**SECOND REPORT OF RESEARCH ON STIFFNESS MATCHING BETWEEN VEHICLES FOR FRONTAL IMPACT COMPATIBILITY**

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Paper Number 07-0261

## ABSTRACT

Through the global research of the past decade, it can be said that fundamental issues of frontal impact compatibility have been almost fully understood. The first step is to enhance the structural interaction between the front-end structures of colliding vehicles and the next step is to help match the stiffnesses between vehicles. In the previous ESV conference, the authors reported the results of a study in which stiffness matching in SUV-to-car frontal impact was accomplished by increasing the car's stiffness only[9]. In this paper, the stiffness matching in SUV-to-car frontal impact will be accomplished by only reducing the SUV's stiffness using FE (finite element) vehicle models. These two studies would contribute to furthering the research for more practical compatibility countermeasures.

## INTRODUCTION

Automobile manufacturers' continuous efforts to improve vehicle safety performance in cooperation with the introduction of various vehicle safety standards and the new car assessment programs have led to significant improvement of vehicle self-protection performance over the past years. As a consequence, the improvement of impact compatibility for partner-protection is recognized as an indispensable approach to further help enhance vehicle safety performance.

Many studies in the past several years have indicated that the fundamental issues of frontal impact compatibility were to enhance structural interaction between the front-end structures of colliding vehicles as the first step, and to help match stiffnesses between vehicles as the subsequent necessary step. On the basis of this philosophy, various approaches to improve frontal impact compatibility have been proposed and discussed around the world [2]-[8].

The authors have been focusing their attention on the stiffness matching issue in the case where good structural interaction was ideally achieved and reported the results of a study in which stiffness matching in SUV-to-car frontal impact was tried only by increasing the car's stiffness[9]. The results were reported in the previous ESV conference. The conclusion of that study was that achieving good stiffness matching between a SUV and a car only by increasing car's stiffness was unrealistic due to substantial weight increase by the necessary reinforcement of the body structure.

On the other hand, NHTSA(National Highway Traffic Safety Administration) is now studying the effect of reducing the SUV's stiffness on stiffness matching by the introduction of new metrics called KW400[10]. In this paper, stiffness matching in SUV-to-car frontal impact (see Table 1) was performed only by reducing the SUV's stiffness to a certain level of KW400. In order to focus on stiffness matching, it was assumed that structural interaction between the vehicles is ideal. The study was done using FE vehicle models(see Figure 1). The FE vehicle models were respectively correlated with fixed-barrier physical impact tests.

**Table 1.**
**SUV-to-car impact conditions**

| **Vehicle type** | SUV | Car (Middle-sized sedan) |
|---|---|---|
| **Curb mass** | 2500kg | 1400kg |
| **Overlap ratio** | Full overlap | |


**Figure 1. FE vehicle models.**

## INFLUENCE OF KW400 ON VEHICLES

NHTSA's report shows that KW400 is calculated as shown in Figure 2 using a vehicle force-deformation curve obtained in a 56km/h full overlap frontal impact test. Although the appropriate upper limit of KW400 for SUVs has not been decided yet, NHTSA indicates that the occupant injury probability in impacts between vehicles whose KW400 is between 1300N/mm and 1700N/mm is lower than that in impacts between other vehicles[11]. Therefore in this study, it was assumed that the SUV's KW400 shall not exceed 1700N/mm.

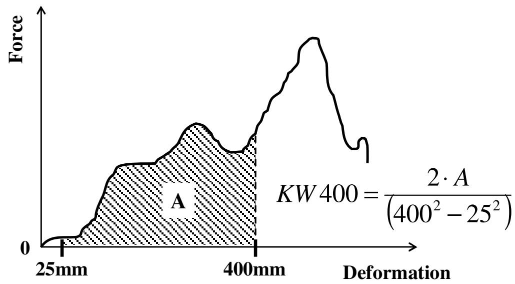


**Figure 2. Difinition of KW400.**

Figure 3 represents the force-deformation curve of the SUV shown in Table 1, which is obtained from the result of FE simulation for a 56km/h full overlap impact test. The SUV's KW400 is approximately 2400N/mm and larger than the assumed upper limit of 1700N/mm. The measure that was considered was to decrease the KW400 below the upper limit.

