WorldAutoSteel

New global steel industry study shows how to shrink the environmental footprint of next-generation car bodies by up to nearly 70 percent with use of new steels, latest design optimization techniques and electrified powertrain

FutureSteelVehicle

Nature's Way to Mobility

Resolution of Front Rail Manufacturability and Further *Nature's Way* Methodology Exploration in a Near-Term Design

Executive Summary & Engineering Reports April 2013

www.worldautosteel.org

FutureSteelVehicle (FSV) is a program of WorldAutoSteel, the automotive group of the World Steel Association comprised of eighteen major global steel producers from around the world:

Members of WorldAutoSteel are:

- Anshan Iron and Steel Group Corporation
- Arcelor Mittal
- Baoshan Iron & Steel Co. Ltd.
- China Steel Corporation
- Hyundai-Steel Company
- JFE Steel Corporation
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- Kobe Steel, Ltd
- Nippon Steel & Sumitomo Metal Corporation
- Nucor Corporation
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- United States Steel Corporation
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- voestalpine Stahl GmbH

WorldAutoSteel's mission is to advance and communicate steel's unique ability to meet the automotive industry's needs and challenges in a sustainable and environmentally responsible way. We are committed to a low carbon future, the principles of which are embedded in continuous research in and advancement of automotive steel products, for the benefit of society and future generations. To learn more about WorldAutoSteel and its projects, visit www.worldautosteel.org.

The FSV program is the most recent addition to the global steel industry's series of initiatives offering steel solutions to the challenges facing automakers around the world to increase the fuel efficiency of automobiles and reduce greenhouse gas emissions, while improving safety and performance and maintaining affordability. This program follows the UltraLight Steel Auto Body 1998, the UltraLight Steel Auto Closures 2000, UltraLight Steel Auto Suspension 2000, and ULSAB-AVC (Advanced Vehicle Concepts) 2001, representing nearly €60 million in research and demonstration investment.

Acknowledgments:

FutureSteelVehicle Technology Partners (Phase 2):

- EDAG AG
- Engineering Technologies Associates Inc.
- LMS Engineering Services

FutureSteelVehicle Integrated Incremental Forming Simulation Technology Partners: Engineering Technologies Associates Inc.

FSV Program Chair: Jody Shaw, United States Steel Corporation

FSV Program Manager: Harry Singh, EDAG Int'l Inc.

Integrated Incremental 3B Forming and Crash Optimization Manager: Akbar Farahani, Ph.D, ETA

This report summarizes the forming analysis and crash optimization work conducted to verify manufacturability of FSV's radically different front rail design. Please review the following reports for a comprehensive understanding of the complete scope of work conducted under the FutureSteelVehicle program, many of which are available at www.worldautosteel.org:

- FutureSteelVehicle Phase 1 Engineering Report, May 2009
- FutureSteelVehicle Phase 2 Engineering and Overview Reports, dated April and May 2012, respectively
- Platform development for HEV & EV, Frontloading NVH brings benefits to FutureSteelVehicle, October 2011
- Resolution of Front Rail Manufacturability and Further *Nature's Way* Methodology Exploration in a Near-Term Design, March 2013

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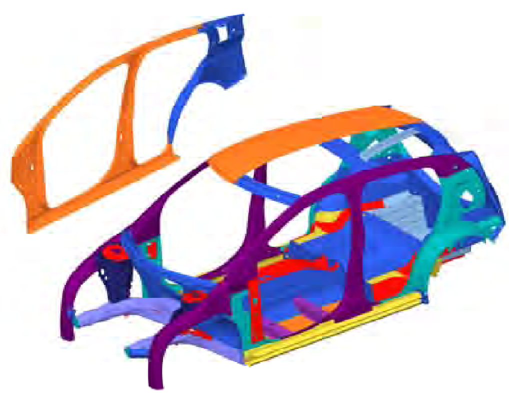
1.0 Project Background

Figure 1-1: FSV BEV Body Structure

WorldAutoSteel launched Phase 2 of its FutureSteelVehicle (FSV) program to show automakers how the latest and future steel grades and technologies can provide light-weight body structures for electrified vehicles. The program developed detailed, optimized design concepts for radically different steel body structures that address the unique requirements of electrified vehicles in production in the 2015-2020 timeframe. These steel body structure concepts (Figure 1-1), innovations which also can be applied to more conventional internal combustion engine-powered vehicles, achieved the aggressive mass target of 190 kg, while meeting global crash performance, NVH and stiffness objectives, as well as total life cycle greenhouse gas emissions targets.

The agent for these achievements is 97 percent use of High-Strength (HSS) and Advanced High-Strength Steels (AHSS) (Figure 1-2), of which nearly 50 percent reach into GigaPascal strength levels and are the newest in steel technology offered by the global industry. These are combined with advanced steel technologies and a new state-of-the-future engineering design approach, Multi-Disciplinary Optimization (MDO) Process. Full details of this work can be found in the FutureSteelVehicle Phase 2 Engineering and Overview Reports, which can be downloaded at *http://www.worldautosteel.org/projects/future-steel-vehicle/phase-2-results/*



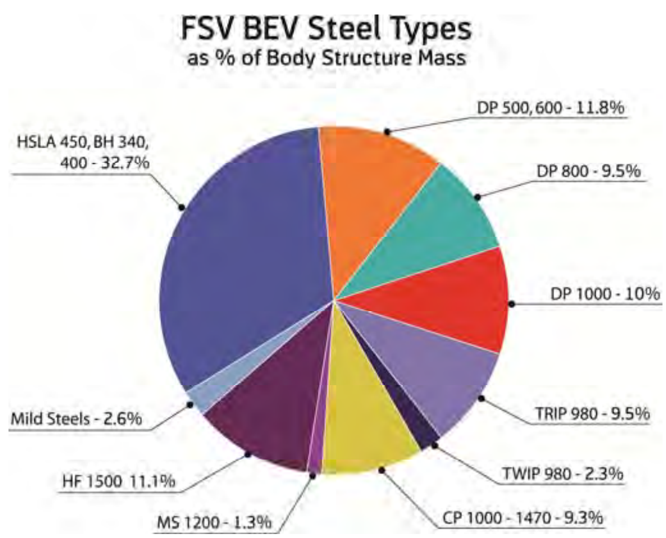


Figure 1-2: FSV BEV Body Structure and Steel Material Content

Steel's design flexibility and long list of options of material properties makes best use of this optimization process that develops non-intuitive solutions for structural performance. The resulting optimized shapes and component configurations often mimic Mother Nature's own design efficiency, referred to as "Nature's Way" design, where structure and strength are placed exactly where they are needed for the intended function.

FSV's steel portfolio is utilized during the material selection process with the aid of full vehicle analysis to determine material grade and thickness optimization.

Consequently, the FSV concepts are very efficient and light weight. FSV's Battery Electric Vehicle (BEV) concept body structure (Figure 1) weighs 188 kg and reduces mass by more than 35 percent over a baseline ICE body, adjusted for a battery electric powertrain and 2020 regulatory requirements. FSV's A-/ B-Class Plug-in Hybrid Electric Vehicle 20 (PHEV20) vehicle structure weighs 175 kg, and C-/ D-Class vehicle Fuel Cell and PHEV40 versions weigh 201 kg.

This continuation of the FutureSteelVehicle design development process (Figure 1-3) includes **A)** an integration of final work performed in FutureSteelVehicle's Task 5 design optimization; **B)** continuance with Task 6 Integrated 3B Incremental Forming and Optimization to prove manufacturability of FSV's radically different "Nature's Way" front rail design; **C)** Final gauge and crash optimization which re-integrated the front rail design into the full body structure and completed a final gauge optimization to take advantage of any further mass reduction opportunities, while still meeting crash requirements; and finally, **D)** the Near-Term Front Longitudinal Rail Shape Study explores the benefits to mass reduction of the unconventional sections proposed by the Nature's Way MDO process.

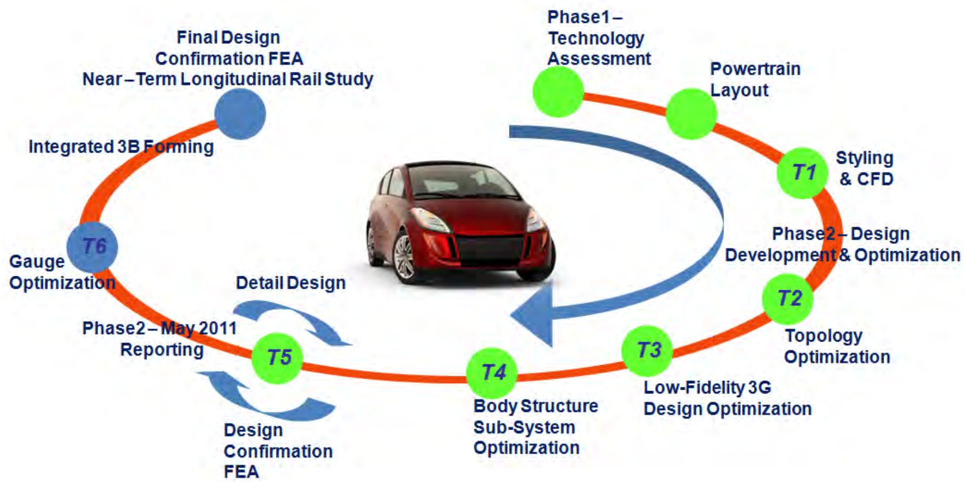


Figure 1-3: FSV Mass Evolution

1.1 Program Continuation -- Integrated 3B Study

The FSV MDO Process produced structures that are unlike anything currently seen in automotive applications. But like any dramatically different innovation, the question that begs to be answered is, "Can they be manufactured?"

By exploiting the flexibility of AHSS and modern, advanced steel manufacturing technologies, these types of designs are now possible in the real-world production environment. However, due to severe formability challenges, many design iterations are required to create high-performing, formable solutions. As a subset of the FSV MDO Process that was applied to the FSV program, formability has now been integrated directly into the optimization-based design process.

The Integrated Incremental **3B** (Draw **B**ead, **B**lank Geometry and **B**inder Pressure) Forming and Crash Optimization approach balances forming parameters such as draw bead force and geometry, blank shape and size, and binder pressure to achieve manufacturable conditions. This is followed by design and crash gauge optimization to achieve the lightest, most structurally efficient results, which meet the vehicle performance targets. It accomplishes this by optimizing the component design for formability while simultaneously validating in-vehicle crash performance.

The FSV MDO Process that was applied to formability as well as structure optimization in the FSV program may provide a new tool in the effort to expand the forming design space of AHSS.

Combining this process with steel's design flexibility and the long list of steel grades and gauges available today provides a robust tool for efficient development of very light-weight automotive structures that are manufacturable, affordable and low in life cycle greenhouse gas emissions.

1.2 Program Continuation – Final Gauge Optimization Study

Following FSV's Integrated 3B Forming and Crash Optimization exercise, it was necessary to bring the design back together for a final optimization of the material gauges. The final front rail structure resulting from the MDO process was re-integrated in the total body structure system. However, it is important to note that following the announcement of public results in 2011 and before the 3B forming optimization began, the FSV engineering team continued to optimize the body structure, further streamlining the design and exploring additional mass reduction potential. Therefore, the engineering team for this final gauge optimization, headed by ETA, Inc., wanted to include these additional optimizations in the Baseline vehicle.

The Final T6 Gauge Optimization began with the integration of additional T5-D336 design optimization conducted after the public announcement of the T5-Final FutureSteelVehicle results in May 2011. Also integrated in this design was the updated front rail sub-system design which was the subject of an Integrated 3B Forming and Crash Optimization to prove out its manufacturability. The T5 Final updated with the T5 Design 336 optimization as well as the outcomes of the 3B Forming Optimization of the front rail sub-system became the T6 Baseline vehicle design.

In a four-step design optimization process, each with its own set of parameters for performance and mass reduction, 865 design iterations were completed. The Step 4 Design #225 was selected as the T6 Final optimized design. This final design meets all of the load case targets with a mass of **176.8** kg, which is an **11.6 kg** mass reduction over the T5 Final design. Table 1-1 below provides a recap of the performance evolution.

Overall, the FSV T6 Final optimized design achieves a **39% mass reduction** over the FSV benchmark. These results demonstrate the capabilities of Advanced High-Strength Steel to close the gap in mass reduction potential compared to high cost, low density materials.

1.3 Near-Term Front Longitudinal Rail Shape Study

The optimized design that resulted from the original T6 process using the Nature's Way approach identified an optimized load path, which would carry loads through not only the rocker and roof-rail structures, like conventional designs, but additionally through the vehicle tunnel. The 3B and Final Gauge Optimization studies showed the efficacy of this strategy.

However, one characteristic of the final T6 optimized design, which yielded additional mass reduction while meeting crash performance and cost targets, is unconventional geometry in the shapes of the front rail tips. This would pose manufacturing challenges. In view of this, the non-intuitive shapes of the T6 design raised questions. "Are we limited to the single design solution suggested by T6?" And, "What mass and performance advantages can we specifically attribute to the unusual shapes?" The Near-Term front rail study addresses these issues.

The study comprised reshaping the longitudinal rails, running crash simulations, iterating both the design and crash simulations, allowing software to optimize for mass, and assessing the formability of the optimized design.

The results show almost identical mass, crash and cost outcomes for the T6 final design incorporating the non-intuitive shapes, and the Near-Term optimized design using more conventional geometry. Thus, the alternative Near-Term design addressed critical manufacturing challenges, accelerating the implementation of this technology into production vehicles.

The alternative solutions (T6 and Near-Term) provide two different, but comparable, answers, reinforcing steel's capability to expand the range of available solutions for designers and engineers faced with difficult constraints. With steel's enabling flexibility, unconventional shapes may yet offer additional benefits, if unconventional, outcomes. In any case, there is ample opportunity for further study.

The Near-Term study also confirmed that the "Nature's Way" MDO process is key to designing the very efficient structures that created the FSV's optimized load path.

Table 1-1 summarizes the performance results of the T5, T6 and Near-Term designs. Figure 1-4 provides a complete mass evolution encompassing all FSV development tasks.

Table 1-1 – Summary of Performance Results

Design	Mass kg	NCAP	Front ODB	IIHS Side	Side Pole	IIHS Rear	IIHS Roof	Bending	Torsion
Targets	<188	38 g	Good	125mm	125mm	Pass	37.5kN	12	20
T5-Final Design	188.4	39.7	Good	142	150	Good	55	15.5	19.6
T6-Final	**176.8** **- 11.6 kg**	**37.8**	**Good**	**152**	**138**	**Good**	**44.5**	**14.2**	**19**
Near-Term Optimized Design #73	**176.83**	**37.3**	**Good**	**152**	**138**	**Good**	**44.5**	**14.2**	**19**

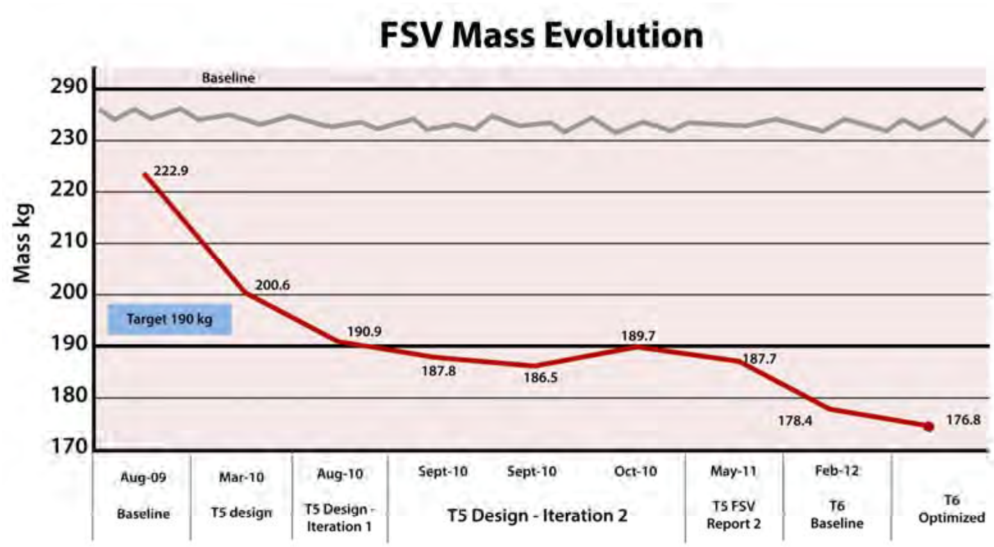
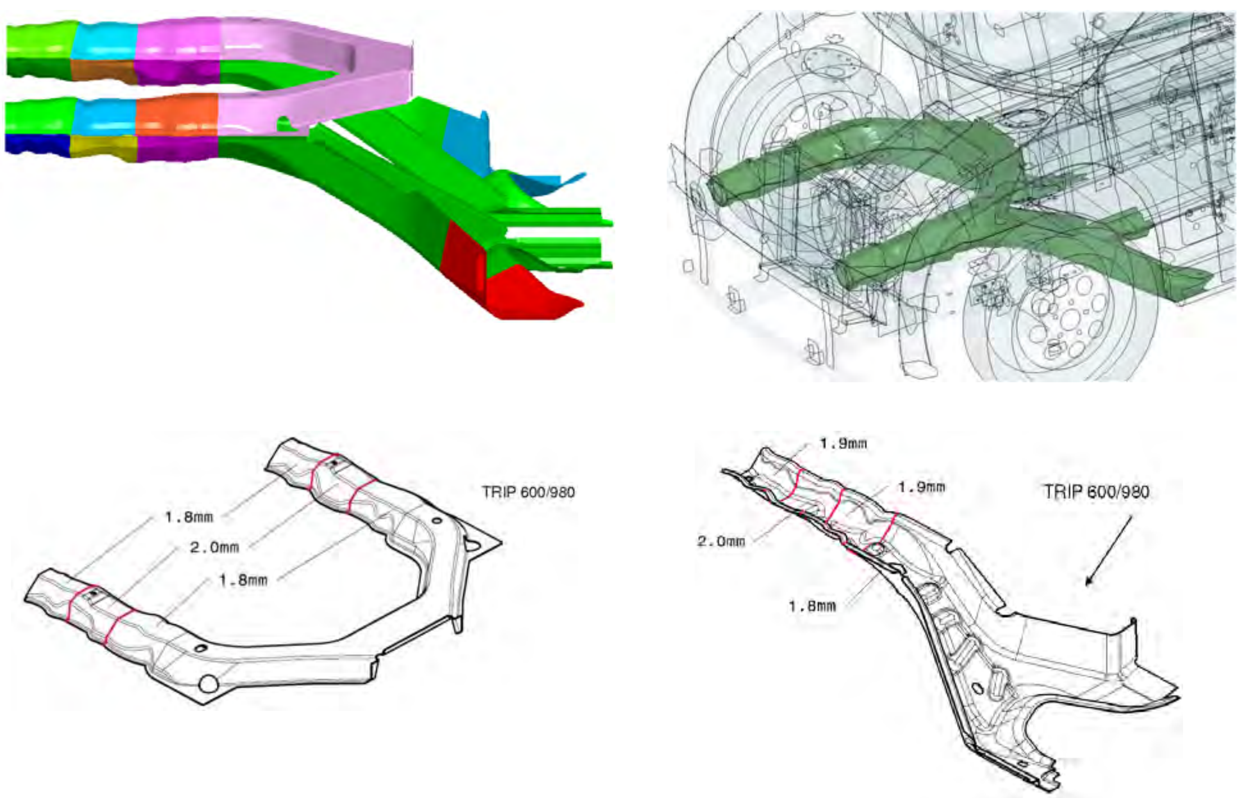


Figure 1-4: FSV Mass Evolution

2.0 Integrated 3B Incremental Forming and Crash Optimization Process

2.1 Objectives

The baseline Front Rail sub-system, Figure 2-1, is a new design for automotive front crash structures. Traditional design would carry the loads primarily through the rocker and roof rail structures, but the optimization indicated the need for an additional direct path, such as through the vehicle tunnel, dispersing the load away from the passenger compartment through multiple load paths. The structure is made up of two parts (Upper and Lower Rail) using laser welded blanks of varying gauges of TRIP 600/980 material. The mass of the complete sub-system is 17.6 kg.



Front Rail Upper – Blank Layout **Front Rail Lower – Blank Layout**

Figure 2-1: FSV Baseline Front Rail Stamped LWB Solution

Incremental forming simulations of this complex part, however, indicated a number of cracking and wrinkling areas in both the upper and lower rails that were not addressed though conventional approaches of engineering judgment forming analysis .

The FSV engineering team, therefore, set two objectives:

- Develop a optimization process that will find solutions to resolve the formability issues through tool design and blank configuration.

- Resolve formability issues of FSV Upper and Lower Front Longitudinal Rail through this above process while maintaining NCAP and IIHS front Crash (40% ODB Impact) performance.

This optimization process would use optimization like a search engine, searching within the design space parameters simultaneously finding the right combination of variables that achieve best solution in terms of mass and performance.

2.2 Steel Material Properties

The same portfolio of materials used throughout FSV's engineering development was used in the forming simulation work conducted through the FSV MDO Process. See Appendix 2 to review the portfolio of steels available in this project.

2.3 Project Methodology

Figure 2-2 provides the steps taken to complete the optimization, which are described following in Sections 2.3.1 through 2.3.4.

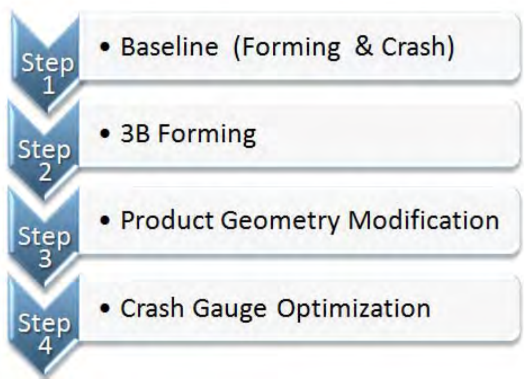


Figure 2-2: Projects Steps

2.3.1 Step 1 - Establishing Baseline

Since the FSV MDO Process is an automated one, the FSV engineering team allowed the software to continue to run optimization iterations after the FSV program's final reporting deadlines. Consequently, slightly more mass efficiency was gained beyond what was reported. Before the forming simulations began, it was decided that this post-report Task 5 design concept for the FSV BEV variant would be incorporated and used in the 3B Forming and Optimization. It was this design that was used to establish the baseline front rail performance and forming results. Following are the targets set for forming results:

- **No predicted material folding.** Material folding is not acceptable, since it can act as initiators during high stress concentration under severe static loads and undesired buckling modes under crash/impact loads.

- **No predicted cracks.**

Figure 2-3 indicates the zone between wrinkling and cracking within which designs would be considered feasible.

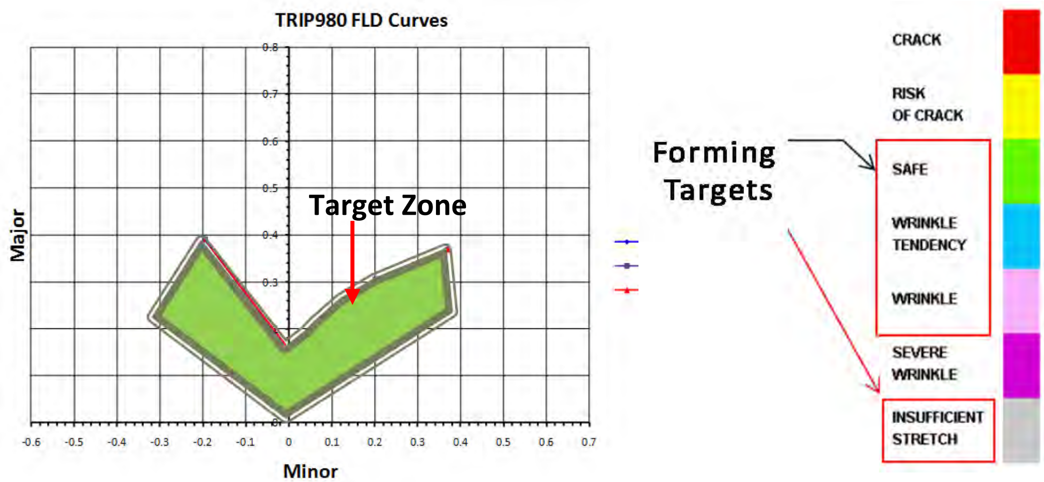


Figure 2-3: Feasible designs in zone between wrinkling & cracking

2.3.2 Step 2 - 3B Forming and Optimization

FSV project design methodology was established based on optimization technology, not only as a tool to be used for weight reduction, but also as a tool that can find the optimum design solution, whether this addressed the first topology of the vehicle packaging, load path, shape/geometry, or grade and gauge of vehicle components. For this analysis, enablers were added to include optimization of the forming process.

This optimization is used as a search engine to find the best solution in selection and use of specified forming enablers, such as binder pressure, draw beads and blank size and shape, and product enablers, such as part geometry and material gauge and grade. The consideration of ***B***inder pressure, ***B***ead and ***B***lank, provides the "**3B**" portion of the Integrated 3B Incremental Forming and Crash Optimization Process name. Table 2-1 indicates the rating of these enablers in terms of desirability for forming, establishing a hierarchy for the process methodology. Table2-1 also provides the list of lubricants considered.

Table 2-1: 3B Methodology, Desirability of Forming Enablers

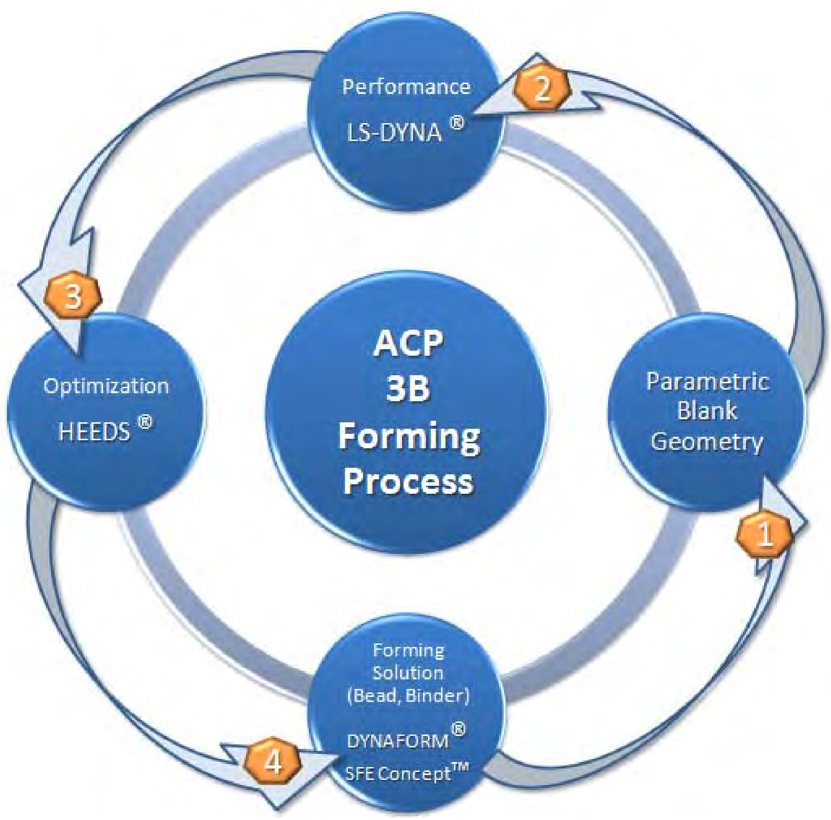
Desirability	Design Variable	Comments
High	Lubricant	Discrete Selection Of Friction Coefficient*
	Binder Pressure	
	Draw Beads	
	Size & Shape of Blank	
Med	Product – Geometry	
Low	Product – Gauge	
	Product - Grade	
*Selection from a discrete list of lubricants: ▪ Mill Oil: μ = 0.125 ▪ Drawing Lube or Pre-Phosphate with Mil Oil: μ = 0.100 ▪ Dry Film Lube: μ = 0.065		

The Integrated 3B Incremental Forming and Crash Optimization is an automated, multi-disciplinary process which uses LS-DYNA, DYNAFORM, HEEDS and SFE-Concept in an iterative operation (Figure 2-4).

