model has more homogeneous force distribution in its front-end structure. As for AHOF, the Optimized structure lowered the AHOF400 by 87.8 mm, compared to the Baseline Model. These simulation results indicate that the metrics for frontal impact compatibility can discriminate the difference between the Optimal and Baseline models.

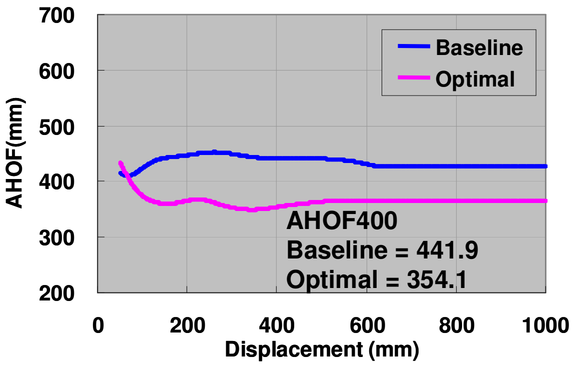


**(a) Full Width Deformable Barrier test simulation**




| | Baseline | Optimal |
|---|---|---|
| Vc*a | 0.411 | 0.252 |
| Vr*b | 0.116 | 0.092 |
| Vr*b | 0.219 | 0.155 |
| V | 0.746 | 0.498 |

**(b) Relative Homogeneity Criteria**

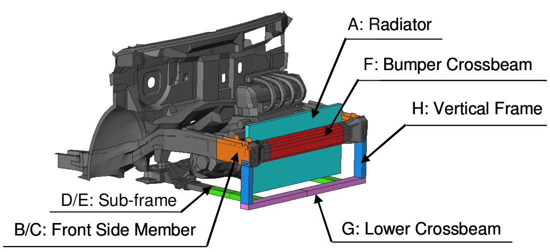



**(c) Average Height Of Force**

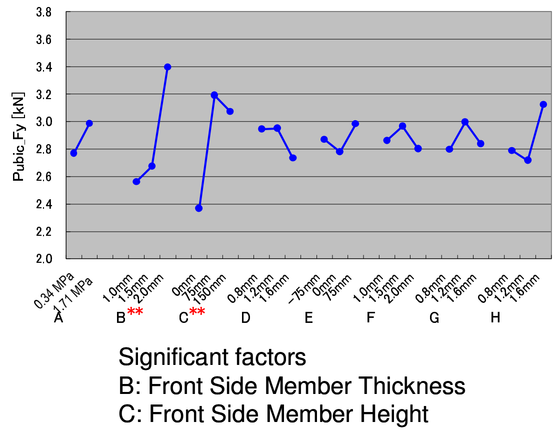
**Figure 12. Comparison of frontal compatibility metrics in FWDB test simulation**

## MODIFIED VEHICLE-TO-VEHICLE CRASH TEST

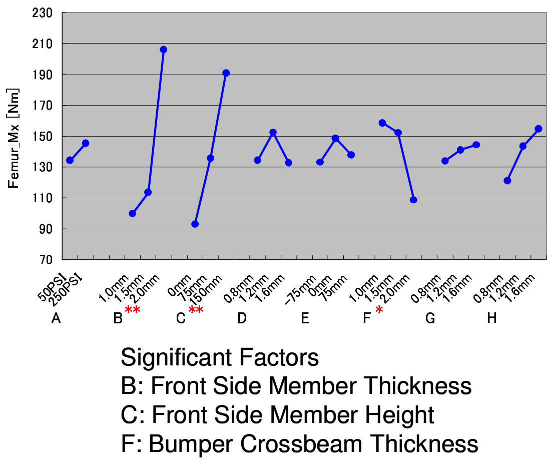
In the Baseline Car-to-Car test, the intrusion into the passenger compartment resulted in some higher pelvis and femur injury values, which were similar to those in the main bullet vehicle structure. In the FE analysis, the influence on those main structures was investigated in an effort to reduce injury values for the pelvis and femur. Figure 13 shows the variation in injury values between the pelvis and femur. These graphs indicate that the stiffness of the front side member was the most significant factor.




**(a) Structural factors**




**(b) Influence on pubic symphysis force**




**(c) Influence on femur moment**

**Figure 13. Influence on each design factor**

Since modification of the front side member significantly reduced the pelvis and femur injury values in FE analysis, a physical Car-to-Car test was performed. The modified Car-to-Car test aims to demonstrate the principles behind improved side impact compatibility, as identified in the FE simulation of this study, by modifying existing structures on the bullet vehicle. The results from tests with the modified bullet vehicle were compared to the results from the Baseline Car-to-Car test to demonstrate how the modifications affected the target vehicle's performance. A reduction in the crush strength of the front side member to prevent localized loading of the target vehicle was implemented to increase the amount of energy absorbed by the bullet vehicle in the impact. The modifications to the front section of the front side members were designed as the result of computer simulations, which indicated the optimum target vehicle performance could be achieved by reducing the thickness of the steel in the front side member from 2 to 1 mm. The modified section was approximately 250 mm in length, 100 mm high, excluding flanges, and 50 mm wide. The addition of a strengthened bumper cross beam was not implemented as the simulation work indicated that this would likely overload the B-pillar. The modified section of the front of the lower rails is shown in Fig. 14. The reparability issue associated with low speed impacts is not our present concern.