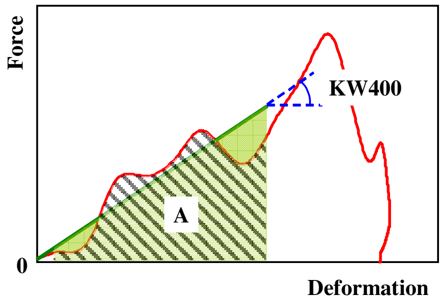


**Figure 3. Force-deformation curve of SUV in 56km/h full overlap impact.**

According to the KW400 definition, it is expected that reducing the front longitudinal stiffness where vehicle deformation ranges from 0mm to 400mm will lead to the achievement of preferable KW400 values. However this causes the reduction of energy absorption in the engine compartment. As a result, it is believed that passenger compartment intrusion increases and occupant injury indexes increase. The increase in occupant injury results from a combination of delay in occupant restraint and changes in allowable relative occupant displacement due to deformation and intrusion.
Therefore reducing the front longitudinal stiffness to decrease the KW400 has to be combined with some of the following measures to improve vehicle safety performance.

- To prevent increased passenger compartment intrusion
  - Prevent the energy absorption in engine compartment from decreasing by means of extending vehicle front overhang.
  - Increase vehicle stiffness where vehicle's deformation is over 400mm.
- To prevent increased relative displacement of occupant to vehicle
  - Improve the restraint system performance.

At the same time, automotive manufacturers generally take into consideration the following viewpoints when deciding on which measures should be adopted.

- Minimizing vehicle front overhang in order to maintain vehicle exterior design flexibility and good handling performance among other factors.
- Keeping cabin strength below a certain level to

avoid the increase of relative displacement of occupant to vehicle.

- Technical limitations associated with improving restraint system performance.

Based on the above-mentioned factors, a set of measures to decrease the SUV's KW400 below 1700N/mm without an increase of occupant injury indexes in a 56km/h full overlap impact was determined using FE simulation. The result is shown in Table 2 and Figure 4.

**Table 2.**
**A set of measures to decrease the SUV's KW400**

| | |
|---|---|
| **Front overhang** | Increased |
| **Restraint system** | Improved |
| **Vehicle force-deformation curve** | See Figure 4 |

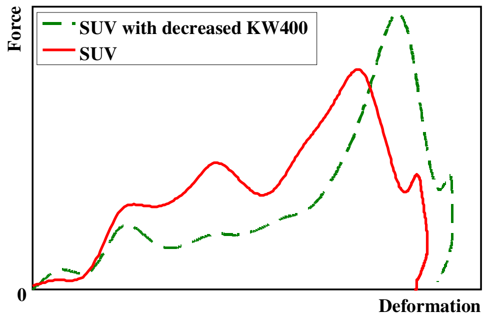


**Figure 4. Force-deformation curve in 56km/h full overlap impact of SUV with decreased KW400.**

## EFFECT OF KW400 ON STIFFNESS MATCHING IN SUV-TO-CAR IMPACTS

In the previous chapter, a set of measures to achieve the preferable SUV's KW400 from a compatibility viewpoint without an increase of occupant injury indexes in a 56km/h full overlap impact was shown. As a next step, we compared whether the car's deformation decreased or not in a SUV-to-car frontal impact with an SUV that had preferable KW400 values.

At the beginning, the following basic study was conducted.

When an SUV with a mass m1 impacts a car with a mass m2 at a relative speed of V, the deformation energy of both vehicles E, is given by:

$$E = \frac{1}{2} \cdot \frac{m_1 \cdot m_2}{m_1 + m_2} \cdot V^2 \qquad (1).$$

In the above equation, it is assumed that the impact is perfectly inelastic. When the force-deformation curves of both vehicles are known, the deformation of each vehicle in this impact can be derived from the relationship identified in the hatched area of Figure 5 is equal to E.

