# THE STUDY OF THE FRONTAL COMPATIBILITY WITH CONSIDERATION OF INTRERACTION AND STIFFNESS.

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## ABSTRACT

To reduce the amount of casualties in traffic accidents that involve various types of vehicles, the improvement of compatibility performance is important. In case of accidents, there are mismatches between colliding vehicles, which are in structural geometry, vehicle frontal stiffness and so on. For improving compatibility, helping minimize these mismatch issues as the first step.

The concept investigated in this research study, has three aspects. The first one is "Multi load path including mechanical parts". To ensure good interaction between colliding vehicles under existing mismatch of structure parts, it is effective to make use of mechanical parts as 'a substitute' load path, such as an engine with transmission or tire. The second is "To increase the amount of energy absorption (EA) of front body parts". The third is "Sufficient stiffness of the passenger compartment". To crush the front body parts for attaining additional EA, a proper stiffness of the passenger compartment is the prerequisite.

For improving compatibility, to satisfy above three items simultaneously is effective. According to the results of crash analysis, the concept for improving compatibility is investigated. Then structures applied for this concept are studied from the viewpoint of load flow and energy absorption, mainly by conducting CAE simulation. The improved structures were subsequently tested using actual vehicles for verification and the effectiveness of the concept is confirmed.

## INTRODUCTION

In general, frontal crash performance of a vehicle is significantly affected by interaction and stiffness of frontal structures as already shown in previous publications. [1], [2]

In case of a crash between actual vehicles, crash members, like front rails, do not always have a good interaction with each other because of their mismatch in design layout. When crash members miss each other, not enough crash load for energy absorption is generated and could cause a severe deformation of the passenger compartment. Crash members, here, mean members that carry crash load and dissipate kinetic energy. The design concept to improve structural interaction was proposed in [3].

Vehicle frontal stiffness correlates mainly with the mass as shown in Figure 1. The stiffness is obtained from FRB (full overlap rigid barrier) test results, by supposing the kinetic energy is equal to the strain energy of linear stiffness structure. The tendency to increase with vehicle mass is influenced by the barrier test with constant speed, regardless of the vehicle mass. Considering these differences in stiffness, a lightweight, small car will suffer more severe damage in a collision with a large, heavy vehicle.

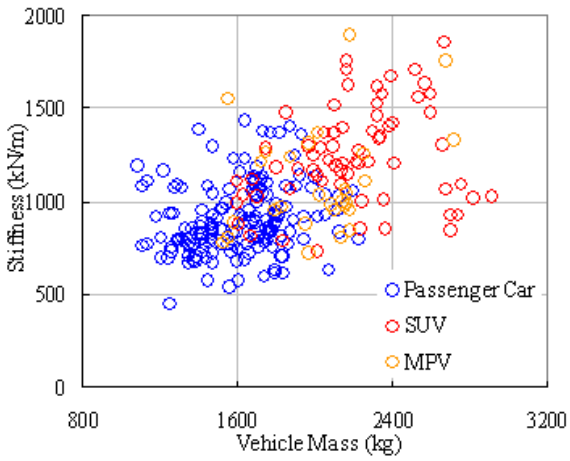



**Figure1. Vehicle Mass and Frontal Stiffness.**
**(Source: US/JPN NCAP results & TMC inside tests)**

To explain a crash phenomenon simply, momentum of a vehicle decreases by a reaction force that is generated in

the crash of both vehicles. This is shown in the equation 1:

$$\Delta m \cdot V = m \cdot V_o - m \cdot V_a = \int F dt \qquad (1).$$

$\Delta m \cdot V$ :Variation of momentum.
$m$ : Mass of a vehicle.
$V_o$ :Velocity before crash.
$V_a$ : Velocity after crash.
$F$ : Force generated during crash.