HEEDS is an optimization program that evaluates and learns from the forming performance predicted by LS-DYNA. Based on this learning, HEEDS then establishes a new set input parameters that fed to DYNAFORM and SFE where the next input deck is created for LS-DYNA. Through many iterations of this process HEEDS improves its understanding of the problem and the influence of the parameters on the desired objectives.

There are alternative comparable software packages which can be integrated into the optimization process. This particular combination represents the programs utilized by the primary contractor ETA in their SAE award winning Advanced Concept to Production (ACP) Process.

Literally thousands of iterations can be completed, each reviewing the specified enablers (bead, binder, blank) and examining the resultant solution in terms of performance with each iteration. This 3B Incremental Forming and Crash Optimization, combined with the FSV MDO Process described in the FSV program, is envisioned to take design optimization all the way to the manufacturing of components, including identification of springback and other similar manufacturing issues.



. *Figure2-4: ACP - Integrated 3B Incremental Forming and Optimization Process*

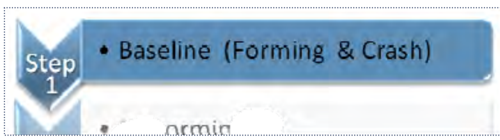
2.3.3 Step 3 – Product Geometry Modification

Once the draw beads, binder pressure and blank size are determined by the optimization, further improvements are sought through modification of the product geometry. Boundaries are set to identify the limits to which the optimization process could change the geometry in order to solve a formability issue. Though the capability exists to automate this process, for this project the geometry modification was completed by engineering judgment.

2.3.4 Step 4 – Crash Gauge Optimization

Finally, crash simulation was conducted on the new design, including the US NCAP Full Frontal and the Insurance Institute for Highway Safety's (IIHS) 40% Offset Deformable Barrier (ODB), to optimize material gauge and bring performance to acceptable levels.

2.4 Project Scope



2.4.1 TRIP 600/980 3B Forming and Optimization Process

2.4.1.1 Step 1 – Baseline

The final T5 design (described in Section 2.3.1) presented significant forming issues as shown in Figures 2-5 and 2-6. Figures 2-7 and 2-8 provide the baseline crash performances for the US NCAP and IIHS ODB.

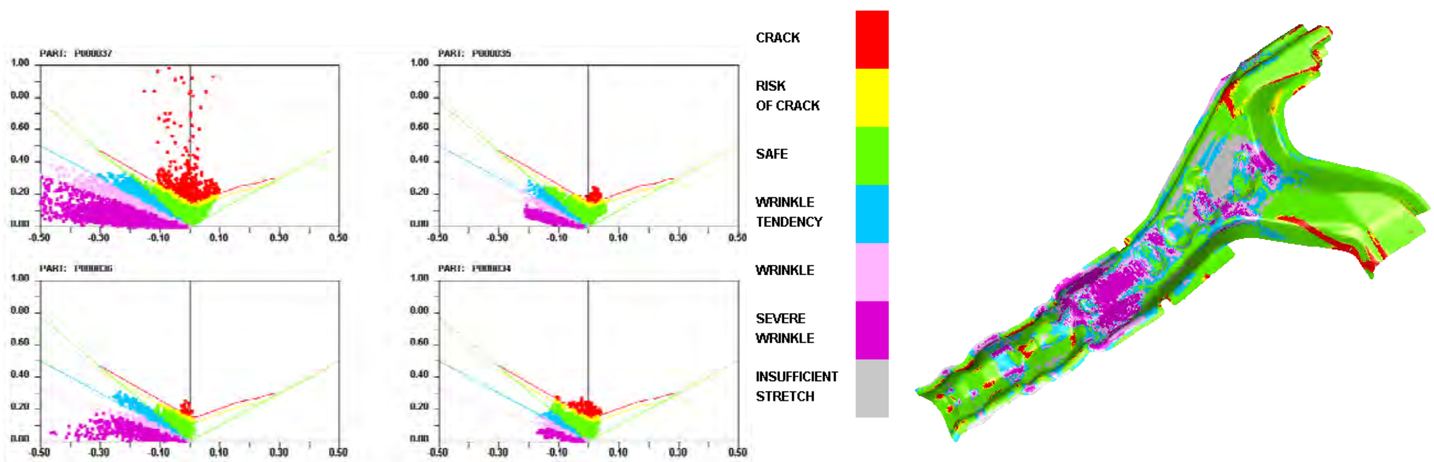


Figure 2-5: Baseline FSV T5 Design Lower Rail Forming Results

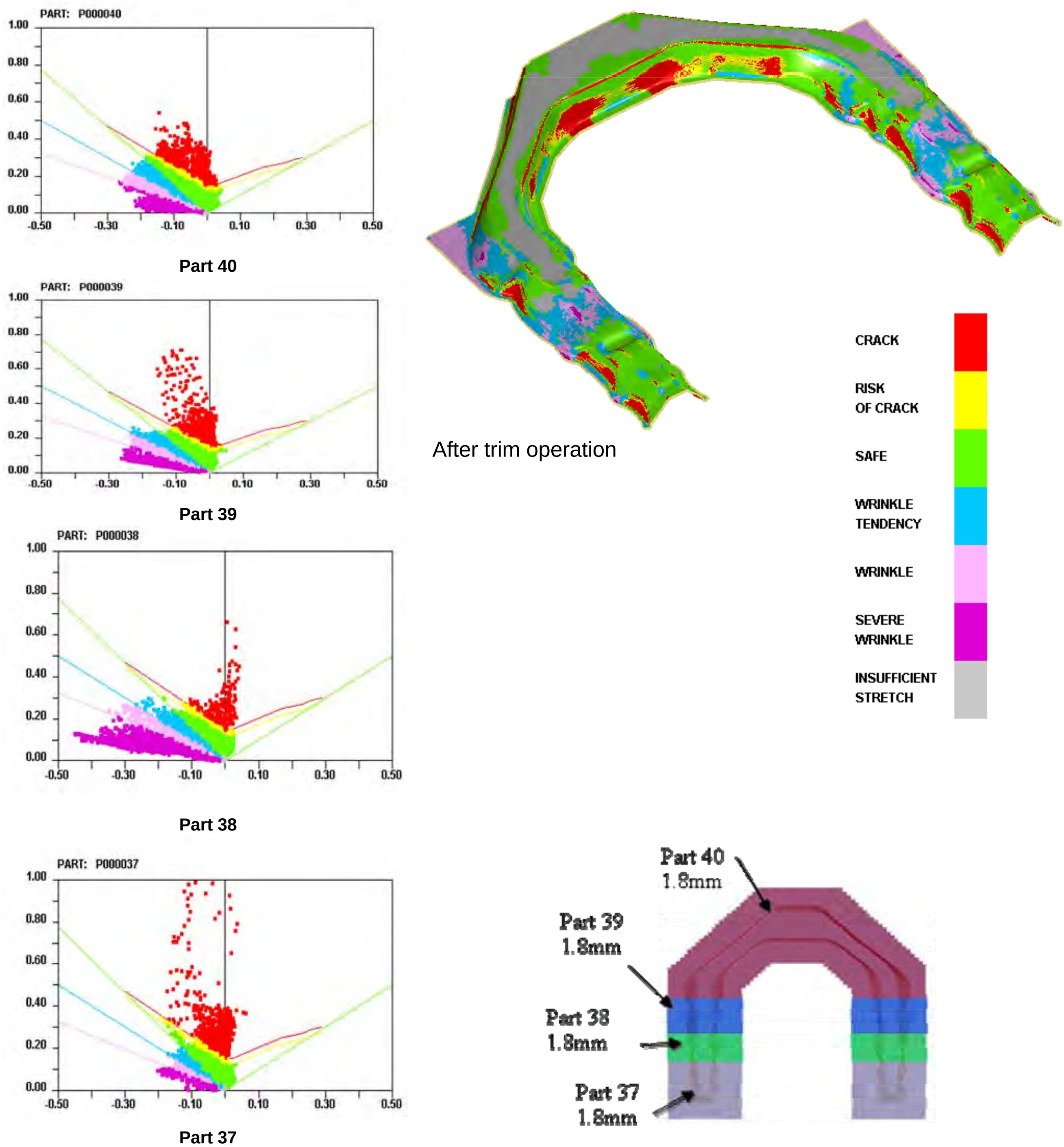
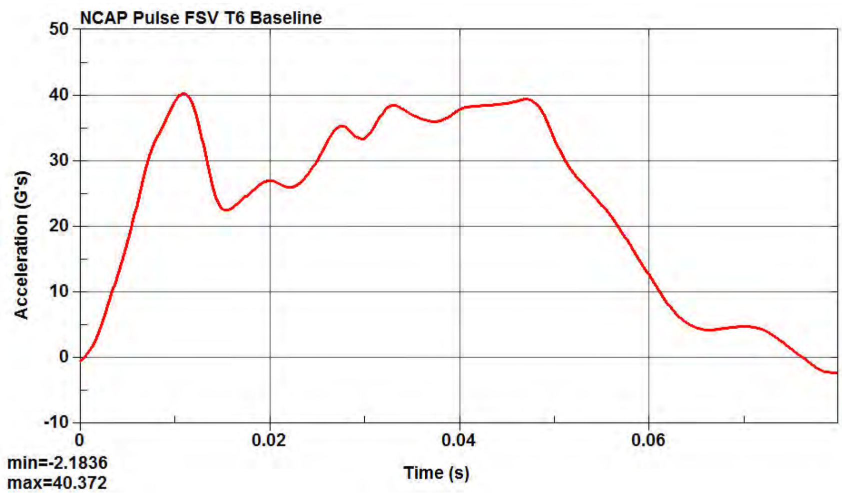


Figure2-6: Baseline FSV T5 Design Upper Rail Forming Results



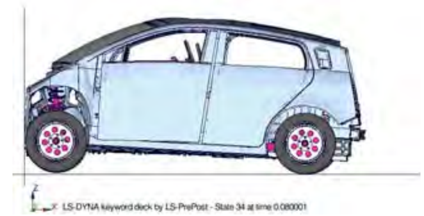


Figure 2-7 Baseline FSV T5 Design Front Rail Crash – US NCAP

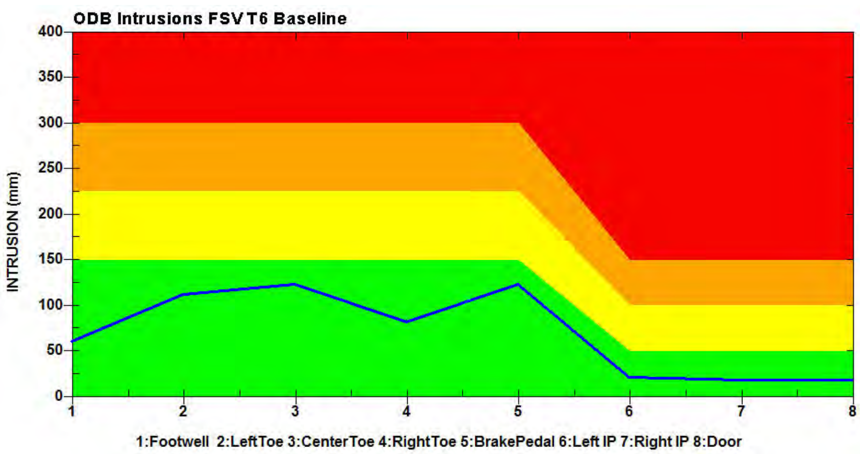
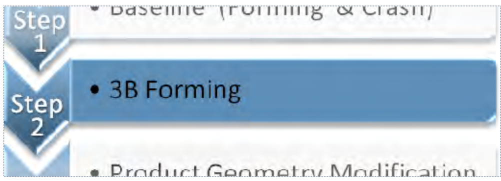


Figure2-8: Baseline FSV T5 Design Front Rail Crash – IIHS ODB

2.4.1.2 Step 2 – 3B's Forming Optimization (Bead Force, Binder Pressure and Blank Size)



Line beads, non-geometric representations of draw bead geometry and forces, are added to control material flow. Each line bead is unique (see varying colors in Figure 2-9), allowing the FSV MDO Process to locally tune the bead to constrain material flow. Bead force is allowed to range from 100 percent, which represents a locked bead, to 0 percent, which is no bead. A total of 57 line beads were used for the Upper Rail and 35 in the Lower Rail. With these parameters in place, the optimization analysis is conducted to tune the parameters to improve part formability.

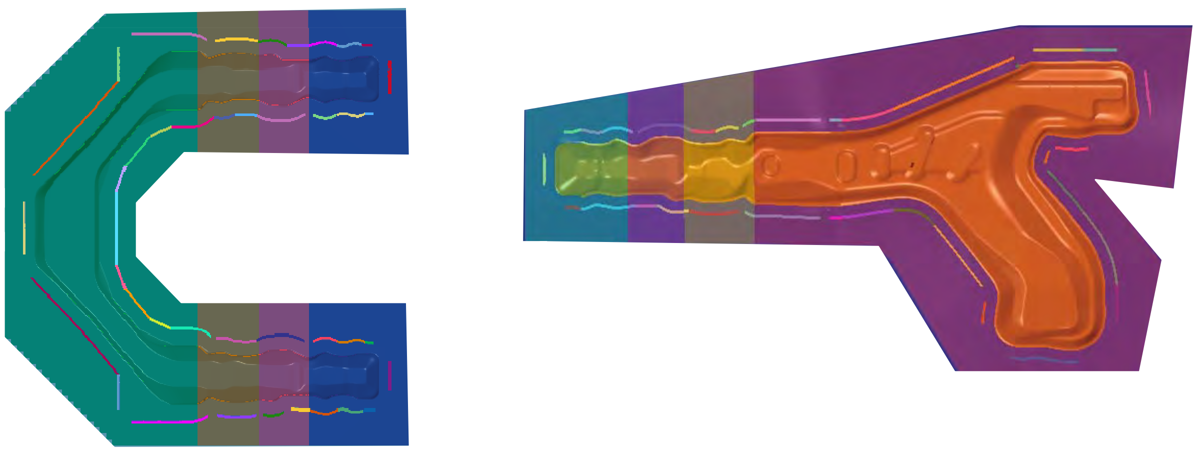


Figure 2-9: Line bead configuration for Upper Rail (left) and Lower Rail

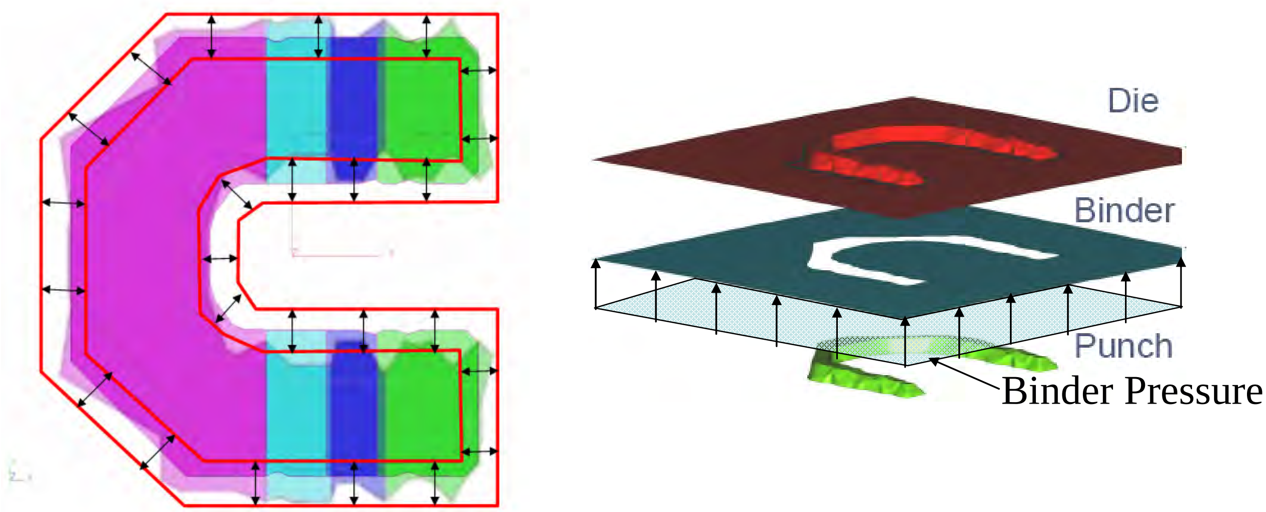


Figure 2-10: Blank geometry modification boundaries (left). Blank, Bead and Binder Pressure (Optimum Binder Force = 660 N/mm) are analyzed simultaneously (right)

Simultaneously, the software analyzes binder pressure, as well as the geometry of the blank itself, to arrive at the optimum combination of bead force, binder pressure and configured blank geometry (Figure 2-10) for successful part forming. The FSV MDO Process evaluates different combinations and values of Binder pressure (normal force changes within 60 to 6000 N/mm), Bead values and, Blank geometry and learns from each iteration run, getting "smarter" in order to approach its objectives. The movie in Figure 2-11 shows the learning process of the optimization program as the number of splits and wrinkles are reduced. Shown on the graph on the horizontal axis is the number of model elements with predicted splits, and on the vertical axis, the number of elements with predicted severe wrinkles. The objective is to move into the lower left corner of the graph where the part is safe with no splits or severe wrinkles.

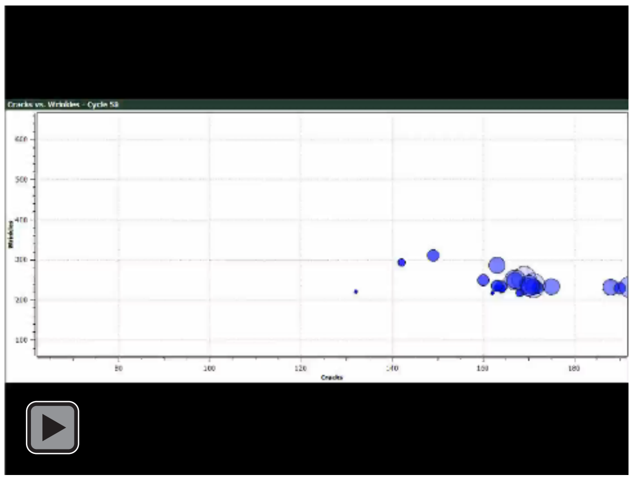
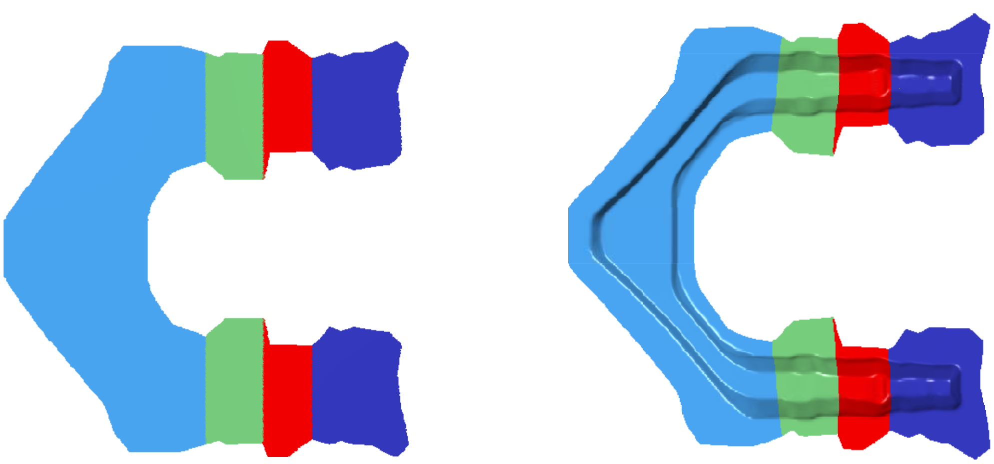


Figure 2-11: [Movie]ADP Process improving wrinkling and cracking with each iteration

2.4.1.2.1 Upper Rail Results

Of the more than 2000 design iterations the best solution was obtained at Design No. 1959. Figures 2-12 through 2-13 provide Design No. 1959's blank parameterization and bead force configuration.
While the design optimization did not solve all of the forming issues, as shown in Figure 2-14 and Table 2-2, it is dramatically improved.



A. B.

Figure 2-12: Design 1959 Upper Rail - Configured Blank Geometry Optimization

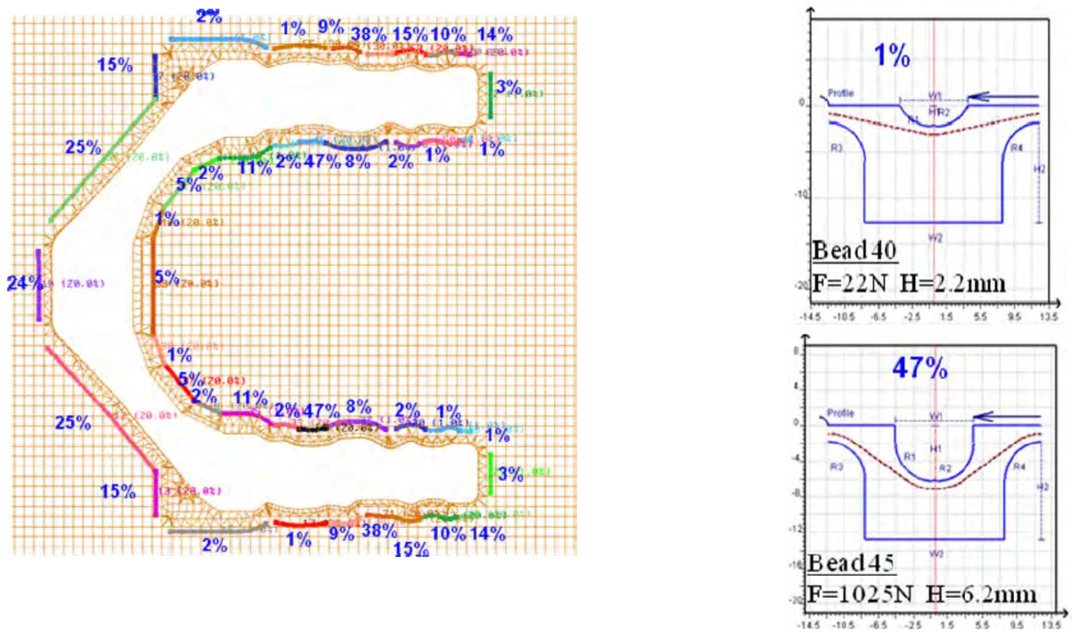


Figure 2-13: Design 1959 Upper Rail - Bead Force Results

To take advantage of the optimization process, many beads were used to individually control the material flow. In designing the final die, the overall bead distribution can be consolidated and simplified to reduce the press loads. For example, consecutive bead forces that have a similar range can be replaced by one bead, or if bead force is low (1%, 5%, etc.), they can be removed. The optimization provides the best material flow to form the part. It would be at the discretion and experience of the die maker to interpret those results to a final die.

