# THE INFLUENCE OF SUB-FRAME GEOMETRY ON A VEHICLE'S FRONTAL CRASH RESPONSE

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## ABSTRACT
The importance of a vehicle sub-frame is often discussed in vehicle compatibility. To observe how the sub-frame geometry influences the vehicle response, three different sub-frame configurations were modeled and simulated in US NCAP crash test configurations as well as car-car simulations. The former simulations were used to observe how the design changes would influence self protection in a crash test influencing the original design of the vehicle. The latter simulations were to observe how the modification would influence vehicle compatibility under "real world" conditions.

The rigid barrier impacts could detect the changes in the design. The most forward placement of the sub-frame had a stiffer response than the other configurations as observed in acceleration pulse and barrier wall loads. Self protection also tended to be improved over the baseline configuration. In car-car testing, it was difficult to identify a clear subframe configuration that provided improved compatibility. Both the standard and forward placed subframe had better performance than the most rearward configuration. Neither the baseline nor extended sub-frame versions were clearly better for all car-car impact configurations but an extended sub-frame exhibited better self protection, especially when the vehicle was lower than its collision partner.

## INTRODUCTION
The main problem in frontal collisions between two vehicles with similar - or even identical - structures and mass are the geometrical mismatches that can occur. The geometric incompatibility has two main origins, the pre-impact alignment of the vehicles and the structural layout. The horizontal misalignment is often called the fork effect and a vertical misalignment is referred to as under/overriding. Horizontal overlap of the vehicles is highly unpredictable and can vary more than 1.5m for different crash scenarios. Vertical misalignment is not influenced as much by vehicle alignment as the vertical positions of structures seldom varies more than a few centimeters from a reference condition. Thus variations within the vehicle structures are the main source of vertical misalignment.

The challenge to design vehicles for compatibility is to achieve good vehicle crash performance that can accommodate the foreseeable impact orientations for lateral overlap and interact with the vertical structural variations within the vehicle fleet. Because of the large range of geometric possibilities, many researchers promote the concept of structures with many vertical load paths with strong lateral connections [1,2]. The idea is that the distribution of load carrying elements across the vehicle front can interact with a wide variation of vehicle designs and impact configurations. One proposal for vehicle designs to improve compatibility is the inclusion of a lower load path and many vehicles already have a sub-frame that can provide this function.

The structural layout of different vehicles was investigated in a recent European Community funded projects VC-Compat [3]. The database developed in VC-Compat is the most relevant information as it contains relatively modern vehicles. To demonstrate the role of a sub-frame in frontal crashes, the alignment between vehicle structures was analysed [4] and

Figure 1 shows the results for longitudinals and subframes.

Crash testing of vehicles with and without sub-frames has been conducted in various research activities[2,3,5]. However controlled changes in overlap height and horizontal offset has not been possible due to the costs. As a first step to understand how the front structures perform due to different vertical and horizontal alignments, a simulation study of the NCAC Ford Taurus model was conducted [6]. This study provided important information describing how the loads in the front structures changed due to vehicle alignment. One interesting performance feature was that the vehicle response (measured by vehicle accelerations and intrusions) did not vary monotonically with changes

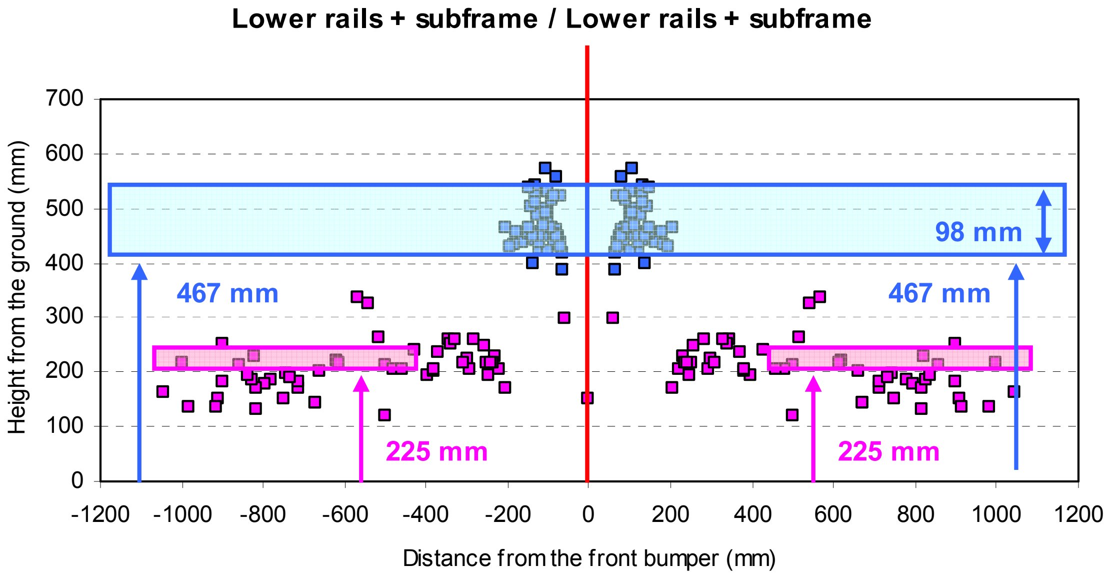



**Figure 1: Vertical and Longitudinal Positioning of Vehicle Structures [4]**

in the vertical overlap. To further understand how specific vehicle structures altered the vehicle crash performance, a study of the influence of the subframe geometry was conducted using the same numerical vehicle models.

