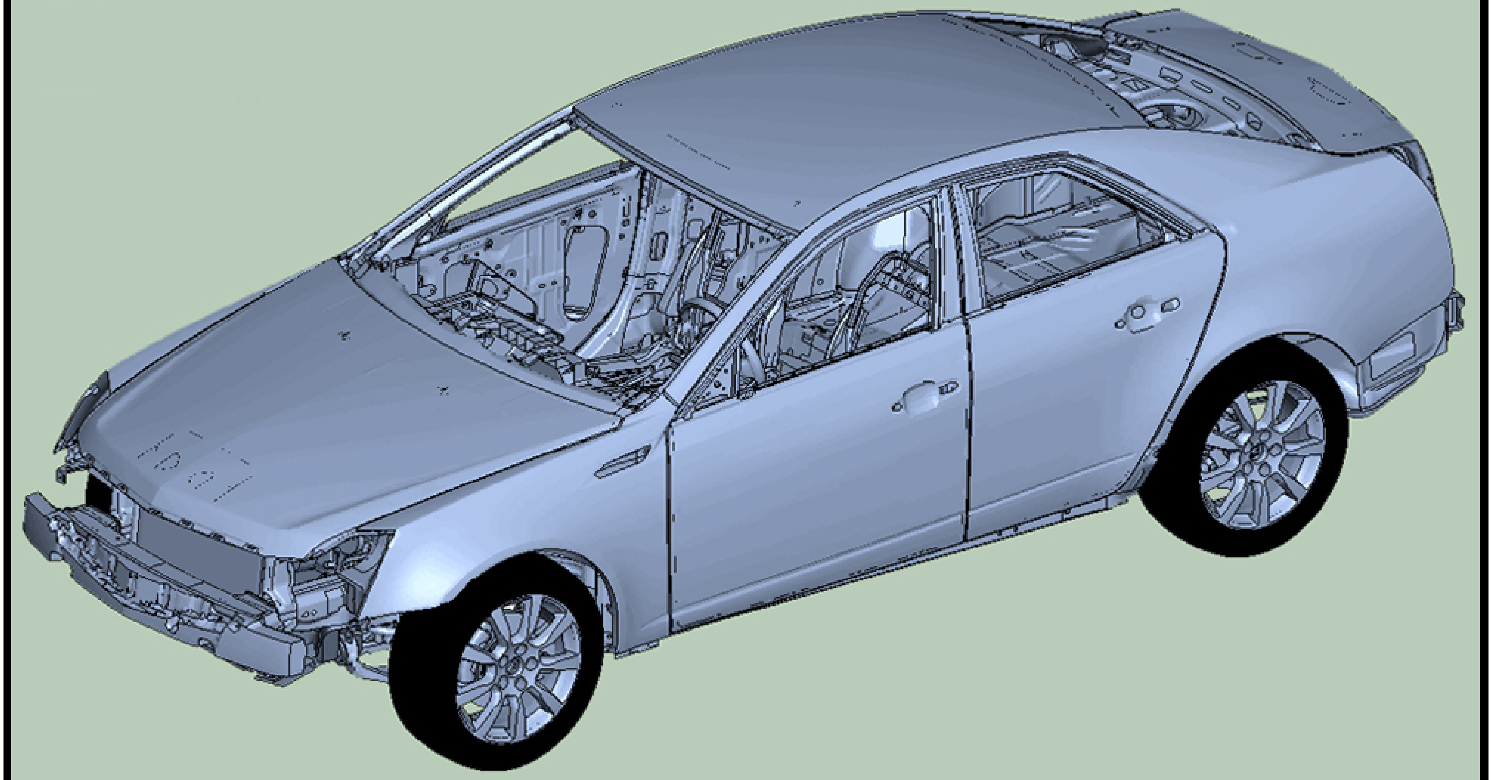

A/S P Auto/Steel Partnership

Future Generation Passenger Compartment (FGPC) Validation Report
FINAL REPORT

Mass Optimization
Study

October 2010

Future Generation Passenger Compartment (FGPC)

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FGPC- Validation: Executive Summary

EXECUTIVE SUMMARY

The highlights from the FGPC-Validation (Future Generation Passenger Compartment) project are presented in this summary. A detail discussion of each task may be found in its individual report.

1. INTRODUCTION

Initially FGPC-Validation was divided into eight tasks but upon request from A/SP Tasks 2.5, 8.0a and 8.0b were added to the project. An individual report is provided for each task, which includes its own appendices.