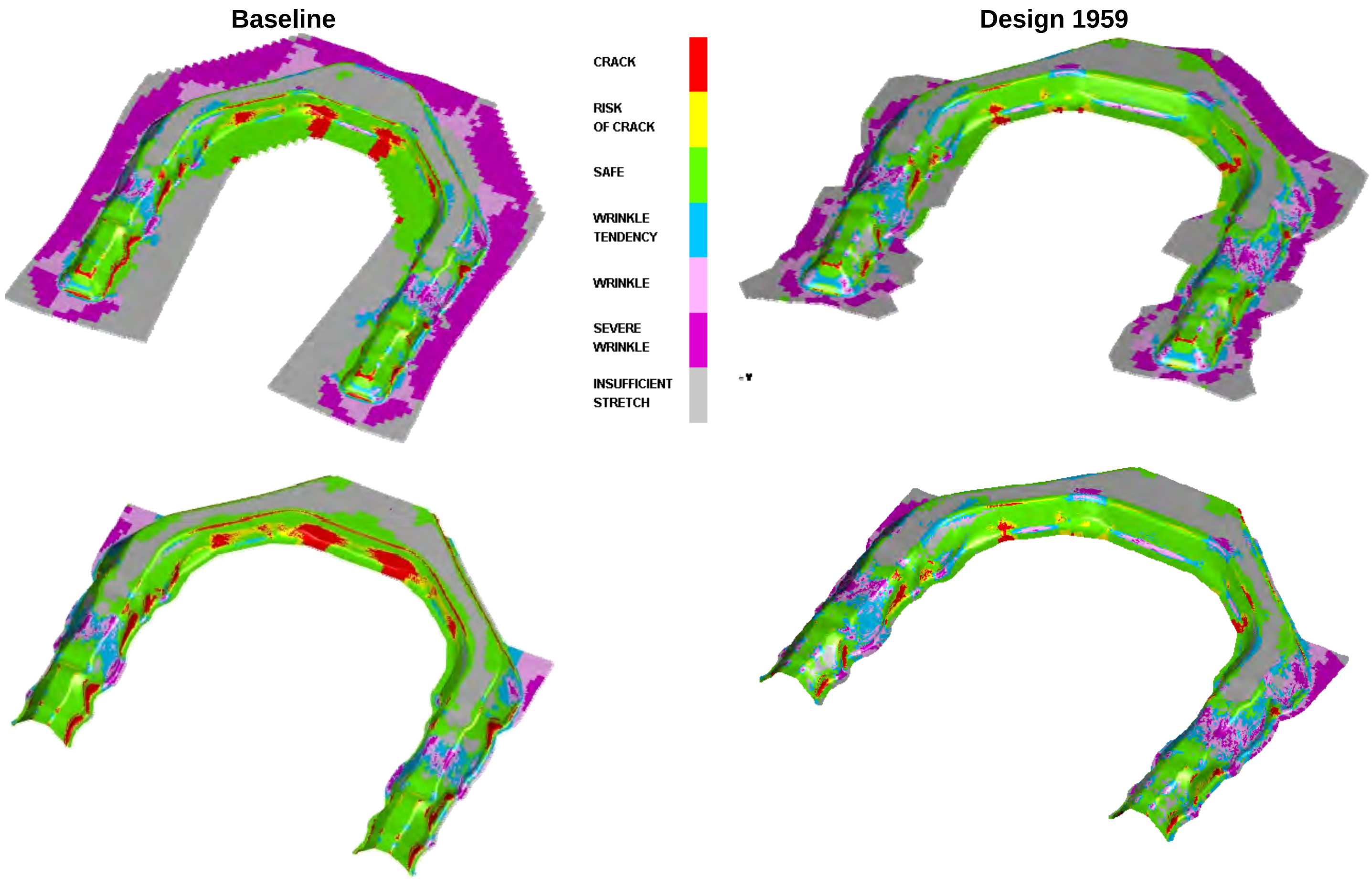


Figure 2-14: Design 1959 Upper Rail – 3B Forming Process Results

Table 2-2: Upper Rail 3B Forming Results

Upper Rail Results	No. of Crack Points	No. of Wrinkle Points
Baseline	**3017**	**3253**
Design 1959	**88**	**117**

2.4.1.2.2 Lower Rail Results

Similar improvements can be seen in the Lower Rail optimization results in Design No. 1664 in Figure 2-15 and Table 2-3:

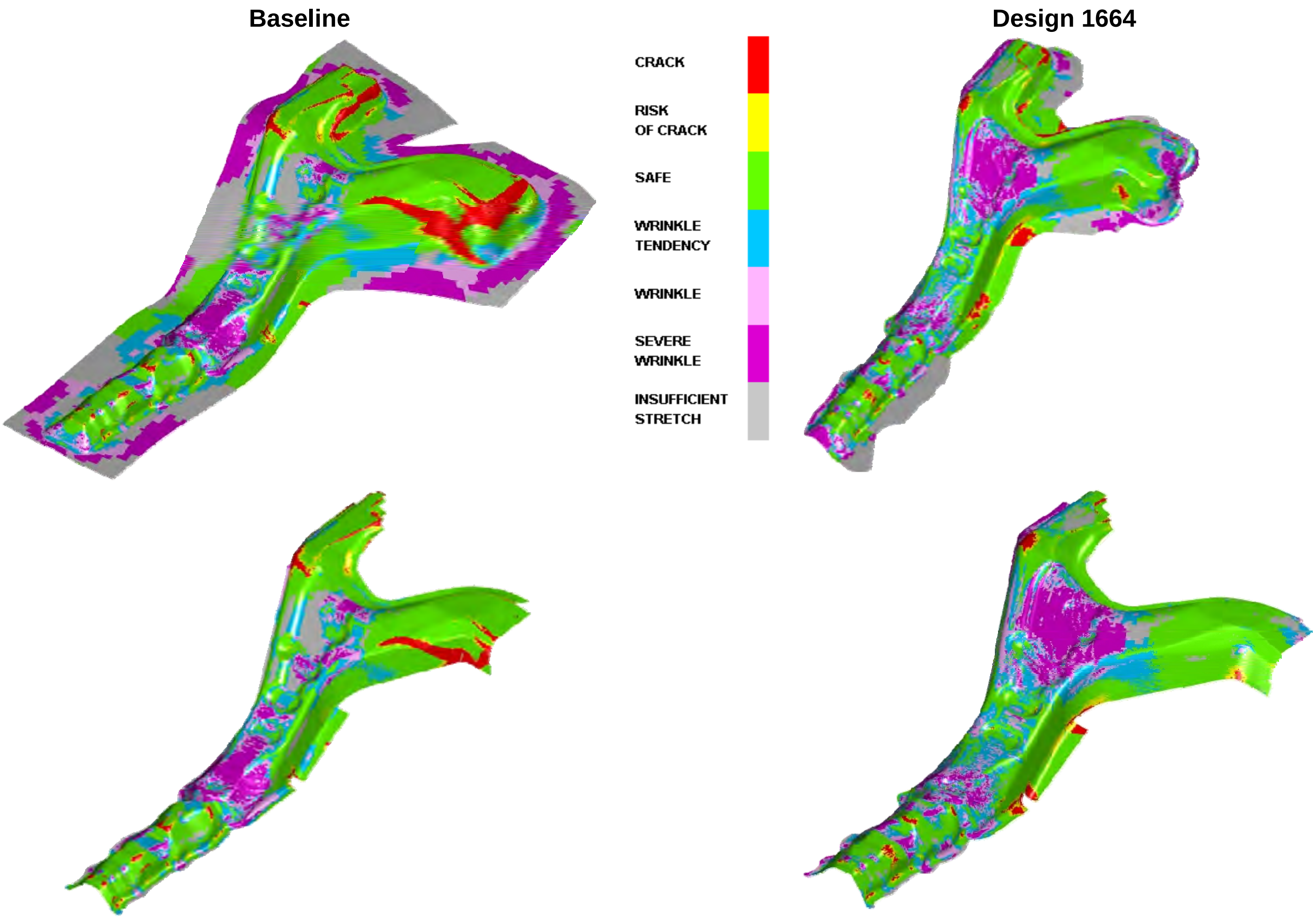
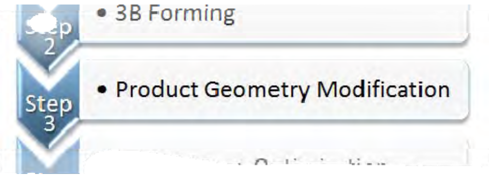


Figure2-15: Design 1664 Lower Rail Forming – 3B Forming Process Results

Table 2-3: Lower Rail 3B Forming Results

Upper Rail Results	No. of Crack Points	No. of Wrinkle Points
Baseline	**1413**	**1568**
Design 1664	**90**	**176**



2.4.1.3 Step 3 – Product Geometry Modification

2.4.1.3.1 Upper Rail

Since all forming problems were not resolved, product changes now need to be considered. However, because of the improvements that have been achieved in the 3B Forming Optimization, the number of locations that need to be considered for design concessions have been minimized. Engineering judgment was used to make these modifications. In the Upper Rail, the radii and draw angles were softened at locations still predicted to split, shown in Figure 2-16.

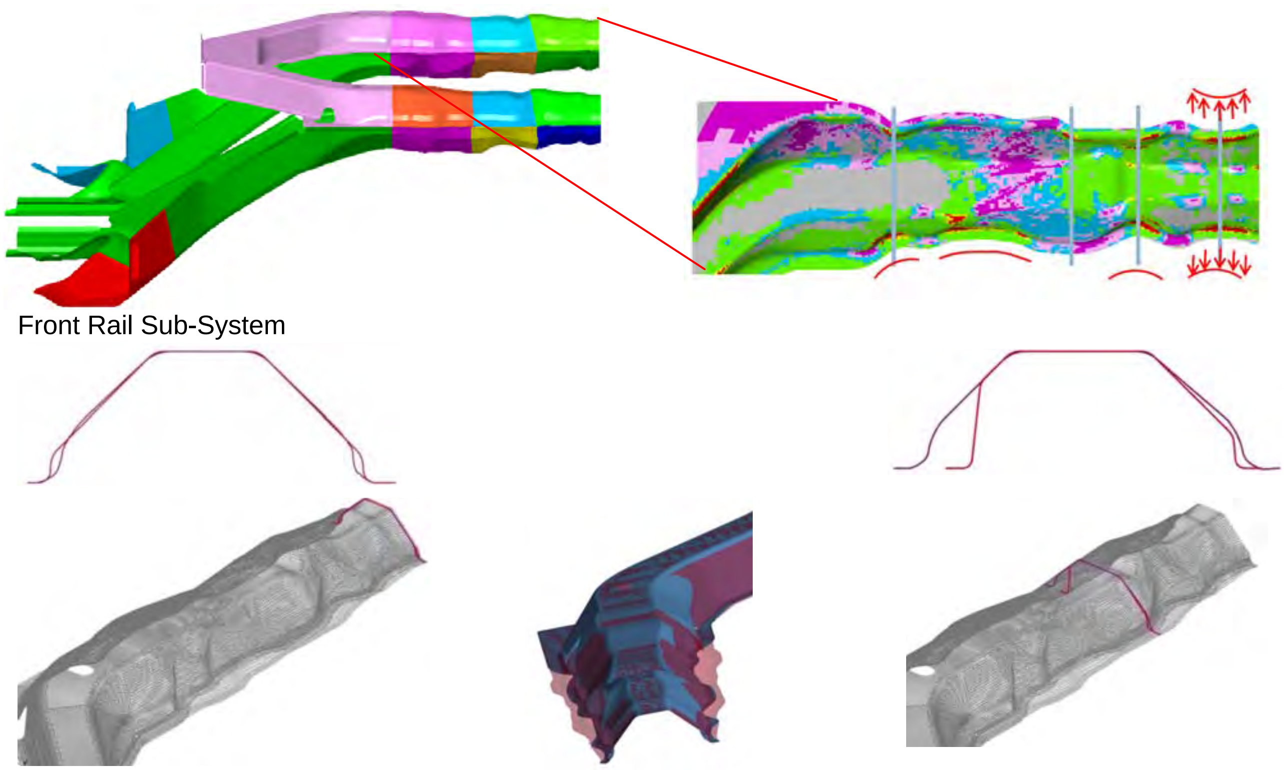


Figure 2-16: Upper Rail Product Modifications

3B Forming simulations were conducted on the modified part and the results showed safe formability with manageable wrinkles (see Figure 2-17).

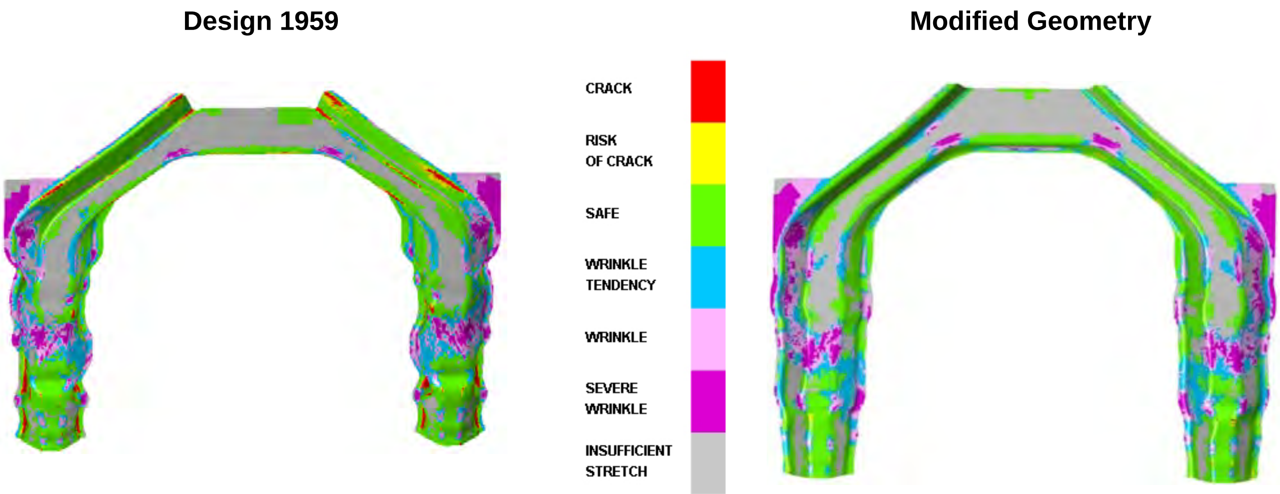


Figure 2-17: Upper Rail – 3B Forming Results on Modified Geometry

2.4.1.3.2 Lower Rail

Similar modifications were made to the Lower Rail as shown in Figure 2-18. Flanges were smoothed and the fillet radii at the flanges were increased. The lower rail had a large kick in the back of the part that caused major splits. It was determined that dividing the Lower Rail into two pieces, separating the Tip and Fork, would allow tipping the part back, reducing cracks. The new two-piece part can be seen in the formability results shown in Figure 2-19.

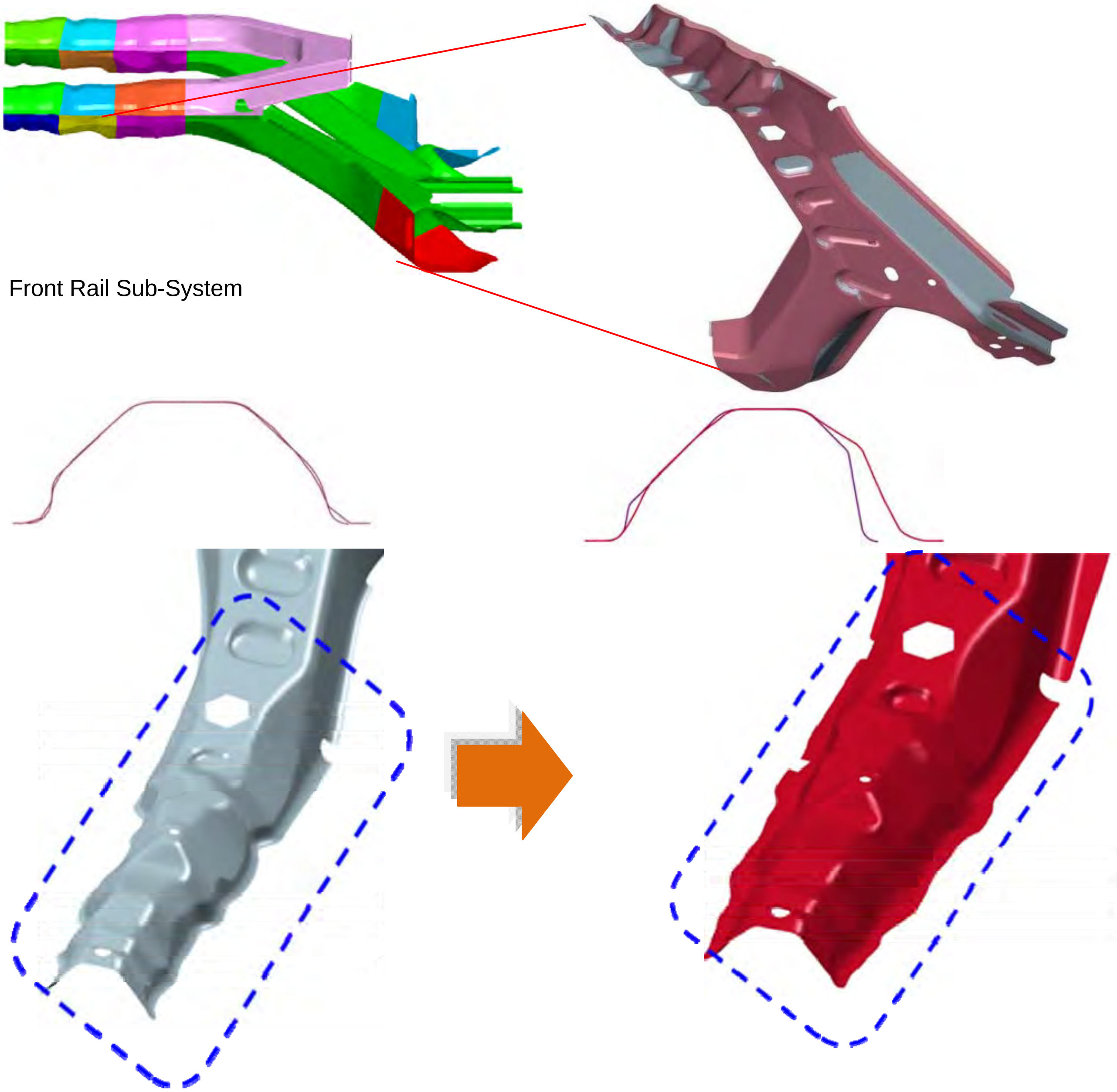


Figure 2-18: Lower Rail Product Modifications

3B Forming simulations were conducted on the modified part and the results show safe formability (see Figure 2-19).

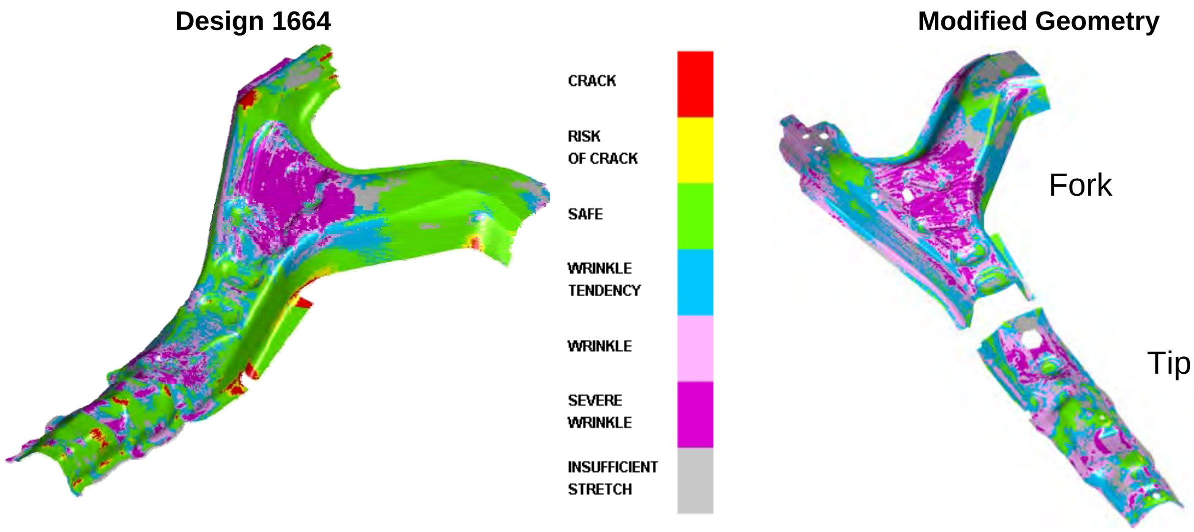
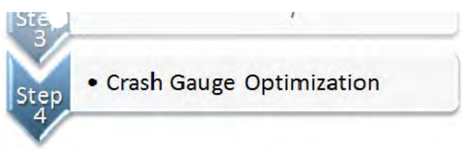


Figure 2-19: Lower Rail – 3B Forming Results on Modified Geometry



2.4.1.4 Step 4 – Crash Gauge Optimization

Now that the product concessions have been made regarding the geometric changes to the front rail, the impact on part crash performance must be re-evaluated. The geometric changes had minimal influence on the US NCAP crash performance (Figure 2-20), but the IIHS ODB performance was negatively impacted, lowering performance from ‘Good’ (green) to ‘Acceptable’ (yellow). (See Figure 2-21).

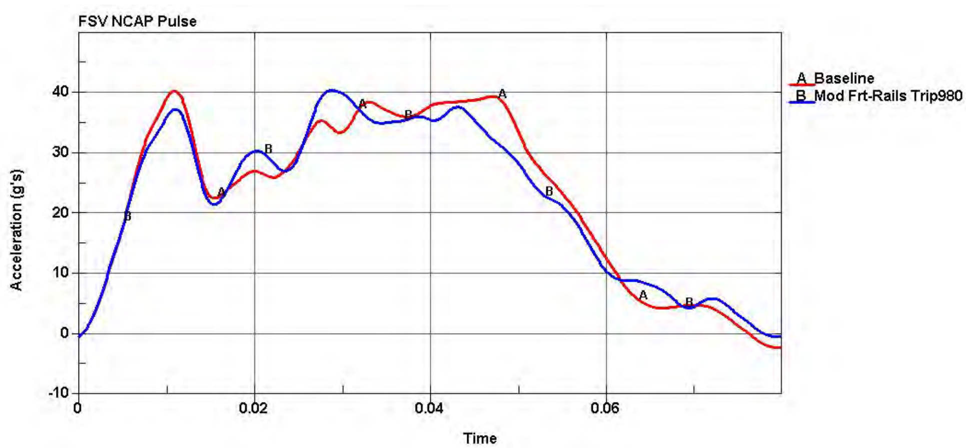


Figure 2-20: Modified Geometry US NCAP Performance Compared to Baseline

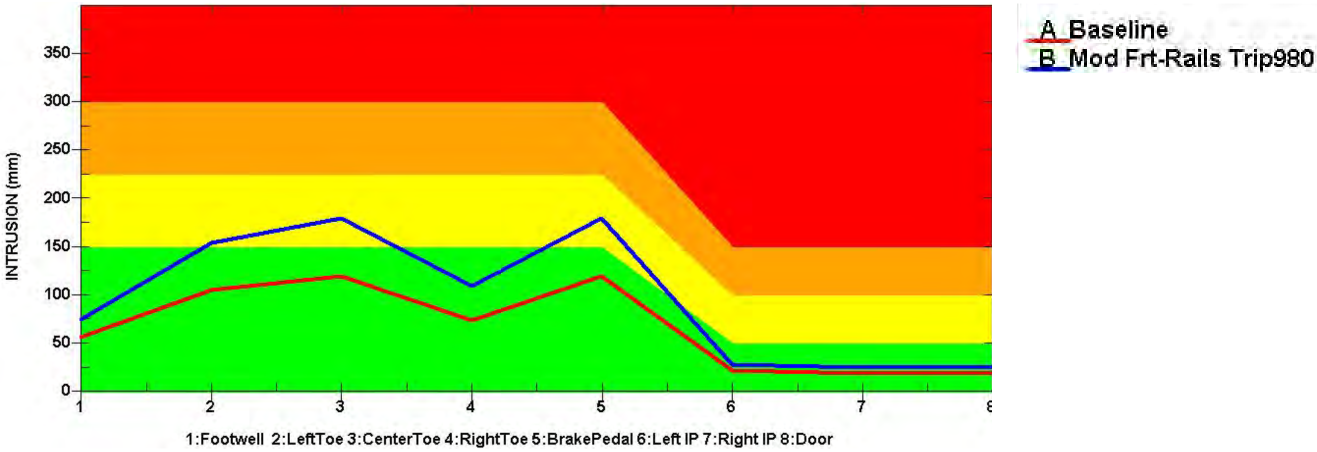


Figure 2-21: Modified Geometry IIHS ODB Performance Compared to Baseline

To address this, the optimization process was allowed to modify the gauge of the TRIP 600/980 material with the objective of returning performance in the IIHS ODB to a 'Good' rating. A total of 90 design evaluations were conducted and the best design selected, Design No. 87, based on performance and mass. Figure 2-22 compares the baseline material gauges to the gauges specified in Design 87. It is notable that the optimization discovered the right mix of gauges to meet the crash criteria yet at a slightly lower mass than the already efficient FSV T5 Baseline structure. However, additional mass will be required to create the flanges necessary to assemble the now two-piece lower rail.

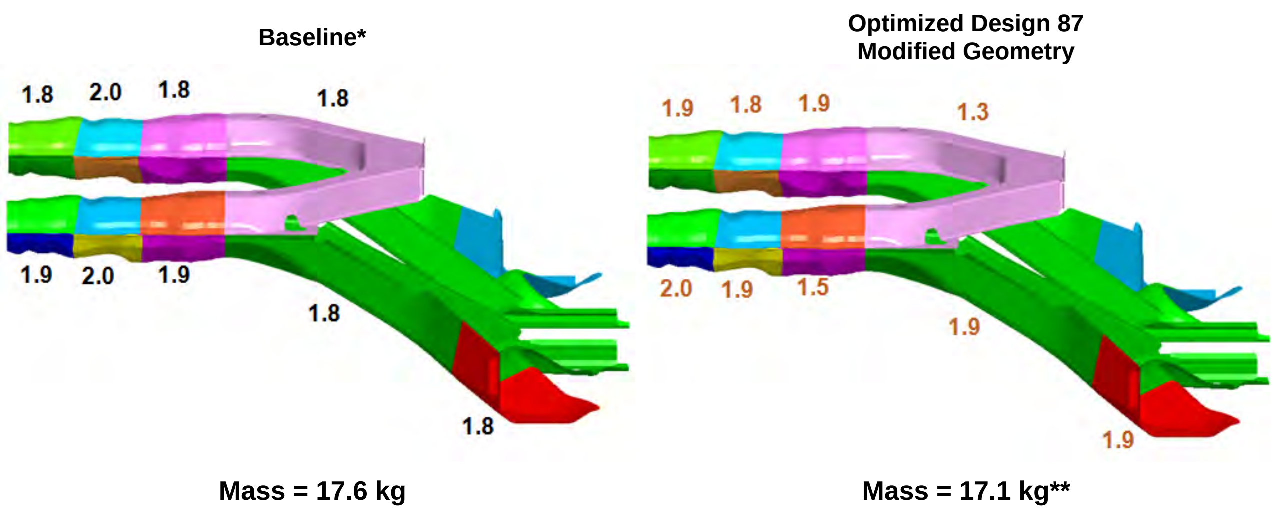


Figure 2-22: Modified Material Gauges, Design 87 Compared to Baseline

* The FSV T5 Design BOM reported the mass of these parts at 17.9 kg, which includes manufacturing-driven design concessions over the intended geometry defined in T4 and because it was never fully gauge optimized in the 3G process. The weight of the base line shown in the T6 formability study is 17.6 (.3 kg less) because it represents the uncompromised geometry defined in T4. The optimized design 87 has some geometric design concessions relative to the baseline on the left and should logically weigh more but since it is fully gauge-optimized, it weighs less.

** not including weight for added flanges

Figures 2-23 and 2-24 show the return to 'Good' performance according to the IIHS ODB criteria and the maintenance of the US NCAP performance.

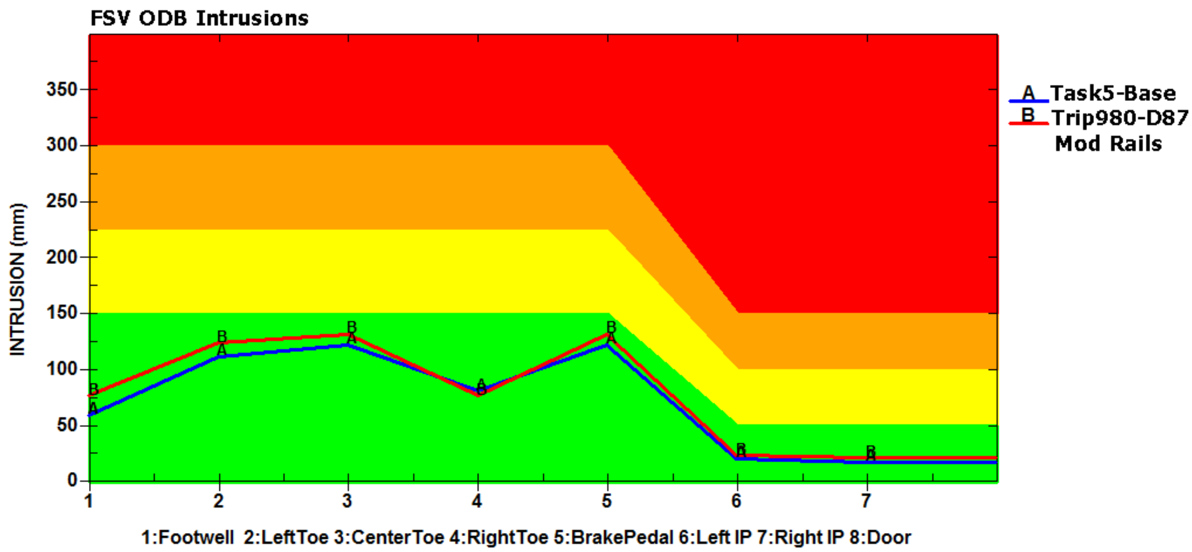


Figure 2-23: Results of Modified, Gauge Optimized Front Rails (red 'B' line) for IIHS ODB

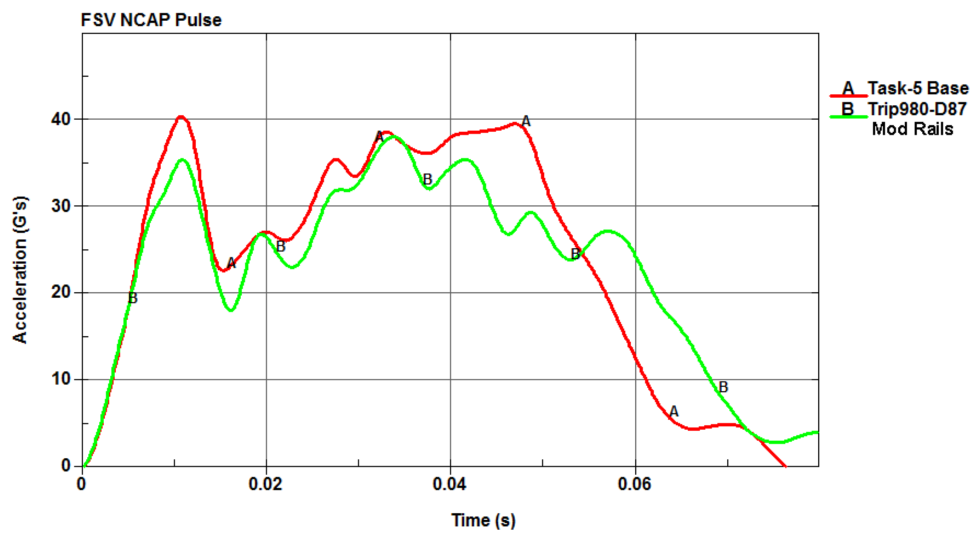


Figure 2-243: Results of Modified, Gauge Optimized Front Rails (green 'B' line) for US NCAP

2.4.1.5 Summary of Results for TRIP 600/980 Front Rail Sub-System

After completing the Integrated 3B Incremental Forming and Crash Optimization process, the Upper Rail is formable with no cracks and small and manageable wrinkles.