## METHODOLOGY

In order to study the performance of the vehicle structures, it was important to control as many confounding variables as possible. The same basic vehicle model was used as a basis for the study to avoid any influence of different mass and/or global frontal stiffness.

The FE vehicle of study was the 2001 model year Ford Taurus available from the FE model achieve of National Crash Analysis Center (NCAC) [7]. This model was chosen because it was the closest representation of a European mid-sized vehicle that was publicly available. The Taurus was developed for the US market where the FMVSS 208 full frontal crash test defines the primary performance criteria. As a result, the vehicle design exhibits a deformation response for the longitudinals and occupant compartment which were not completely representative of a similar European vehicle designed for an offset deformable barrier test. Some modifications of the vehicle model were made to provide a more "European" performance. The main change to the model was the introduction of a beam, shown in Figure 2, to restrict the upward rotation of the longitudinals.

To shorten the simulation time, a simplified version of the model was used. Parts with a low priority for frontal structural interaction were taken out and the rear components of the vehicle were made rigid. Essentially all components forward of the B-Pillars were deformable to allow intrusion to be included in the analyses [6]. This simplified Finite Element (FE) Taurus model is referred to as the Basic model and is the basis for subsequent modifications.

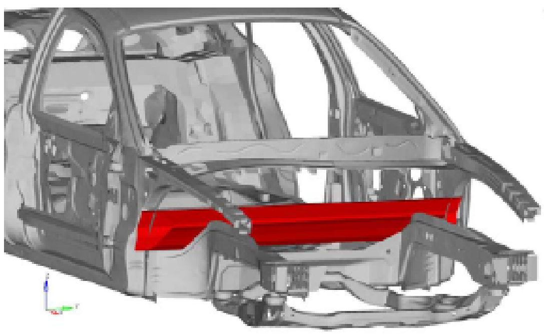
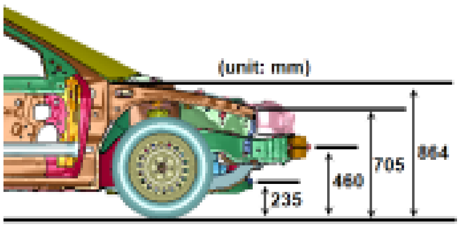


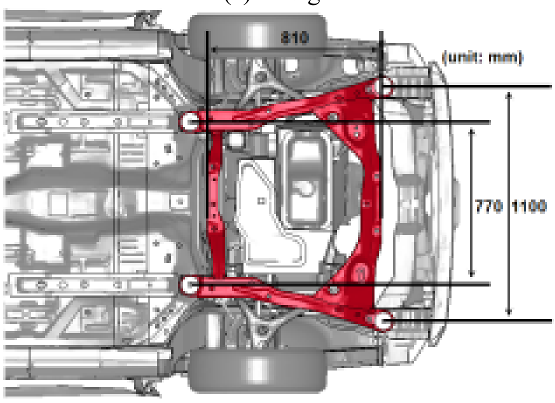
**Figure 2: Simplified FE vehicle model of Taurus**

The weight of vehicle is about 1.39 ton. Failure of the mounts between the sub-frame and floor of vehicle are defined in the FE model when the load reaches the (50 kN).

It is assumed that the outputs of the simplified model in crash simulations are not directly comparable with the real crash test data quantitatively. The results are considered comparable with simulation results under different crash conditions with the same simplified model.




(a) Height




(b) Sub-frame

**Figure 3: Dimension of frontal structure of Taurus**

The simulations of frontal Full Width Rigid Barrier (FWRB) and Car-to-Car (C2C) tests were performed by LS-DYNA [8]. The Basic mode was used for both reference and partner vehicles. In future discussions, the reference vehicle is called Vehicle 1 (V1) and the partner vehicle is Vehicle 2 (V2). The reference vehicle was then modified to investigate the influence of different sub-frame geometries. The original sub-frame geometries are shown in Figure 3. The three configurations investigated were the original, a 100 mm forward extension (ExSub) and a 100 mm shortened sub-frame (ShSub) shown in Figure 4. The speed of each vehicle in a FWRB or C2C tests is 56 km/h. The partner vehicle is horizontally and vertically offset from the reference vehicle. In the horizontal offset, there are three cases, full, 60% and 40% overlap of vehicle. In the vertical offset, there are 2 cases, full and 25% overlap of vehicle. The partner vehicle in 60% and 40% horizontal overlap is translated 742mm and 1080mm in lateral direction respectively. The partner vehicle in 25% vertical overlap is moved 105mm up. Table 1 summarizes simulation cases. There are many cases so