The reaction force is determined by a structural strength or inertia force of the vehicle. This force deforms the vehicle structures. The deformation continues until the kinetic energy of the vehicles is reduced to the final quantity that is determined according to physical law. In a crash event, the vehicles absorb the kinetic energy as deformation energy. This is shown in the equation 2:

$$\frac{1}{2} M_s \cdot V_s^2 + \frac{1}{2} M_l \cdot V_l^2 = \int_{small} F ds + \int_{large} F ds + E_r \quad (2).$$

$M_s$ : Mass of a small car.
$M_l$ : mass of a large vehicle.
$V_s$ : Velocity of a small car.
$V_l$ : Velocity of a large vehicle.
$E_r$ : Remaining kinetic energy after crash, etc.

The deformation energy is determined by deforming force and length, in terms of their product. This means that the kinetic energy to be absorbed increases in proportion to the vehicle mass. Frontal crash compatibility of the heavier vehicle means to better balance the energy, i.e. absorb more energy. Compatibility of the small car means same stiffness to reduce vehicle deformation at higher crash load. For that purpose, an improved interaction is important.

Large deformation of a vehicle in a frontal crash can be caused by insufficient front-end energy absorption. When a vehicle, of 2070 kg mass crashes a car of 1160 kg mass with 50km/h closing speed, the total kinetic energy of both vehicles is 310 kJ. The vehicle run-out kinetic energy would be approximately 100 kJ. 210 kJ of the energy should be absorbed as strain energy of both vehicles, in case of a frontal offset crash. The energy should be absorbed before the cabin to help minimize the intrusion.

During ride-down, it is also important to control deceleration G for not to exceeding human tolerance levels. In general, the vehicle front should be designed as an energy absorbing area to absorb the energy effectively.

From the above, to improve compatibility, 1) Good interaction of crash members to generate crash load, 2) Adequate stiffness balance of energy absorbing area of both vehicles, 3) Cabin stiffness high enough to limit deformations to the front area, are seemed to be important. From this point of view, the study of improving the compatibility is conducted as follows.

## ANALYSIS OF CRASH PHENOMENON

Analysis of crash phenomenon was carried out with crash tests between a small car and various large vehicles. There were 3 types of large vehicles, one is a large passenger car, the second was a SUV with frame structure (SUV-A), and the third was a SUV of unitized body (SUV-B). The weight of the large vehicles was about 2000 kg and that of the small car was ~1200 kg. Such the mass ratio was is in the range of 1.7. To represent a severe offset crash condition, the frontal offset tests were conducted with 50% overlap, at a closing speed of 55km/h each.

### Vehicle deformation and crash load

The deformation of the small car was severe after the crash with the SUVs, especially in case of SUV-B. In case of the large passenger car, the deformation of the small car was much less as shown in Figure 2.

**Crash to a Large Car.** **Crash to SUV－B.**

**Figure 2. Deformation of a Small Car.**

Comparison of the crash load is shown in Figure 3. Here, crash loads were calculated by multiplying vehicle deceleration G and mass. In Figure 3, the corresponding curves of the small car and the large vehicles that impacted each other are shown in the same color. The left

side of the figure shows curves of the large vehicles, and right side shows those of the small car. The load of the large passenger car (shown in green, left) is relatively low and its deformation is larger than the SUVs. Therefore, the deformation of the small car that crashes into SUV-B (shown in red, right) is larger than in the large passenger car's case.

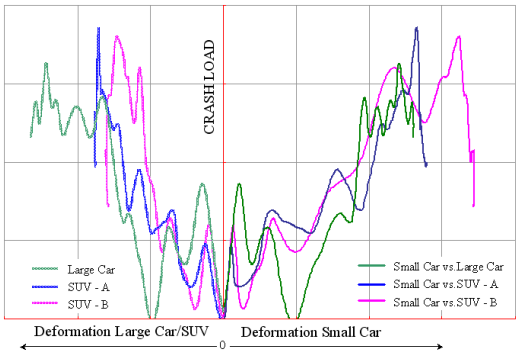



**Figure 3. Comparison of Crash Load.**

**Energy absorption**

Energy absorption ratio estimated from the load-deformation curve is shown in Figure 4.
In a crash between large passenger car and small car, the EA amount of the large car is larger than that of the small car. The compatibility of the large passenger car is very good. For the tests with SUVs, the EA amounts of both SUVs are smaller than that of a small car.