**Figure 14. Modification of front side member for Car-to-Car test**

**Dummy Injury Measures**

Comparison of the driver dummy's results from Modified Car-to-Car test with the Baseline Car-to-Car test showed that there were only slight differences in the chest injury levels. However, the most significant difference between the two tests was the force of impact on the pubic symphysis, which was approximately 60 % lower in the modified car. Comparison of the additional dummy injury parameters showed that there was a significant reduction in femur load and bending moment in the modified car, compared to those in the Baseline Car-to-Car test.

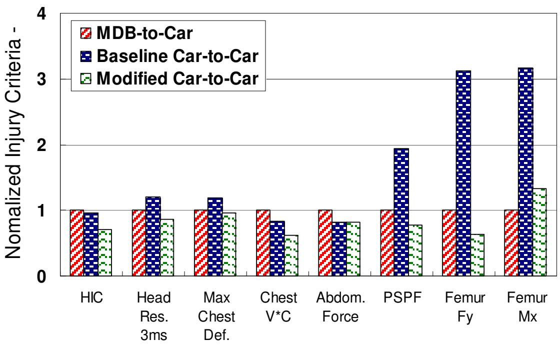
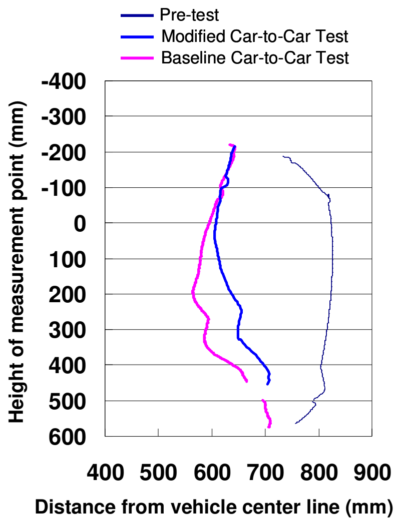



**Figure 15. Comparison of injury measures**

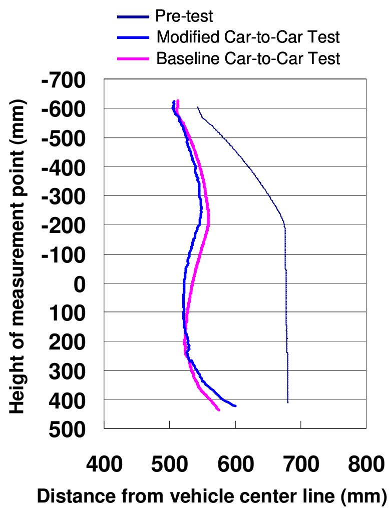
**Body Deformation**

A comparison of the deformation of the target cars from the Modified Car-to-Car test and Baseline Car-to-Car test is shown in Fig. 16. It can be seen that there was a significant difference in the deformation between the two test cars. The localized intrusion of the target car in alignment with the bullet vehicle's front side member was significantly reduced in the test with the modified bullet car. The B-pillar intrusion of the target car in the Modified Car-to-Car test was also reduced, compared to the Baseline Car-to-Car test.

**(a)Baseline Car-to-Car (b)Modified Car-to-Car**




**(c) Front door intrusion**



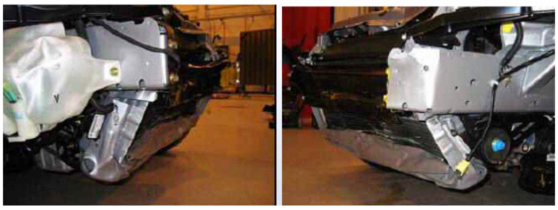

**(d) B-pillar intrusion**

**Figure 16. Comparison of body deformation between two Car-to-Car tests**

Comparison of the left-side front side member for the modified and unmodified vehicles showed a similar pattern (Fig. 17). The modified front side member section exhibited approximately 150 mm of axial crush, whilst the unmodified front side member had bent slightly inward. The deformation patterns indicated that there had been more energy absorbed by the modified bullet car's front side member in impact than there had been in the

Baseline Car-to-Car test. In addition, the overall deformation of the bullet vehicle's front side member and bumper cross beam was more homogeneous, as compared to the unmodified vehicle. These appeared to be significant factors in the reduction of localized deformation and target car intrusion. This reduction in intrusion appears to have most likely been the main contributory factor in the reduction of the driver's femur load and bending moment observed in the Modified Car-to-Car test.

**Modified car's front side members (post-test)**



**Unmodified car's front side members (post-test)**

**Figure 17. Comparison of front side member deformation mode between two Car-to-Car tests**

The optimized structure by FE simulation calls for further investigation into the stiffness and geometric properties of the sub-frame in order to achieve good structural interaction and stiffness matching. A further direction of this study will be to perform physical Car-to-Car testing with a modified sub-frame.