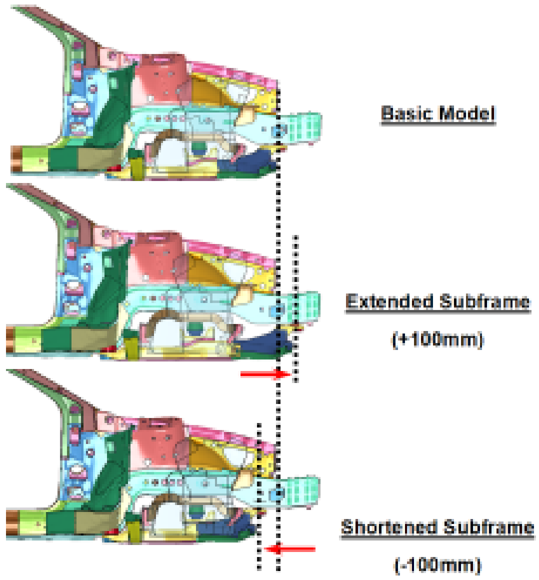


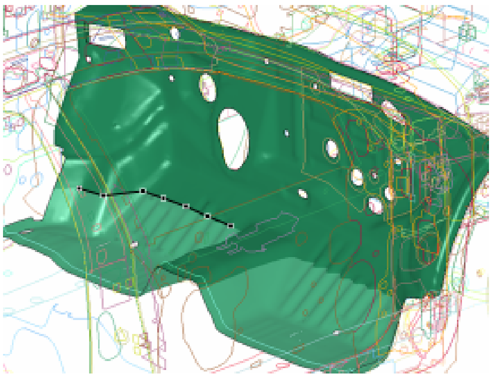

**Figure 4: Description of modification of the length of sub-frame of vehicle**

abbreviations for the simulation cases are used. For example, B2E_H60V25 means that the reference vehicle (the first letter, B) is the Basic model and the partner vehicle (the next letter, E) is the ExSub model in C2C test. H60 means 60% horizontal overlap and V25 is a 25% vertical overlap.

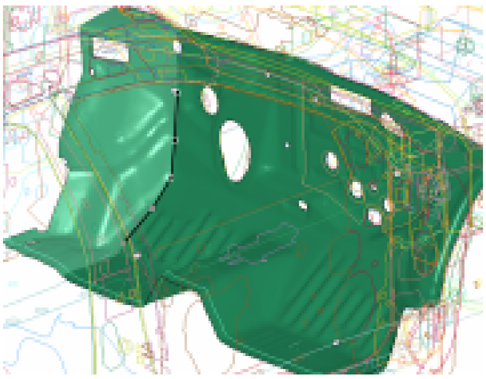
In any vehicle crash test, there are many measurable outputs. Among those outputs, however, some specific ones are essential measurements to evaluate safety and crashworthiness performance. In a compatibility test, it's not yet been clearly agreed what measurements are objective and relevant to evaluate the self and partner protection of vehicles. In this study, the intrusion profiles of vehicles are mainly considered. The measurement locations of the intrusion of vehicle are described in Figure 5

**Table 1: List of simulation case**

| | Vehicle 1 (under-ridden) | Vehicle 2 (over-riding) | Horizontal Overlap | Vertical Overlap | Cases (Abbreviation) |
|---|---|---|---|---|---|
| FWRB | Basic | - | - | - | Basic or B |
| | ExSub | | | | ExSub or E |
| | ShSub | | | | ShSub or S |
| C2C | Basic | Basic | Full | Full | B2B_H100V100 |
| | Basic | ExSub | | | B2E_H100V100 |
| | Basic | ShSub | | | B2S_H100V100 |
| | Basic | Basic | | 25% | B2B_H100V25 |
| | Basic | ExSub | | | B2E_H100V25 |
| | ExSub | Basic | | | E2B_H100V25 |
| | Basic | ShSub | | | B2S_H100V25 |
| | ShSub | Basic | | | S2B_H100V25 |
| | Basic | Basic | 60% | Full | B2B_H60V100 |
| | Basic | ExSub | | | B2E_H60V100 |
| | Basic | ShSub | | | B2S_H60V100 |
| | Basic | Basic | | 25% | B2B_H60V25 |
| | Basic | ExSub | | | B2E_H60V25 |
| | ExSub | Basic | | | E2B_H60V25 |
| | Basic | ShSub | | | B2S_H60V25 |
| | ShSub | Basic | | | S2B_H60V25 |
| | Basic | Basic | 40% | Full | B2B_H40V100 |
| | Basic | ExSub | | | B2E_H40V100 |
| | Basic | ShSub | | | B2S_H40V100 |
| | Basic | Basic | | 25% | B2B_H40V25 |
| | Basic | ExSub | | | B2E_H40V25 |
| | ExSub | Basic | | | E2B_H40V25 |
| | Basic | ShSub | | | B2S_H40V25 |
| | ShSub | Basic | | | S2B_H40V25 |