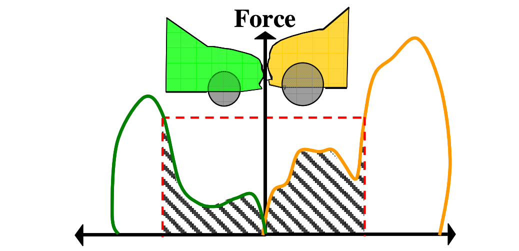


**Figure 5. Prediction method of vehicle deformation.**

Using the above-mentioned method, the deformation of each vehicle was predicted. Additionally, prediction of two impact scenarios using different impact speeds was performed. The detailed impact conditions are shown in Table 3. The prediction of Case 1 was done using force-deformation curves obtained in 56km/h full overlap impact FE simulations. In contrast, in the prediction of Case 2, a force-deformation curve of a car was obtained in a 70km/h full overlap impact FE simulation because it was expected that the car's deformation in Case 2, SUV-to-car impact, was larger than that in a 56km/h full overlap impact.

**Table 3.**
**SUV-to-car impact conditions**

| **Case** | 1 | | 2 | |
|---|---|---|---|---|
| **Vehicle type** | SUV | Car (Middle-sized sedan) | SUV | Car (Middle-sized sedan) |
| **Curb mass** | 2500kg | 1400kg | 2500kg | 1400kg |
| **Impact speed** | 32km/h each vehicle | | 56km/h each vehicle | |
| **Overlap ratio** | Full overlap | | Full overlap | |

Figure 6 shows the prediction result. In both Cases 1 and 2, the car's deformations were larger than SUV's deformations. These results are not considered compatible.

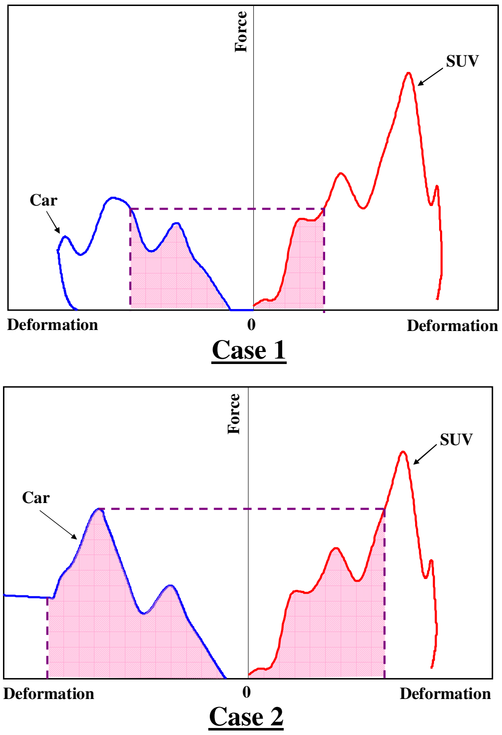


**Figure 6. Deformation prediction of SUV and car.**

Next, the deformation of each vehicle when a SUV with decreased KW400 was modeled (by installing the measures shown in the previous chapter), and the impacts on a car were predicted. Also, prediction of two impact scenarios using different impact speeds was performed.. The detailed impact conditions are shown in Table 4.

**Table 4.**
**SUV-to-car impact conditions**

| **Case** | 3 | | 4 | |
|---|---|---|---|---|
| **Vehicle type** | SUV with decreased KW400 | Car (Middle-sized sedan) | SUV with decreased KW400 | Car (Middle-sized sedan) |
| **Curb mass** | 2500kg | 1400kg | 2500kg | 1400kg |
| **Impact speed** | 32km/h each vehicle | | 56km/h each vehicle | |
| **Overlap ratio** | Full overlap | | Full overlap | |

The prediction result is shown in Figure 7. The car's deformation in Case 3 decreases in comparison with that in Case 1 and compatibility is improved. However the car's deformation in Case 4 increases in comparison with that in Case 2 and compatibility is deteriorated. The reason of this deterioration is that the energy absorbed by the SUV at this comparatively high impact speed has decreased due to measures meant to achieve the preferable SUV's KW400.

