V. Future Generation Passenger Compartment

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Objective:

The objective of the Future Generation Passenger Compartment (FGPC) project is to incorporate current propulsion systems and fuel-cell technologies into concept architectures. The project is separated into five (5) phases: Phase 1 - Concept Development; Phase 2a - Validation on a donated vehicle; Phase 2b – Development of Advanced Steels; Phase 3 – Roll-out learnings into advanced vehicle development; and Phase 4 - Production design. Phases 3 and 4 are Original Equipment Manufacturer (OEM) internal.

Approach:

The FGPC project team will benchmark, develop and document integrated solutions that will balance the interaction of materials, manufacturing, performance and cost. The study will focus on solutions that will address high-volume manufacturing and assembly applied to fuel-cell technology vehicles. The project supports the goals of FreedomCar as follows:

- High-strength steels are a mass-efficient solution in crash-dominated vehicle structures (e.g., body, closures, chassis, etc.) at a significant cost advantage versus other materials.
- A passenger compartment is thus an enabler to facilitate the application of other lighter weight materials to achieve half the vehicle mass while maintaining affordability.
- Steel has the proven and existing infrastructure for high-volume production and 100% recycling.

- This and other projects also allow the industry to migrate to lightweight structures that will accommodate fuel-cell powertrains.
- Immediate project initiation is required to establish the foundation required to develop a FreedomCAR solution.

Accomplishment:

A benchmarking study and fuel-cell development calibration baseline have been completed.

Future Direction:

- Validation of the Phase 1 results into a donated vehicle.
- Develop additional advanced high-strength steels.
- Roll-out learnings into advanced vehicle development.
- Incorporate into future production vehicles.

Project Progress: October 1, 2004 to September 30, 2005.

The project was initiated on January 1, 2005.

The Future Generation Passenger Compartment (FGPC) project is divided into nine (9) sections. Each of these sections will have a presentation and report.

1.0 Benchmarking
2.0 Calibration Baseline
3.0 IIHS/ Roof Crush DoE Study
4.0 Concept Design Study
5.0 Design Concept Analysis Check
6.0 Final DoE Mass Optimization
7.0 Final Design Check
8.0 CAD Data for the final Design
9.0 Final Report

The following definitions are used throughout this report:

ULSAB-AVC:	Ultra Light Structure Automobile Body-Advanced Vehicle Concept
FGPC:	Future Generation Passenger Compartment
FGPC-D:	Diesel Vehicle
FGPC-F:	Fuel-Cell Vehicle

1.0 Benchmark Study completed:

The goal of the Benchmarking Study was to gather information that would identify the latest technology trends used by worldwide OEMs for crashworthiness in general and specifically the Insurance Institute for Highway Safety (IIHS) side-impact and rollover tests. The FGPC project team members will use this knowledge to enhance the OEM designs for better performance.

The strength or weakness of a particular design investigated during benchmarking is a relative statement and could only be graded if the design targets and their performance constraints were known. Therefore, we have to believe each design has its own philosophy.

Design philosophy is defined as a target that designers would like to achieve for overall vehicle behavior and vehicle component behavior in different proving-ground tests and attributes, such as front crash, side impact and rear crash.

The design philosophy or vehicle definition is based on target performance, development cost, vehicle rank, manufacturing, material, styling, etc. Definitions should be known so one can identify whether or not a particular design is within that design envelope. Since the design philosophy and constraints of the benchmarked vehicles are not known, the team would not categorize a design as good or bad. Such a categorization is also not within the scope of this project.

The key question in the crash and safety environment of the auto industry is how it should meet Federal Motor Vehicle Safety Standards (FMVSS), New Car Assessment Program (NCAP), IIHS, Japanese and other regulations within one vehicle system package with no major architectural changes in the packaging and tooling to control cost and weight.

At the same time, there exists a challenge to meet all safety issues, reduce the vehicle mass, and make the vehicle fuel efficient for current and future types of drivetrains, including future vehicles with a Hydrogen Fuel-Cell drivetrain.