(a) Horizontal intrusion



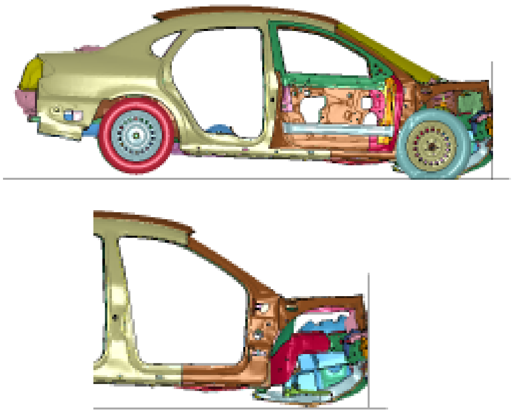
(b) Vertical Intrusion

**Figure 5: Description of measurement locations**

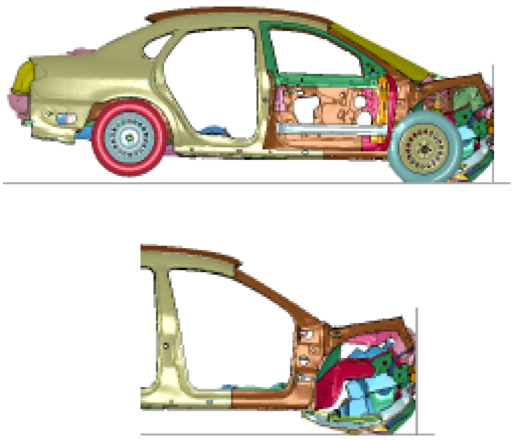
## FRONTAL FULL WIDTH RIGID BARRIER (FWRB) TEST

The simulations of the FWRB test with three vehicle models were performed to check how the crash performance (self-protection) of vehicles is changed when the sub-frame of the vehicle is extended or shortened. The impact speed of the vehicle was 56km/h (35mph).

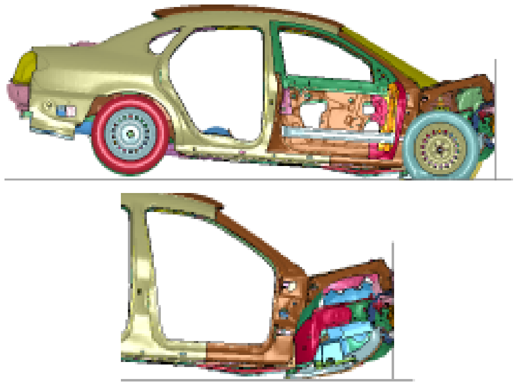
Figure 6 shows the deformation of the vehicles in FWRB test when the speed of vehicle reaches zero (maximum dynamic crush). In the ExSub model, the sub-frame is quite bent which absorbs a lot of crash energy. The sub-frame in not as bent as much in the ShSub model, instead the whole frontal unit of the vehicle is bending upwards.



a) Basic model



(a) ExSub model



(c) ShSub model

**Figure 6: Deformation of vehicle in FWRB test**

Figure 7 shows the acceleration and velocity profiles of vehicles in FWRB test. There are four peaks in the acceleration profile of the Basic model. The first peak occurs when the rails of the vehicle impact the rigid wall, the second peak happens when the front cross-member of the sub-frame impacts the rigid wall, the third peak comes when the engine of vehicle impacts the firewall of the vehicle, and the fourth peak appears before the vehicle rebounds. The acceleration profile of the ExSub model is similar to the Basic model, but peak times occur earlier in the crash event. In the ShSub model, the engine of vehicle hits the rigid wall at the second peak and the cross-member of sub-frame of vehicle impacts the rigid wall at the third peak.

The dots in the acceleration profiles indicate the impact time of the sub-frame cross-member against the rigid wall. In the Basic model, it occurred near the highest acceleration level and at 80% of vehicle crush. In the ExSub model, it occurred earlier when accelerations are still climbing and at 50% of vehicle crush and, in the ShSub model, the sub-frame cross-member contact with the wall occurred at the time of peak acceleration and at 90% of vehicle crush.

The wall forces in FWRB tests are shown in Figure 8. Dots indicate the time (or crush) when the cross-member of the sub-frame of the vehicle impacts the rigid wall. The initial stiffness (Ks), which is the slope of the curve from 0 to 200mm of vehicle crush [9,10,11], are similar in all three models. After 0.015sec (or 150mm of vehicle crush), however, the ExSub model becomes stiffer but the ShSub model becomes softer than the Basic model.