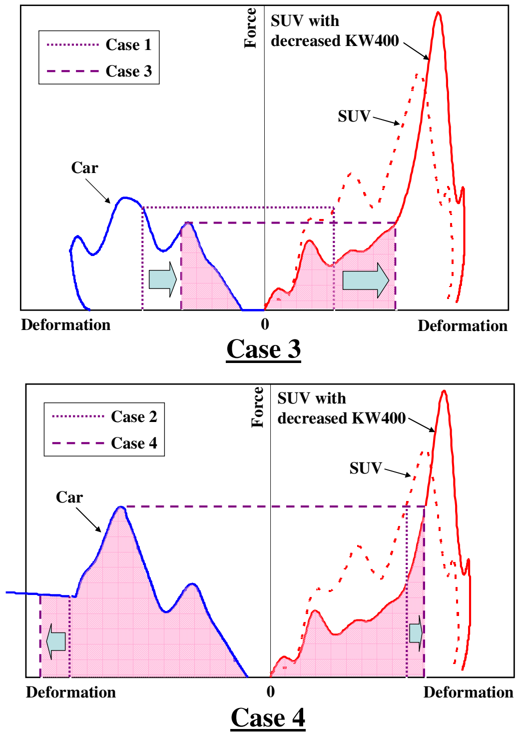


**Figure 7. Deformation prediction of SUV with decreased KW400.**

From these results, it is expected that there is a critical impact speed at which the effect of decreasing the SUV's KW400 below the assumed upper limit on the car's deformation changes from reduction to increase. The method described above indicates that the critical impact speed is approximately 52km/h(see Figure 8).

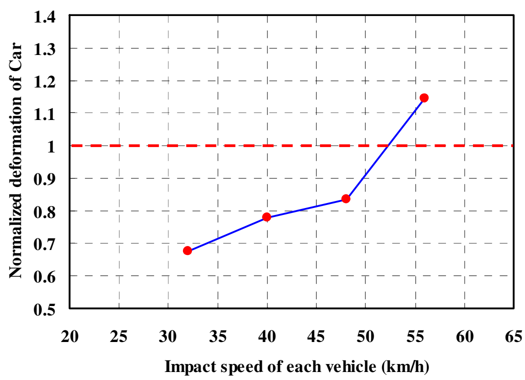


**Figure 8. Relation between variation of car's deformation and impact speed.**

The result obtained by the above basic study suggests that, depending on how to decrease the SUV's KW400, compatibility in SUV-to-car frontal impact under a critical impact speed is improved while compatibility in SUV-to-car frontal impact over the critical impact speed could be deteriorated.

In the above-mentioned basic study, it was assumed that impact is perfectly inelastic, but an actual impact is not. In addition, vehicle force-deformation curves in SUV-to-car impacts may not correspond to those in full overlap impacts, especially at a late impact stage due to static/dynamic ratios and other factors. Therefore in order to verify the result more accurately, SUV-to-car frontal impact FE simulations were conducted (see Figure 9) for all four cases shown in Table 3 and 4. In these FE simulations, a plane perpendicular to a vehicle's longitudinal direction was set at the junction between both vehicles to assume that structural interaction between both vehicles is ideal. The plane can move only in a vehicle's longitudinal direction.

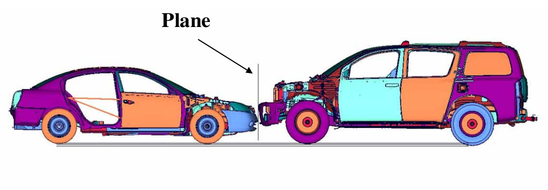


**Figure 9. SUV-to-car frontal impact FE simulation model.**

Figure 10 shows the result. In the cases that impact speed of each vehicle is 32km/h, the car's deformation in Case 3 decreases in comparison with that in Case 1. However, in the case where the impact speed of each vehicle is 56km/h, which slightly exceeds the critical impact speed obtained from the basic study, the car's deformation in Case 4 does not decrease but rather slightly increases in comparison with that in Case 2. The FE simulations correspond well to the basic study.

