COMBINING THE FINITE ELEMENT MODELS OF THE FORD FALCON AND SUBARU LEGACY TO IMPROVE VEHICLE COMPATIBILITY

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ABSTRACT

This paper firstly describes how the finite element models of the Ford BA Falcon and the Subaru Legacy were combined so that a parametric study varying design features of each vehicle could be conducted to determine their effect on compatibility. The Ford Falcon is a front engine, longitudinal 6-cylinder, rear wheel drive sedan. The Subaru Legacy is a front engine, horizontally opposed, all wheel drive sedan. The two vehicles are not in the same mass and size category. The paper then reports on how the compatibility of the two vehicles, in an offset frontal crash, is affected when the following design features are changed:

- Ride height
- Stiffness of main longitudinals
- Stiffness of upper load path
- Stiffness of lower subframe
- Stiffness of passenger compartment
- Strength of vertical connections between load paths
- Strength of lateral connections between load paths
- Changes to improve the structural interaction between the two vehicles.

INTRODUCTION

Frontal crashes are the cause of the majority of serious injuries and fatalities on the roads. Vehicle compatibility involves trying to minimise the injury outcomes of occupants when vehicles of different mass, stiffness and geometry crash into each other.

One of the main goals in improving vehicle compatibility is to design vehicles which maximise the structural interaction of vehicles with different geometry, mass and stiffness. Any compatibility test procedure must be able to assess the shear connections of the vehicle front structure as well as providing for correct energy management between dissimilar crash partners so as to guarantee passenger compartment integrity, which is particularly important in smaller vehicles. This paper details part of the research conducted by the Australian Department of Transport and Regional Services (DOTARS) which will be provided to the IHRA Vehicle Compatibility Working Group to consider in its deliberations to develop a vehicle compatibility test. This research has been done with cooperation between Ford Motor Co of Australia Ltd, DOTARS and Subaru.

The aim of this research project was firstly to combine the validated Finite Element (FE) models of the Ford BA Falcon and Subaru Legacy that have been used in the development of the respective vehicles. Once the combined FE model was shown to successfully run, a parametric study was conducted by changing several design parameters to investigate their effect on the frontal offset crash compatibility of the two vehicles. An offset frontal car-to-car test of the two vehicles at 50 km/h, 50% overlap was conducted to validate the combined baseline FE model.

The scope of this project was to use the FE model to study the structural response of the sedans. Occupants were not included in the model to keep the computational task to a practical limit. Parameter changes were made to the Falcon model while keeping the Legacy model constant. Both models were analysed for structural response.

FE MODELLING

The combined FE model of the two vehicles amounted to approximately 720,000 elements. The model was solved using the Massively Parallel Processing (MPP) version of LS-DYNA 960 on a SGI Origin 3000 supercomputer. Computational time with 32 CPUs was typically 35 hours for each run simulating a 130-millisecond event.

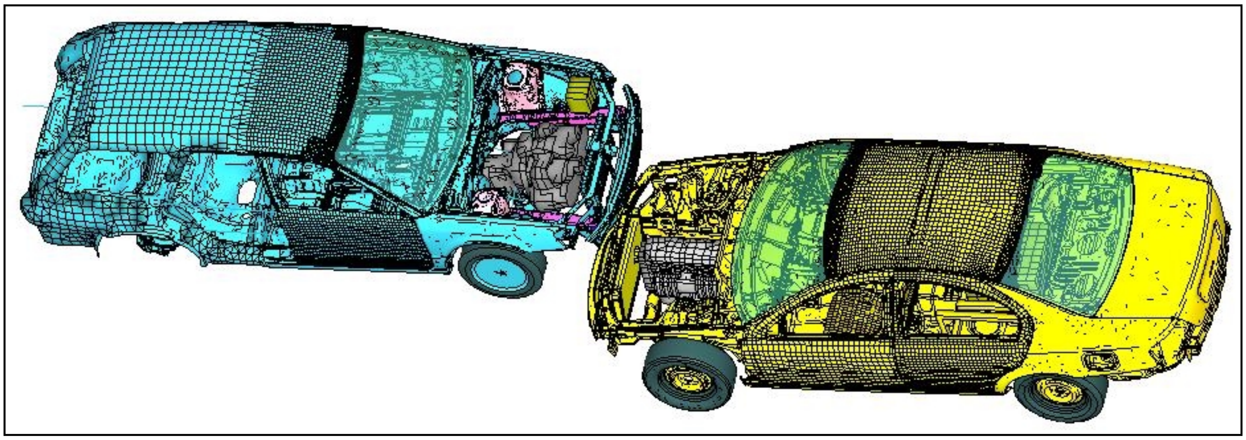

Figure 1. Overall view of the combined FE model.

For comparison, specifications of the two vehicles are shown below in Table 1.

Table 1.
Table comparing vehicle specifications

	Falcon	Legacy
Kerb mass (kg)	1694	1365
Width (mm)	1864	1695
Wheelbase (mm)	2829	2650
Length (mm)	4916	4605

Each of the vehicle models was exercised and developed in the European offset frontal test mode (96/79/EC directive) before merging into one model. The mass of two Hybrid III 50^{th} percentile dummies, (i.e. 152 kg) was included in each vehicle. For the 50% overlap, centreline of the Legacy was aligned to the widest point of Falcon, which is near the rear wheel arch.