Most automakers and their key suppliers predict that hydrogen fuel-cell technology would be able to demonstrate commercial feasibility and production validation by 2010, with vehicles ready for public sale by 2015.

OEMs worldwide are developing crash load paths using all available tools to meet FMVSS, ECE, IIHS and NCAP front, side and rear crash requirements. Although crash load paths are similar on all vehicles, each manufacturer has its own strategies for managing the crash energy and load paths.

- For front impact, the trend is to more evenly distribute loads to improve passenger protection, and to be more crash-compatible with vehicles of differing ride heights using energy management and load path mechanisms.

- For side impact, controlling the B-pillar intrusion and deformation mode by balancing the lower and upper regions of the body structure is critical. Reinforced B-pillar, rocker, and roof structures are generally needed to meet performance targets.

- For rear crash, similar strategies as used in front impact are under development, using energy-management and load-path mechanisms within one system to meet all rear crash scenarios.

All benchmarked vehicles in this study have used all of the above techniques to meet the targets. However, some, more than others, used layers of reinforcements with steel material to resist the loads. It is predicted that future technological advancements may provide an alternative approach to meeting crash and safety goals.

Overall, it has been observed that a few vehicles have incorporated a considerable amount of reinforcement within the body side in the rocker, A-pillar, B-pillar and roof rail sections. It is possible that the original architecture was not designed for some events and designs had to be reconfigured by adding reinforcements to meet specific targets.

Other design features that were found to be common in this benchmarking effort include the use of bulkheads, used for the prevention of local buckling, and a wider B-pillar section, which provides better resistance in side impact and rollover and better load transformation for vehicle dynamics and also helps to stiffen the body in torsion. This could reduce the number of reinforcements that are used inside of the B-pillar, or weight reduction using geometry. Styling could be an issue in this type of design.

A deep rocker section with multiple-layer reinforcements is used because it will not allow the section to collapse in FMVSS 214 and ECE side impact where the barrier hits the rocker section. The rocker is used for the load path for front crash as well.

To meet the requirements of rollover, IIHS front and side impacts, we observed a deep section in the roof rail between the A and C pillars. This contrasts the strategy used by many vehicles that use a smaller section with multiple reinforcements.

If all these ideas are used properly based on design philosophy, it is considered a smart design, one that if it is used outside of its envelope, it would be considered over-designed.

In the design of vehicle components, beading will be used to improve local and overall stiffness and crash modes of body panels.

In summary, the strategy to meet FGPC Project Team objectives will be:

1. The use of geometry to design the load path to meet crashworthiness performance, while absorbing energy using total-system topology optimization.

2. Investigate the usage of advanced high-strength steel (AHSS) materials and manufacturing

techniques (e.g., tailor-welded blank) that can reduce weight and increase performance.

2.0 Fuel Cell Development Calibration Baseline Report was also completed:

The purpose of this report is to document the design and packaging effort that provided a baseline configuration for the subsequent CAE assessment of vehicle performance for different crashworthiness scenarios.

A/SP provided the initial vehicle model, which was developed for the ULSAB-AVC program. The model was validated and used as the baseline configuration. Two variations were developed:

- Fuel-cell power (FGPC-F)
- Conventional rear-wheel drive with diesel engine (FGPC-D)

Objective:
To provide evaluation of the FGPC design for fuel-cell and traditional engine configurations for five different performance attributes:

- FMVSS 208 Front Crash (US-NCAP)
- IIHS Front Crash
- IIHS Side Impact
- FMVSS 301 Rear Crash
- FMVSS 216 Roof Crush

The objective is 1) to compare the FGPC vehicle performance with ULSAB-AVC in all above mentioned attributes and 2) to compare the performance of the fuel-cell and traditional engine configurations for each crash attribute and then use the worst case to evaluate the performance of the vehicle with the new underbody design.