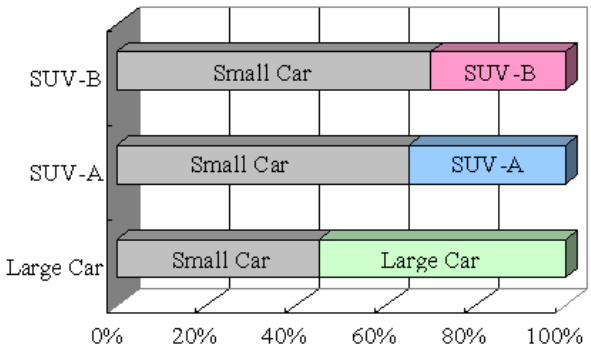



**Figure 4. Ratio of the Energy Absorption.**

The front body structures of the small car and the large passenger car were well deformed as shown in Figure 2 and Figure 5 left. On the other hand, the front body of the SUV was less deformed, shown in Figure 5 right, and it seemed that the EA amount of this section was not fully utilized. One of the reasons of less deformation is due to the difference of frontal stiffness between small car and SUV. The structure of the small car that has lower stiffness deformed one-sidedly. Another reason may be due to the misalignment of crash members, resulting in reduced crash loads for energy absorption. One of the reasons is the difference in ground clearance of front rails between SUV and small car, of about 75mm. An aggressiveness of SUV was shown in previous study. [4]

**Large car.** **SUV-B.**

**Figure 5. Deformation of Large Car/SUV.**

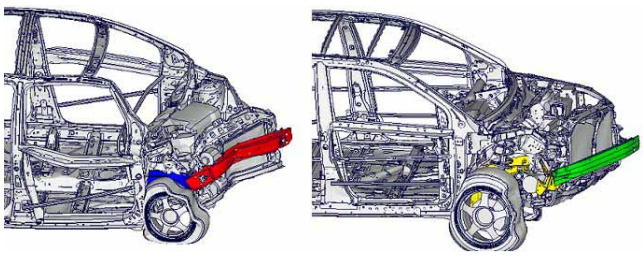
**ANALYSIS BY CAE SIMULATION**

To further comprehend the results of test analysis, a study using CAE simulation was conducted. The crash between small car and SUV-B was simulated, which represents the most severe case. The investigation was conducted from the viewpoint of interaction, load flow and energy absorption. The crash condition is given below:

50% Overlap, Closing speed each: 50 km/h,
Mass : small car 1162 kg, SUV-B 2078 kg.

**Vehicle deformation**

The deformation of the small car was severe as predicted from above analysis. It extended into the cabin area. As for the SUV, its deformation was limited to the front end only.



**Small car.** **SUV-B.**

**Figure 6. Body Deformation in CAE simulation.**

**Crash load and interaction**

A crash load is analyzed from the viewpoint of interaction. The load is classified in to three stages according to the characteristics,

**First stage**-Low load term from the beginning up to ~20 ms. Front-end structures hit each other. In this case, the interaction of front rails of both vehicles is not sufficient because of geometry mismatch.

**Second stage**-Load increasing term from 20 ms to 35 ms. Front structures are proceeding their deformation and starting to interact with opposite mechanical parts, like power train unit, tire and so on. With progressing interaction of these mechanical parts, the crash load increases drastically. The tires of both vehicles start to hit the opposite bumper beam. However, these interactions are not satisfying because of over-riding or bending of the beams.

**Third stage**-High load term from 35ms. Mechanical parts, such as tire and power train unit, are slightly deformed and pushed back, and some cabin structures become deformed.

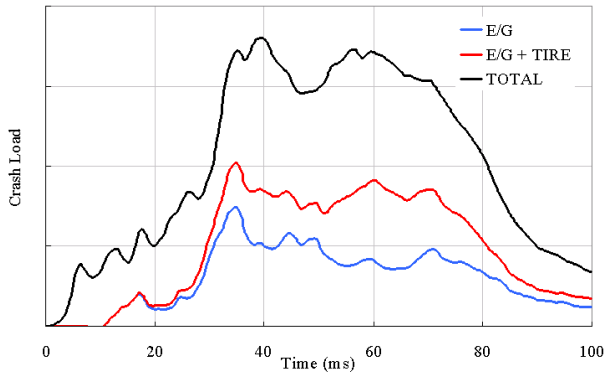



**Figure 7. Crash Load – Time Curve.**

**Load Path**

There are three load paths in this combination of the vehicle. The first one is the structural load path, mentioned in many papers. The second path is the power train path through the engine and transmission. The third path is the suspension path that consists of tire, wheel and suspension arms, etc. These paths are shown in Figure 8. The loads in the paths are changing during the crash, as described below. Only the load path of the small car will be mentioned here.