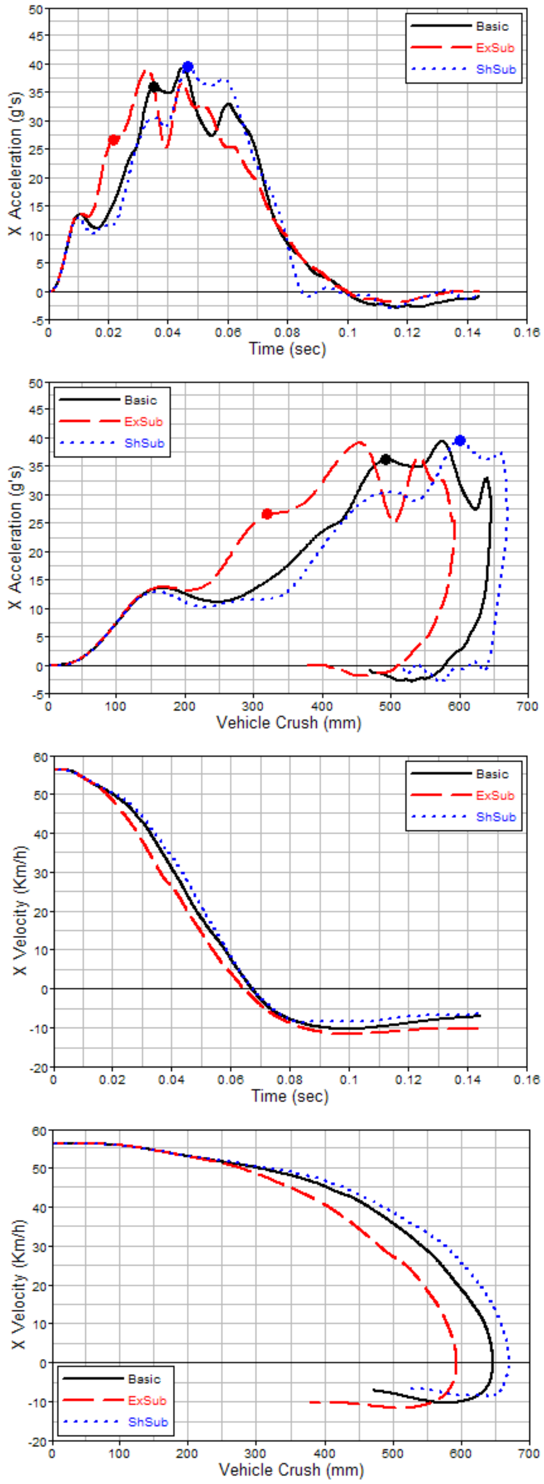



**Figure 7: Acceleration, velocity, and deflection histories of vehicle in FWRB test**

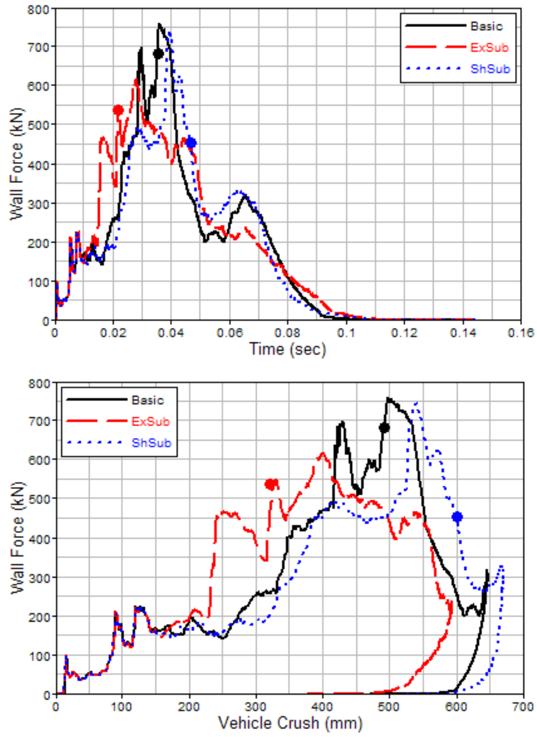


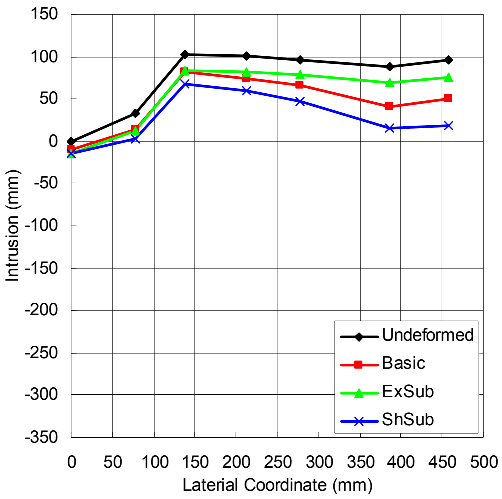

**Figure 8: Wall force histories of load cells in FWRB test**

The work stiffness (Kw400) [10,11], which is the area of the curve from 25mm to 400mm of vehicle crush, AHOF [12,13] and AHOF400 [10,11,14] are summarized in Table 2. It shows that the work stiffness of ExSub model is stiffer but the ShSub model is softer than the Basic model. The AHOF and AHOF400 of the ExSub model is lower than one of the Basic model but the ShSub model is higher. The intrusion profiles of the three models are shown in Figure 9. The ExSub model has less intrusion at right toepan but the ShSub model has more intrusion at the right toepan and dashboard than the Basic model.