Task 1.0: Calibration
Task 2.0: Optimization
Task 2.5: Parts Consolidation
Task 3.0: Concept Design
Task 4.0: Concept Design Validation
Task 5.0: Final Optimization
Task 6.0: Final Concept Design
Task 7.0: Final Concept Design Validation
Task 8.0a: Sensitivity Part 1 (Seat Position & Pole Impact to MMV targets)
Task 8.0b: Sensitivity Part 2 (Continuous Joining)

2. PROJECT BACKGROUND

FGPC-Validation is the second part of a research project that aims to create a lightweight passenger compartment utilizing modern high strength steels. The first part of the project, FGPC-Phase 1, developed an optimization strategy, which was applied to the ULSAB-AVC (UltraLight Steel Auto Body - Advanced Vehicle Concepts) vehicle. The optimization identified and then enhanced a variety of efficient loadpaths. These new loadpaths achieved the requirements of the crashworthiness loadcases considered, while reducing the mass of the passenger compartment through the use of high strength steel. The second part of the project, FGPC-Validation, will take the lessons learned from FGPC-Phase 1 and apply them to a current production intent vehicle called the Donor Vehicle. FGPC-Validation will use the same optimization methodology to develop a new passenger compartment structure for a modern production intent vehicle.

3. PROJECT STRATEGY

FGPC-Phase 1 clearly demonstrated that AHSS (Advanced High Strength Steel) can be effectively utilized in automotive lightweighting, or mass avoidance strategies, to provide the required performance at a lower overall cost. However, the ULSAB-AVC upon which it was based is a concept vehicle and so did not represent the very mature constraints of a modern production intent vehicle.

FGPC-Phase 1 did however successfully prove the following strategy;

1. Efficient use of geometry to define the loadpath that meets crashworthiness and stiffness requirements, while absorbing energy through total system topology optimization.
2. Investigate the usage of AHSS materials and manufacturing techniques, such as laser-welded blanks, to reduce vehicle mass and increase its performance.
3. Reduce the vehicle mass by using topology and shape optimization.

Applying this strategy to the ULSAB-AVC enabled the creation of new concept loadpaths such as the Side Impact cross member and the roof bow. However, integration of these loadpaths into a concept vehicle was relatively simple. While FGPC-Validation will use the same proven geometry based strategy, it is based on the much tighter constraints of a production intent vehicle. Though still valuable, adaptation of the conceptual loadpaths will be more difficult and so possibly less effective.

FGPC-Validation aims to develop a robust design with a long-term perspective of 10 years. Hence this means developing concepts that would require manufacturing components from materials that are not presently available or in gauges that current design practice would not view as practical. Hence the steel industry will require further research to meet these challenges.

4. RELATIVE MATERIAL COSTS

In order to discourage the use of higher strength steel in parts where it is not required, a cost function was setup to estimate the relative cost of different design configurations. The cost factors defined in Table 1 were used to calculate the relative cost of each design. The cost of each part was calculated by multiplying the mass of the part with the normalized cost factor for the material considered.

MATERIAL NAME	Relative Cost
IF 140/270	1.0
DQSK 210/340	1.104
HSLA 350/450	1.1948
DP 300/500	1.169
BH 250/550	1.13
DP 350/600	1.39
DP 500/800	1.506
DP 700/1000	1.584
Mart 1300	1.688
Boron 1550	1.805

TABLE 1: Relative Material Costs

5. FGPC STRUCTURE, MATERIAL INDEPENDENCY

The strategy implemented by this project concentrated primarily upon multi-disciplinary loadpath optimization, which addressed all the crashworthiness, stiffness and NVH loadcases under consideration. Once the most efficient loadpaths were defined, the second optimization was then allowed to review the gauge and material of each individual component. Thus when considering another material such as composite, aluminum or multi-material vehicle, the knowledge and technology developed by the load path optimization in this project is still valid. However, the FGPC project has demonstrated, the geometry, gauge and the impact of manufacturing, joining and assembly must be considered for each material proposal.

6. PARTNERSHIP

This project was managed and executed by ETA with the partnership of EDAG Engineering and Red Cedar Technology.