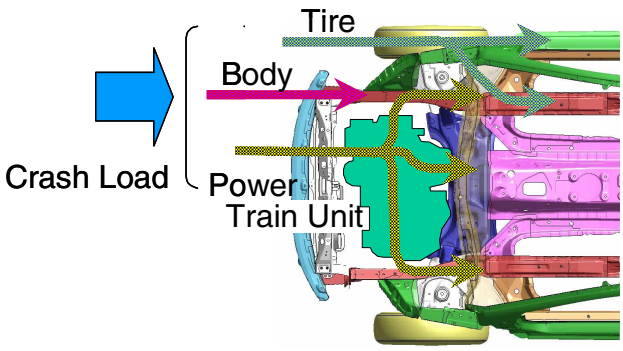



**Figure 8. Load Path.**

**First stage** - The structural load path is a main path at this stage. The front bumper beam hits the opposite structures and/or parts like the radiator, and generate a crash load. Crash load is translated to the front members. The load deforms these rails, and the load flows through cabin structures distributed to upper and under structures, shown in Figure 9. The bumper beam was not able to translate a satisfactory crash load to the front rail, because of its smaller cross section.

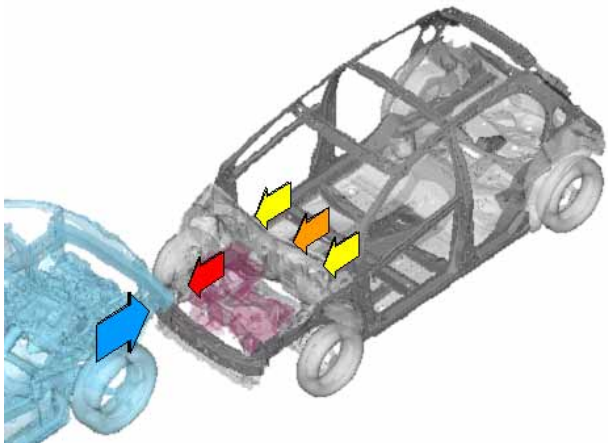


**Figure 9. Load Path of the First Stage.**

**Second stage** – In addition to the structural parts, mechanical parts e.g. tire, power train unit of both vehicles push each other through the crushed front-end structures. Load translation to cabin parts through body structures continues, and the load through a mechanical path is increasing rapidly. The load is translated to the rearward parts through mounting portion of the mechanical parts. At half of this stage, a tire impacts the opposite structures hard and the load through suspension is increasing. This load goes through suspension parts to under body structures. The load paths are shown in Figure 10.

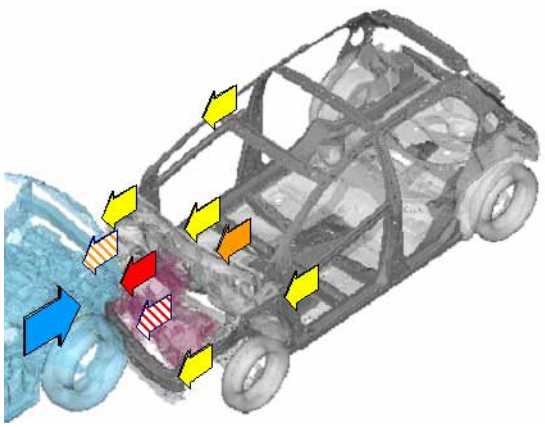


**Figure 10. Load Path of the Second Stage.**

**Third stage** - Mechanical path becomes a main path at this stage. After the deformation of the body has progressed, the tire starts to hit the side sill. The power train unit is pushed back into the dash panel and the sub frame. In this case, the bumper beam of the SUV hits the small car's strut. The load flow of the third stage is shown in Figure 11.