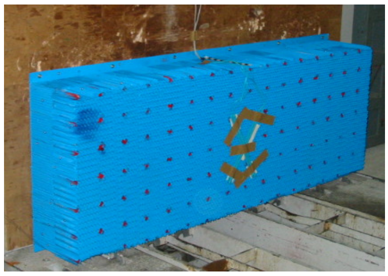
## DISCUSSION

According to the International Harmonized Research Activity (IHRA) report, relevant aspects for compatibility in a frontal impact are [11]

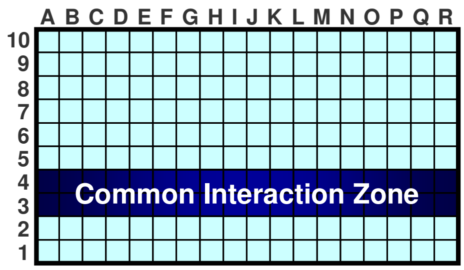
- Good structural interaction
- Frontal stiffness matching
- Occupant compartment strength
- Control of the deceleration time histories of impacting vehicles

Since these four factors had been proposed for an improvement of frontal impact compatibility, other impact configurations were not taken into account. However, it was found from this study that these factors could be considered for side impact compatibility as well as for frontal impact compatibility. From the results of a numerical simulation, side impact compatibility was able to be achieved when the front-end structures of the bullet vehicle interacted well with the body side structure of the target vehicle with stiffness matching between those structures. This is in agreement with items 1 and 2, in relation to compatibility improvement in frontal impact, as reported in the IHRA report. In the real world, there are vehicles with various structures and stiffnesses. As such, how structural interaction and stiffness matching are realized to enhance side impact compatibility should be further examined. Currently, test procedures for frontal impact are being studied in various countries. The role of side compatibility, however, has yet to be examined as a contributing factor. Therefore, development of the test procedure and assessment criteria for side impact compatibility is needed.

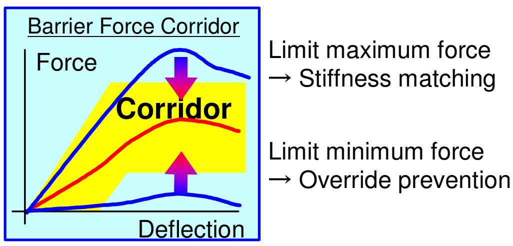
Note that in addition to the various crash directions, such as in the frontal and side directions, the benefits for/detriment to pedestrian protection and damageability ultimately need to be addressed as well. The future may require some portion of the vehicle front structure be developed to accommodate pedestrian protection, damageability, side impact and frontal impact, with corresponding crush displacement. To achieve this, controlling force-displacement characteristics by load cell wall data within the common interaction zone in the FWDB test may be one way of managing crash energy (Fig. 18) [12].



**(a) Full Width Deformable Barrier test**




**(b) 125 mm x 125 mm barrier load cell wall**




**(c) Barrier force corridor for each load cell**

**Figure 18. Common interaction zone and interaction force**

The structural geometry and stiffness characteristics of the front of a bullet vehicle play a role in influencing the risk of injury. For good occupant protection, it is desirable for the main impact loads to be transferred to the target vehicle through the side sill and door pillars. To be fully effective, strengthening the target vehicle's side structures will also be necessary for stiffness matching.

## CONCLUSION

In this research, to clarify the factors that influence side impact compatibility, actual-vehicle crash tests and computer simulations were performed. Moreover, computer simulations were utilized to investigate the influence on vehicle deformation and injury values of the target vehicle when the stiffness of the front side member, bumper crossbeam and sub-frame of the bullet vehicle were altered.

In summary,

- Localized deformation was observed in the Car-to-Car test due to a concentrated loading effect imparted from the front side member, whereas the B-pillar deformed uniformly in the MDB-to-Car test. It was found from the results that the localized intrusion into the door produced higher pelvis and femur injury values.
- In order to enhance side impact compatibility, structural interaction between the target vehicle body side structure and bullet vehicle front-end structure as well as stiffness matching of those structures are important, and are the same contributing factors for frontal impact.
- When the front side member was modified by the FE analysis, there was a significant reduction in the localized intrusion of the target vehicle in alignment with the bullet vehicle's front side members, as compared to the Baseline Car-to-Car test. The performance of the driver dummy was significantly improved in the Modified Car-to-Car test for the body regions in alignment with the bullet vehicle's structure, as compared to the Baseline Car-to-Car test.

The results of this study indicate that to improve compatibility for side impact, the bullet vehicle should be designed in such a way that it engages the structure of the target vehicle more effectively, through improved geometrical interaction. The results also showed that matching the geometry and stiffness between front-end structures of the bullet vehicle and body side structures of the target vehicle contributed significantly during side and frontal impacts.

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