7. SOFTWARE/HARDWARE

Software:
- eta/VPG – FEA Pre/post-processor
- eta/DYNAFORM – Metal Forming pre/post-processor
- LS/DYNA - Explicit FEA Solver for Crash and Safety Simulation
- SFE-Concept – Geometry Parameterization
- HEEDS – Optimization

Hardware:
- 64 - CPU Linux cluster
- 44 - CPU Single PC’s interconnection process for Optimization
- 12 - CPU SGI Altix

8. LESSONS LEARNED

General Comments

- The Donor Vehicle is a current production intent vehicle and so represents a fully matured design. Thus manufacturing constraints played an important role in constraining the degree of change available to the optimization.

Loadpath Optimization

- The Kickdown gauge was reduced to 0.5mm indicating that it was not a critical component for the optimization loadcases. This is a very different result from FGPC-Phase 1, which implied that the Kickdown was a critical load for IIHS Side Impact. This illustrates how important the unique architecture of an individual vehicle can be and why it is not possible to blindly implement its optimization results to a different design
- Pole impact performance was significantly higher than the target. Though removal of the pole impact counter measures reduced the passenger compartment's performance, it was still high enough to achieve the required target. However, during the Pole Impact sensitivity study they were added back into the design in order to meet the higher performance requirements of the MMV target. Though the pole counter measures were never optimized themselves, they demonstrate the validity of the project's primary strategy. That loadpath should be used before any other enablers such as section geometry, material or gauge selection to determine the structure's performance.

Part Consolidation

- By varying the loadpath's location, shape, gauge and material, the optimization process has balanced the stiffness and load distribution within the structure. It has therefore allowed the components to maximize their potential. Loadpath optimization is an essential ingredient in the project's optimization process that enables the AHSS steels under consideration to reduce structural mass through down gauging and parts consolidation.

- The optimization created a sophisticated solution which addresses each loadcase while developing a balanced solution to meet all performance targets in a minimum mass package. In comparison, the parts consolidation analysis considered IIHS Side Impact and Roof Crush only. However, it is not without value. It verified the merit of the Seat Cross-member loadpath and demonstrated that there was little opportunity to consolidate parts further. Finally it proved that in order to maximize the potential mass reduction the optimization must consider all possible passenger compartment loadcases.

Shape Optimization

- The front rail structure is outside the passenger compartment and so beyond the influence of the optimization. This means for the Front NCAP & ODB loadcases it is not possible for the optimization to condition the loading coming into the passenger compartment. Thus for components such as the Rocker it may be possible to reduce their mass further had the optimization been able to consider the complete BIW.
- The external styling surfaces of the vehicle were considered fixed. However, if even minor styling changes were allowed it may have been possible to develop more effective loadpaths and so increase the mass reduction further.

Final Optimization

- Using the experience gain in Task 3: Optimization it was possible to reduce the number of material choices for a number of components. This significant improved the speed of the optimization and allowed it to reach a solution in the least amount of time.
- The Optimization did not automatically reduce the mass of all parts. In fact in some cases it increased their mass. What the Optimization did do was balance the performance of the complete structure in order to achieve the necessary performance. This is what enabled it to create the minimum mass solution.
- The mass of certain components was driven by Torsional Stiffness requirements. Since this is a static loadcase upgrading the material choice of such a component to a higher strength will not increase its stiffness. Without changing its geometry only a change in gauge could achieve this, consequently increasing the overall mass.

Seat Position & Pole Impact Sensitivity Studies

- The Final Concept Design successfully achieved the required performance for both sensitivity studies and thus established the robustness of the optimized structure. The pole counter measures used for the pole impact sensitivity study were not optimized and so it may be possible to reduce their current mass of 4.18kg, while still maintaining the structure's performance.

Continuous Joining Sensitivity Study

- Both Continuous Joining methods, Laser Welding and Adhesive Bonding achieved improved performance compared to the Final Concept Design. Overall continuous joining methods strengthened the joints leading to improved performance
- Adhesive Bonding performed better than Laser Welding
- Adhesives offer the opportunity to join materials and gauges that may not be compatible using traditional welding methods. However, until the adhesive has cured it is typical to use spot-welding or similar methods to hold the structure together
- Laser Welding offers the benefits of continuous joining without the need for the separate curing process of adhesive. Just as with other forms of welding there are material and gauge compatibility issues that may limit its use.