Figure 1 is an overall view of the complete model. Both vehicles are of right hand drive. For each vehicle, structural deformation was monitored at 45 points for eleven main items as follows:

- Front rail crush
- Spring cap at suspension structure
- Dash panel opening at steering column
- Foot well intrusion
- Power train intrusion
- Cowl intrusion
- Steering column mounting
- Driver seat attachment
- Passenger compartment rail crush
- A pillar deformation
- Rocker panel crush

These items nominally indicate deformation in the engine or passenger compartment. The dash panel opening at the steering column was monitored as a risk to steering column stability. Global coordinates axis are defined as X for longitudinal axis, Y for lateral and Z for vertical.

ANALYSIS

Ride Height Factor

For the overlap alignment, at its respective standard ride heights; the front rails of the two vehicles were well matched in geometry. Alignments in the plan and side views were good for full engagement. This is shown in Figure 2.

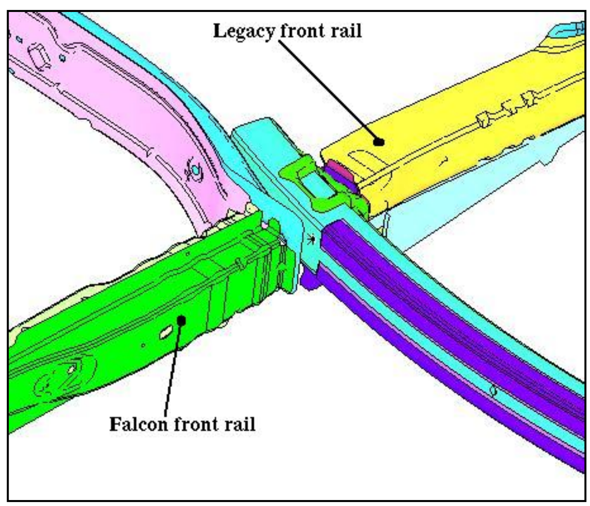

Figure 2. Alignment of front rails occurred in baseline model.

Ride height of the Falcon model was raised and lowered by 100 mm from standard, as two levels of this factor. Appendix 1, Fig A shows that at these new configurations, the front rails would override each other.

Results For Ride Height Factor

When the Falcon ride height was reduced by 100 mm below standard, the Legacy was seen to override. Unexpectedly, the Falcon rail deformation was more than baseline but most of this occurred at mid span due to the Legacy rail engagement with the Falcon suspension housing structure. This load acted on the Falcon rail to cause the mid span crush. The battery

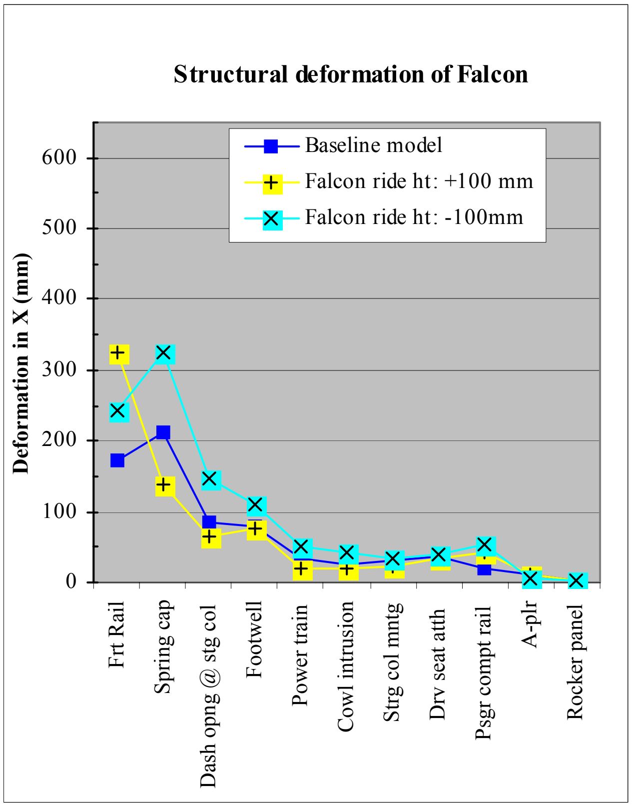

Figure 3. Deformation of Falcon in X direction for Falcon at different ride heights.