A new underbody was designed based on the ULSAB-AVC vehicle platform for FGPC. The new underbody was modified and packaged to allow the vehicle structure to be capable of having two different types of drive train: traditional rear-drive diesel engine and fuel-cell power. Engineering Technology Associates (ETA), Engineering Design, Inc. (EDAG), and A/SP team members developed fuel-cell packaging requirements based on information gathered in the benchmarking phase and from the OEMs (GM, Ford and DCX). These requirements include the mass of fuel-cell components, and volume of fuel-cell tanks and modules. The packaging and design of the new underbody was targeted in a way that the volumes of the fuel-cell storage tanks are maximized and shapes of the fuel-cell tanks are acceptable to be manufactured today or by 2010. The final design of the fuel-cell modules includes two oblong-shaped tanks under the rear seat and a conical-shaped fuel cell tank under the modified center tunnel.

The FGPC program vehicle targets were developed based on ULSAB–AVC performance targets:

1. Front Crash – Meet U.S.-NCAP and IIHS 40% Offset Deformable Barrier (OBD) Impact structure performance
2. Rear Crash – Meet FMVSS 301
3. Side Impact – Meet IIHS Dynamic Side Impact
4. Roof Crush – Meet FMVSS216

The scope of the design and packaging effort includes the following tasks:

- Review available space for packaging
- Determine and subsequently maximize volume of fuel-cell storage tanks
- Develop alternative body design options
- Review sections of fuel-cell storage
- Evaluate possible alternative shapes for fuel storage if applicable
- Study possible concessions in packaging
- Incorporate suspension data (if available)
- Establish material thickness of fuel storage containers

The first portion of the design study was to determine the overall volume of the space that was available for fuel-cell storage using the existing ALSAB/AVC-PNGV vehicle structure.

The packaging of the components for the fuel cell option was determined using dimensions obtained from the A/SP team. These components (fuel-cell stack, batteries and electronic box) were positioned in strategic areas and reviewed by the committee members to best determine a viable location. The repositioning of the components in the front engine compartment was the starting point for all components and acceptability would be determined using the analytical front-end crash results.

Multiple fuel-cell shapes and sizes were packaged to determine the actual fuel storage area that would be available with the existing structure and possible alternative revisions that could be made were determined. A revision to the tunnel area in size and shape was one option along with other revisions to the existing structure. Some considerations include:

- The width of the tunnel remained the same and the joint connections to the rail members did not change. The height of the tunnel was raised, holding the front portion at its present height but raising the rear connection to the rear floor pan and kick-up panel as high as possible; this would impact the middle rear seat passenger (Figure 1).
- Alternative shapes other than cylindrical were considered (oblong, conical and irregular). These would be held as possible options and would be packaged with the various revisions to the current structure (Figures 2-4).

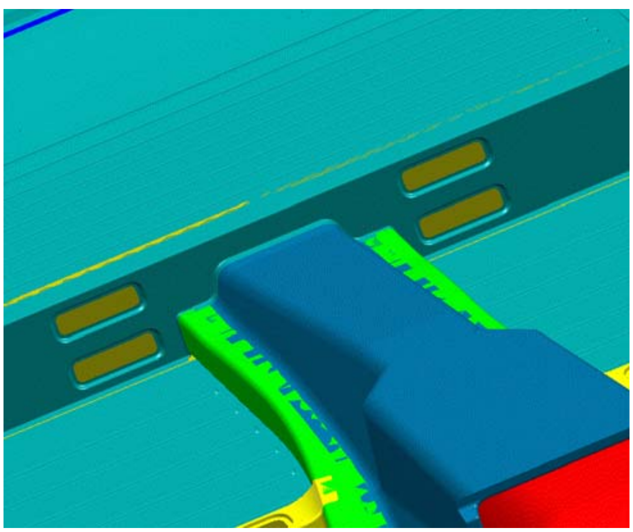

Figure 1. Revised Transmission Tunnel.