According to the above investigation, the mechanical load path should be considered to improve compatibility performance.

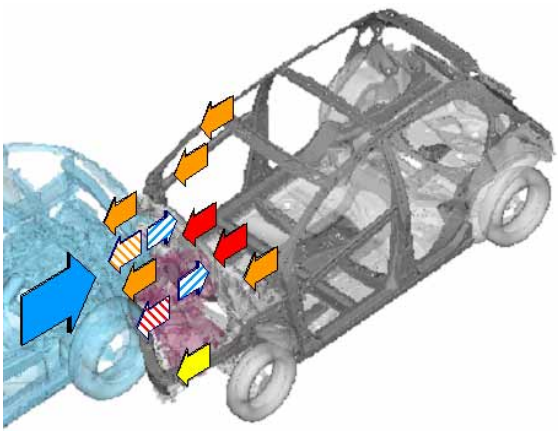


**Figure 11. Load Path of Third Stage.**

## Crash Energy Absorption

As mentioned before, it is important to make a careful design of the energy absorption area. In other words, increasing the amount of energy absorption of front structures can help reduce the cabin intrusion in turn. Figure 12 shows the variation of strain energy per unit of time, absorbed by the parts of the small car. In this graph, the vertical axis is differentiation of EA amounts with respect to time and horizontal axis is time, so an area below the curve means EA amount of the parts. The blue line means EA amount differentiation of front body parts, the red line means the sum of the differentiation of front body parts and that of cabin parts.

Front body parts start to absorb the energy from the beginning of the crash and continue to the third stage. As for the cabin parts, strain energy starts to be absorbed after 30 ms. In case of the small car in this study, some 70 % of the strain energy of body structures was shared by the front structures, and 30 % by the cabin structures. The EA amount of the small car cabin absorbed is 1.4 times as much as that of the cabin structures absorbed in an Euro NCAP 64km/h ODB crash. On the contrary, in case of the SUVs, most energy was absorbed by front structures only.

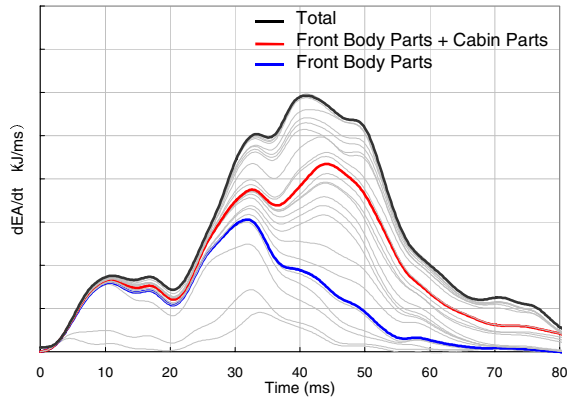



**Figure 12. Energy Absorption History.**

## How to improve the Energy Absorption

It is important to crush the front structures effectively. For this purpose, it is needed to direct the crash load to energy absorbing parts, and to back up these parts from behind with stiffness higher than the actual crushing load. Requirement for the parts is shown below,

**Front bumper beam** - The cross beam should have a large area under load to transmit it to the front rails. This helps the front rail to deform well and as a result, it can absorb higher energy. Moreover, in case of a crash with misalignment in longitudinal members, a better interaction in lateral direction is expected, if the beam has enough stiffness. The effectiveness of a bumper beam is described in [5].

**Front body structure parts** - It is important to ensure a good balance in stiffness of each vehicle's front structures. To stiffen the cabin front area will allow deforming parts in the engine compartment, thus in turn maintaining the integrity of the cabin. In addition, it is

important to improve the front rail deformation mode as described in previous work. [6]

**Mechanical Parts** - The power train unit plays an important role in the load translation in the second and third stage of crash. The unit itself represents a rigid block, and could be rather considered as an interaction part. There is a possibility to make use of it as a load distributing part. Tire and suspension parts can also provide the same kind of function. By utilizing these mechanical parts, it seems possible to prevent weight increase for structural reinforcement. The effect of mechanical parts utilization is more effective, when the bumper beam stiffness is increased.