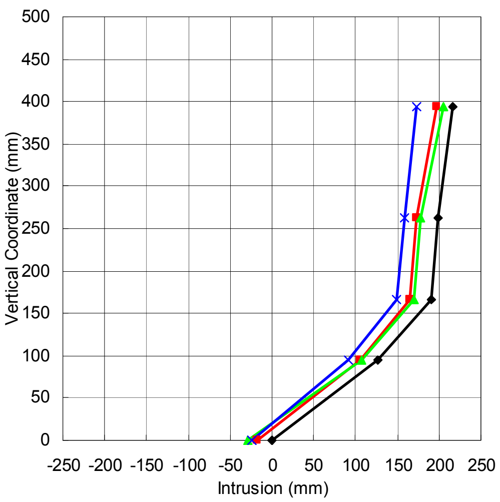
According to the results, the modification of the sub-frame of the vehicle in terms of length makes the effective stiffness of vehicle change. The extended or shortened sub-frame of vehicle makes the vehicle stiffer or softer respectively. This change of the stiffness of vehicle affects the crash performance (self-protection) of the vehicle structure. The stiffer vehicle shows less intrusion in the vehicle (better crash performance) and is exhibited in the longer sub-frame case.

**Table 2: Summary of work stiffness, AHOF and AHOF400 of vehicles in FWRB test**

| | Basic model | ExSub model | ShSub model |
|---|---|---|---|
| Work stiffness (Kw400) | 950 N/mm | 1,521 N/mm | 763 N/mm |
| AHOF (Difference from Basic model) | 363 mm | 346 mm (-17mm) | 419 mm (+56mm) |
| AHOF400 (Difference from Basic model) | 450 mm | 386 mm (-64mm) | 475 mm (+25mm) |




(a) Horizontal intrusion profile




(b) Vertical intrusion profile

**Figure 9: Intrusion profiles of vehicles in FWRB test**

**FRONTAL CAR-TO-CAR (C2C) TEST**

The simulations of frontal C2C test with three vehicle models were performed to check how the compatibility performance (self and partner protection) of vehicles is changed when the sub-frame of the vehicle is extended or shortened. The impact speed of both vehicles was 56km/h. The intrusion profiles of vehicles in the C2C tests with modified vehicles are compared with baseline conditions in B2B cases to evaluate the compatibility performance of the modified vehicles.

**Horizontal offset**

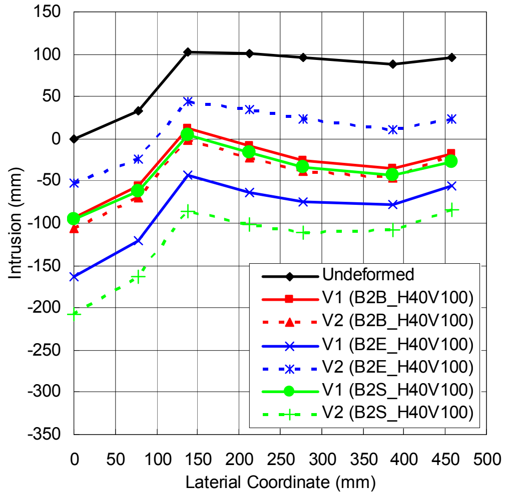
Figure 10 shows the most extreme case for intrusion profiles of both vehicles for a 40% horizontal and full vertical overlap. The results from C2C tests with all three sub-frame models are displayed. The range of intrusions values is much greater than in the FWRB tests. This is not unexpected as the FWRB provides the best structural interaction possibilities.

In B2E cases, the intrusions in the ExSub model are smaller, but for one of the partner vehicles (Basic model) the intrusions are larger than those in the B2B cases. In B2S cases, the intrusions of both the ShSub and the partner vehicle (Basic model) are larger than one in B2B cases. The results show that the vehicles which have a longer sub-frame in C2C tests have the best self protection since the vehicle with the longer sub-frame is stiffer. However, the longer sub-frame gives worse partner protection. One exceptional case is B2S_H60V100 in which the ShSub model has less intrusion than the Basic model even though the Basic model has a longer sub-frame than the ShSub model. This difference was explained by the deformation mode of the vehicle. In the horizontal offset C2C test, the vehicles are rotated and a large moment is applied on the vehicle body. There is a particularly large moment on the body of the Basic model in B2S_H60V100 and this caused the buckling deformation on the floor near left B-pillar of the Basic model which is shown in Figure 11. Therefore, the larger intrusions of the Basic model in B2S_H60V100 are reported than for the ShSub model. This phenomenon underlines the need for a strong occupant compartment for self protection.