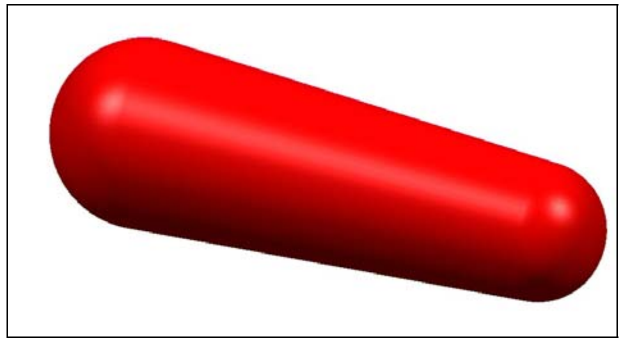

Figure 2. Cone shape for tunnel fuel storage 79,390,000 cmm at a weight of 20.65 kg.

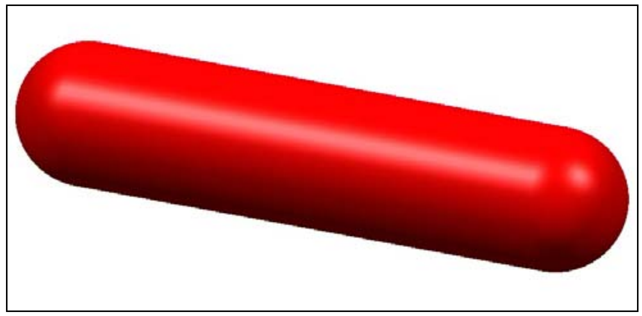

Figure 3. Cylindrical shape for the tunnel fuel storage 50,710,000 cmm at a weight of 13.18 kg.

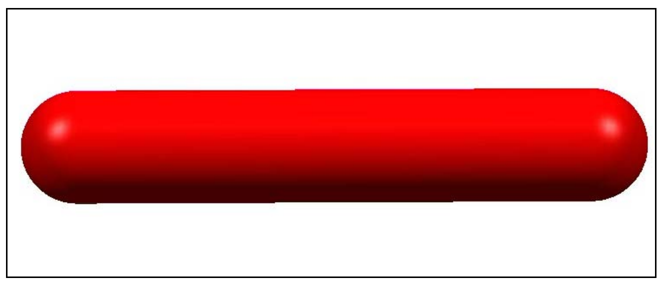

Figure 4. Fuel storage tank under rear seat.

The cylindrical shape for under the rear seat and the trunk was 23,920,000 cmm at a weight of 6.22 kg. Six tanks would be utilized for this space, 3 cylinders under the seat area and 3 cylinders under the trunk. The total weight would be 37.32 kg at a total volume of 143,520,000 cmm.

After initial review of the various fuel-cell storage alternatives with the team, one fuel-cell tank would be considered in the tunnel and cylindrical tanks or oblong tanks would be considered under the rear seat and trunk. After reviewing all the design options, it was decided that an irregular fuel-cell shape would be used for the tunnel space to maximize the volume (94,450,000 cmm at 24.56 kg)

(Figure 5). An oblong shape would be used under the rear seat and the depression for the cushion on the floor in that area would be eliminated in order to maintain maximum height for the fuel-cell tank (95,950,000 cmm at 24.96 kg) (Figure 6). Another oblong fuel-cell tank of duplicate shape and size would be positioned under the trunk floor. Figures 7-9 show the fuel tanks' positions in the vehicle. Brackets were developed to support the fuel-cell storage tanks. No revision was made to the trunk floor for packaging the storage tank.

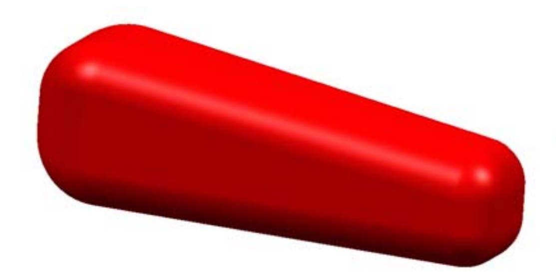

Figure 5. Final Front Fuel Tank Shape.

Figure 6. Final Rear Fuel Tank Shape.