According to the above, subjects for improving energy absorption of the front structures are,

1) Direct crash load adequate to the members,
2) Enough supporting stiffness of front structures,
3) A tuned, progressive balance of frontal stiffness of each vehicle.

## STUDY FOR IMPROVING STRTUCTURES

### Studied Structures

The concept for improving crash compatibility, described above, is checked by conducting a structural study using CAE simulation. Condition of the simulation is the same as mentioned before. Only the small car structures were modified, here. Modified parts are shown in blue color in Figure 13.

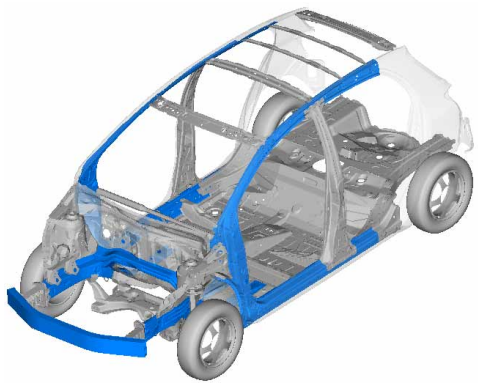


**Figure 13. Modified Parts of the small car.**

Items studied are listed below:

1) Increase the bending stiffness of bumper beam,
2) Optimize a deformation mode of front rail,
3) Increase the supporting stiffness of front rail,
4) Increase the cabin stiffness,
5) Stiffen the power train unit mounting.

### Improvement of Crash Load and Interaction

Load curve of the modified structure is shown in Figure 14. In the first stage, no significant change has occurred in spite of increased bumper beam stiffness. Obviously, the reason is mismatch of the beams. On the contrary, there is a great increase of crash load in the second stage.

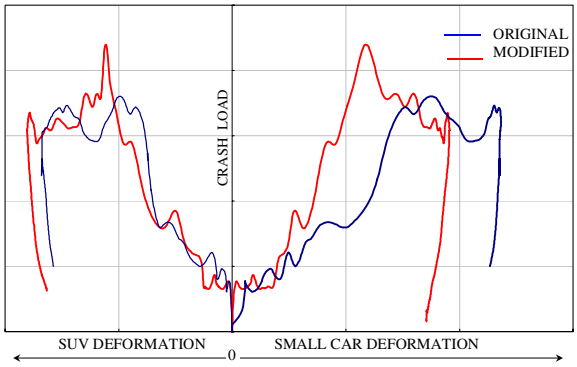



**Figure 14. Comparison of Crash Load.**

This is caused by the interaction improvement of the bumper beam. The beam kept its function during crash, and generates high load activating the opposite structure and hitting tire and power train unit, etc. Increase of the interaction force during the latter stage of crash is shown in Figure 15.

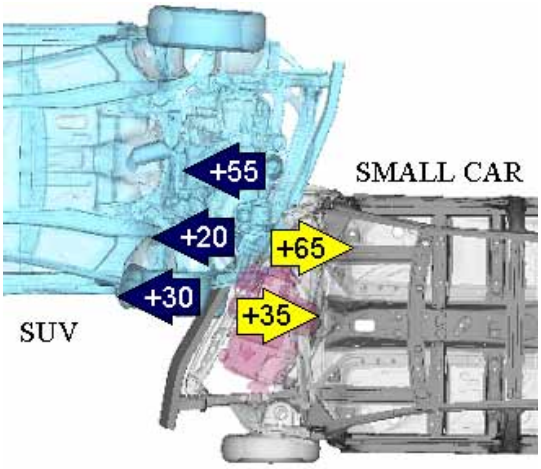



**Figure 15. Increase of Interaction Force.**

The bumper beam with increased stiffness works as a bridge among front rail, tire and power train unit, and increases the crash load significantly. To continue the crash load, supporting stiffness of the beam mainly pro-

vided by a front rail, is also important.