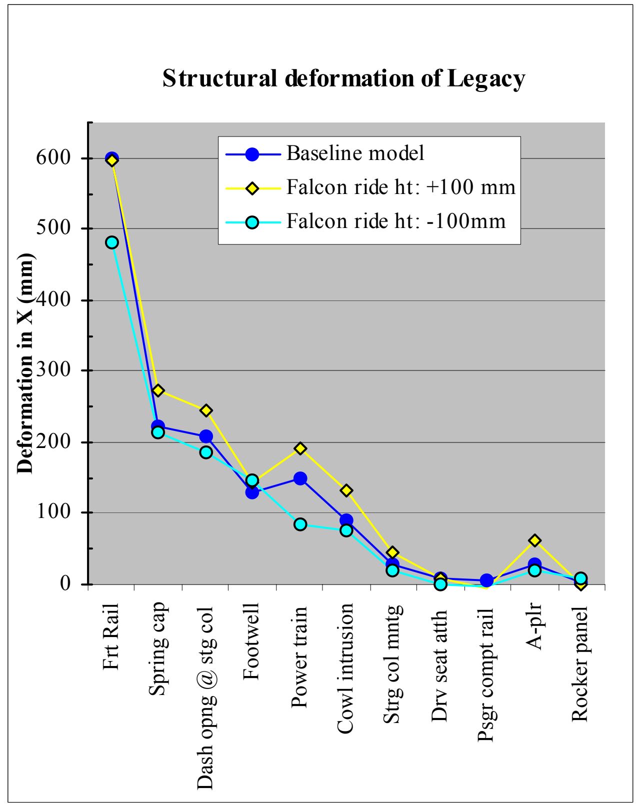

Figure 4. Deformation of Legacy in X direction for Falcon at different ride heights.

Falcon Response

In Figure 3, for the Falcon with a ride height increase of 100 mm, there was little change in the deformation of the Falcon structure except for front rail crush and spring cap. Override by the Falcon was observed but unexpectedly, its front rail crush was more for this condition. Examination of the model showed that Falcon rail engaged the suspension housing structure of Legacy and this caused the Falcon rail to crush and bend downwards.

In the baseline condition, rail-to-rail engagement of the vehicles diminished from about 42 milliseconds. Engagement with the suspension housing was observed to prolong the interaction of the Falcon front rail and increase its deformation.

in Falcon was located in front of the RH suspension housing and this contributed to a solid stack-up with that sheet metal structure. It appears that this stack-up may have acted to transmit loads to the crushable rail as soon as possible. Despite an override condition by the Legacy; passenger compartment metrics appeared to have only increased slightly.

Legacy Response

Figure 4 shows that in the case of Falcon override (+100 mm), deformation of the Legacy had only increased moderately. Of particular interest, power train intrusion increased from 149 mm to 192 mm and A pillar intrusion increased from 29 mm to 63 mm. The model showed that as well as engagement of the Legacy suspension housing with the Falcon rail, the horizontally opposed engine of the Legacy also engaged the impacting Falcon tyre as an additional load path. This resulted in an increase in power train displacement in Figure 4. Despite the override by Falcon, rail deformation of Legacy was similar to baseline results. This was due to deformation occurring at the rear of that rail when that suspension housing was bearing the significant impact load.

In the case of Legacy override, the deformation had not changed much except for a reduction in power train displacement. This was due to a lesser extent of its engine engagement in this condition. Rail crush was maintained at a similar level because of engagement with the Falcon suspension housing structure. It was also noted that the Legacy structure deformed differently in the lateral direction; more toward the left hand side of that vehicle. This could have moderated intrusion into the Falcon structure.

Main Longitudinal Stiffness Factor

For the factor of main longitudinal stiffness, the Falcon front rails were changed in strength and thickness. Compared to the standard rail, this effectively gave a rail compression strength of about 50% and 250% for the minus and plus levels respectively

Results For Main Longitudinal Stiffness Factor

Falcon Response

Figure 5 shows that with the exception of the front rail, this factor did not change the deformation of the Falcon significant levels. Front rail deformation in the stiffer (plus) level was negligible while for the minus level it more than doubled. It was interesting to note that despite a large increase in rail crush, the other deformations were not affected significantly. This would suggest that the backup structure in the Falcon engine compartment was not sensitive to this range of load inputs. Within this factor of study, an impacted vehicle with higher stiffness may produce higher deformations in the Falcon.

Legacy Response

Figure 6 shows that deformation in the Legacy was affected by the Falcon rail stiffness. Rail deformation of the Legacy changed inversely with that of the Falcon. It was noted that in each case, the sum of their rail deformation is about 750 mm to 800 mm. When the Falcon rail stiffness was decreased, only small changes occurred in the passenger