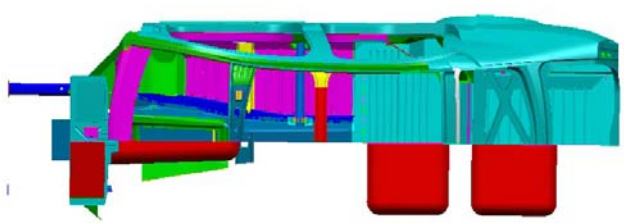

Figure 7. Centerline split view showing body structure and fuel tank - top view.

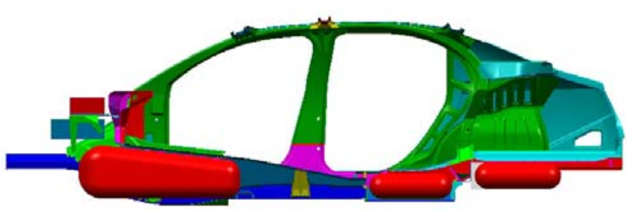

Figure 8. Centerline split view showing body structure and fuel tank - side view.

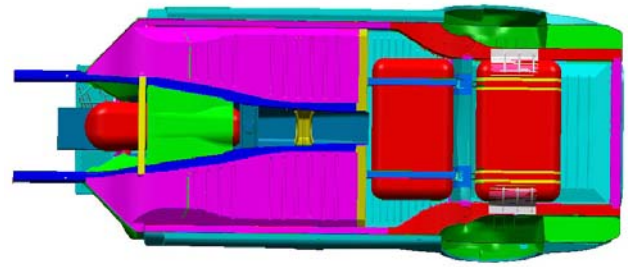

Figure 9. Underbody showing fuel-cell tank locations and tunnel fuel shield.

- A possible revision to the rail member was evaluated by straightening its shape from the front seat to the rear running parallel to the centerline of the vehicle. This could possibly obtain additional width at the tunnel between the rails and create more space for fuel-cell storage. If feasible, this would change the width of the tunnel and could possibly affect the rear seat passenger's foot clearance (Figure 10).
- The fuel-cell storage in the rear compartment area (trunk) could only be utilized in the forward area because of the intrusion zone identified from the rear-impact analytical run. This would be taken into consideration when attempting to package the fuel-cell storage in this location.

The existing ground clearance was a determining factor for the size and location of many of the fuel cells, and was therefore used as a guideline for the packaging of the fuel cells.

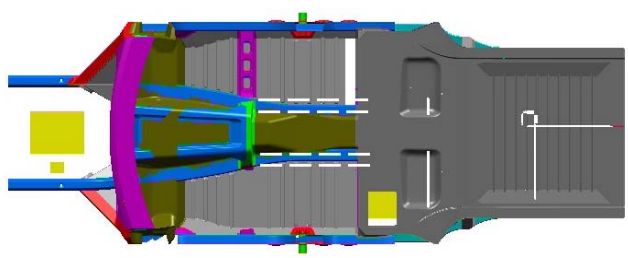

Figure 10. Revisions for passenger's foot clearance.

To accept the height change and shape through the tunnel area, crossmembers were redesigned and the kick-up area from the front to rear floor was revised (Figure 11).

The crash results showed buckling in the floor pan at the tunnel in the kick-up area. This was possibly due to the kick-up area on the floor and the kick-up reinforcement being revised from the original design. It was agreed to revise this area and to obtain a cross-car vertical wall connection on the floor pan, tunnel, and the reinforcement. The kick-up reinforcement would then revert to a single-piece part. The tunnel would also be revised to accommodate this change.

The straightening of the rail members was eliminated from the options due to intrusion into the foot space of the rear-seat passenger.

Fuel-cell components were packaged under the hood and a front package tray was designed to support these components.

The tubular support extending laterally that was utilized as an attachment point for the rearward portion of the front seat was revised due to the height of the tunnel being raised. The original design crossed over the top of the tunnel but had to be cut off at the tunnel because of the height change (Figure 11). A connecting bracket was placed at either side of the tunnel to accommodate the attachment of this tube. A bracket was designed in the tunnel at this location in an attempt to continue the flow of a cross-car support from a side impact.