For the Lower Rail, cracking and severe wrinkling was alleviated by cutting the part in two pieces, the Tip and Fork. The Lower Rail Tip has fewer wrinkles than the Fork area. There is the potential of reducing these wrinkles by applying further optimization iterations and adding metal gainer (relief holes) to individual parts. Crash performance (NCAP, ODB) meet the targets after Crash Gauge Optimization.

However there were still enough severe wrinkling issues that the engineering team questioned the 100% formability of the Front Rail Sub-System using TRIP 600/980. Consequently, this project continued with the objective of evaluating the performance of another AHSS material for the Front Rail Sub-System, TRIP 450/800.

2.4.2 TRIP 450/800 3B Forming and Optimization Process

2.4.2.1 Baseline

TRIP 450/800 was suggested as an option for material substitution since it is very close in strength to TRIP 600/980, but has a very high N-value (0.26 compared to 0.15 of TRIP 600/980). It was assumed that it would provide the properties needed for a more formable Front Rail solution, and the 3B Optimization Process would take quick advantage of the higher N-value to reach safe parts.

The final FSV Task 5 design for the Front Rail Sub-System and the TRIP 600/980 optimization solutions for draw bead forces, binder pressure and blank size (3B) were carried over as the baseline for the TRIP 450/800 evaluation.

Baseline forming simulations were conducted to ensure that the TRIP 600/980 solutions applied to the TRIP 450/800 material. The TRIP 450/800 performed considerably better. The Upper Rail (Figure 2-25) was formable with the amount of wrinkles reduced compared to the TRIP 600/980 solution. The amount of severe wrinkles in the back of the Lower Rail (Fork area) was reduced.

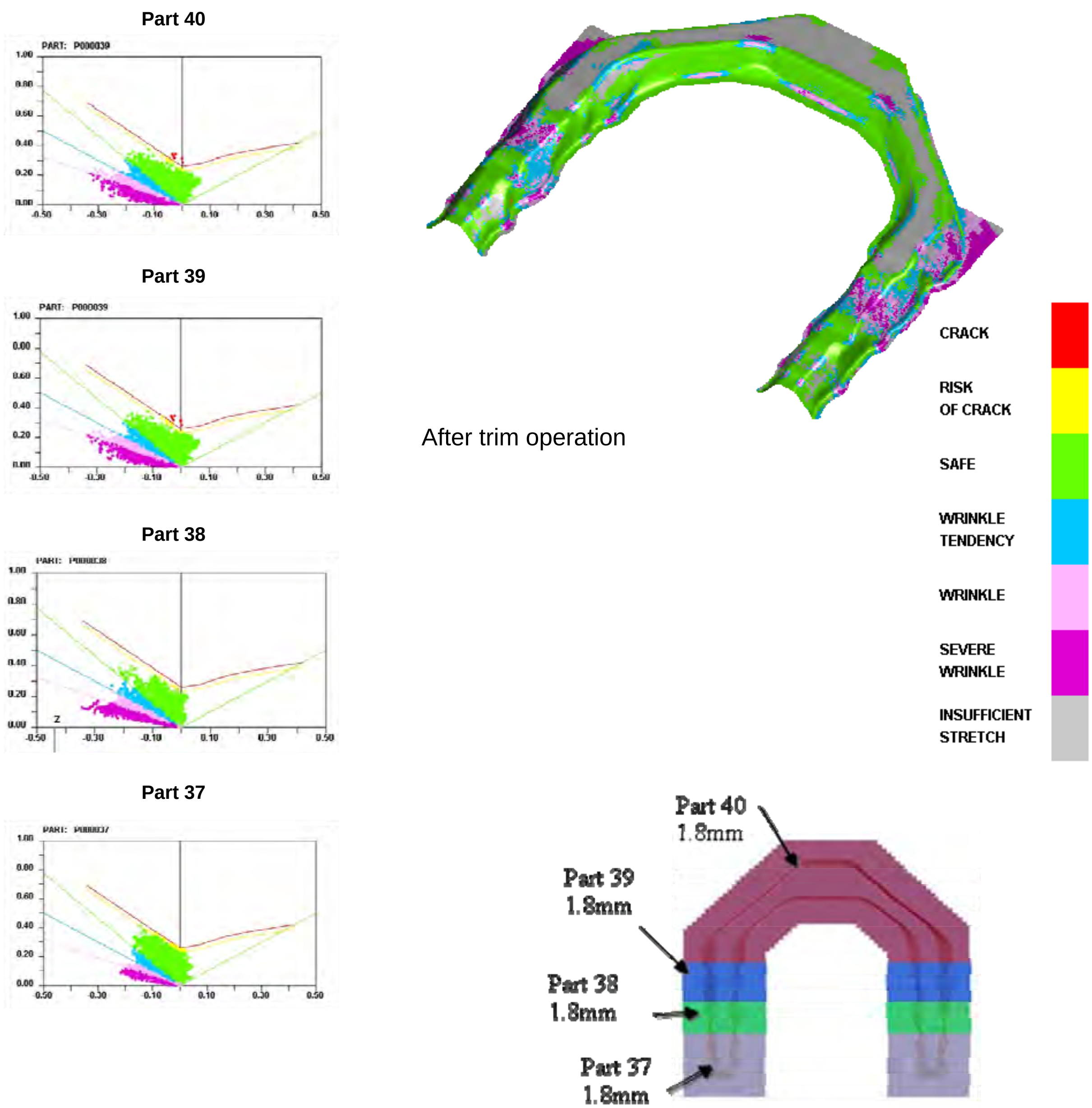
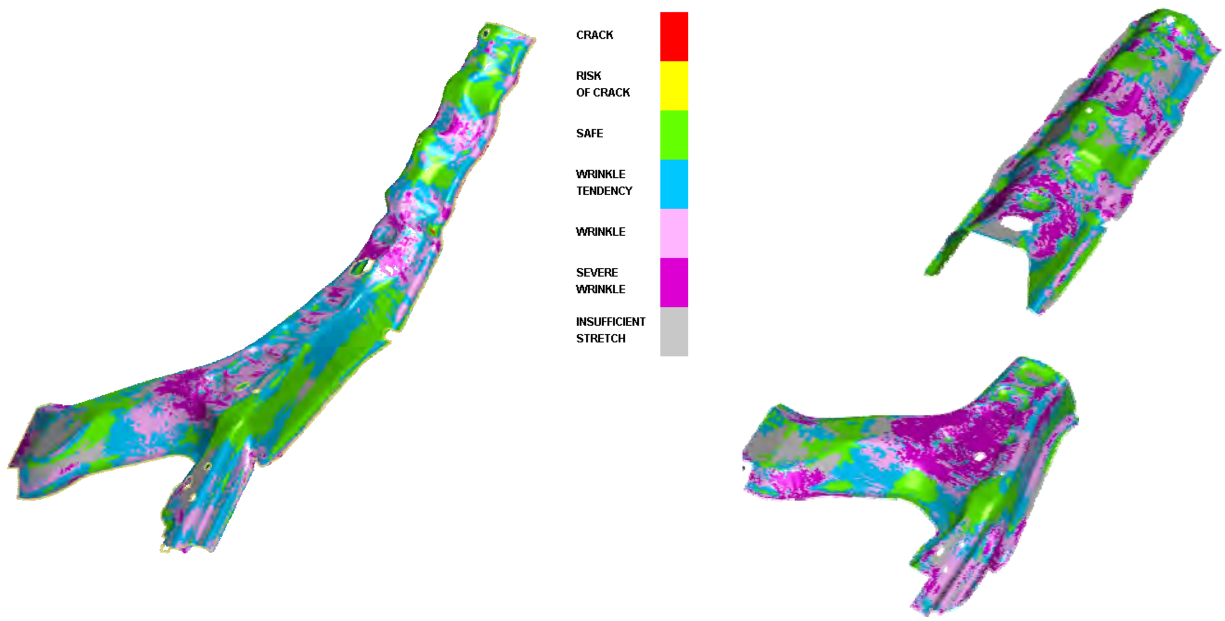


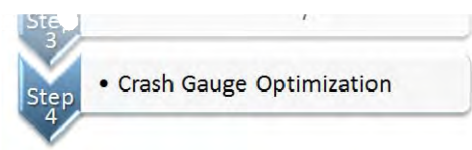
Figure 2-25: TRIP 450/800 Baseline Upper Rail Forming

Though the more formable TRIP 450/800 (Figure 2-26) lower rail could now be stamped as a single component, the two- piece Lower Rail was included in the Baseline evaluation as well to uncover all possible options.



Baseline Modified Geometry (two piece)

Figure 2-26: TRIP 450/800 Baseline and Modified Geometry (two-piece) Lower Rail Forming Results

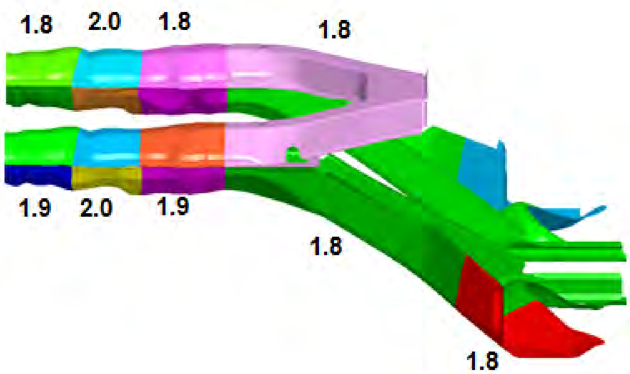


2.4.2.2 Step 4 Crash Gauge Optimization

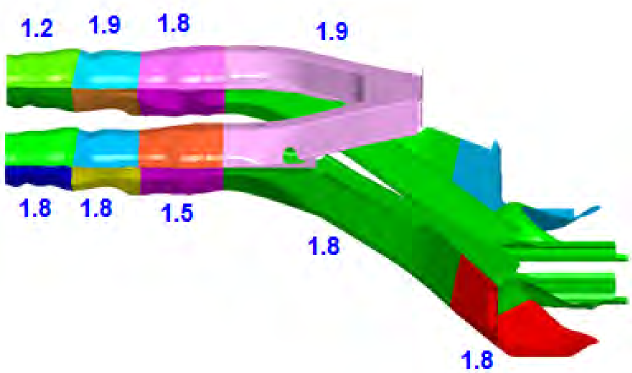
Since the TRIP 600/980 3B Forming simulation results were directly applied to the TRIP 450/800 design, Crash Gauge Optimization is the next step (Step 4 in the process methodology). Crash performance proved to be less than satisfactory on the Baseline one-piece design, falling short of the targets for the US NCAP Full Frontal simulation. The IIHS ODB results for the TRIP 450/800 Baseline fell within the 'Good' range. Therefore, gauge optimization opportunities are sought to improve the US NCAP performance. A total of 70 design iterations were conducted for the Baseline one-piece design and 88 design iterations for the Modified Geometry (two-piece) design.

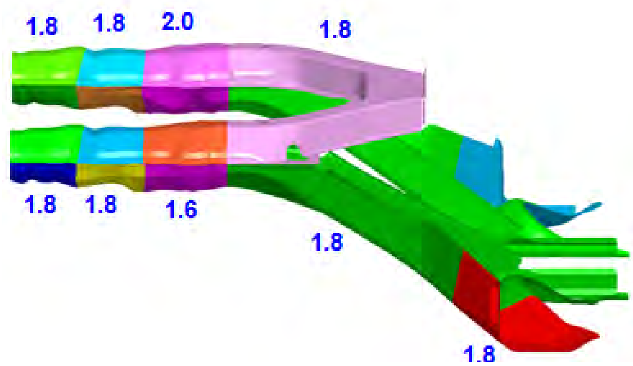
The best design for the Baseline (one-piece Lower Rail) was Design No. 63, which improved US NCAP Full Frontal results from FSVs T5 design's from 39.8g to 38g and mass by 0.5 kg, while maintaining 'Good' results for the IIHS ODB.

For the Modified Geometry (two-piece Lower Rail) design, the best results were achieved by Design No. 66, which improved US NCAP from 39.8g to 35g, while maintaining a 'Good' rating for the IIHS ODB and shaving 0.1 kg in mass. Figures 2-27 through 2-29 show results.



FSV T5 Front Rail Gauge Geometry

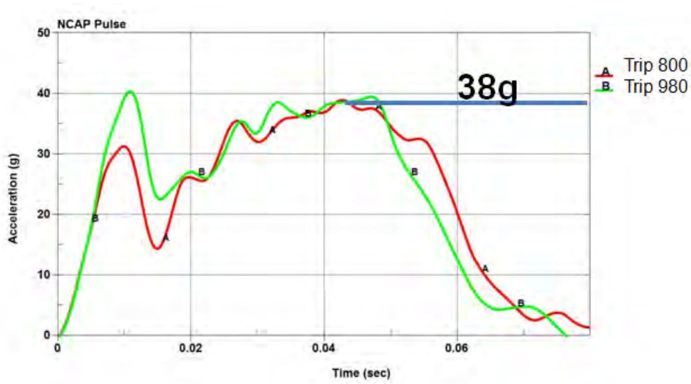


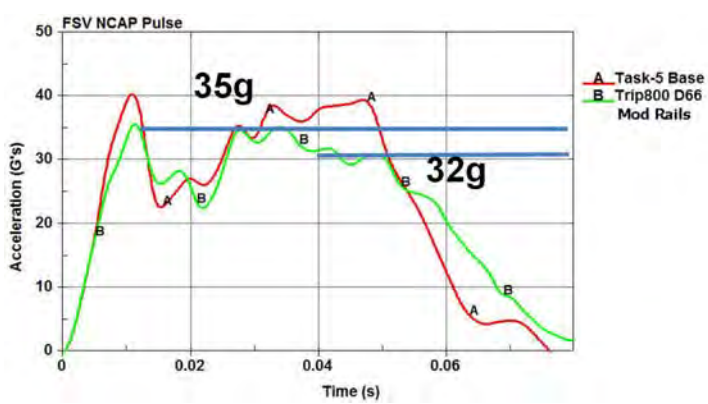


Design 63 Baseline (one-piece Lower Rail) Gauges

Design 66 Modified Geometry (two-piece Lower Rail) Gauges

Figure 2-27: TRIP 450/800 Crash Gauge Optimization Results

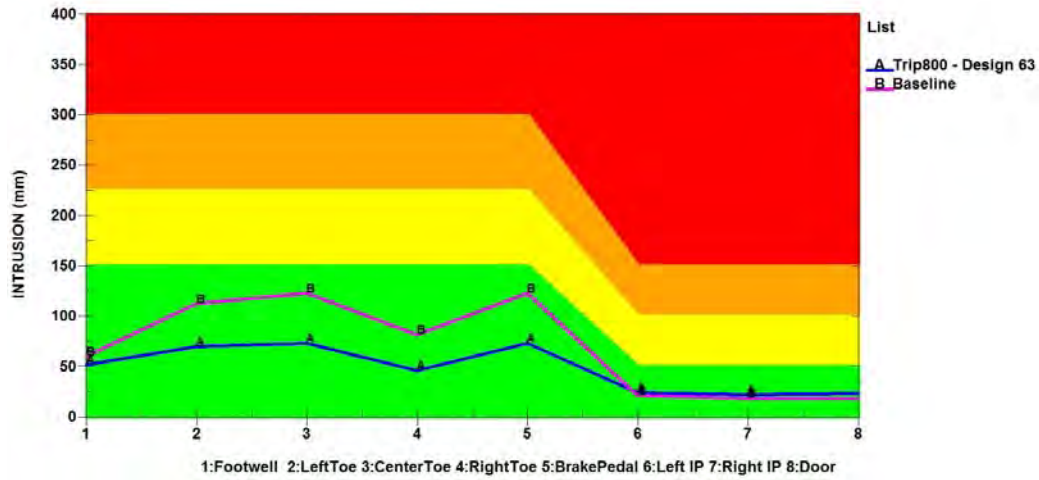




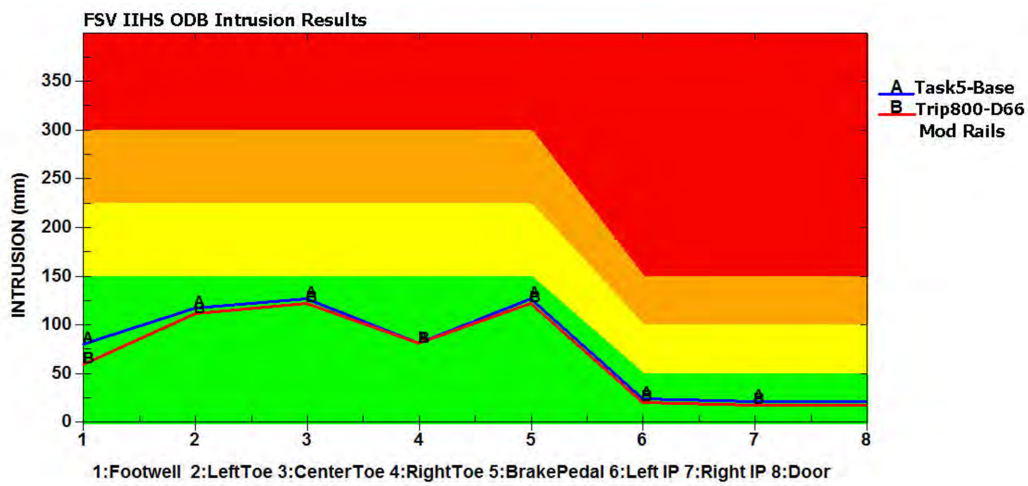
Design 63 Baseline (one-piece Lower Rail)

Design 66 Modified Geometry (two-piece Lower Rail)

Figure 2-28: TRIP 450/800 US NCAP Results



Design 63 Baseline (one-piece Lower Rail)



Design 66 Modified Geometry (two-piece Lower Rail)

Figure 2-29: TRIP 450/800 IIHS ODB Results

2.4.2.3 TRIP 450/800 Front Rail Sub-System Summary of Results

Applying TRIP 450/8000 the FSV Task 5 Upper Rail and including the 3B Forming Simulation results from the TRIP 600/980 trials in the design resulted in a safely formable part with no cracks and manageable wrinkles.

The Lower Rail is formable by two solutions:

- Baseline Geometry: No cracks, less wrinkles as compared to TRIP 600/980 forming results
- Modified geometry (two-piece lower rail solution): no cracks with severe wrinkles.

Crash performance for both US NCAP and IIHS ODB meet the targets with both design solutions (Baseline and Modified Geometry) after Crash Gauge Optimization.

TRIP 450/800 with Baseline Geometry (FSV T5 one-piece design) demonstrates the best formability and was selected as a final design solution.

2.4.3 Conclusions

Using a multi discipline optimization tool such as the Integrated 3B Incremental Forming and Crash Optimization to balance draw beads, binder pressure, lubricant and blank size can successfully address the formability of complex parts, including the non-intuitive solutions offered by the FutureSteelVehicle Front Rail Sub-System design. This project illustrates that this optimization process can be used as an effective search engine to find the best formable solution while maintaining crash performance through Crash Gauge Optimization. Its use provides rapid resolution of forming issues presented by the unique qualities of Advanced High-Strength Steels.

3.0 Program Final Task: Final Gauge Optimization following the Front Rail Sub-System Analysis

Following FSV's Integrated 3B Incremental Forming and Crash Optimization Process, it was necessary to bring the design back together for a final optimization of the material gauges. The final front rail structure resulting from the MDO process was re-integrated in the total body structure system. However, it is important to note that following the announcement of public results in 2011 and before the 3B Forming Optimization began, the FSV engineering team continued to optimize the body structure, further streamlining the design and exploring additional mass reduction potential. Therefore the engineering team for this optimization, headed by ETA, Inc. (ETA), wanted to include these additional optimizations in the Baseline vehicle for this final gauge optimization. For clarification following is the nomenclature that will be used throughout this report to identify the various FSV design versions:

- **T5 Final** = T5 FE Model, publicly announced in 2011 and reported in the FutureSteelVehicle Phase 2 Engineering and Overview Reports, May 2011, with a body structure mass of **188.4 kg**
- **T5 Design 336** = design that was further optimized following the public announcement with a mass of **188.0 kg.**
- **T6 Baseline** = T5 Final + T5 Design 336 optimization + post 3B Forming Optimization of Front Rail Sub-System, as follows:
    - Integrated final formable parts in front rail sub-system (Design 63) after 3B Forming Process using TRIP800
    - Updated shot gun to reflect tailored tempering of Hot Form material
    - Mapped final grade and gauge of T5Design 336 Optimization that satisfied one step formability (i.e., were manufacturable designs)
    - Used no gauges less than 0.5 mm (D336 had panels less than 0.5 mm)
    - Integrated D336 Optimization Gauges that are **less** than T5
    - Mapped all Tailor Welded Blanks
- **T6 Final** = final fully optimized body structure design resulting from the gauge optimization described in this report

FSV and the additional optimization work completed in this and the Integrated 3B Incremental Forming and Crash Optimization Process (see Section 1.1) validates the design for structural performance and the potential for significantly more mass reduction with steel. FSV's final mass savings of 39%, as documented in this report, set the vision for what can be achieved with steel and optimized design for a new generation of low emissions, safe vehicles that are affordable to manufacture.

3.1 Objectives

The objective of this work was to perform gauge optimization for the final T5 Final design, considering further potential mass reductions as well as the affect of the following parameters:

- Ensure parts are all manufacturable
- Finalize packaging
- Improve Joining (Laser welding, Adhesive)
- New parts

The diagram in Figure 3-1 illustrates the task flow followed in order to meet the objectives.

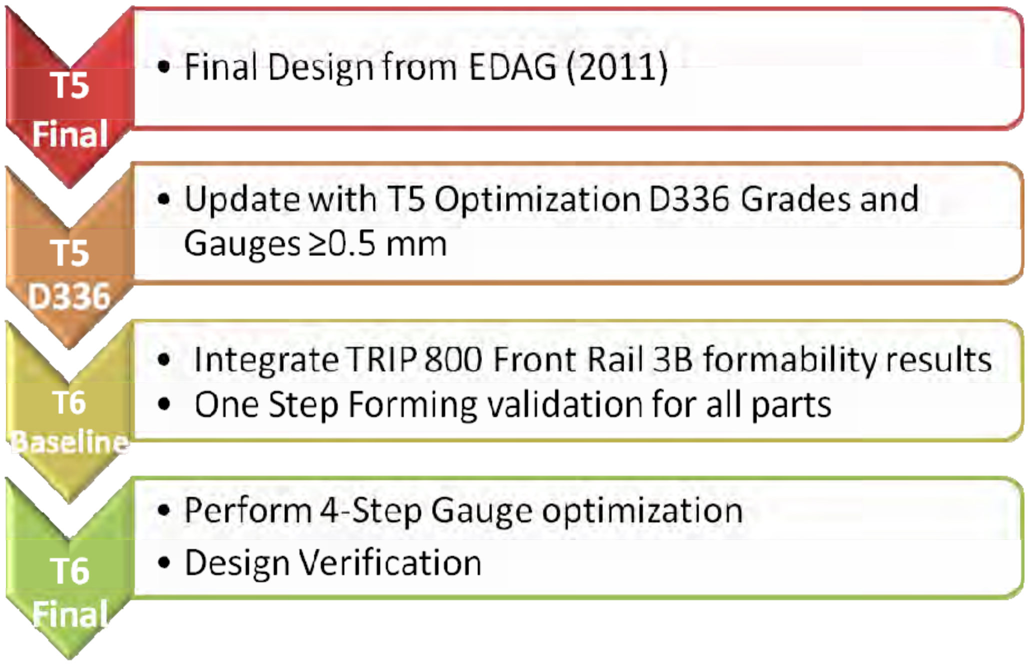
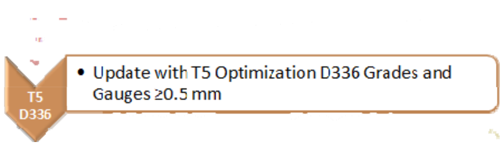


Figure 3-1: Final Gauge Optimization Tasks

3.2 Project Scope



3.2.1 Baseline Grade and Gauge Changes

Following is a summary of the grade and gauge changes completed as a part of the project scope. A complete review of the changes that constitute the T6 Baseline vehicle is available in ETA's *T6 Gauge Optimization Study Full Report*, August 2012, available at www.worldautosteel.org. Figure 3-2 and 3-3 show the parts that were updated by changing grades and/or gauges to represent T5 Design 336 optimization results.

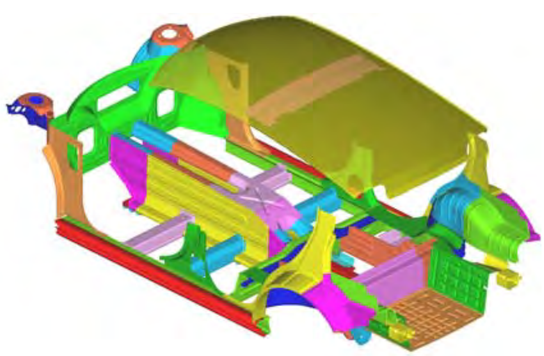


Figure 3-2: FSV parts that were updated according to T5 Design 336 Grades

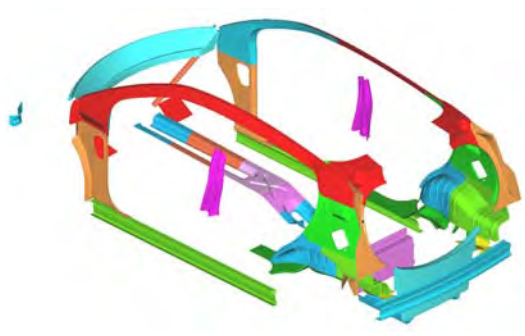


Figure3-3: FSV parts that were updated according to T5 Design 336 Gauges

3.2.1.1 Optimized Front Rail Design Integration

The final front rail sub-system design (Design 63) that resulted from the afore-mentioned 3B Forming Optimization was re-integrated into the body structure, which resulted in another 0.5 kg of mass savings over the T5 design. Figures 3-4 and 3-5 provide an overview of the differences between the system's T5 Final and T6 Baseline versions of the front rail sub-system.