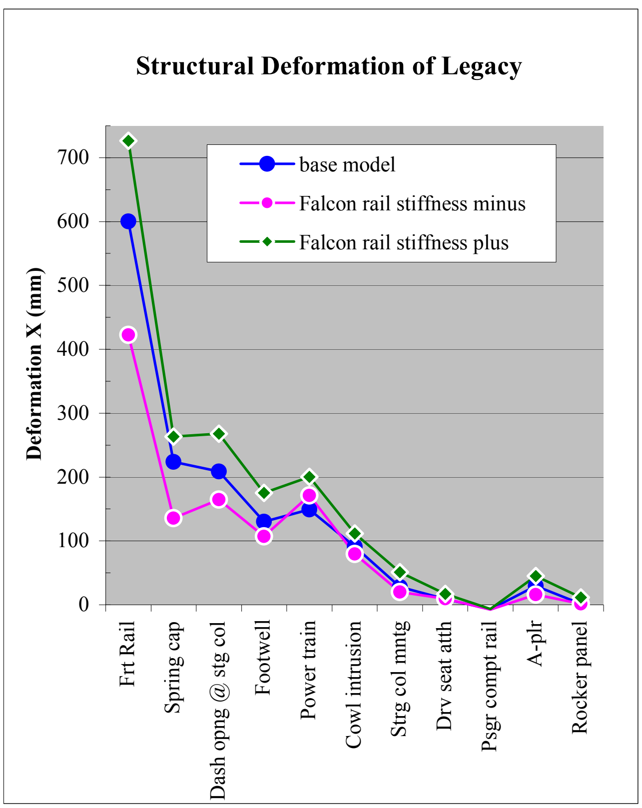

Figure 5. Deformation of Falcon in X direction for Falcon with different front rail stiffness.

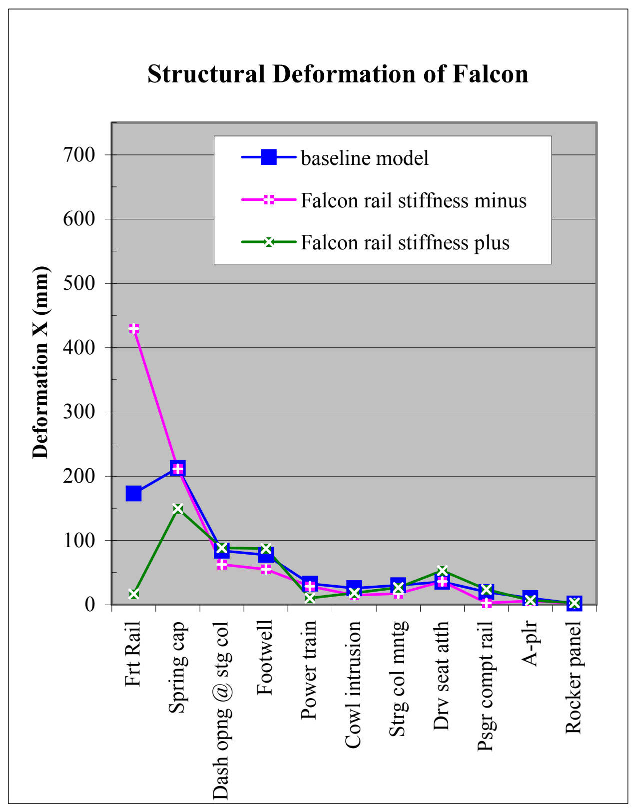

Figure 6. Deformation of Legacy in X direction for Falcon with different front rail stiffness.

compartment metrics.

In the case of the stiffer Falcon rail, moderate increases in deformation were shown. However, the FE model showed that the Legacy right hand engine compartment had crushed extensively close to its limit. In addition, this extent of crush also minimised the interaction of Legacy engine with the Falcon tyre.

Upper Load Path Stiffness Factor

Variation for this factor was provided by changing thickness and material strength in the components of shotgun brace, spring cap and upper radiator cross member. In the high stiffness level, thickness was typically increased by 70% and yield strength was typically increased from 200 MPa to 300 and 400 MPa.

Results for Upper Load Path Stiffness Factor

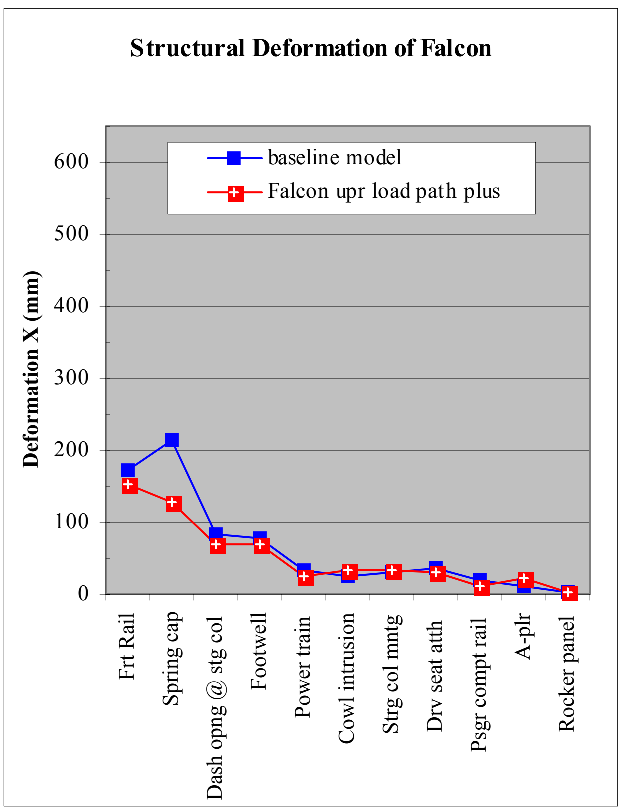

Figure 7. Deformation of Falcon in X direction for Falcon with different front upper load path stiffness.