The team wanted the configuration of the top of the tunnel to the rear floor to have the same plane transition, meaning the top of the tunnel would be at the same height as the rear floor at the rear seat area. The step-down area on the revised tunnel was changed per the request from the previous meeting. This made the rear kick-up reinforcement two parts compared to one in the original, because of the height of the tunnel. The joint connections to the tunnel were revised to accommodate the change. The front tunnel reinforcement was also revised to agree with the tunnel revision, and it kept its basic shape with minor alterations.

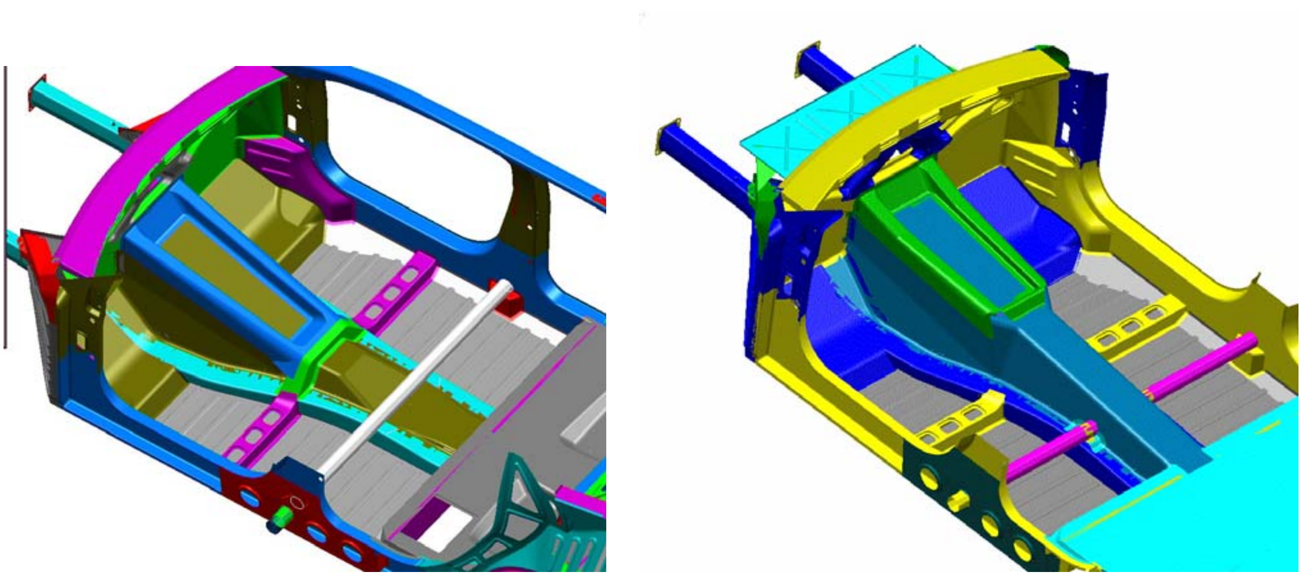

Figure 11. Modifications required to increase tunnel height.

A shield was designed for the tunnel fuel cell trying to incorporate two functions:

- Utilize as a support for the fuel-cell tank
- Utilize as a protective barrier

Brackets for the front shield were designed to assist in supporting the shield, and the shield was revised to better accommodate the routing of the fuel-cell lines (Figure 9).

To strengthen the upper load path for side impact, a roof bow was designed at the B pillar similar to the roof bow used on the C-Class vehicle. Subsequent analysis results showed the roof bow needed revision, so three separate roof bows were designed:

- Move roof bow rearward to be more in-line with the B-pillar from the side view (Figure 12).
- A wider roof bow was positioned strategically at the B-pillar (Figure 13).
- A double roof bow in the area of concern at the B-pillar along the side roof rail (Figure 14).