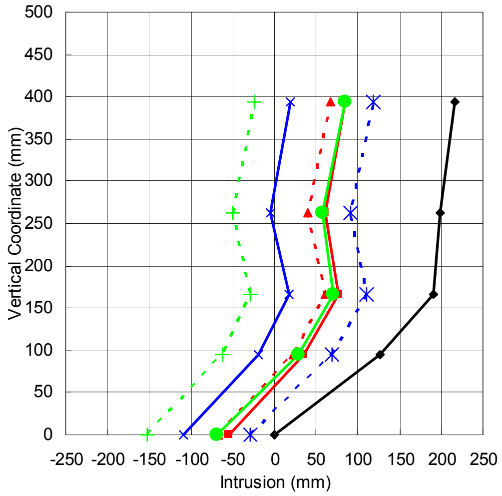
**Mixed offset**

Figure 12: Intrusion profile of vehicle in 60% horizontal and 25% vertical overlap test (V1)Figure 12 and Figure 13 show the intrusion profiles of both vehicles in a frontal crash with 60% horizontal and

25% vertical overlap. Figure 12 shows the cases with the Basic model as the reference and in Figure 13 all three sub-frame configurations are the reference vehicle with the Basic model acting as the partner. The partner vehicle is positioned relative to the reference vehicle. The first feature to notice is that more intrusion occurs in the mixed offset conditions




(a) Horizontal intrusion profile

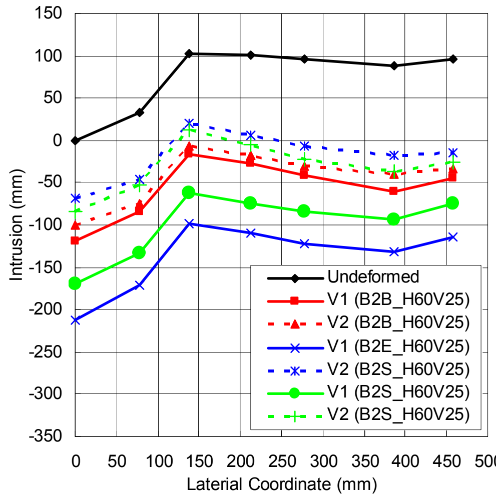



(b) Vertical intrusion profile

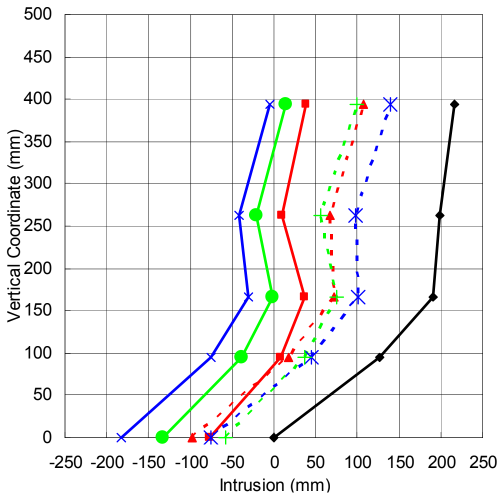
**Figure 10: Intrusion profile of vehicle in 40% case**

Changes in the Y-velocity of vehicles in C2C tests could be used to identify sudden changes in the behaviour of the Basic model in B2E_H60V25 and B2S_H60V25. This means that the buckling deformation, as previously shown in Figure 11 occurred. This resulted in intrusions of the Basic model in B2S_H60V25 which were larger than those in ShSub model even though the sub-frame of Basic model is longer.

**Figure 11: Buckling deformation of vehicle induced by moment force in B2S_H60V100**




(a) Horizontal intrusion profile

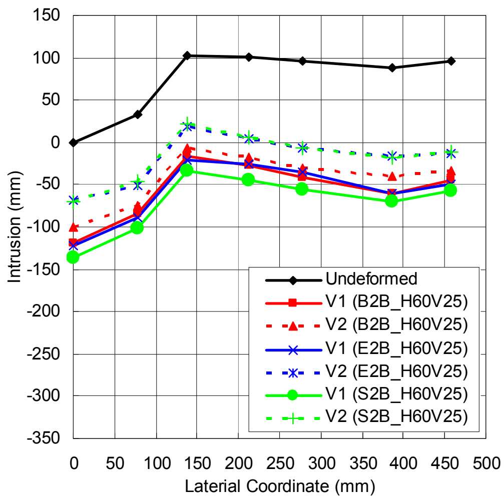



(b) Vertical intrusion profile

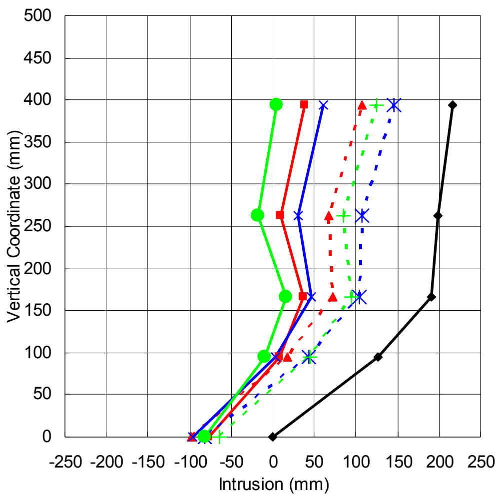
**Figure 12: Intrusion profile of vehicle in 60% horizontal and 25% vertical overlap test (V1)**