<u>**Falcon Response**</u>

The plot in Figure 7 shows negligible change in deformation with the exception of the spring cap. This is due to the substantial attachment of the stiffened spring cap to a stiffened shotgun brace. Investigation into the model suggested that this structure would have to be further developed to sustain longitudinal loads if it were to be effective in this study. Longitudinal section members here tended to have a high slenderness ratio.

<u>**Legacy Response**</u>

Figure 8 shows that the Legacy was not sensitive to changes in this particular configuration of upper load path in the Falcon. A small change in spring cap displacement could be detected as a direct result of higher stiffness in the Falcon shotgun brace but this did not have any significant effect elsewhere.

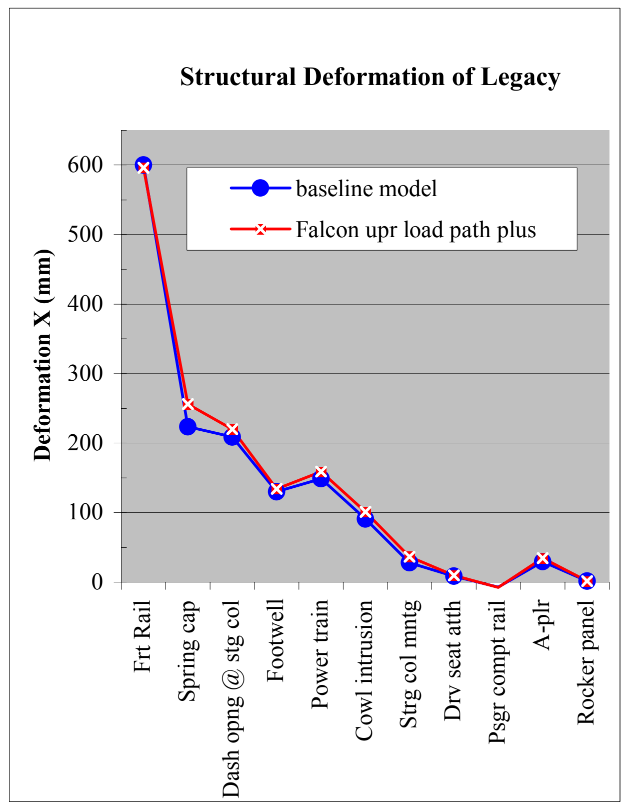

Figure 8. Deformation of Legacy in X direction for Falcon with different front upper load path stiffness.

Passenger Compartment Stiffness Factor

To provide variation in this factor, the strength and thickness of key passenger compartment structural components in the Falcon were increased and decreased and compared to the base model. The components in the upper and lower a-pillar, roof rail, rocker panel and underfloor member (sled runner) were typically up-gauged by 30% and upgraded to have most parts with yield strengths in the vicinity of 400MPa (for the stiffened run). For a reduction in stiffness, these components were down-gauged by about 25% and the yield strengths of all parts were reduced below 250MPa.

Results For Passenger Compartment Stiffness Factor

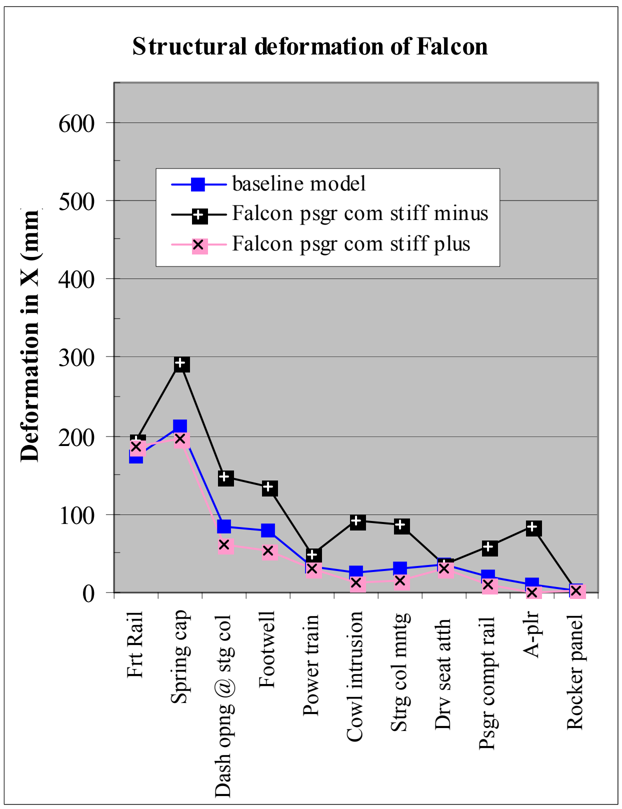

Figure 9. Deformation of Falcon in X direction for Falcon with different passenger compartment stiffness.

Falcon Response

In Figure 9, it can be seen that when the stiffness of the Falcon passenger compartment was reduced, there was increased deformation for all points, although there was little change in the power train and seat attachment points. The passenger compartment rail and upper A-pillar region deformed noticeably more than the baseline, resulting in an increased intrusion in the passenger compartment. A-pillar intrusion increased from 10mm to 85mm and foot well intrusion increased from 78mm to 136mm. Rail crush was similar, while the spring cap, although being displaced further in vehicle for this run, did not intrude further into the dash and cowl area.