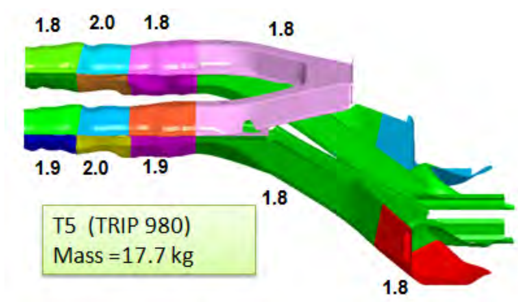


Figure 3-4: FSV T5 front rail subsystems

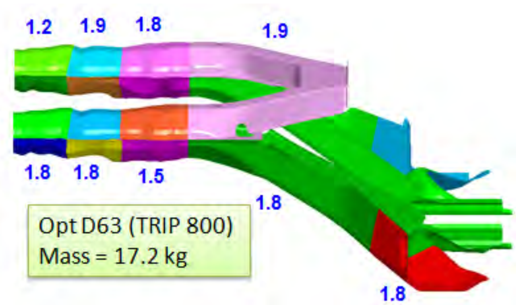


Figure 3-5: T6 Baseline front rail design

3.2.1.2 Baseline Performance Results Summary

The updates summarized in Section 2.0 became the T6 Baseline vehicle used for the final gauge optimization. With the updates incorporated, the T6 Baseline body structure was reduced to **179 kg** mass.

The T6 Baseline exhibited significantly better crash performance than the T5 Final version in several of the load cases, indicating potential additional mass saving. See Table 3-1 for a summary of results. The next task was to improve NCAP and Torsion results by balancing the gauges, particularly for the new TRIP 800 front rail sub-system, for better performance and potential additional mass reduction.

Table 3-1: T6 Baseline Crash Simulation Results

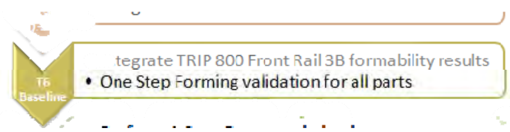
Design	Mass kg	NCAP	Front ODB	IIHS Side	Side Pole	IIHS Rear	IIHS Roof	Bending	Torsion
Targets	<188	38 g	Good	125mm	125mm	Pass	37.5kN	12	20
T5-Final	188.4	39.7	Good	142	150	Good	55	15.5	19.6
T6-Baseline	179 -9.4 kg	43.0	5-6% Improved	170 (16.5% Improved)	150	Good	51 %23> IIHS	14.5	18.3

3.2.1.3 Steel Material Properties

The same portfolio of materials used throughout FSV's engineering development was used in the forming simulation work conducted through this final gauge optimization process. See Appendix 1 to review the complete steel portfolio available in this project. Following in Table 3-2 is a list of the gauges that were used in the final gauge optimization.

Table 3-2 Material Gauges used in the Final Gauge Optimization

Item #	Steel Grade	FSV Portfolio/Steel Capabilities (mm)		D336 (T5) Optimization Gauge Recommendation - (mm)		T6 Optimization Range (mm)	
		Min t	Max t	Min t	Max t	Min t	Max t
1	Mild 140/270	0.35	4.60	0.50	0.50	0.50	4.60
2	BH 210/340	0.45	3.40	0.50	1.20	0.50	3.40
3	BH 260/370	0.45	2.80	0.50	0.50	0.50	2.80
4	BH 280/400	0.45	2.80	0.50	0.50	0.50	2.80
8	HSLA 350/450	0.50	5.00	0.50	1.00	0.50	5.00
9	DP 300/500	0.50	2.50	0.50	0.65	0.50	2.50
13	DP 350/600	0.60	5.00	0.60	1.00	0.60	5.00
21	DP 500/800	0.60	4.00	0.50	2.00	0.50	4.00
22	TRIP 450/800	0.60	2.20	1.20	1.90	0.60	2.20
25	TRIP 600/980	0.90	2.00	1.80	2.00	0.90	2.00
27	DP 700/1000	0.60	2.30	0.60	1.00	0.60	2.30
30	MS 950/1200	0.50	3.20	0.50	2.40	0.50	3.20
31	CP 1000/1200	0.80	2.30	1.00	1.00	0.80	2.30
33	MS 1150/1400	0.50	2.00	0.65	0.65	0.50	2.00
35	HF 1050/1500	0.60	4.50	0.60	1.50	0.60	4.50



3.2.2 Forming Feasibility

3.2.2.1 Objectives

One Step Forming analysis was performed on all of the upgraded parts (Figure3-6) using DYNAFORM to establish a formability performance baseline. In order to select the right grade of material for manufacturability a comparison of One Step results was completed between T5-Final and T5-D336 grades. One Step Forming results for each component can be reviewed in more detail in ETA's engineering report.

It is important to note that the formability analysis was 'One-Step' only in this phase of the work, and the analyses highlighted some manufacturing issues. With further analysis of the concept in a detailed validation and demonstration, these issues can be improved. An example is FSV's front rail subsystem which revealed significant manufacturing issues in the T5 Final design that were resolved during the 3B Forming Optimization process. WorldAutoSteel members work closely with automotive customers to solve these types of AHSS implementation issues.

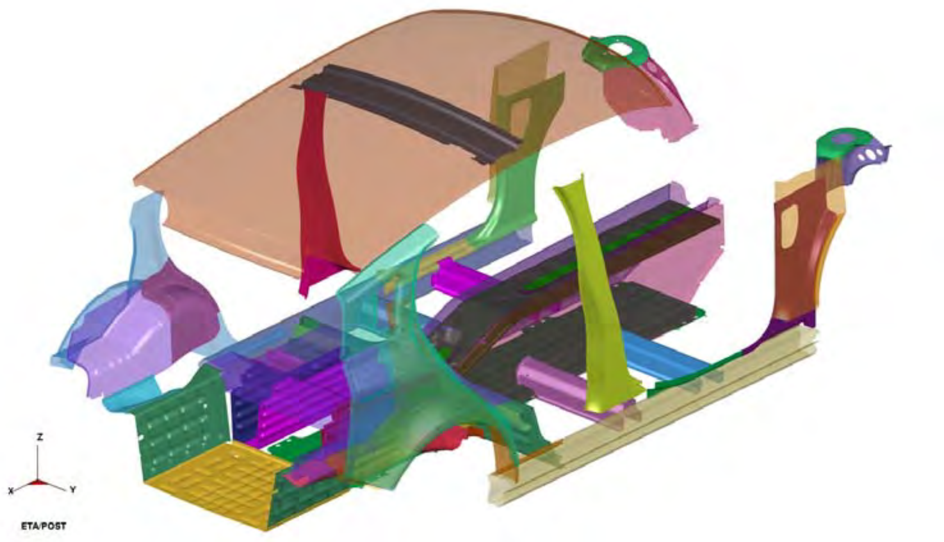
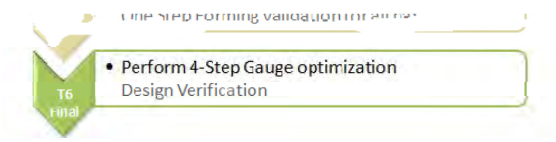


Figure 3-6 Components with Material Changes from T-5 Final to T5-D336



3.2.3 T6 Optimization

3.2.3.1 Strategy and Process

The optimization strategy was to meet the design targets while optimizing the mass of the FSV body structure. As the vehicle development progressed throughout the MDO process, the design space became increasingly smaller and more sensitive. Therefore, a new streamlined MDO strategy was adopted, which enhances the normal MDO with a manual process separation that provides a more detailed search within the design space. The optimization process was conducted in four steps for a total of 865 design runs:

- Step 1: Sensitivity Analysis – Conduct all of the load cases with pre-identified parts
- Step 2: Performance Targets – Conduct Front crash (NCAP and IIHS ODB) with relevant parts
- Step 3: Mass Reduction – Use results from frontal crash optimization to reduce body mass for other load cases
- Step 4: Mass Reduction and Torsional Stiffness – Review Torsion load case only
- Verification

3.2.3.2 Step 1 Optimization: Sensitivity Analysis

Following the implementation of the T5 Design 336 optimization into the T6 Baseline, a sensitivity analysis optimization was conducted with 155 design iterations completed. Six performance loads were considered during the optimization (NCAP, IIHS ODB and Side, Rear Impact and Roof Crush, and Torsion), and it was noted that the design still missed the performance target for the NCAP crash event. There was only one feasible design (Design #12) out of the 155 iterations, which was heavier than baseline.

The strategy at this stage of the project was to meet the design targets and optimize the mass of the FSV BIW. The design space has become much smaller and more sensitive. However, since the vehicle has been optimized several times at different stages of vehicle development, the engineering team therefore decided to develop a new strategy to streamline the optimization process. This strategy enhances the normal process with manual process separation, so that a much more detailed search within the design space can be accomplished.

Sensitive Phase Highlights:

- As is standard in this step, optimization seeks to first meet performance. The results showed that the system is sensitive to two load cases: NCAP and ODB Frontal Crash and torsional stiffness.
- Frontal NCAP and ODB are controlling load cases; all other load cases meet the target.
- Frontal NCAP and ODB conflict, meaning only one load case meets the target at a time.
- Significant mass was attributed to non-body structure parts.
- To improve optimization process speed to meet targets, using Step 1 results, front crash load cases and torsional stiffness would be optimized individually in Step 2.

Table 3-3: Step 1 optimization results for Design #12

Design	Mass kg	NCAP	Front ODB	IIHS Side	Side Pole	IIHS Rear	IIHS Roof	Bending	Torsion
Targets	<188	38 g	Good	125mm	125mm	Pass	37.5kN	12	20
T5-Final	188.4	39.7	Good	142	150	Good	55kN	15.5	19.6
T6-Baseline	179 **- 9.4 kg**	43.0	5-6% Improved	170 (16.5% Improved)	150	Good	51kN %23> IIHS	14.5	18.3
Design #12	**Heavier**	**38.6**	**Good**	**196.37**		**Good**	**61.2kN**		**>20**

3.2.3.3 Step 2 Optimization: Performance Targets

In this Phase 2 optimization, only the two frontal load cases, and their related components (Figure 3-7) were considered, NCAP and ODB. The remainder of the body structure components did not change. A total of 140 design iterations were completed. Design #54 met the performance targets, but with little mass savings. Step 2 optimization improved the NCAP vehicle pulse from 43 G to 38.9 G, with a 9.6 kg mass reduction over the T5 Final design (compared to the Baseline's - 9.4 kg). Table 3-4 summarizes results.

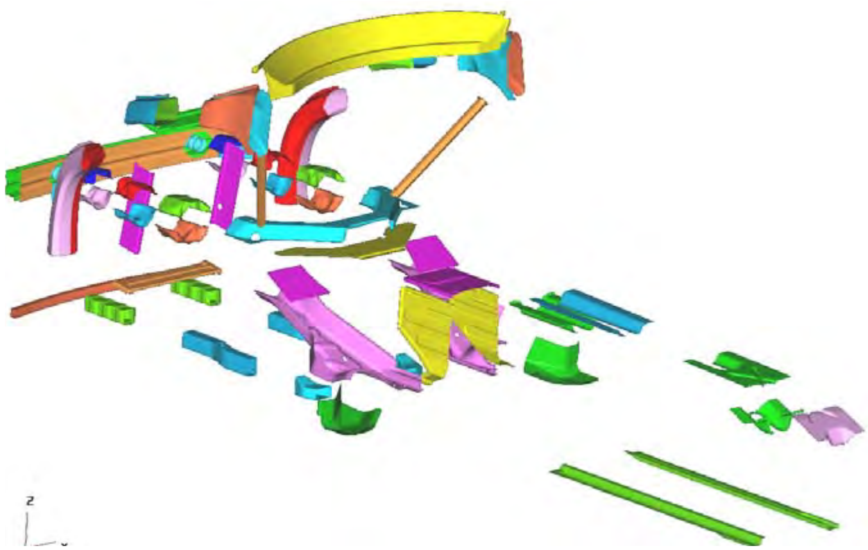


Figure 3-7: Components considered in front crash gauge optimization

Table 3-4: Step 2 optimization results for Design #54

Design	Mass kg	NCAP	Front ODB	IIHS Side	Side Pole	IIHS Rear	IIHS Roof	Bending	Torsion
Targets	<188	38 g	Good	125mm	125mm	Pass	37.5kN	12	20
T5-Final	188.4	39.7	Good	142	150	Good	55kN	15.5	19.6
T6-Baseline	179 - 9.4 kg	43.0	5-6% Improved	170 (16.5% Improved)	150	Good	51kN %23> IIHS	14.5	18.3
Design #54	**178.8** **- 9.6 kg**	**38.9**	**Good**						**18**

3.2.3.4 Step 3 Optimization: Mass Reduction

In this step, the optimization focus was to reduce mass from the body sides for Side Impact, Rear Impact and Roof Crush load cases, using Design #54 from the previous step as the starting point. The six load cases applied in Step 1 were once again applied in this optimization phase with 60 design iterations completed. Design #147 provided an additional 6.3 kg for a total 15.7 kg mass saving, 8.3% lighter than the T5 Final. It meets the targets for all load cases, with the exception of the torsion performance of 17.8 kN-m/deg. This will be addressed in the final Step 4 optimization. Table 3-5 provides a summary of results.

Table 3-5: Phase 3 optimization results for Design #147

Design	Mass kg	NCAP	Front ODB	IIHS Side	Side Pole	IIHS Rear	IIHS Roof	Bending	Torsion
Targets	<188	38 g	Good	125mm	125mm	Pass	37.5kN	12	20
T5-Final	188.4	39.7	Good	142	150	Good	55kN	15.5	19.6
T6-Baseline	179 - 9.4 kg	43.0	5-6% Improved	170 (16.5% Improved)	150	Good	51kN %23> IIHS	14.5	18.3
Design #54	178.8 **- 9.6 kg**	38.9	Good						**18**
Design #147	**172.7 - 15.7 kg**	**39.3**	**Good**	**148.7**		**Good**	**46.9 kN**		**17.8**

3.2.3.5 Step 4 Optimization: Mass Reduction and Torsional Stiffness

Based on past experience with the FSV body structure mass reduction tasks, torsional stiffness is a sensitive case for the body structure. In general, stiffness cannot be improved by the application of AHSS alone, but needs to be addressed with improved joint design, which is beyond the scope of this study. The components considered for this final optimization (Figure 3-8) were selected so as not to disrupt any other load case performances. The starting point for optimization is Step 3's Design #147 with a mass of 172.7 kg. A total of 500 design iterations were completed.

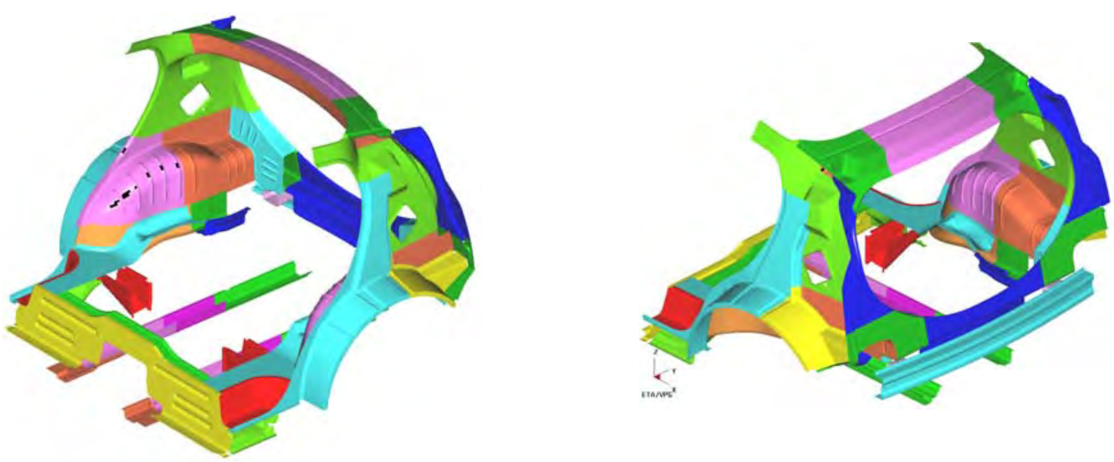
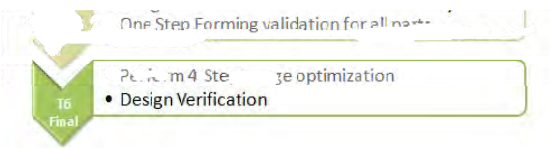


Figure 3-8: Components Considered for Final Optimization

Design #225 exhibited the best performance for torsional stiffness compared to Design #147 and the Step 4 iterations. Table 3-6 gives a summary of the Step 4 design progression.

Table: 3-6: Progression of final Phase 4 optimization

Design	Mass (kg) Mass Reduction	Torsion	Comments
Torsion Optimization Baseline (Design #147 from previous optimization)	**172.7** **- 15.7**	**17.8**	Meets all other targets and is the lightest design with **15.7 kg** or 8.33% mass savings compared to T5-Final.
Design 143	**176.1** **- 12.3**	18.7	Meets all other targets and is **12.3 kg or 6.5%** lighter than the T5-Final.
Design 225	**176.8** **-11.6**	19. 1	Meets all other targets and is **11.6 kg or 6.2%** lighter than the T5-Final.



3.2.3.6 Final Design Verification

With a final design complete as a result of the gauge optimizations, the engineering team verified the design by running all load cases with Design 225 gauges and grades to ensure that it met all targets. Final results are provided in Section 3.3 and Table 3-7.

3.3 Conclusions and Final Design Results

The Final T6 Gauge Optimization began with the integration of additional T5-D336 design optimization conducted after the public announcement of the T5-Final FutureSteelVehicle results in May 2011. Also integrated in this design was the updated front rail sub-system design which was the subject of an Integrated 3B Forming and Crash Optimization to prove out its manufacturability. The T5 Final updated with the T5 Design 336 optimization as well as the outcomes of the 3B Forming Optimization of the front rail sub-system became the T6 Baseline vehicle design.

In a four-step design optimization process, each with its own set of parameters for performance and mass reduction, 865 design iterations were completed. The Step 4 Design #225 was selected as the T6 Final optimized design. This final design meets all of the load case targets (see Table 3-7) with a mass of **176.8** kg, which is an **11.6 kg** or **6.2%** mass reduction over the T5 Final design. Overall, the FSV T6 Final optimized design achieves a **39% mass reduction** over the FSV benchmark (Figure 3-9). These results demonstrate the capabilities of Advanced High-Strength Steel to close the gap in mass reduction potential compared to high cost, low density materials.

Table 3-7: FSV T6-Final Optimized Design Results

Design	Mass kg	NCAP	Front ODB	IIHS Side	Side Pole	IIHS Rear	IIHS Roof	Bending	Torsion
Targets	<188	38 g	Good	125mm	125mm	Pass	37.5kN	12	20
T5-Final Design	188.4	39.7	Good	142	150	Good	55	15.5	19.6
T6-Final	**176.8** **- 11.6 kg**	**37.8**	**Good**	**152**	**138**	**Good**	**44.5**	**14.2**	**19**

4.0 Near-Term Front Longitudinal Rail Shape Study

4.1 Objectives

FSV began in 2007 with a Phase 1 engineering study (subject of the *FutureSteelVehicle Phase 1 Engineering Report* May 2009 see Appendix 6), which set the parameters for the design and development work that followed in Phase 2. As a part of that engineering study, FSV's unique MDO process was evaluated in a pilot project development process, which explored the "Nature's Way" approach, proposed by the development process, for its benefits in achieving greater degrees of mass reduction, applying it to the Front Rail of the Auto/Steel Partnership's Lightweight Front End (LWFE) project to establish any additional mass savings. The LWFE achieved a 25% mass savings over the benchmarked donor vehicle. Using FSV's MDO process, the total mass savings reached 45% over the benchmark, but did not impose manufacturing constraints. The design methodology appeared to be very promising for mass reduction and it was decided to incorporate the design methodology, but with consideration for manufacturing constraints.
.
Consequently, the original T6 design, optimized for manufacturability (3B) and mass (Gauge Optimization), yielded non-intuitive shapes that nonetheless met crash performance targets. However, producing some of the FSV sections would be difficult, so it was useful to understand the specific mass and performance benefits, as applied to the FSV designs. To investigate and define any advantages of the unconventional sections, the design team set these objectives:

- Design and optimize a more conventionally shaped longitudinal rail and crush-can ("Near-Term") based on the T6 final design
- Compare mass and performance of T6 and Near-Term designs.

The team would pursue the objective with a process that comprised reshaping the longitudinal rails, running crash simulations, iterating both the design and crash simulations, allowing software to optimize for mass, and assessing the formability of the optimized design.

4.2 Project Scope

The study would begin with the T6 final design (essentially the same design geometry as the T5 model) and maintain:

- The same topology (load path) to top and bottom of the tunnel and to the rocker
- Straight-only tip section, allowing diameter at front and back to move so it remains conic
- Package space (engine, tire flop, suspension travel, etc.)
- Welding flanges and connections close to original T6 design

Engineering judgment was used to modify the front rail design to conform to the objectives. The hexagonal shape of the initial Near-Term re-design of the rails is a modification of the original T6 configuration into a more conventionally shaped tip. Figures 4-1 and 4-2 compare the two designs.

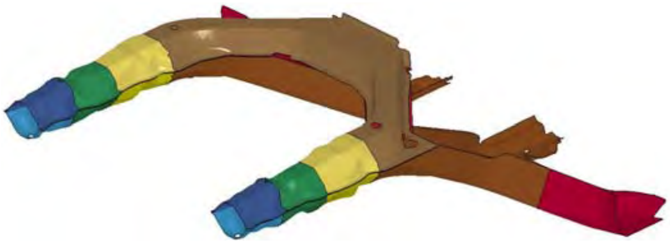


Figure 4-1: FSV Final Optimized Rail Design (T6)

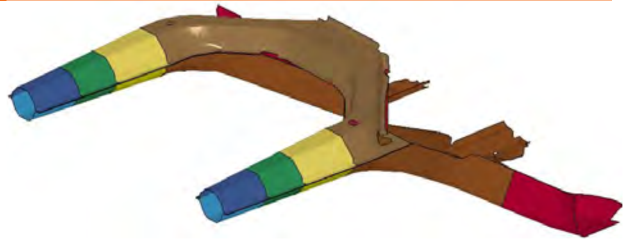


Figure 4-2: Near-Term Design (Hexagonal shape)

4.2.1 Near-Term Design Iteration

The initial Near-Term design failed in a first-run crash simulation, in which the rails did not crush and the ODB intruded unacceptably (Figure 4-3).

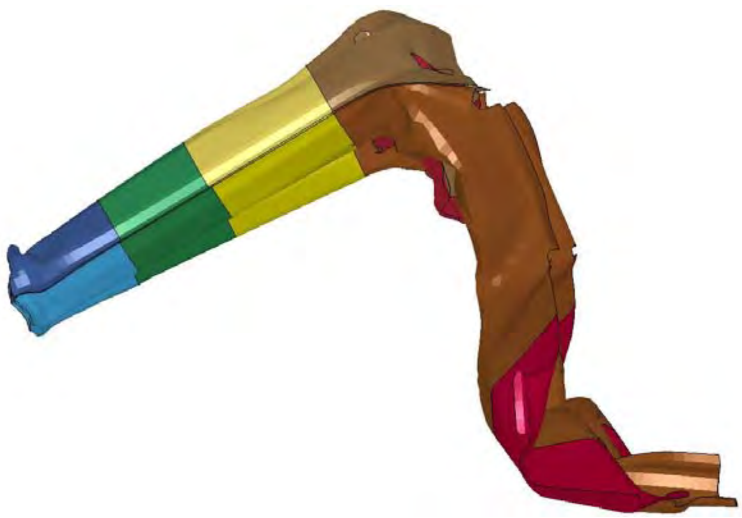


Figure 4-3: Initial Near-Term design failure in ODB

After the initial Near-Term design failed, crush initiators (5mm deep x 15.6 mm wide) were added, which generated acceptable pulse and ODB performance. Figure 4-4 shows the crush initiator locations.

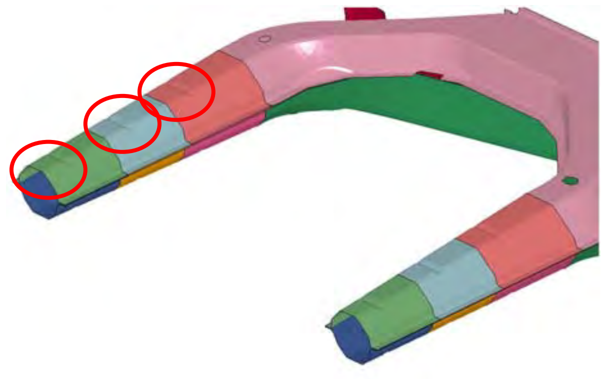


Figure 4-4: Crush Initiators

The front rail design uses TRIP 800 material in various thicknesses, applied according to engineering experience and judgment. However, the Near-Term design increased mass by 2.7 kg. Figures 4-5 and 4-6 provide the FSV T6 final gauges and the Near-Term Gauges, respectively.

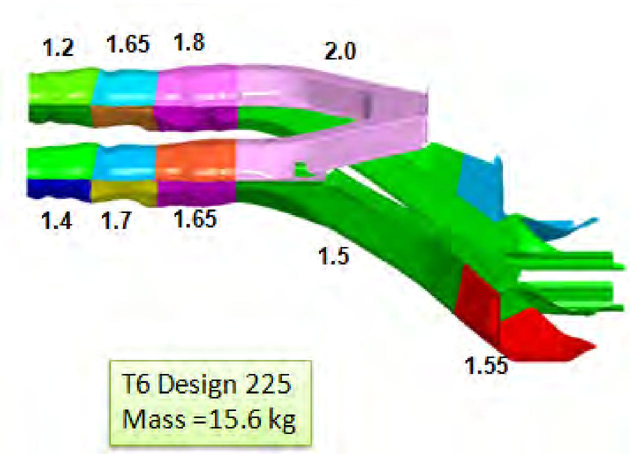


Figure 4-5: FSV T6 Final Front End Design and Material Gauges (TRIP 800)

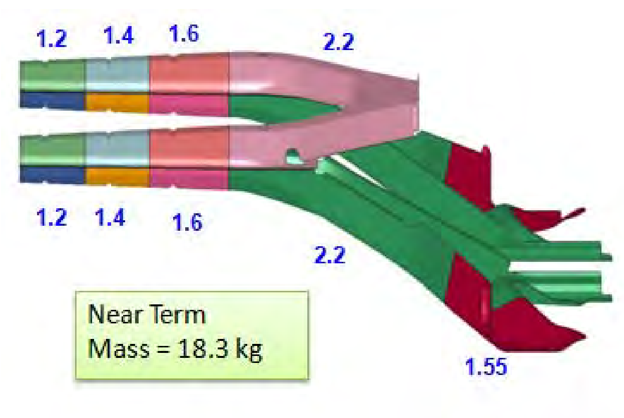


Figure 4-6: Near-Term Gauges (TRIP 800)

Following the modifications, baseline performance was analyzed. Figure 4-7 shows acceptable ODB and NCAP crash results achieved with the Near-Term design's modifications.