The front-end crash results showed intrusion of the motor into the shield and tank. The shortening of the tunnel fuel-cell tank will be investigated based on additional information for tank hook-up. The fuel-cell motor dimensions were revised slightly to address the front-end crash intrusion. The original volume was maintained but the front of the box was set further rearward.

2.3 Conclusions

2.3.1 Front Impact

NCAP – Uses Baseline Model

Simulation results for front-impact analysis indicate that the performance of FGPC-D case is similar to the ULSAB-AVC model, whereas the FGPC-F performance degraded compared to ULSAB-AVC. The front fuel-cell tank contacted the electric motor/gear box causing a higher deceleration pulse, which resulted in lower dynamic crush resistance.

IIHS-ODB – Uses Baseline Model

Simulation results for offset-impact analysis indicate that the performance of FGPC-F vehicle degraded from the ULSAB-AVC model as the fuel-cell footwell intrusion is much greater than the FGPC-D model. The reason is because the subframe impacts the fuel-cell tank causing an increase in bending of the longitudinal rails.

In summary, the evaluation of the vehicle performance of both drivetrains for NCAP and IIHS case showed that Fuel-Cell Engine configuration is the worst case compared with the traditional engine configuration. Also, the vehicle will not meet NCAP flat rigid-barrier and IIHS front-crash structural performance requirements with the fuel-cell powertrain. In the fuel-cell configuration, the conical front fuel storage tank will be impacted by the motor/transmission. The IIHS vehicle performance measure was moved from good status to acceptable level; also the fuel-cell tank was impacted by front structure components.

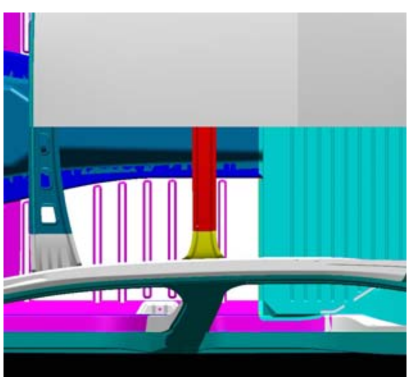

Figure 12. Roof Bow at B-Pillar.

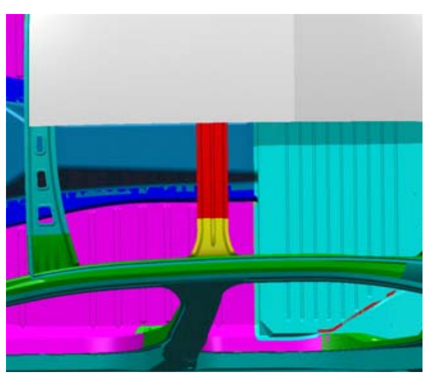

Figure 13. Wider Roof Bow.

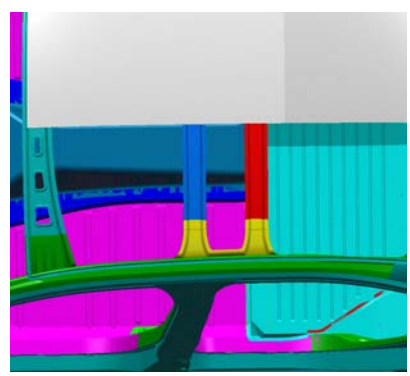

Figure 14. Double Roof Bow

2.3.2 Side Impact – Uses Baseline and Modified Models

In IIHS side impact regulation, the vertical range considered for the structural rating extends from the base of the B-pillar interior up to a point that is 540 mm above the H-point measurement taken with the seat in full-rear and full-down position are summarized in Table 1 below.

Evaluation of the vehicle side-impact performance for each drivetrain configurations showed that both the traditional-engine and fuel-cell configurations showed weakness. ETA added a roof bow at the B-pillar to the side-rail intersection in order to improve the performance of both vehicle configurations that have different mass distributions. The results showed that vehicle performance is below "good" status (125 mm intrusion, see IIHS side impact requirements) for both conditions. However, the results showed that vehicle structural performance with the conventional engine is better than fuel-cell powertrain case. The conventional engine configuration is therefore identified as the baseline for the IIHS side-impact optimization study, which is Task 3 of this project.