When the stiffness of the components was increased, little change was seen in the measurements. This suggested that benefits of adding stiffness in the passenger compartment may have plateaued for the Falcon. There was a small reduction of measurements across all points, except the rails, where there was a slight increase in crush over the base. This could be expected due to the increase in stiffness of the backup structure to the rail.

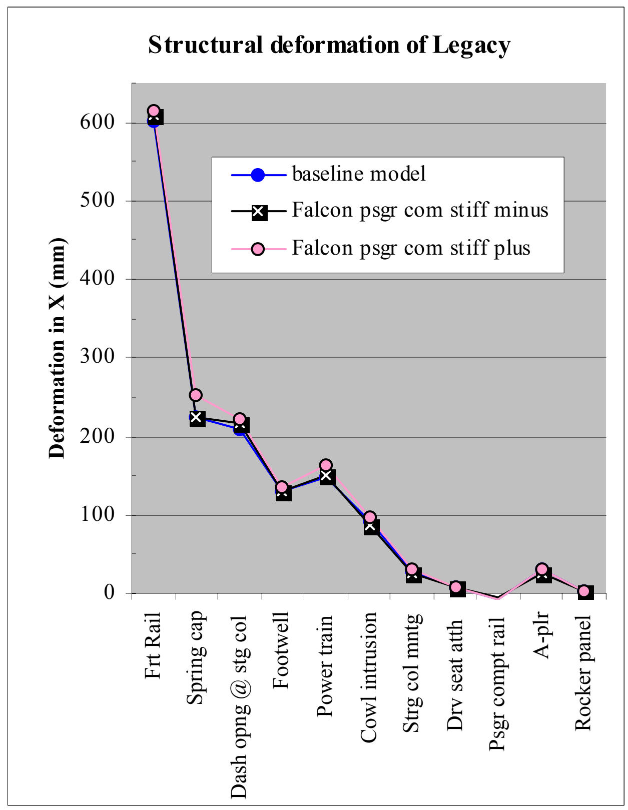

Figure 10. Deformation of Legacy in X direction for Falcon with different passenger compartment stiffness

Legacy Response

Figure 10 shows that changes in the Falcon passenger compartment stiffness had little effect on the measurements for the Legacy. There was a slight increase in the spring cap deflection when the Falcon passenger compartment was stiffened.

The reduction in Falcon passenger compartment stiffness had no significant effect on the Legacy, with the initial deformation modes caused by the Falcon rail producing similar deformation to the baseline run.

Effects were low in the Legacy for this factor because the Falcon passenger compartment was too rearward in the structure to contribute as an input into the interaction.

Strength Factor of Lateral Connections Between Load Paths

For this parameter, the strength and gauge of the Falcon bumper beam and upper radiator cross member were increased. In addition, two members of beam elements were added in a cross brace format to diagonally connect main longitudinals from the dash panel area to just below the front seats. There was typically a 30% up-gauge from baseline thickness in the sheet metal components mentioned above. Upper cross member yield strength was increased to 400 MPa. The added beams were of hollow tubular section, with an outer diameter of 30mm, wall thickness of 3 mm and material yield strength of approximately 250 MPa.

Results For Strength Factor of Lateral Connections between Load Paths

Falcon Response

In Figure 11, it is shown that increasing the stiffness of the baseline lateral connections between main longitudinals and between upper load path, as well as adding diagonal connections between underfloor members, had only small effects on the Falcon metrics. The rail crush had increased by 48mm and the foot well intrusion had increased by 18mm, while the driver seat attachment points have displaced by 27mm instead of the base 36mm. As seen in the crash animation, this indicated a reduction in the shearing of the floor pan and dash panel as the response of left and right hand main longitudinals were more aligned.

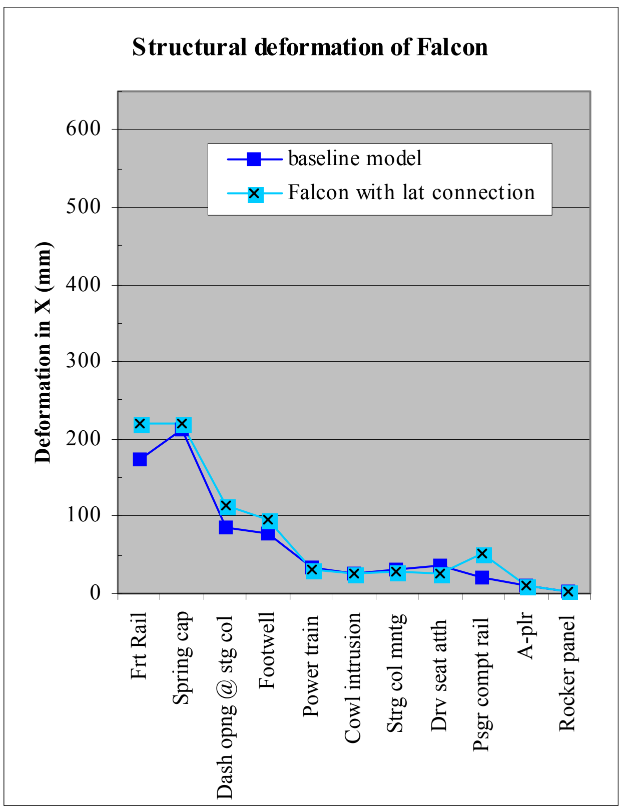

Figure 11. Deformation of Falcon in X direction for Falcon baseline and with lateral connections between load paths.