The maximum load value increased about 20%. This seems caused by the higher cabin stiffness. The improvement of load flow mentioned above drastically decreased the cabin intrusion of the small car.

Comparison of the body deformation is shown in figure 16. For the test conditions analyzed, the integrity of the cabin of the small car has greatly improved. Intrusion of toe-board and A –pillar is reduced to under the half. The deformation of the SUV, remained in the front body area. Though, it has somewhat increased, it is not significant because of the initial deformation was fairly small.

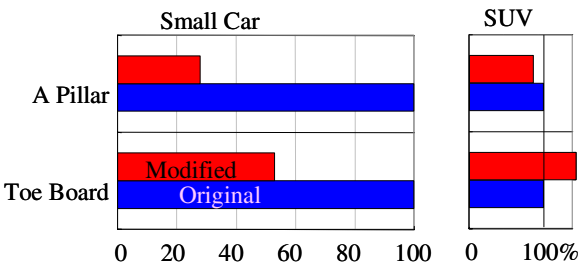



**Figure 16. Comparison of Body Deformation.**

Comparison of the energy absorption is shown in figure 17. The amount of energy absorption of only the small car cabin has decreased by nearly 10%, whereas the SUV has increased about 10% in total.

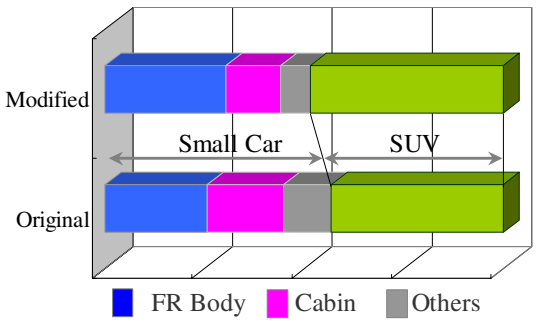


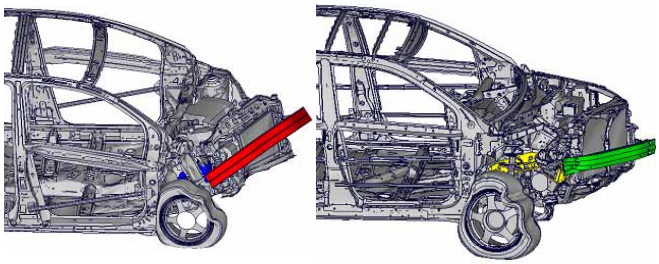

**Figure 17. Comparison of Energy Absorption.**

According to the above research, the concept to improve frontal compatibility is summarized below.

1) Improve the interaction. Not only structural interaction but also mechanical interaction should be considered. Especially, applying a bridging effect of the cross beam is necessary.
2) Balance the frontal stiffness of each vehicle. This makes it possible to adjust each energy absorption area more effectively.
3) Increase cabin stiffness of the small car. This is a requisite to crush vehicle front structures and, of course, contributes to the cabin integrity.

**Small Car.** **SUV.**

**Figure 18. Deformation of Studied Structure.**



## CONFIRMATION BY CRASH TEST

To confirm the above concept, a crash test was conducted using a modified car. The test condition is given below. It is the same as used in CAE simulation:

50% Overlap, Closing speed each: 50 km/h,

Mass: small car 1218kg, SUV 2078kg.

Only the small car was modified and almost the same like the structure studied in CAE investigation.

### Crash Load and Interaction

Crash load estimated from deceleration and actual mass involved is shown in Fig-19. As well as the CAE result, the load of the second stage has increased significantly. Film analysis confirmed that this increase of the load is due to the improvement of bumper beam interaction.

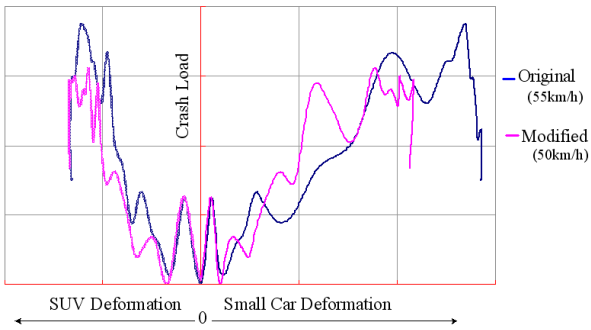



**Figure 19. Comparison of the Crash Load Curve.**

The bumper beam with improved stiffness had a good interaction with the other vehicle. The interaction among power train unit, tire, and bumper beam has proved to be effective in the earlier stage of the crash. It generated a

high load by hitting an opposite tire. To keep the beam from deforming away can make it possible to transmit additional load to the front rail during the crash.