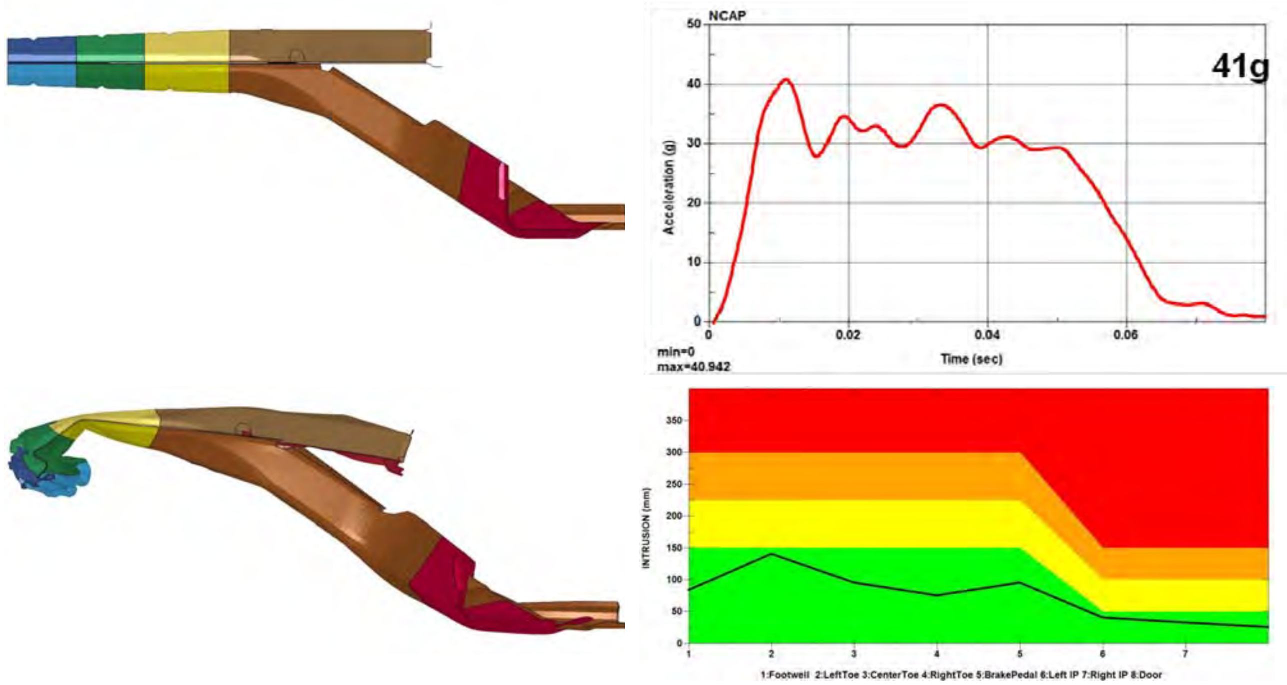


Figure 4:7: Crushed Rail (Bottom) and US NCAP (top right) and IISI ODB (bottom right) Results

Baseline formability results (Figure 4-8) show the amended design's suitability for forming, but indicate some wrinkling due to the angles of the shape itself. However, the engineering team was confident that it could successfully address this issue. For example, the modified shapes could be formed with more conventional DP 780, instead of TRIP 780.

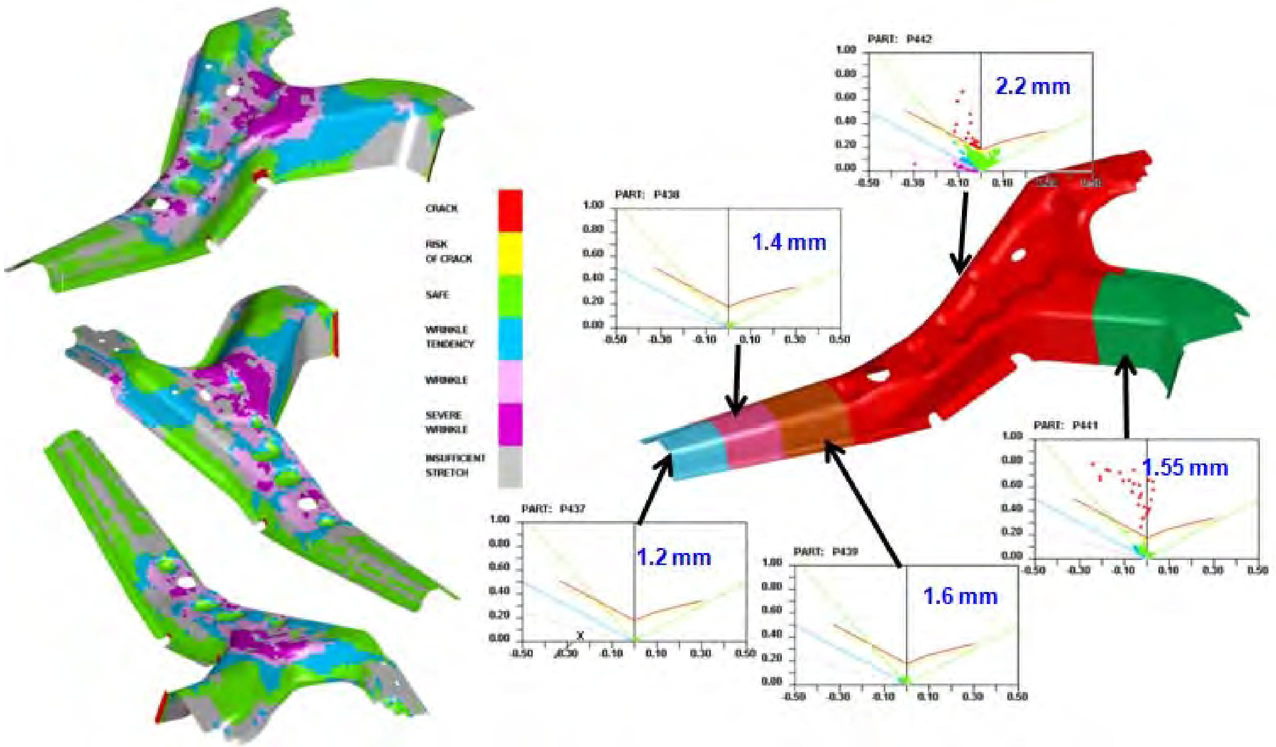


Figure 4-8: Near-Term Baseline Formability Results

4.2.2 Optimization

With baseline performance tested, the team returned to optimize it for mass and resolve the forming issues. The same MDO process used throughout the FSV program was used here to optimize the Near-Term design's material gauges for mass reduction. Maintaining use of tailor-welded blanks, the design was iterated through 92 separate versions, with Design # 73 providing the optimal outcome that met all crash performance criteria and mass of 15.63 kg, a reduction of 2.67 kg. Figures 4-9 and 4-10 show the baseline vs. optimized material gauges.

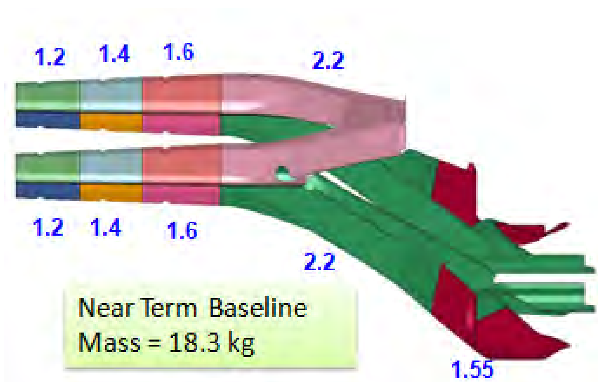


Figure 4-9: Near-Term Baseline

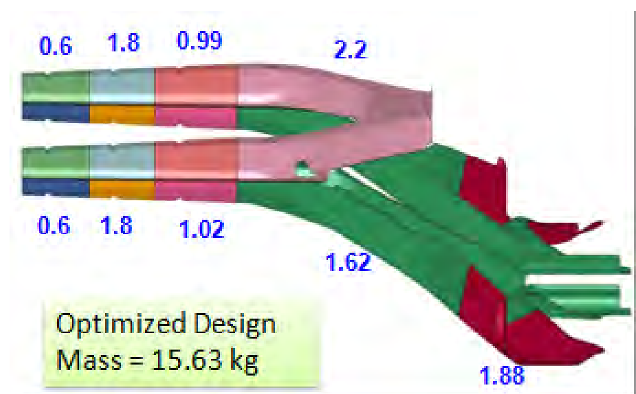


Figure 4-10: Optimized Near-Term Design

4.2.3 NCAP & ODB Results (Design #73)

For both NCAP and ODB simulations, Design # 73 performed acceptably. Figures 4-11 and 4-12 show the results.

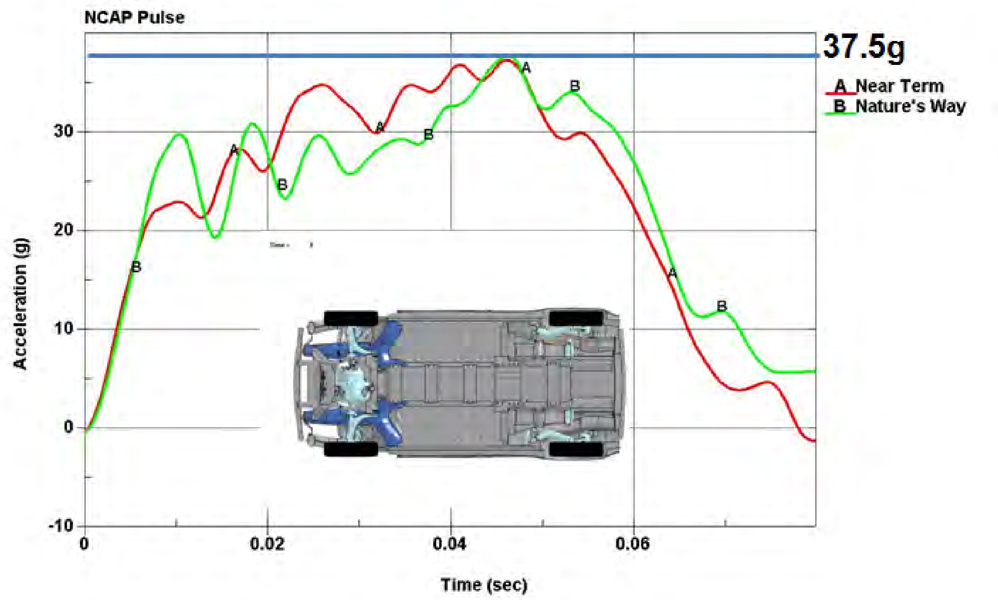


Figure 4-11: NCAP Pulse Results A) Near-Term Optimized Design vs. B) FSV T6 Final Design

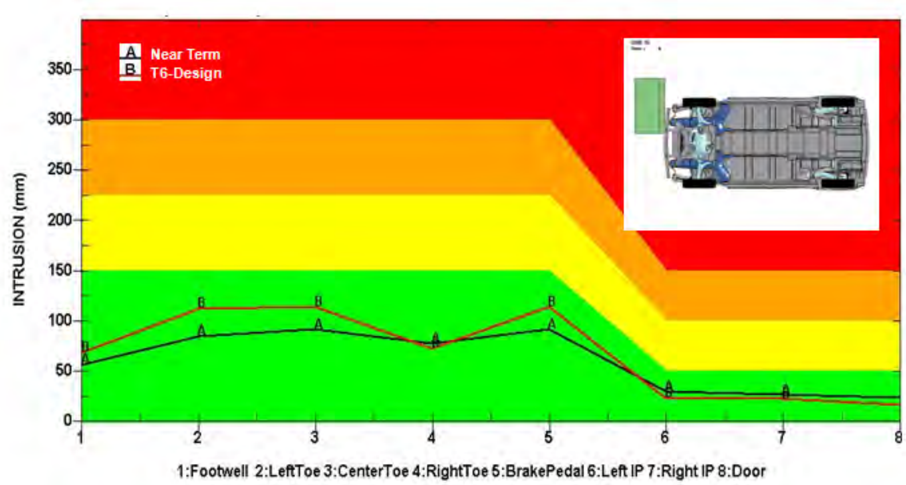


Figure 4-12: Near-Term Optimized Design (A) vs. FSV T6 Final Design (B)

4.2.4 Near-Term Optimized Design #73 vs. FSV T6 Final Design Comparison

4.2.4.1 Formability

Formability simulation was re-run on the mass-optimized design. The comparison between the T6 Final Design and the Near-Term Optimized Design # 73 favors the hexagon shape (Figure 4-13). Though some wrinkling still occurs, this can be solved in manufacturing.

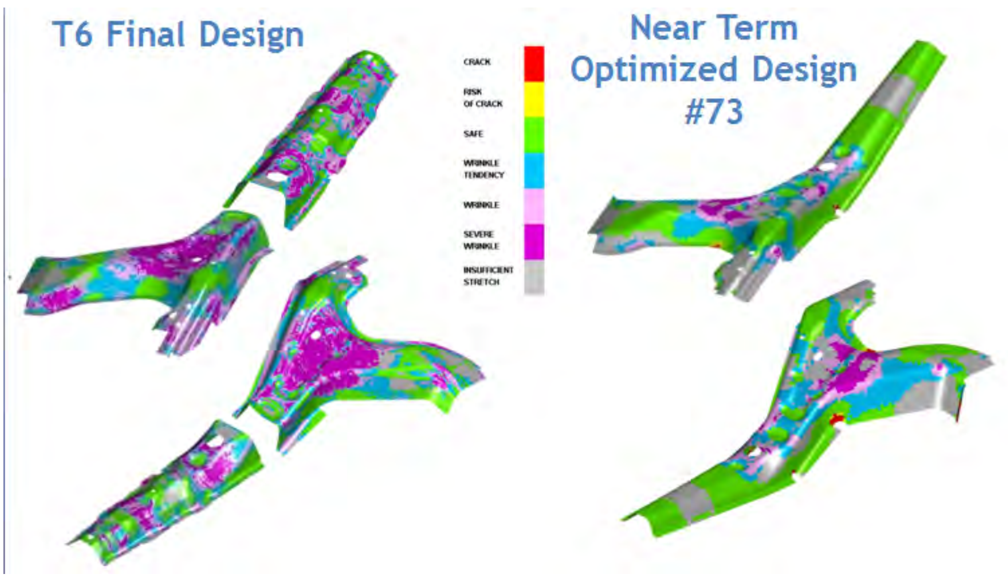


Figure 4-13: T6 Final Design vs. Near-Term Optimized Design #73 Formability

4.2.4.2 Mass

After the optimization process, the Near-Term Optimized Design # 73 is virtually the same mass as the T6 Final Design. Figure 4-14 compares the two.

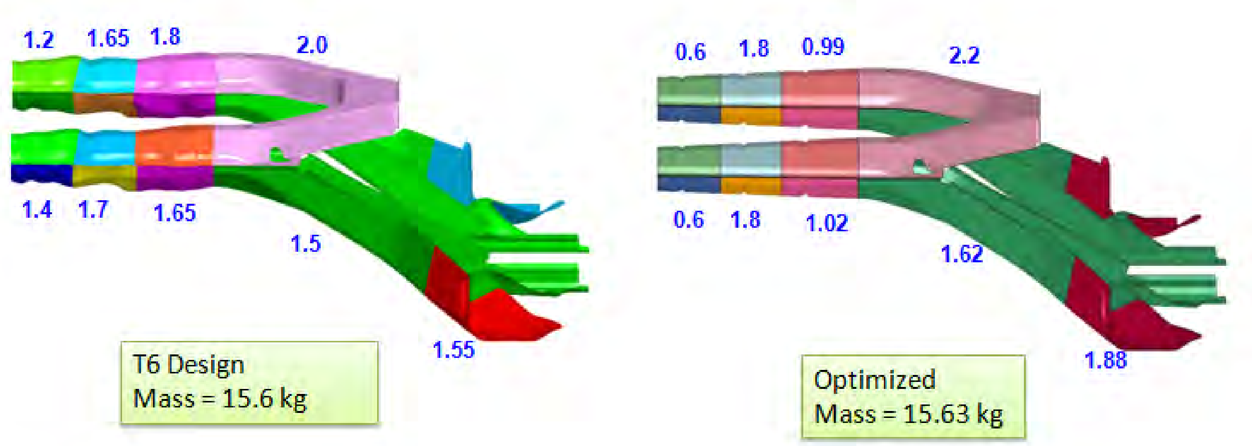


Figure 4-14: T6 Final Design (left) vs. Near-Term Optimized Design #73

4.2.4.3 Load Management and Energy Absorption

A comparison of the T6 and Near-Term shapes show that load management and energy absorption performance of the two designs are nearly identical. Figure 4-15's graphs compare the energy absorption distribution of key load management components of the two designs.

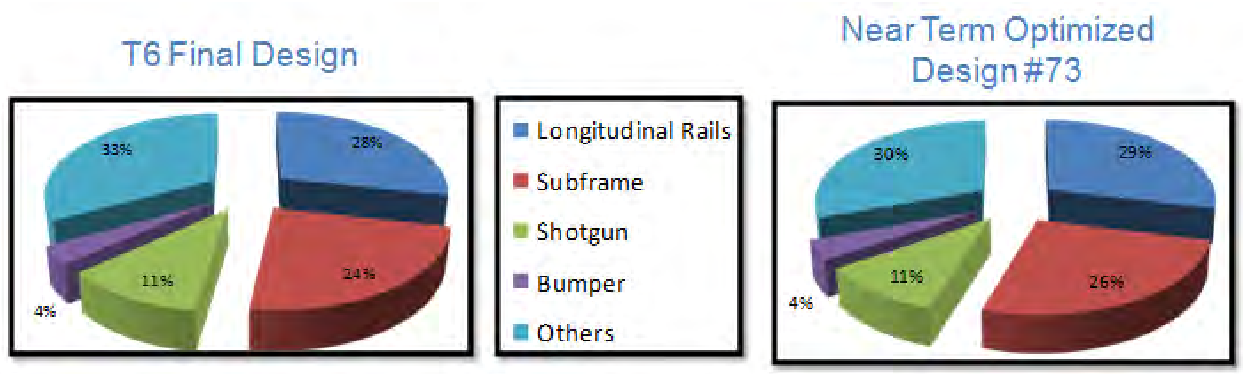


Figure 4-15: Energy Absorption Distribution (by percentage) of Key Load Management Components

4.2.4.4 Crash Simulation

A comparison of the performance of the two designs with the targets validates the success of modifications to the T6 Final Design that resulted in the Near-Term Optimized Design #73's hexagonal shape.

Table 4-1: Performance Comparison, T6 to Near-Term Design

Design	Mass kg	NCAP	Front ODB	IIHS Side	Side Pole	IIHS Rear	IIHS Roof	Bend.	Torsion
Targets	<188	39.6 g	Good	125mm	125mm	Pass	37.5kN	12	20
T6 Final Design	176.8	37.5	Good	152	138	Good	44.5	14.2	19
Near-Term Optimized Design #73	176.83	37.3	Good	152	138	Good	44.5	14.2	19

4.3 Conclusions

The results show almost identical mass, crash and cost outcomes for the T6 final design incorporating the non-intuitive shapes, and the Near-Term optimized design using more conventional geometry.

The final mass calculation for the Near-Term design is 176.83 kg, maintaining the 39 percent weight reduction that T6 attained. NCAP vehicle pulse and ODB intrusion results are very similar to the T6 version, as are other crash performance metrics. The buckling modes of the two design concepts, though, are different based on their respective design strategies.

Additionally, this study validates the FSV - MDO design process as a significant contributor to efficient mass performance when incorporating AHSS. Using the MDO to set the design process, in combination with engineering judgment to develop more conventional sections, ensures the best use of steel's unique design flexibility to achieve superior mass results.

Regarding the pilot project, mentioned in Section 4.1 Objectives, it concluded that the complex sections provide clear mass benefits. However, this Near-Term study provides evidence that these complex sections, e.g., the unique crash initiator sections in the front rails, do not provide a mass benefit, but rather it is the efficiencies in structures to manage the load paths that provided the greater benefit. The alternative solutions (T6 and Near-Term) provide two different, but comparable, answers, reinforcing steel's capability to expand the range of available solutions for designers and engineers faced with difficult constraints. With steel's enabling flexibility, unconventional shapes may yet offer additional benefits. In any case, there is ample opportunity for further study.

The Near-Term study, coupled with its two predecessors, show that car makers can form and fabricate sophisticated steel designs, thus accelerating implementation of this technology into production vehicles.

		Thickness (mm)		Gauge	YS (MPa)	YS (MPa)	UTS (MPa)	UTS (MPa)	Tot EL (%)	N-value	Modulus of	Fatigue Strength	K Value
Item #	**Steel Grade**	**Min t**	**Max t**	**Length**	**Min**	**Typical**	**Min**	**Typical**	**Typical**	**Typical**	**Elasticity (MPa)**	**Coeff (MPa) ***	**(MPa)**
1	Mild 140/270	0.35	4.60	A50	140	150	270	300	42-48	0.24	21.0×10^4	645	541
2	BH 210/340	0.45	3.40	A50	210	230	340	350	35-41	0.21	21.0×10^4	695	582
3	BH 260/370	0.45	2.80	A50	260	275	370	390	32-36	0.18	21.0×10^4	735	550
4	BH 280/400	0.45	2.80	A50	280	325	400	420	30-34	0.16	21.0×10^4	765	690
5	IF 260/410	0.40	2.30	A50	260	280	410	420	34-48	0.20	21.0×10^4	765	690
6	IF 300/420	0.50	2.50	A50	300	320	420	430	29-36	0.19	21.0×10^4	775	759
7	FB 330/450	1.60	5.00	A80	330	380	450	490	29-33	0.17	21.0×10^4	835	778
8	HSLA 350/450	0.50	5.00	A80	350	360	450	470	23-27	0.16	21.0×10^4	815	807
9	DP 300/500	0.50	2.50	A80	300	345	500	520	30-34	0.18	21.0×10^4	865	762
10	HSLA 420/500	0.60	5.00	A50	420	430	500	530	22-26	0.14	21.0×10^4	875	827
11	FB 450/600	1.40	6.00	A80	450	530	560	605	18-26	0.15	21.0×10^4	950	921
12	HSLA 490/600	0.60	5.00	A50	490	510	600	630	20-25	0.13	21.0×10^4	975	952
13	DP 350/600	0.60	5.00	A80	350	385	600	640	24-30	0.17	21.0×10^4	985	976
14	TRIP 350/600	0.60	4.00	A50	350	400	600	630	29-33	0.25	21.0×10^4	975	952
15	SF 570/640	2.90	5.00	A50M	570	600	640	660	20-24	0.08	21.0×10^4	1005	989
16	HSLA 550/650	0.60	5.00	A50	550	585	650	675	19-23	0.12	21.0×10^4	1020	1009
17	TRIP 400/700	0.60	4.00	A80	400	420	700	730	24-28	0.24	21.0×10^4	1075	1077
18	SF 600/780	2.00	5.00	A50	600	650	780	830	16-20	0.07	21.0×10^4	1175	1201
19	HSLA 700/780	2.00	5.00	A50	700	750	780	830	15-20	0.07	21.0×10^4	1175	1200
20	CP 500/800	0.80	4.00	A80	500	520	800	815	10-14	0.13	21.0×10^4	1160	1183
21	DP 500/800	0.60	4.00	A50	500	520	800	835	14-20	0.14	21.0×10^4	1180	1303
22	TRIP 450/800	0.60	2.20	A80	450	550	800	825	26-32	0.24	21.0×10^4	1170	1690
23	CP 600/900	1.00	4.00	A80	600	615	900	910	14-16	0.14	21.0×10^4	1255	1301
24	CP 750/900	1.60	4.00	A80	750	760	900	910	14-16	0.13	21.0×10^4	1255	1401
25	TRIP 600/980	0.90	2.00	A50	550	650	980	990	15-17	0.13	21.0×10^4	1335	1301
26	TWIP 500/980	0.80	2.00	A50M	500	550	980	990	50-60	0.40	21.0×10^4	1335	1401
27	DP 700/1000	0.60	2.30	A50	700	720	1000	1030	12-17	0.12	21.0×10^4	1375	1521
28	CP 800/1000	0.80	3.00	A80	800	845	1000	1005	8-13	0.11	21.0×10^4	1350	1678
29	DP 800/1180	1.00	2.00	A50	800	880	1180	1235	10-14	0.11	21.0×10^4	1555	1700
30	MS 950/1200	0.50	3.20	A50M	950	960	1200	1250	5-7	0.07	21.0×10^4	1595	1678
31	CP 1000/1200	0.80	2.30	A80	1000	1020	1200	1230	8-10	0.10	21.0×10^4	1575	1700
32	DP1150/1270	0.60	2.00	A50M	1150	1160	1270	1275	8-10	0.10	21.0×10^4	1620	1751
33	MS 1150/1400	0.50	2.00	A50	1150	1200	1400	1420	4-7	0.06	21.0×10^4	1765	1937
34	CP 1050/1470	1.00	2.00	A50M	1050	1060	1470	1495	7-9	0.06	21.0×10^4	1840	2030
35	HF 1050/1500												
	Conventional Forming	0.60	4.50	A80	340	380	480	500	23-27	0.16	21.0×10^4	845	790
	Heat Treated after forming	0.60	4.50	A80	1050	1220	1500	1600	5-7	0.06	21.0×10^4	1945	2161
36	MS 1250/1500	0.50	2.00	A50M	1250	1265	1500	1520	3-6	0.05	21.0×10^4	1865	2021