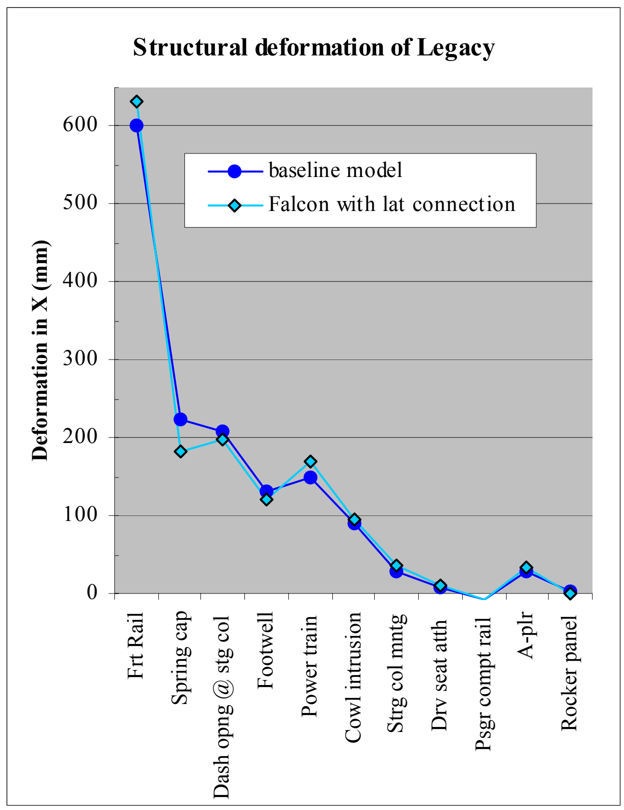

Figure 12. Deformation of Legacy in X direction for Falcon baseline and with lateral connections between load paths

The forward attachment point of the diagonal brace impeded rail crush in this area, resulting in further rotation of the passenger compartment rail (about the y axis) near dash panel. This in turn caused increased foot well intrusion. The extra rail crush was in the forward convoluted section of the rail where some crush and downward bending occurred. The forward rail crush developed from 33 milliseconds. Unlike the baseline model, the front rails remained engaged for the entire crash event.

The increased stiffness bumper beam did not change the deformation of the left front rail, but may have assisted in maintaining the front rail engagement with the Legacy rail.

Legacy Response

Figure 12 shows there was 32 mm more rail crush in the Legacy, due to the increased interaction of the Falcon and Legacy rails. The deformation modes of the rail were notably different to the baseline with increased bending about the y-axis. The full event rail engagement also contributed to a reduced spring cap deflection.

There was a small decrease in the foot well intrusion, while the power train displacement increased slightly. Crash animation showed that this might be due to increased rail crush, which allowed the Legacy engine to engage the Falcon upper structure indirectly.

DISCUSSION AND CONCLUSION

The aim of this research project was to successfully combine FE models of two vehicles with different power train configurations, mass and size, and to conduct a parametric study of the effect of various design features on compatibility.

This analytical method undertaken with the two vehicles yielded insights into compatibility issues whilst being lower in cost and having quicker turn-around times than physical crash testing. The Ford Falcon was the varying input into the simulations by using a range of changes from different ride height, materials and gauges to added parts. The Subaru Legacy model was unchanged throughout all the simulations.

Several conclusions have been developed after the analysis of simulation results and comparison with the baseline model.

It was important to have compatible geometry. Where there was incompatible geometry and a misalignment of major load carrying members, the resulting structural response showed that secondary structure (such as the suspension housing and upper load path) was required to absorb large amounts of energy. Within the limitation of these two vehicles, this was sustainable, resulting in moderate increases in passenger compartment intrusion.

The stiffness of the main longitudinals significantly contributed to the structural response of both crash partners. An overly stiff longitudinal that was unable to crush efficiently in the forward section would create the response of early rail disengagement. This resulted in excessive loading of secondary structures and increased intrusion into the passenger compartment. The decision on longitudinal stiffness would also greatly affect the vehicle performance when impacting very rigid surfaces or structures. The requirements of rigid surface protection may contradict those required to improve compatibility.

The strength of the passenger compartment, and the method of energy distribution throughout the structure will affect compatibility performance. A stronger passenger compartment would allow more energy absorption in the front-end structure, whilst also promoting continued interaction of longitudinals of the crash partners, and reduced structural intrusion.