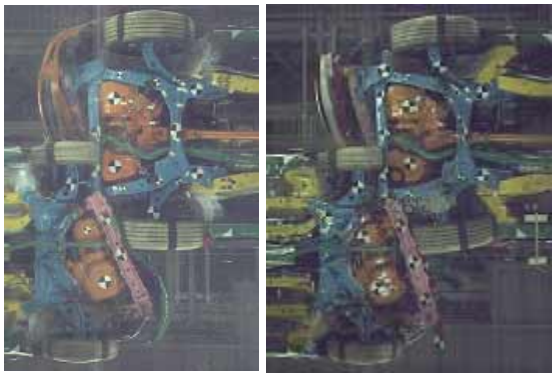
**Modified Structure.** **Original Structure.**

**Figure 20. Bumper Deformation after Crash.**

The higher stiffness of the supporting member of the power train unit helped to raise the overall front end stiffness. This might contribute to the improvement of mechanical interaction.

**Modified structure.** **Original structure.**

**Figure 21. Interaction of Mechanical Parts.**



## VEHICLE DEFORMATION

The vehicle deformations are shown below.

**Small Car.** **SUV.**

**Figure 22. Deformation of the Vehicles (Side view).**

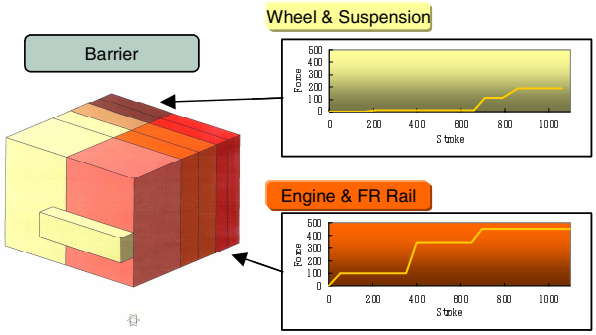
The front-end structure showed the expected deformation by generating high crash load in the middle stage of the crash. Both the intrusion of toe-board and A - pillar were satisfying the deformation target.

The above mentioned concept confirmed that it allows to improve frontal compatibility.

## BARRIER FOR COMPATIBILITY EVALUATION

A barrier can be used for evaluation of compatibility in the vehicle development process. It is necessary to be representative of frontal stiffness of actual vehicles including its distribution both in width and height. The load paths of the frontal crash were composed of three parts, structure path, power train unit path and suspension path, as mentioned before. Of course, due to different stiffness, the reaction load from each path is different. Therefore, it seems to be reasonable that a barrier could have a stiffness distribution adjusted to represent actual vehicles. An example of barrier composition, which is basis of the above idea, is shown in Figure 23.

**Figure 23. Barrier Composition.**




The barrier concept is under investigation. It could be used to help develop compatible structures within TMC in the future.

## CONCLUSION

To improve frontal compatibility, it is essential to properly define the energy absorption area of both vehicles. For the test conditions analyzed in this research, the concept below has proved to be reasonable:

1. A stiff cross beam at the bumper is effective to improve early interaction.
2. To improve the interaction, not only structural interaction but also the mechanical parts interaction should be considered.
3. A good balance of frontal stiffness of each vehicle is required for sufficient energy absorption in the front-end.
4. Proper stiffness of the cabin structure is prerequisite

for improving the energy absorption of the front structure.

The structure studied in this research is only analyzed under limited conditions. However the way of thinking is available for other crash conditions.
Improvement of crash safety performance is associated with weight increase in most cases. Of course, it is desirable to improve the performance without adding mass from the viewpoint of ecology. In view of this, to make use of the mechanical load path effectively is preferable.

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