*** Un-notched specimens, FSc = UTS + 345 (MPa)**
Alternate approximation = 3.45*HB

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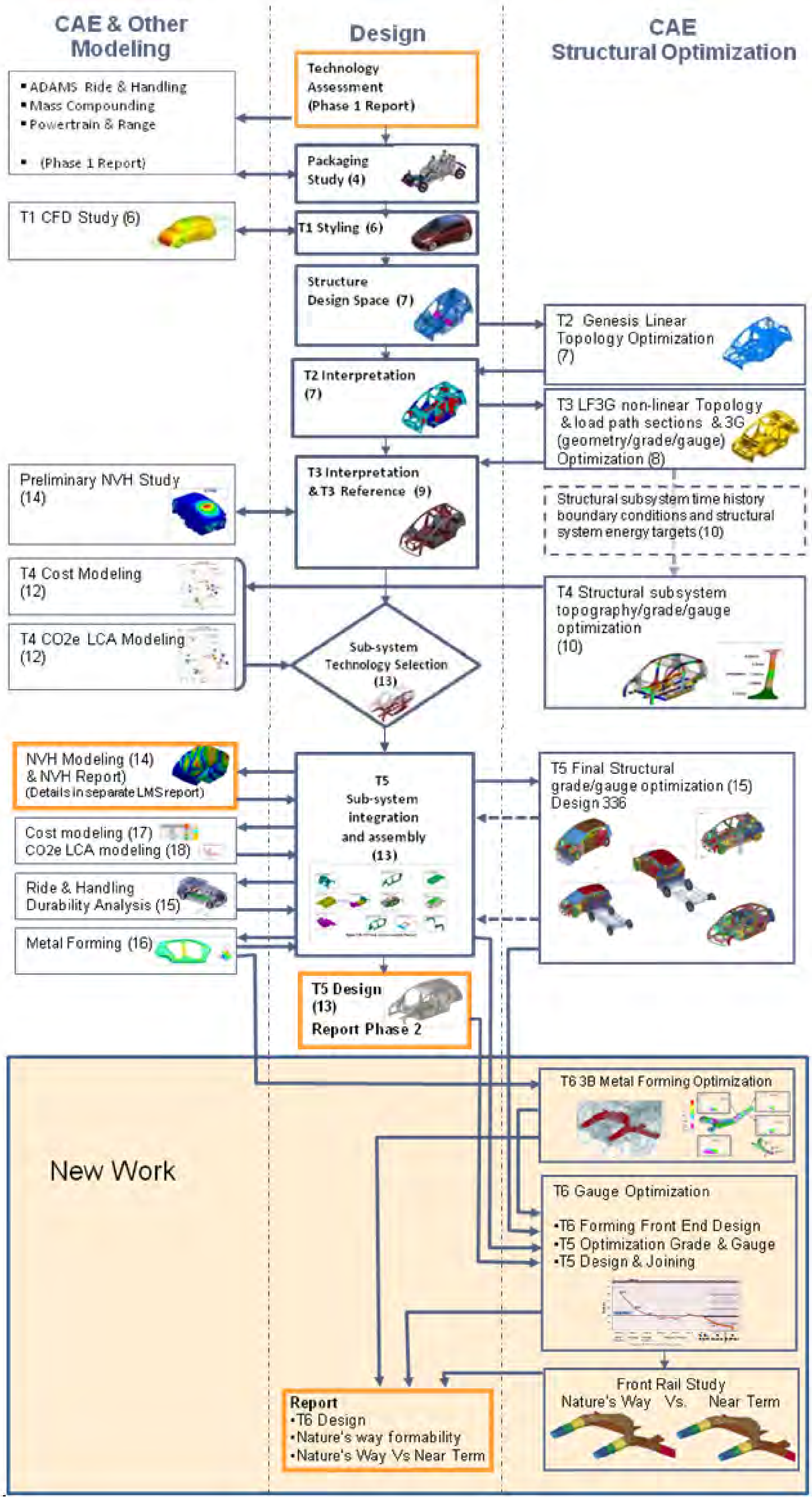
CAE & Other Modeling
Design
CAE Structural Optimization
Technology Assessment (Phase 1 Report)
▪ADAMS Ride & Handling
▪Mass Compounding
▪Powertrain & Range
▪ (Phase 1 Report)
Packaging Study (4)
T1 CFD Study (6)
T1 Styling (6)
Structure Design Space (7)
T2 Genesis Linear Topology Optimization (7)
T2 Interpretation (7)
T3 LF3G non-linear Topology & load path sections & 3G (geometry/grade/gauge) Optimization (8)
Preliminary NVH Study (14)
T3 Interpretation & T3 Reference (9)
Structural subsystem time history boundary conditions and structural system energy targets (10)
T4 Cost Modeling (12)
T4 CO2e LCA Modeling (12)
T4 Structural subsystem topography/grade/gauge optimization (10)
Sub-system Technology Selection (13)
NVH Modeling (14) & NVH Report) (Details in separate LMS report)
T5 Sub-system integration and assembly (13)
T5 Final Structural grade/gauge optimization (15) Design 336
Cost modeling (17)
CO2e LCA modeling (18)
Ride & Handling Durability Analysis (15)
Metal Forming (16)
T5 Design (13) Report Phase 2
New Work
T6 3B Metal Forming Optimization
T6 Gauge Optimization
•T6 Forming Front End Design
•T5 Optimization Grade & Gauge
•T5 Design & Joining
Front Rail Study
Nature's Way Vs. Near Term
Report
•T6 Design
•Nature's way formability
•Nature's Way Vs Near Term

FSV Front Rail Integrated Incremental Forming study

FutureSteelVehicle

Final Report

05/11/2012

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2. Objective
3. Material data available
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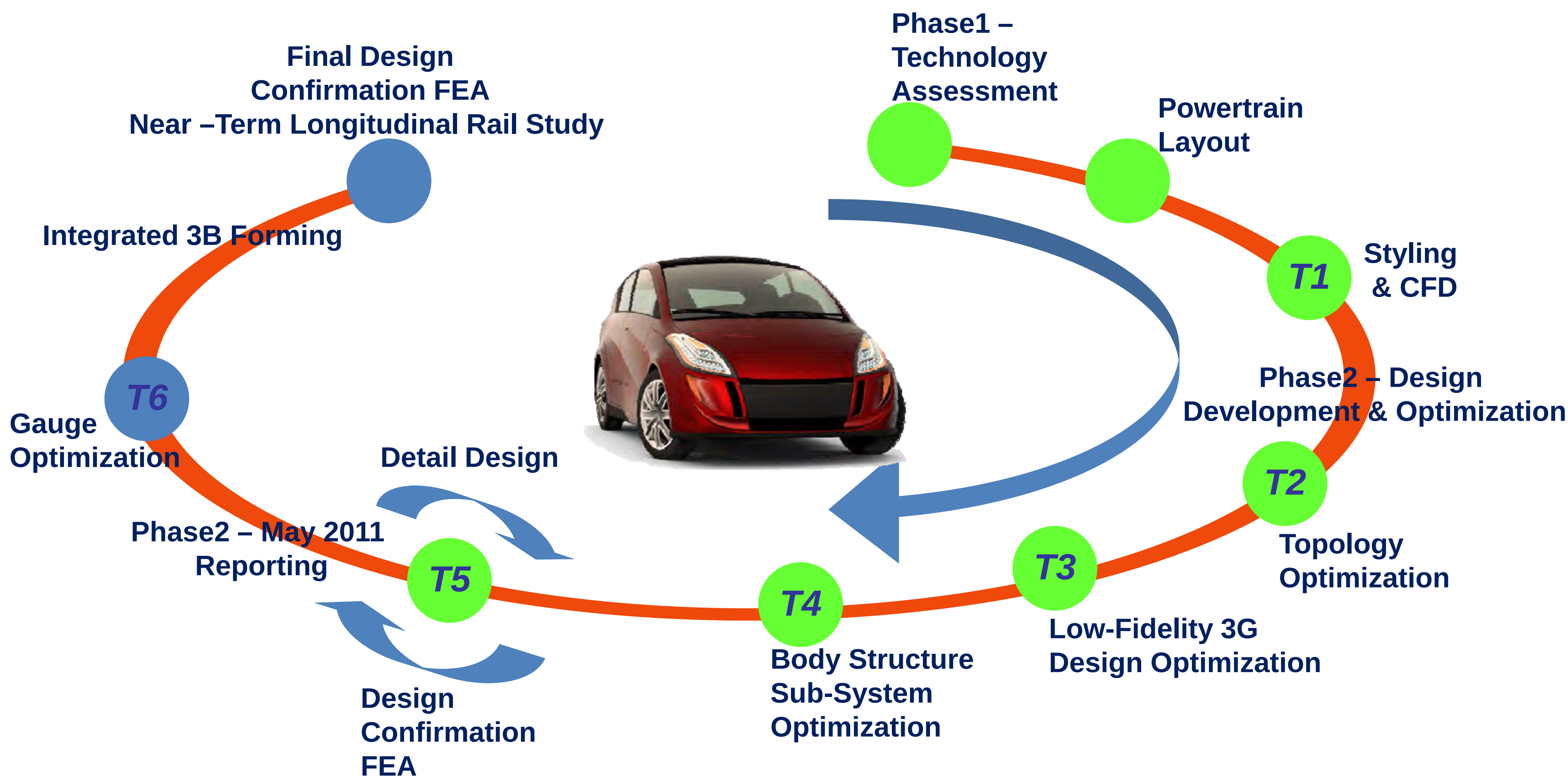
   5.3 Springback Evaluation (TRIP 980 & 800)
6. Discussion and Conclusions

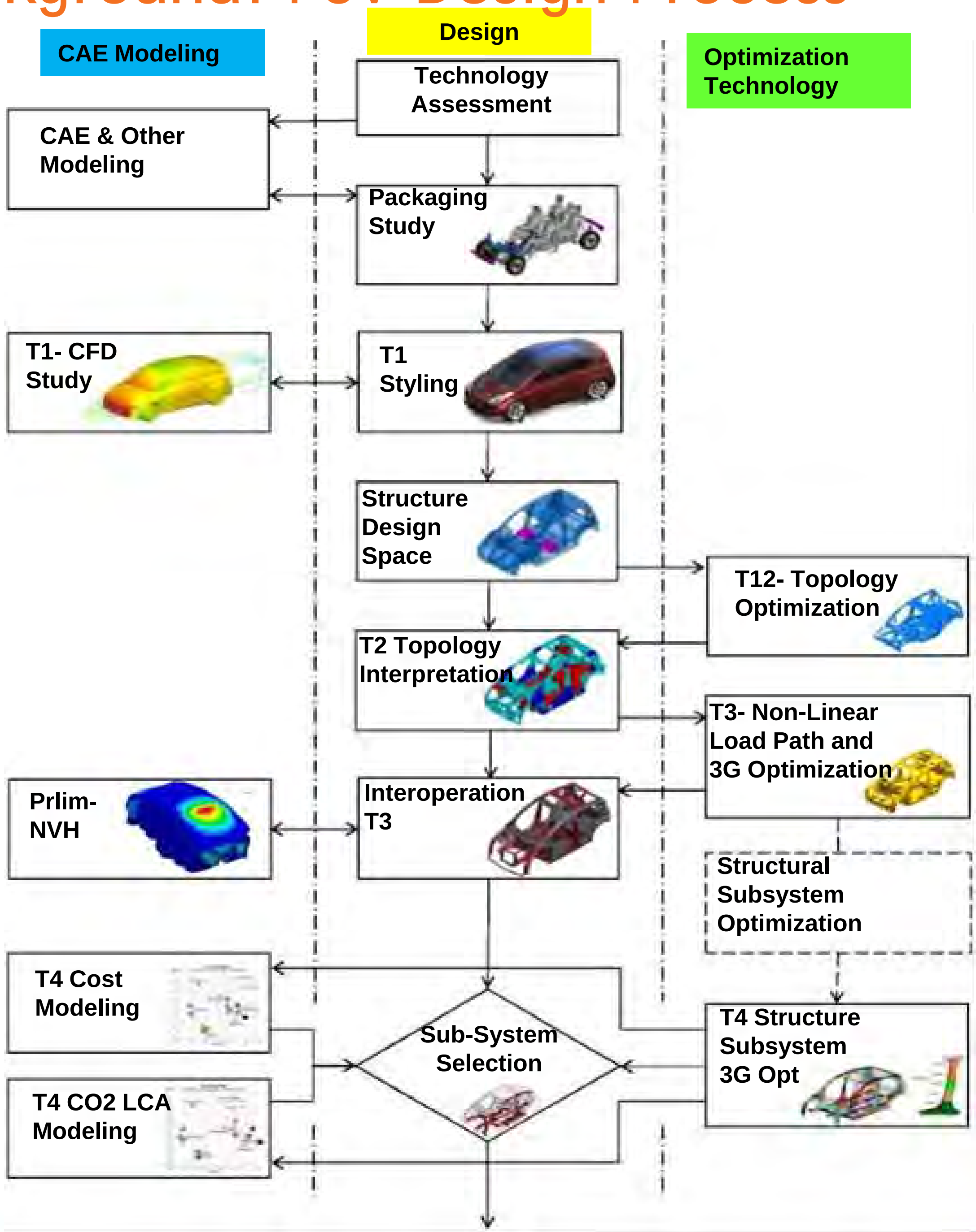
1.0 Project Background

- Based on original work plan, it was decided that after the T5 task, it was necessary to perform gage optimization based on final design model to complete the project. This observation was made based on T5 optimization study, where after finalizing the detailed design, packaging, joining, manufacturing, and gauge and grade selection, there was more mass on the table that could be saved in the BIW (see Page 3-6).
- T5 final results showed that FSV final forming for manufacturability for several parts needed to be looked into much more deeply to ensure there were no stamping forming process issues, especially with parts that contained very non-intutive shapes, such as front and rear longitudinal rails.

1.0 Project Background: FSV Design Process



1.0 Project Background: FSV Design Process



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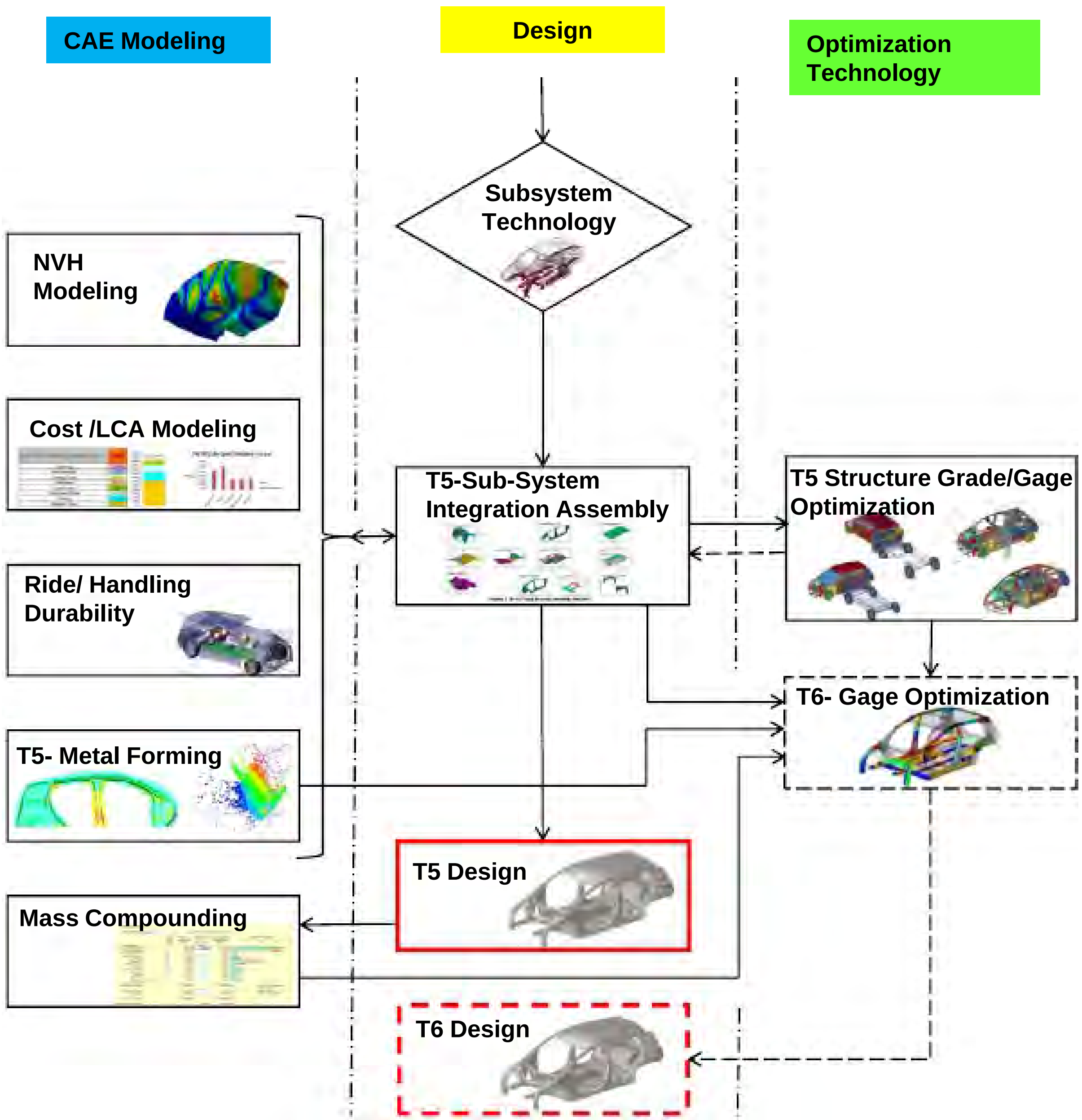
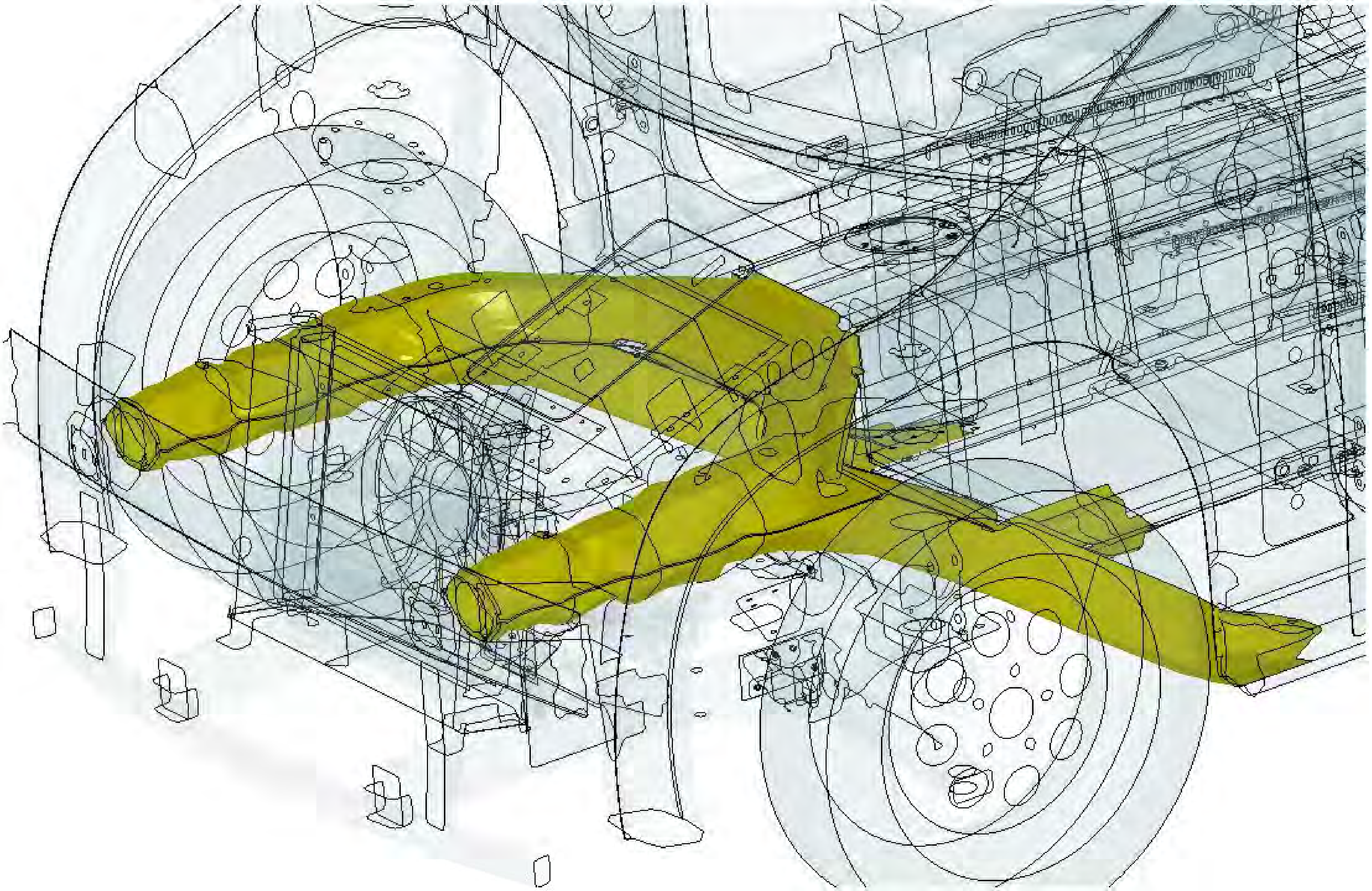
1.0 Project Background: FSV Design Process



FSV Front End



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2.0 Objective

- Develop an optimization process that will resolve the formability issues through tool design and then product design by balancing the usage of different counter-measures.

- Resolving formability issues of **upper and lower front rails** through above process while maintaining NCAP and IIHS front Crash (40% ODB Impact) performance.

3.0 Product material

3.1 Gauge/Grade available for FSV

- FSV team members had the following material table available for FSV for selection of grade and gages
- TRIP 980 was the grade of front longitudinal rail (T5 Baseline). TRIP 800 was selected as an alternative choice for grade in place of TRIP 980 due to its very high N value (26 compared to 15)
- FSV team members provided TRIP800 grade properties

Item #	Steel Grade	Thickness (mm) Min t	Thickness (mm) Max t	Gage Length	YS (Mpa) Min	YS (Mpa) Typical	UTS (Mpa) Min	UTS (Mpa) Typical	Tot EL (%) Typical	N-value Typical
17	TRIP 400/700	0.60	4.00	A80	400	420	700	730	24-28	0.24
18	SF 600/780	2.00	5.00	A50	600	650	780	830	16-20	0.07
19	HSLA 700/780	2.00	5.00	A50	700	750	780	830	15-20	0.07
20	CP 500/800	0.80	4.00	A80	500	520	800	815	10-14	0.13
21	DP 500/800	0.60	4.00	A50	500	520	800	835	14-20	0.14
22	TRIP 450/800	0.60	2.20	A80	450	550	800	825	26-32	0.24
23	CP 600/900	1.00	4.00	A80	600	615	900	910	14-16	0.14
24	CP 750/900	1.60	4.00	A80	750	760	900	910	14-16	0.13
25	TRIP 600/980	0.90	2.00	A50	550	650	980	990	15-17	0.13
26	TWIP 500/980	0.80	2.00	A50M	500	550	980	990	50-60	0.40
27	DP 700/1000	0.60	2.30	A50	700	720	1000	1030	12-17	0.12
28	CP 800/1000	0.80	3.00	A80	800	845	1000	1005	8-13	0.11
29	DP 800/1180	1.00	2.00	A50	800	880	1180	1235	10-14	0.11