Lessons Learned for FGPC-Phase 1 that apply to the FGPC-Validation Project

- B-pillar intrusion should be measured at various heights for the IIHS side impact because the deformation mode may change.
- A cross-member connecting the B-pillars gives the vehicle a robust side impact performance.
- During shape optimization, care should be taken to assure that no connections are lost and that part penetration is minimized.
- Proper loadpaths should be established for the various loadcases before final optimization begins.
- When optimizing for a specific set of loadcases, it is important to consider what other loadcases may be affected because there may be some overlap.
- The optimization should consider as many loadcases as practically possible.
- Unless it is specifically required, for example to evaluate the consequences of styling constraints, the shape optimization should exclude the external A-surfaces of the vehicle and thus avoiding any changes to the styling.
- With respect to material and gauge choice, the initial optimization was free to produce a long-term solution. It was then possible to take the optimization results and produce either a short or long-term solution during the design phase.
- All possible constraints such as the material compatibility for joining need to be specified during the problem setup, so that the final optimized design is manufacturable.

9. CONCLUSION

9.1. MASS REDUCTION

The optimization methods applied to the FGPC-Validation project achieved a 39.8kg (-15%) mass reduction in the optimized components of the combined passenger compartment and doors compared to the Donor Vehicle. See Table 2.

MODIFIED PARTS	**DONOR VEHICLE (kg)**	**FINAL CONCEPT DESIGN (kg)**	**MASS SAVINGS (kg)**	**CHANGE (%)**
Passenger Compartment	205.8	176.5	-29.3	-14
Doors	70.3	59.8	-10.5	-15
TOTAL	**276.1**	**236.3**	**-39.8**	**-15**

TABLE 2: Final Mass Summary For FGPC-Validation - Modified Parts Only

Figure 1 shows the effect of applying these results to the complete passenger compartment, a 12% mass reduction and to the full BIW, a 9% mass reduction. For convenience Figure 2 shows the mass reduction tracked through the complete project. It shows the percentage mass reduction for both the passenger compartment and full BIW after the initial loadpath and shape optimization, the final gauge optimization and the development of the Final Concept Design.