The results in Figure 12 and Figure 13 show that the relative positioning of the vehicles is important. The longer subframe had a different outcome if it was in the underriding (V1) or overriding vehicle (V2).

In Figure 13 the modified vehicles become the reference vehicle and the partner vehicle, Basic model, is offset, which means that the modified vehicles are under-riding the Basic model. In both cases, the ExSub model and its partner vehicle have less intrusion, which means that the ExSub model gives good self and partner protection when it underriding. The extended sub-frame vehicle model was stiffer than the Basic and ShSub models. This shows that the under-ridden vehicle in frontal C2C crash should be stiffer to have good compatibility performance.




(a) Horizontal intrusion profile




(b) Vertical intrusion profile

**Figure 13: Intrusion profile of vehicle in 60% horizontal and 25% vertical overlap C2C test (2)**

## DISCUSSION

According to the result for each C2C test listed in Table 1, the safety performance of the vehicles was evaluated and summarized in Table 3. The compatibility performance was evaluated by two parameters, self and partner protection. These factors were evaluated by comparing the intrusions of the reference and its partner vehicles in C2C tests to the modified vehicle to the intrusion in B2B cases. Table 3 shows that the ExSub model gives good compatibility performance when it is under-riding its crash partner. The case of E2B_H100V25 is exceptional and indicates the importance of sufficient compartment strength.

The intrusions of the partner vehicle (Basic model) were large and the sub-frame mounts in the Basic model were not failed during the E2B_H100V25 crash simulation. However, it can not be said that the compatibility performance is really bad. Actually, the intrusions of the vehicles in the cases of full horizontal and full or 25% vertical overlap C2C tests were not much different with each other. In other words, it can not be clearly said that the compatibility performance is really bad in those cases.

The differences of AHOF and AHOF400 for the two vehicles in C2C tests are also summarized in Table 3. In the case of E2B with 25% vertical overlap test, the differences of AHOF and AHOF400 are large and the compatibility performance is good. In this study, the differences of AHOF and AHOF400 between two vehicles in C2C tests are not consistent, which means that geometric and structural interactions are more important to evaluate and need to be studied further to understand compatibility performance in frontal C2C test.

## CONCLUSIONS

The study of sub-frame geometries in this study resulted should be carefully investigated. The structural changes conducted can be considered outside the basic design criteria of the original vehicle. However these changes are interesting to investigate to understand how structural changes to the subframe influence vehicle compatibility performance.

**Table 3:Summary of results of C2C tests with three vehicle models (O: Good, △: No better, and X: Poor)**

| Cases | | | Difference[1] (mm) in | | Vehicle [12] | | Compatibility Performance[3] |
|---|---|---|---|---|---|---|---|
| | Horizontal Overlap | Vertical Overlap | AHOF | AHOF400 | Self Protection | Partner Protection | |
| B2E | 100% | 100% | -17 | -64 | △ | O | O |
| | 60% | | | | X | O | X |
| | 40% | | | | X | O | X |
| | 100% | 25% | 88 | 41 | △ | △ | △ |
| | 60% | | | | X | O | X |
| | 40% | | | | X | X | X |
| E2B | 100% | 25% | 122 | 169 | △ | X | X |
| | 60% | | | | O | O | O |
| | 40% | | | | O | O | O |
| B2S | 100% | 100% | 56 | 25 | △ | X | X |
| | 60% | | | | X | X | X |
| | 40% | | | | △ | X | X |
| | 100% | 25% | 161 | 130 | O | X | X |
| | 60% | | | | X | △ | X |
| | 40% | | | | O | X | X |
| S2B | 100% | 25% | 49 | 80 | △ | O | O |
| | 60% | | | | X | O | X |
| | 40% | | | | △ | △ | △ |

1. Difference is given by subtracting AHOF or AHOF400 of vehicle 1 from one of vehicle 2.
2. Self- and partner-protection of vehicle 2 is opposite of vehicle 1.
3. The results are compared with B2B under same C2C test condition.

The longer sub-frame provided better self protection in most cases. In particular it provided better self protection when the vehicle was underriding its collision partner. In most cases it even provided an improvement in partner protection. Shorter sub-frames had more intrusions in general and did not exhibit any significant safety benefits in this study.

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