The ability to involve other non-impacted structure, such as the non-struck side main longitudinal, may also assist performance. This could be achieved by adding to the structure absorbing energy or by providing geometric assistance to maintain rail engagement.

For crashes that involve vehicles of different mass, stiffness and geometry, this study suggested that a vehicle which could protect its occupants would have:

- Main longitudinals that could provide suitable forward crush
- A stiff passenger compartment
- Multiple load paths that can be placed in compression to absorb energy
- Geometry to allow continued robust longitudinal interaction.

To date, this project did not draw conclusions on the effect of a stiffened lower sub-frame, vertical connections between load paths, or a combination of parameters to study the interaction between factors.

FURTHER WORK

With a better understanding for each of the vehicle models under such impact conditions, this project would benefit from further work. For example,

- Study of the effect of varying several factors simultaneously to gauge the interactions of these factors.
- In depth analysis of strain energy distribution to identify components that could be improved.
- Larger or different type of partner vehicle
- Improved upper load path design to enhance the balance of energy absorption
- Sensitivity study into overlap ratio.

ACKNOWLEDGEMENT

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APPENDIX 1

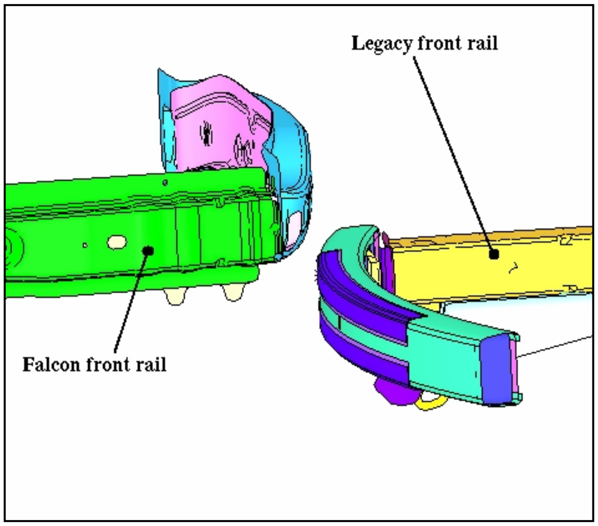

Figure A. Misalignment of front rails when Falcon ride height is raised by 100 mm.

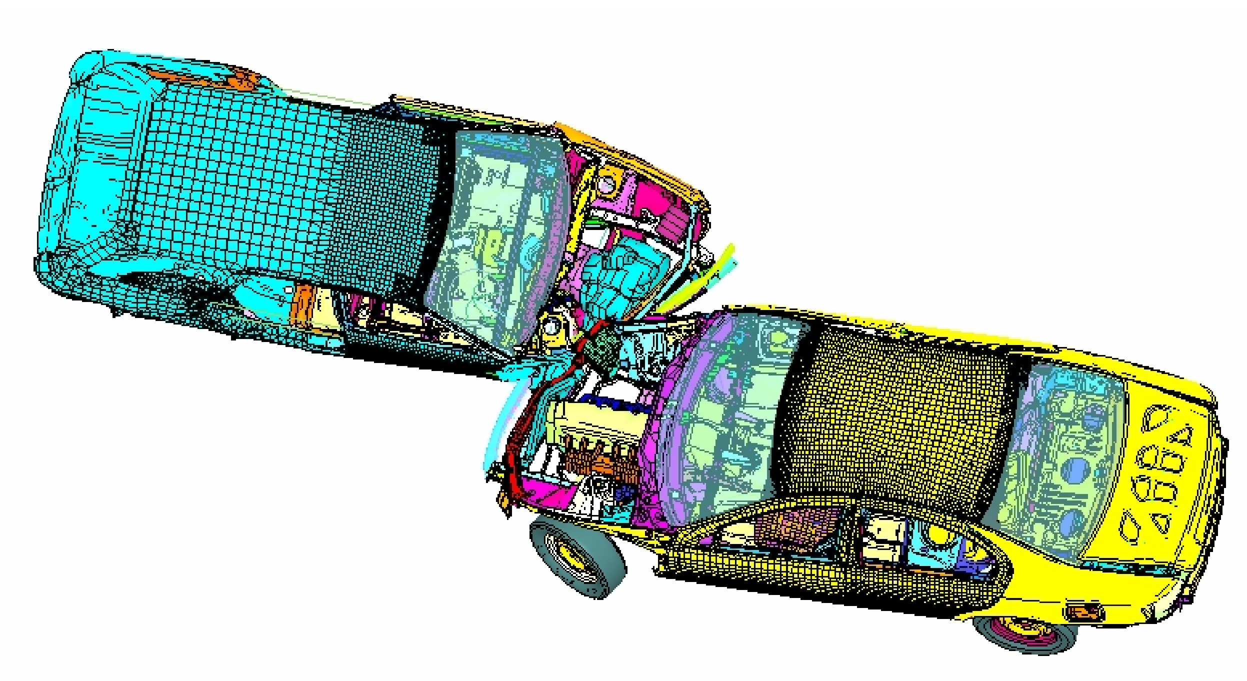

Figure B. Typical deformed shape of the combined FE model.