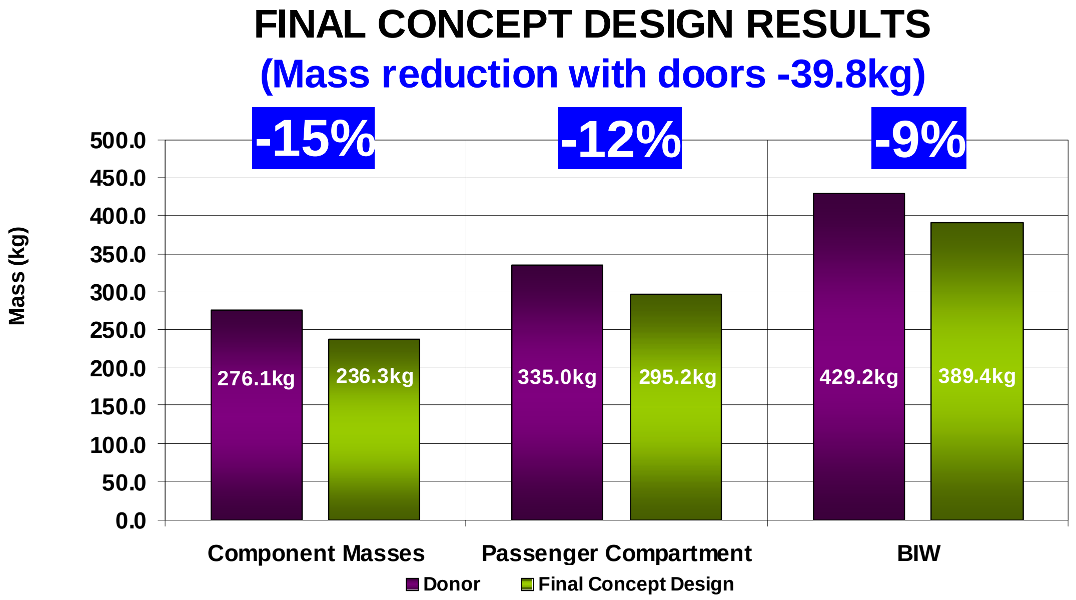


FIGURE 1: Final Concept Design – Mass Reduction including effect of Doors

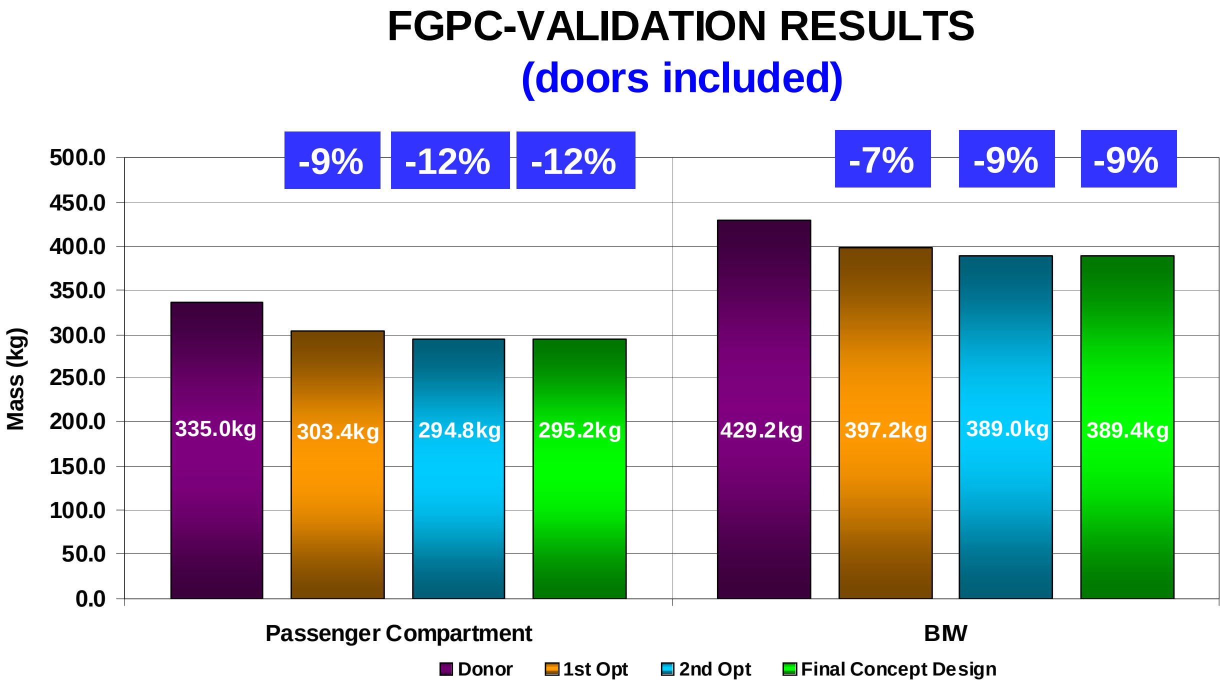


FIGURE 2: FGPC-Validation – Mass Reduction including effect of Doors

9.2. SENSITIVITY STUDIES

Three sensitivity studies were performed on the Final Concept Design. These were;

a) Seat Position Sensitivity
b) Pole Impact Sensitivity using the MMV (Multi-Material Vehicle) targets
c) Continuous Joining Sensitivity

9.2.1. SEAT POSITION SENSITIVITY

The seat cross-member is a primary loadpath for IIHS Side and Pole Impacts developed by this project. During the course of the optimization both the driver's and passenger side seats were placed in the 5th Percentile position as defined by the IIHS test definition. Because the placement of the seat cross-member changes with seat position, the effectiveness of this load path may change. This sensitivity study addresses this concern by evaluating the Final Concept Design's IIHS Side Impact performance for a variety of seat position combinations, see Figure 3.

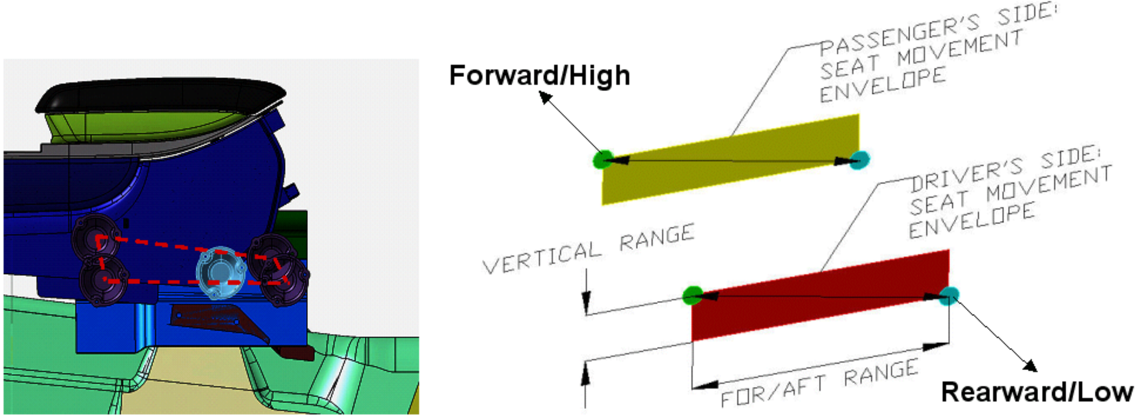


FIGURE 3: IIHS Side Impact Sensitivity – Range of Driver & Passenger Seat Positions