2.3.3 Rear Crash – Uses Baseline Model

The worst-case evaluation of the rear-crash vehicle performance showed that the fuel-cell configuration performs the worst in comparison with the traditional-engine design. Analysis results showed that the modified ULSAB-AVC vehicle would meet rear crash FMVSS 301 requirements for both drivetrain cases. The oblong fuel cell and traditional-engine fuel tank would survive and there would not be any fuel leakage.

Simulation results for rear-impact analysis indicate that both the diesel and fuel-cell configurations of the FGPC can withstand the 35-mph rear-impact test without fuel- tank damage.

The fuel pipe of the diesel model has some plastic (permanent) deformation, but the value is small, only 3 % plastic strain. The diesel fuel tank is well secured.

2.3.4 Roof Crush – Uses Modified Model

The vehicle would meet roof crush targets for both drivetrains. The worst case would be the heavier vehicle, which would be the fuel-cell vehicle, because the force requirement is based on vehicle mass.

Table 1. Side-Impact Results Summary: Distance between B-Pillar and Centerline of Seat (Reference Figure 15).

	Baseline Model	**Modified Model (Added tunnel and modified rear floor crossmembers, added roof bow)**	**Remarks**
Fuel Cell	85 mm	100 mm	29.4 %*
Diesel	70 mm	105 mm	50.0 %*

*Improvements based on iteration #1

Good	**>**	**125 mm**
Acceptable	**>**	**50 mm**
Marginal	**>**	**0 mm**
Poor	**<**	**0 mm**

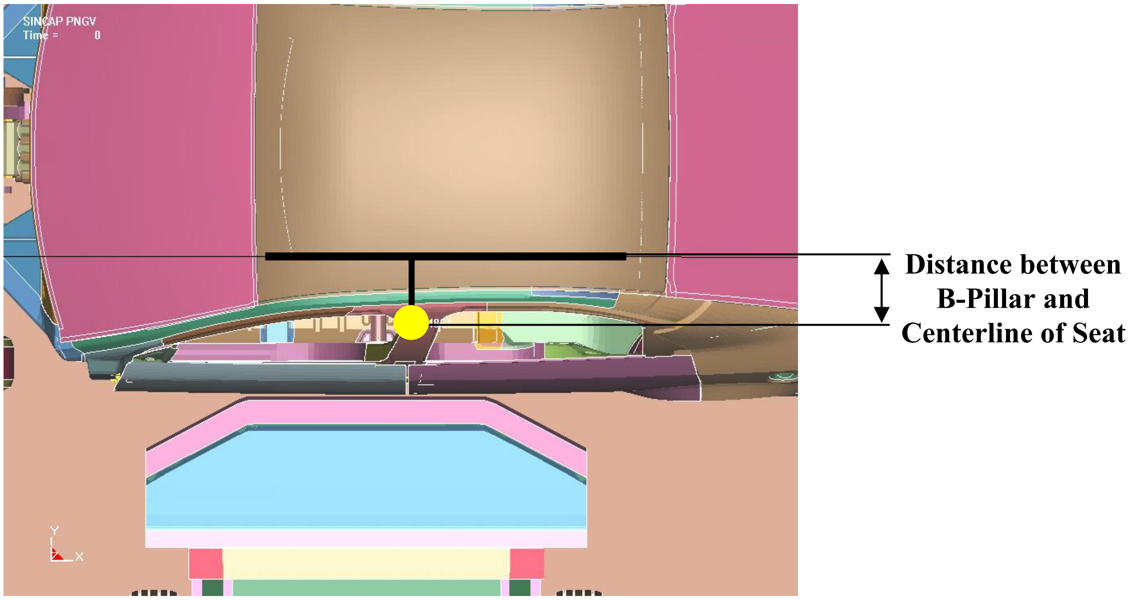

Figure 15. Side-Impact Measurement Definition.