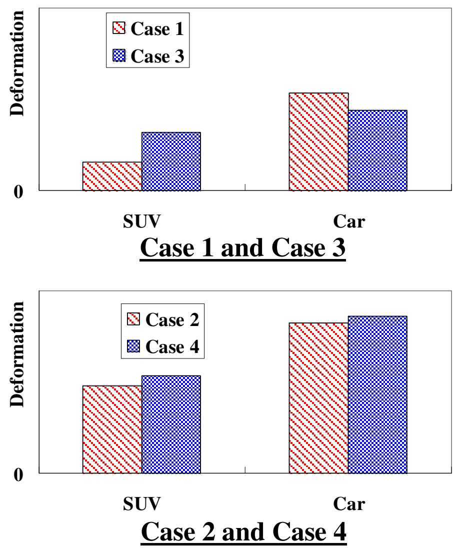


**Figure 10. Calculation result of vehicle deformation.**

## DISCUSSION

The purpose of this study is to validate the effectiveness of the SUV's KW400 reduction as a countermeasure for compatibility improvement in SUV-to-car frontal impact. For that purpose, at the beginning a set of realistic measures to decrease the SUV's KW400 below the assumed upper limit without the increase of occupant injury indexes in 56km/h full overlap impact was determined. The measures are an example of solutions with a practical balance between safety performance and other requirements in actual vehicle design and contain not only vehicle stiffness reduction but also vehicle front overhang extension, restraint system improvements and so on.

However, as a result of subsequent SUV-to-car frontal impact FE simulations using the SUV model installed with the above measures, it turned out that such design changes, which were originally intended to improve compatibility between two vehicles, can be effective in a certain impact speed range, but at the same time could not be effective and worsen the situation over the entire speed range.

In the latter case, it is apparent that the reason why the SUV's stiffness reduction based on KW400 metrics results in an increase of the opponent car's deformation is the deficiency of the SUV's energy absorption capability in the engine compartment per the design change. Such deficiency of energy absorption has often been considered as a result of poor structural interaction.

Perhaps a promising approach to enhance stiffness matching without the problem described above is to establish guidelines for the amount of minimum necessary energy absorption by a certain force level for both vehicles(see Figure 11). However, a wide range of studies about how to decide appropriate energy amounts and force levels and a cautious feasibility assessment from a viewpoint of actual vehicle design are necessary to translate the approach into reality.

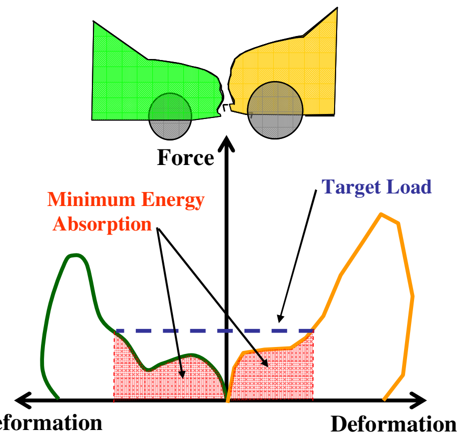


**Figure 11. Overview of target load and minimum energy absorption.**

## CONCLUSIONS

Stiffness matching in SUV-to-car frontal impact by only reducing the SUV's stiffness was studied using FE models of actual existing vehicles in the market. The following conclusions were made.

- In order to decrease the SUV's KW400 below the assumed upper limit, 1700N/mm, without an increase of occupant injury indexes in 56km/h full overlap impact, vehicle front overhang extension, restraint system improvements and other alterations in addition to vehicle stiffness reduction are needed.
- The results of SUV-to-car frontal impact FE simulations using the SUV model installed with the above design changes for KW400 reduction indicates that the design changes can reduce the opponent car's deformation under a certain impact speed, but could increase and worsen the situation at higher impact speeds.

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