In all the combinations of seat positions considered, the structure achieved the required performance by a comfortable margin. See Table 3. This demonstrates that the vehicle's IIHS Side Impact performance is insensitive to seat position. The robustness of the design is due to the creation of a new cross vehicle loadpath through the seats and the ability of the optimization to balance the strength of both this and the more conventional upper and lower loadpaths.

DRIVER'S SEAT POSITION	LOADCASE	PASSENGER'S SEAT POSITION	IIHS SIDE IMPACT RESIDUAL SPACE (Target: 83mm)*	TARGET ACHIEVED
Forward/High	1	Forward/High	116mm	✓
	2	Rearward/Low	101mm	✓
Rearward/Low	3	Forward/High	98mm	✓
	4	Rearward/Low	99mm	✓

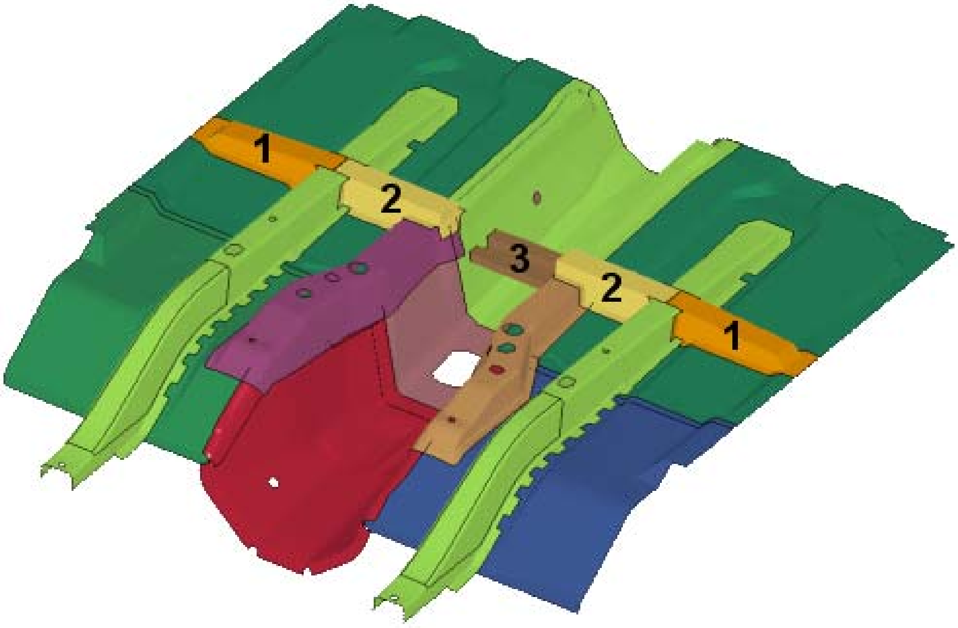
The Final Concept Design was optimized at the IIHS 5th Percentile position for both seats and achieved a residual space of 115mm.

TABLE 3: IIHS Side Impact Sensitivity Results

9.2.2. POLE IMPACT SENSITIVITY USING THE MMV TARGET

The Final Concept Design was optimized to meet a pole impact target of 83mm. At the beginning of the project counter measures were developed to achieve this required pole impact performance. However, during the course of the optimization it was found that the structure could achieve this without the counter measures and so they were removed from the passenger compartment. Now that the passenger compartment has been fully optimized the team asked if it would be possible to allow the structure to meet the higher requirements set by the USAMP MMV project. In this case the residual space target used was 125mm.

The counter measures are shown in Figure 4. In total they added 4.18kg to the mass of the passenger compartment. However, it should be noted that the purpose of this study is not to optimize their added mass or performance but simply to determine if the increased residual space target of 125mm could be achieved.



Pole Members (1, 2 & 3)

Gauge: 1.5mm
Material: DP700/1000
Added Mass: 4.18 kg

FIGURE 4: Pole Impact – Counter Measures (Bottom View)

Inclusion of the underbody counter measures allowed the structure to achieve the required performance. The residual space measured was 127mm compared to the target of 125mm. The current mass of the counter measures in 4.18kg. It should be noted that the counter measures were never optimized and so it may be possible to improve their performance further or maintain the present level of performance and reduce their mass. However, this is beyond the scope of the project.

9.2.3 CONTINUOUS JOINING SENSITIVITY

The Final Concept Design is primarily a spot-welded structure. The first objective of this sensitivity study was defined the baseline performance of both a continuous laser welded and continuous adhesive bonded variants of the Final Concept Design. The performances of both types were measured for IIHS Side Impact, IIHS Front Crash 40% ODB, Roof Crush and Pole Impact. The second objective selected one continuous joining method and optimized it any additional mass reduction. This was be achieved by optimizing the gauge of the major components in the passenger compartment.

Summarizing the performance of all five loadcases considered of both joining methods showed a significant improvement over the Final Concept Design. See Table 4. However, Adhesive model was optimized because its increased performance enabled the greatest mass reduction achievable.

LOADCASE	PERFORMANCE IMPROVEMENT	
	FINAL CONCEPT DESIGN➔LASER	FINAL CONCEPT DESIGN➔ADHESIVE
IIHS Side Impact	2%	16%
IIHS Front Impact ODB	16% to 44%	22% to 60%
Roof Crush	15%	25%
Torsion	10%	15%
Bending	13%	20%

TABLE 4: Summary of Laser Welded & Adhesive Bonded Performance Compared To Final Concept Design

Optimization of the Continuous Adhesive Bonded model resulted in a revised selection of gauges for the components considered and a recommendation to eliminate the Tunnel Reinforcement. Rounding the selected gauges to the nearest 0.1mm and removing the Tunnel Reinforcement resulted in 18.7kg (-8%) mass reduction compared to the Final Concept Design. Combining with the results of the door optimization, the Continuous Adhesive Bonded model achieves 59kg (-21%) mass reduction of the optimized components compared to the Donor Vehicle. See Figure 5.

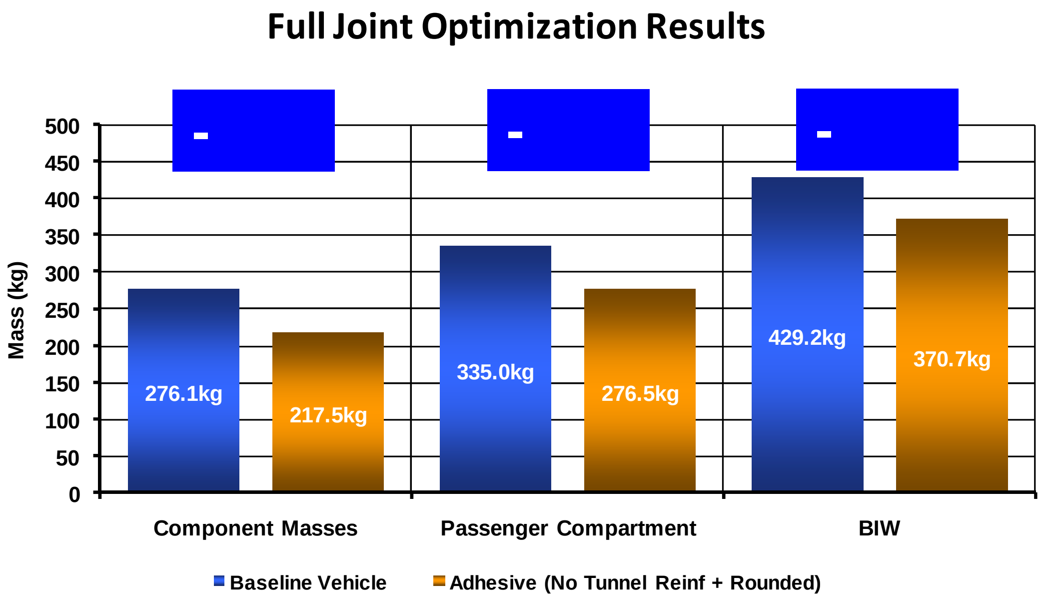


FIGURE 5: Joint Optimization Results – Comparison to Baseline Vehicle