3.2 Lower Rail, Geometry and Properties

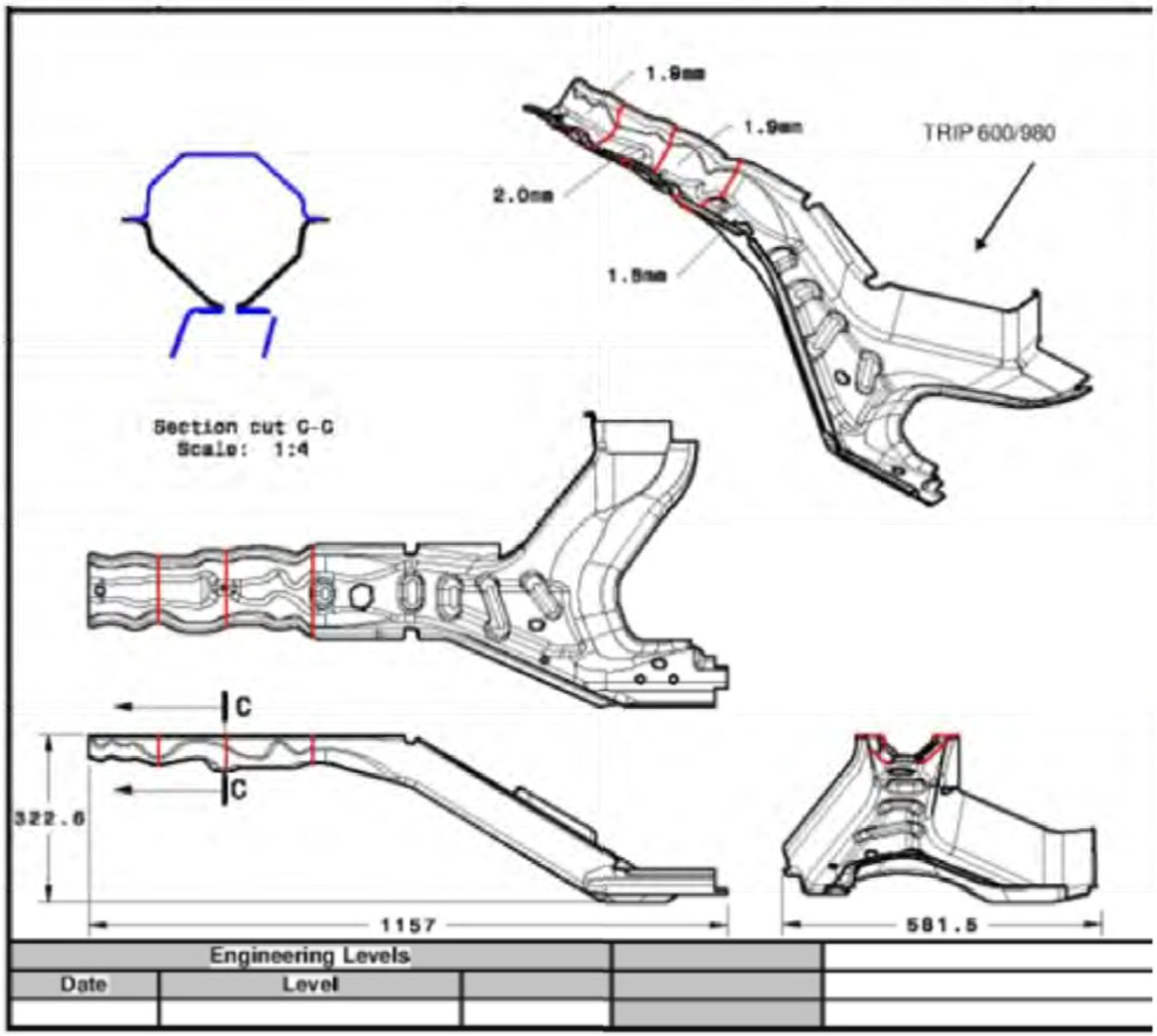

Figure 20.32: *Front F*

Nature's Way to Mobility

FutureSteelVehicle

T6 Gauge Optimization Study

16th August 2012

Full Report R1

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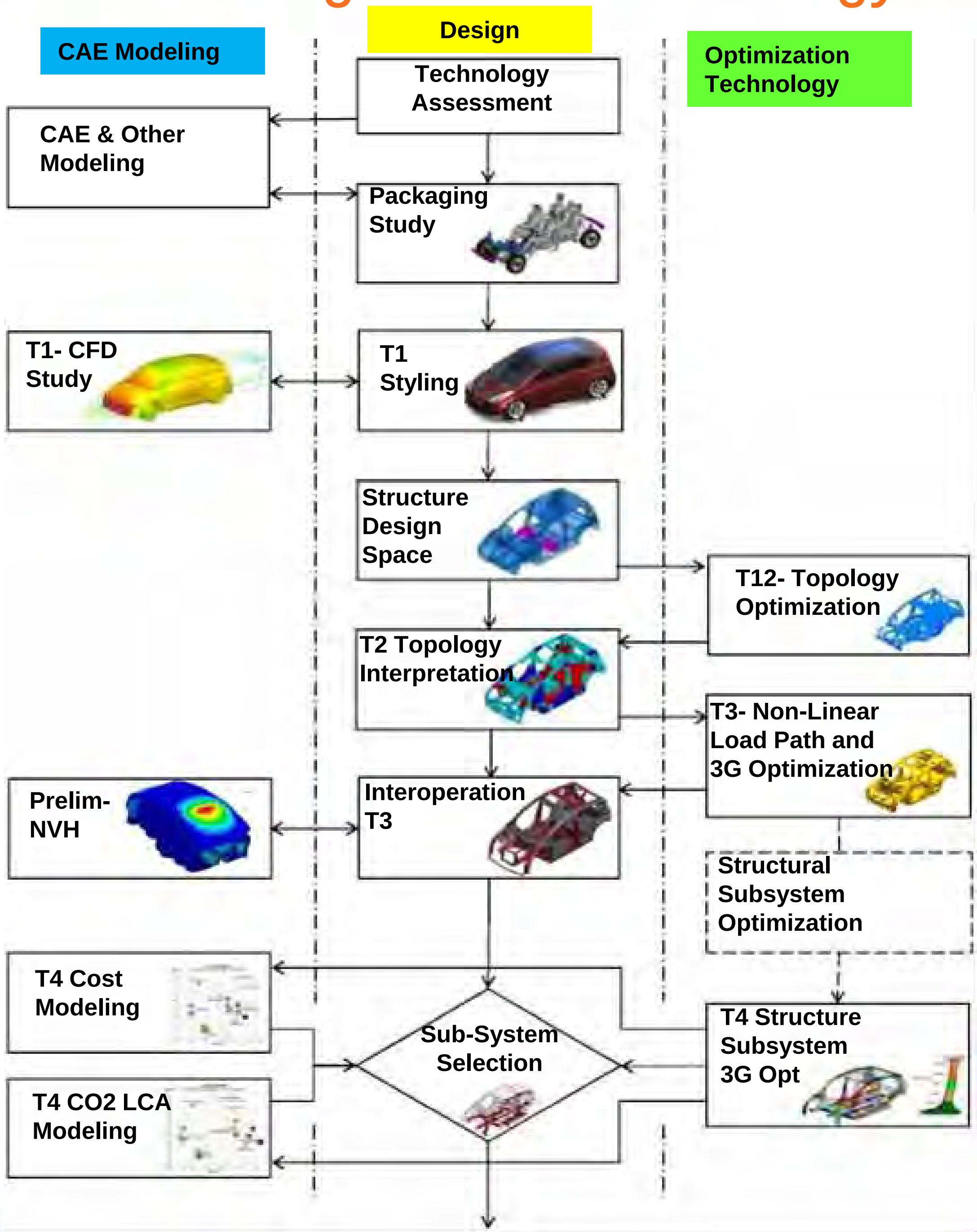
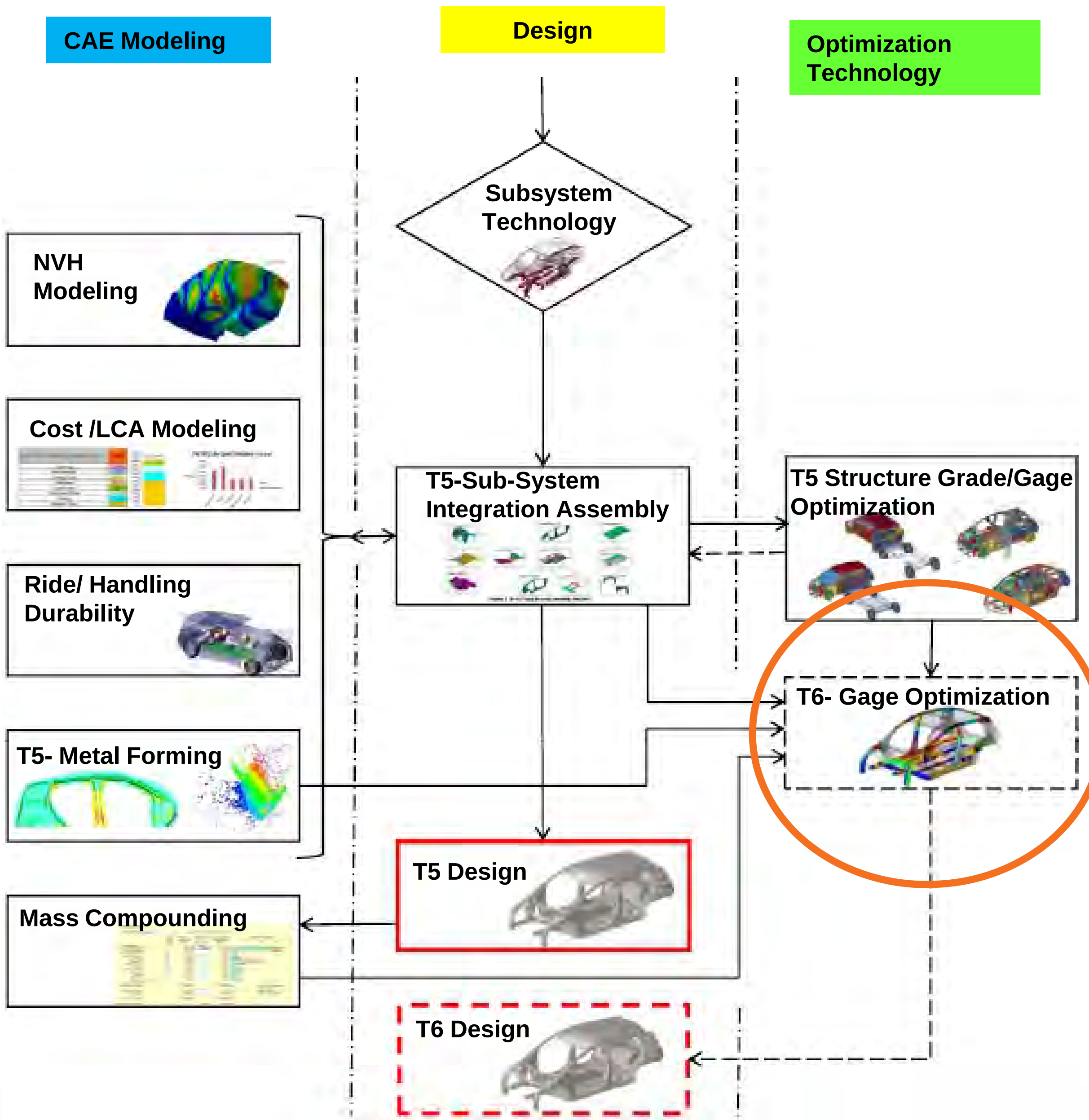
T6 Project Overview

1. Background
   - Design Process Strategy
   - T5 vs Design 336 (T5 Optimization)
2. Objective
3. Project scope :
   - Task1: Baseline Model and Results
   - Task 2a: Grade Selection based on one step forming evaluation (T6 and T5)
   - Task 2b:T6 Gage Optimization
   - Task 2c:

1.0 Background – FSV Design Process Strategy



1.0 Introduction – FSV Design Process Strategy



Models

T5-Final

- Final Design from EDAG

T5
D336

- Update with T5 Optimization D336 Grades and Gages >0.5 mm

T6
Baseline

- Front Long. 3B formability with TRIP 800
- One Step Forming validation for all parts

T6-Final

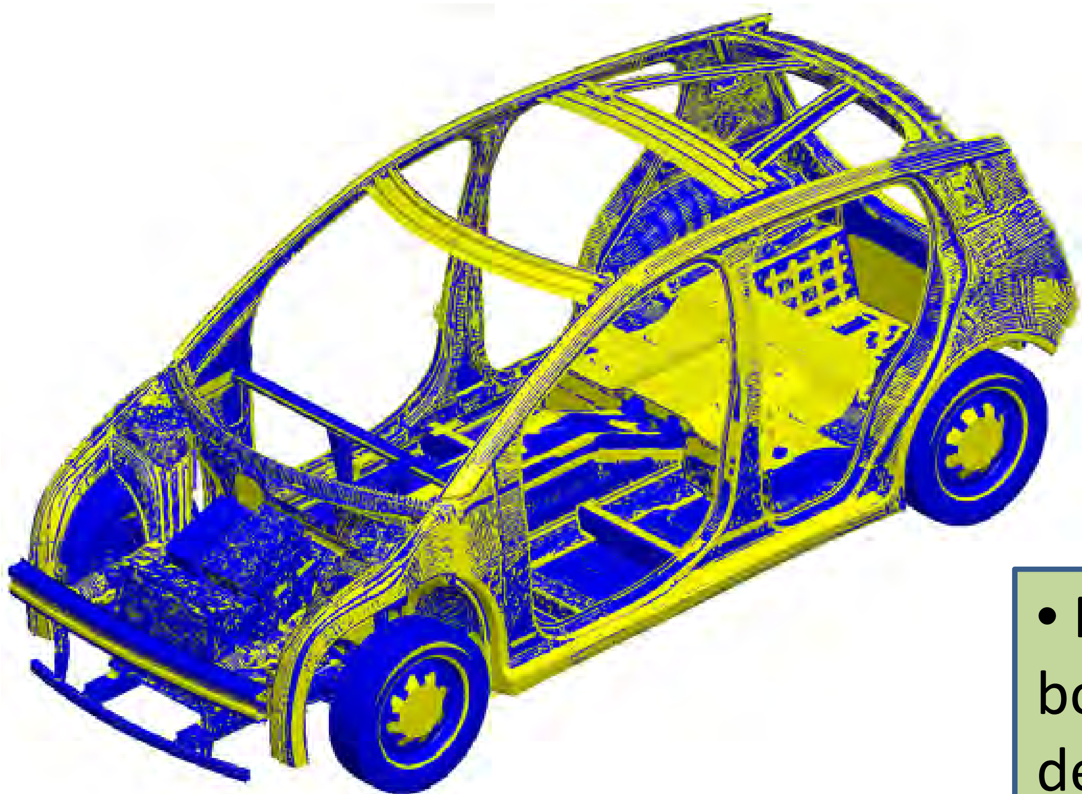
- Perform 4 Phases Gage optimization
- Design Validation

1.0 Introduction – FSV Design Process Strategy

- T5 final design was completed based on optimization design input in parallel with manual design process as shown in FSV design process strategy (see page 2,3 and 4). However, the final T5 design model and T5 optimization model (D336) were not exactly on the same design level (Optimization model was not updated to the final T5 design). Based on past experience it was assumed that some of these design changes could contribute to the vehicle performance. At the same time, more detailed forming (manufacturability) was required for some of the components with challenging geometry (such as longitudinal front rail). The goal of T6 design is to optimize the vehicle body with final T5 design geometry and manufacturing effects (forming) for the most optimum mass reduction.

1. Background :T5 Final vs. T5-D336 (Geometry)

- The overlap of two vehicle BIW shows design difference in two designs



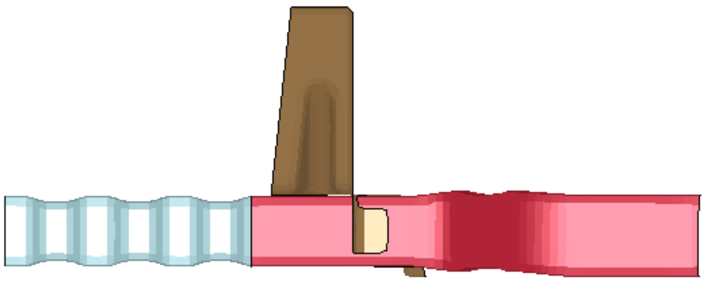
T5 Final Model

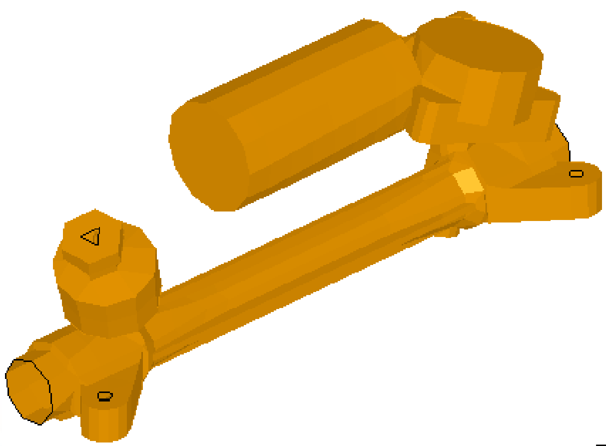
T5 D336 Model

- Minor geometry difference in body side but major noticeable design difference in front end

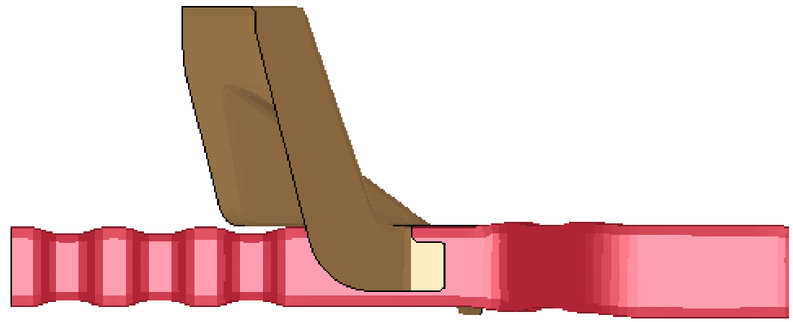
T5 Final vs T5 D336 front end difference

T5 Final

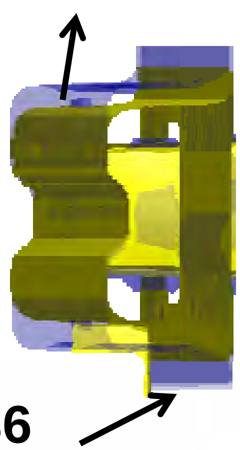




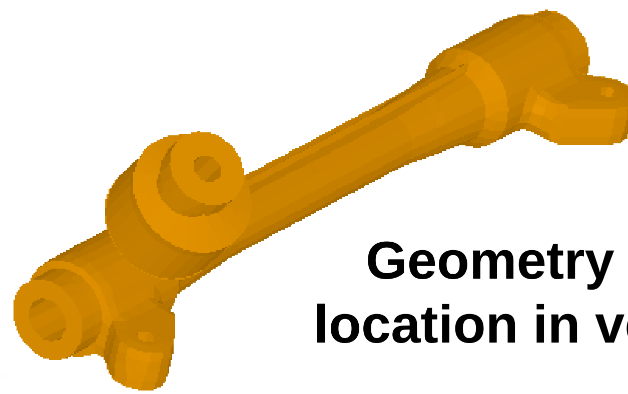
T5-D336



T5 Final

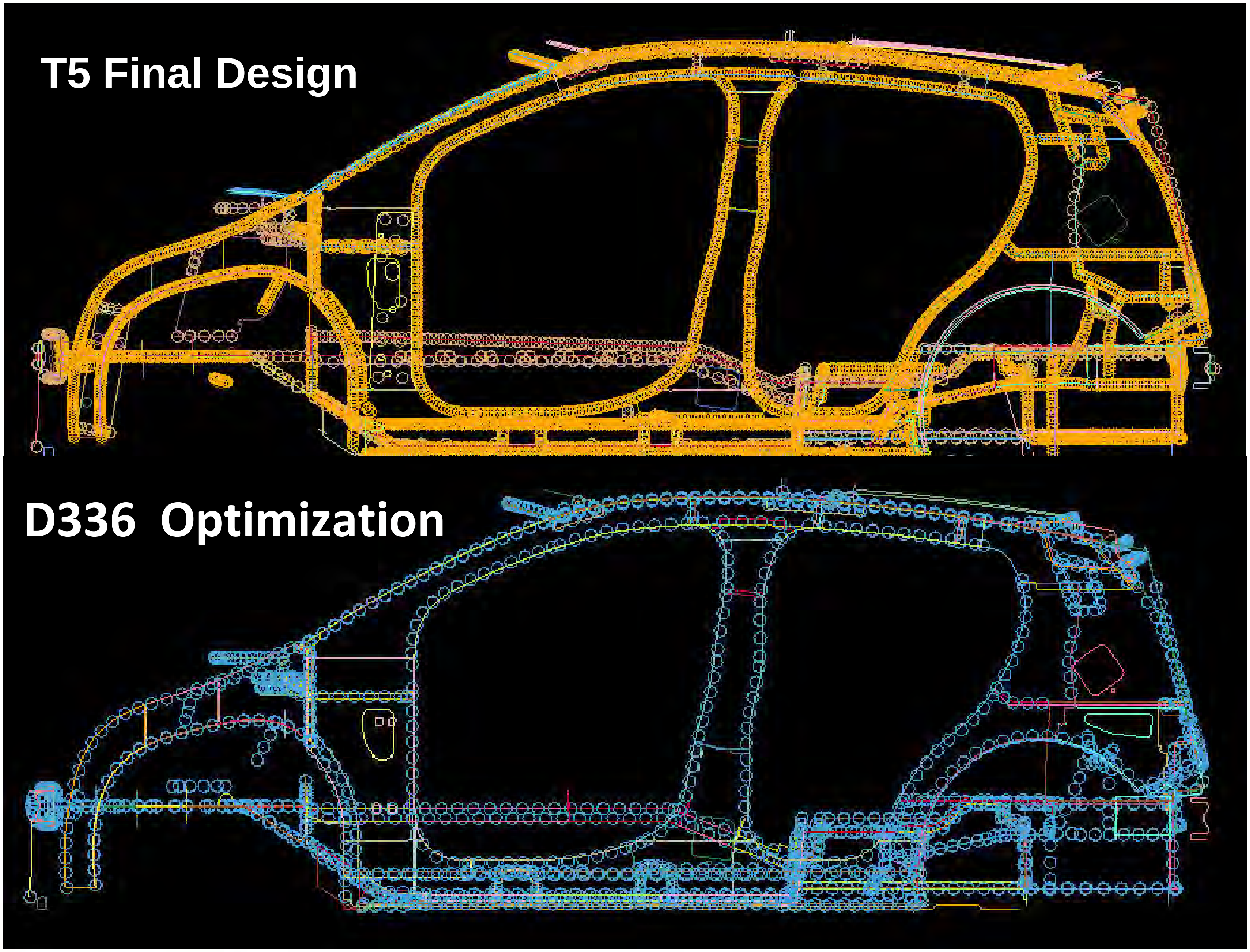


T5-D336



Geometry and location in vehicle

1. Background :T5-Continuous Joining vs T5-D336 Spot Weld



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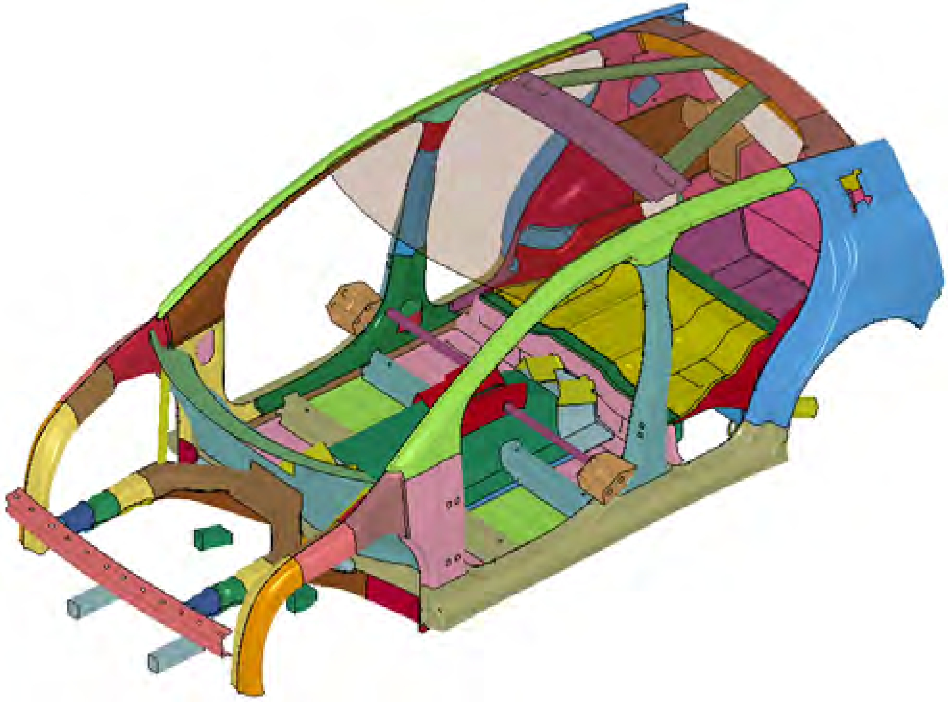
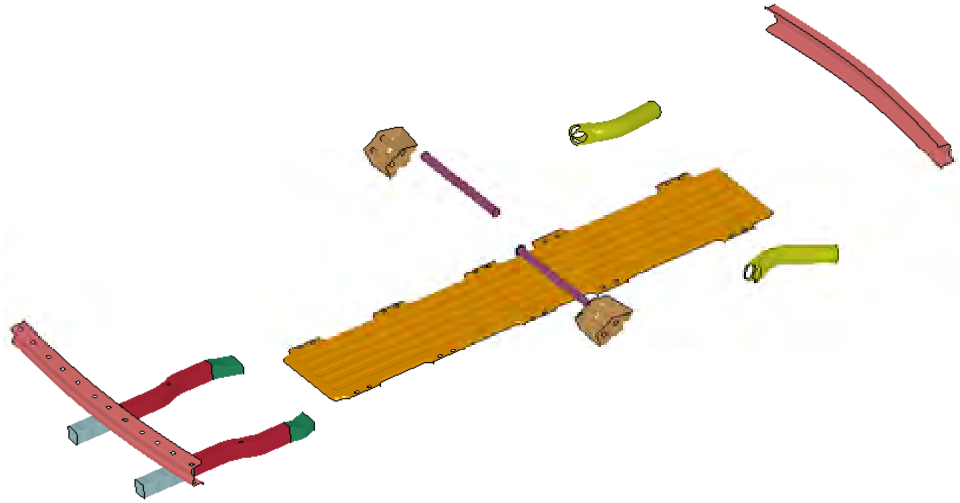
1.0 Background : T5-D336 2G Optimization Results





Baseline OPT Parts Mass	= 213.7 kg
D336 Mass	= 190.6 kg
Total Mass Savings	**= 23.1 kg (10.8%)**
Baseline BIW Mass	= 203.7 kg
Optimized Design 336 BIW	**= 188.0 kg**
BIW Mass Savings	**= 15.7 kg (8.4%)**

2.0 Objective

- Perform gauge optimization for the final T5 design with consideration of using the following advantages for potential mass reductions:
  - – Parts are all manufactureable
  - – Packaging is finalized
  - – Improved Joining (Laser welding, Adhesive)
  - – New parts

3.0 Project Scope: T6 Baseline Definitions

- We will use the following **definitions and acronyms**:

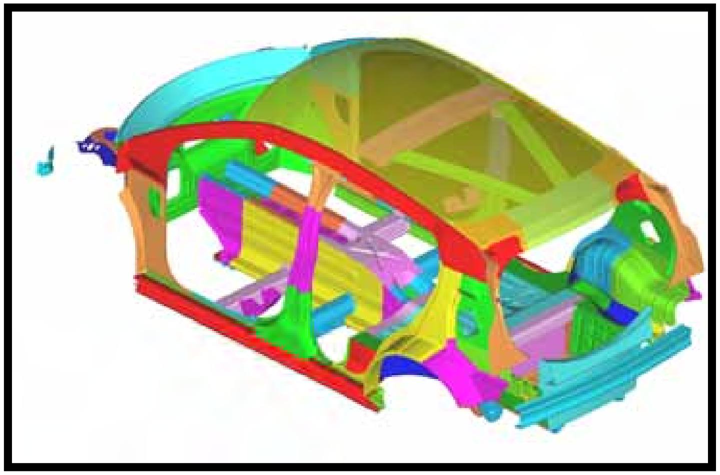
T5 Final = T5 FE Model that was released by EDAG at the end of T5 with BIW mass of **188.4 kg**

T6 Baseline = T5 Final + :

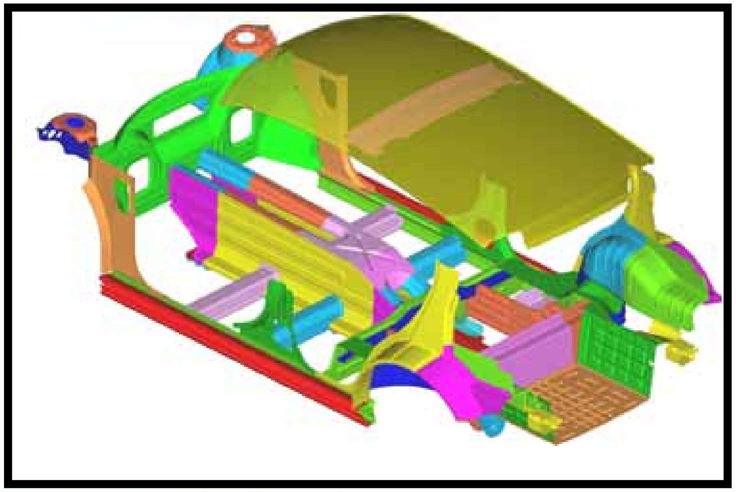
- The front end was carried over from T6 forming (3B Forming) with TRIP800
- Shotgun Material update
- No gauges less than 0.5 mm
- D336 Optimization Grades that satisfied one step formability
- D336 Optimization Gauges that are **Less** than T5
- All TWB were mapped

3.0 Project Scope: T6 Baseline Grade /Gage Changes

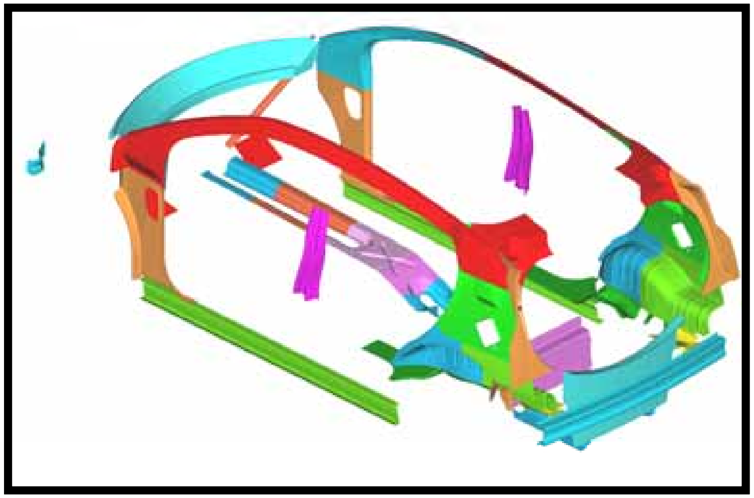
- The following parts were updated by changing grades and/or gages to represent T5-D336 optimization results.
- Front End of sub-system of FSV from T5 was used with longitudinal from 3B forming optimization.



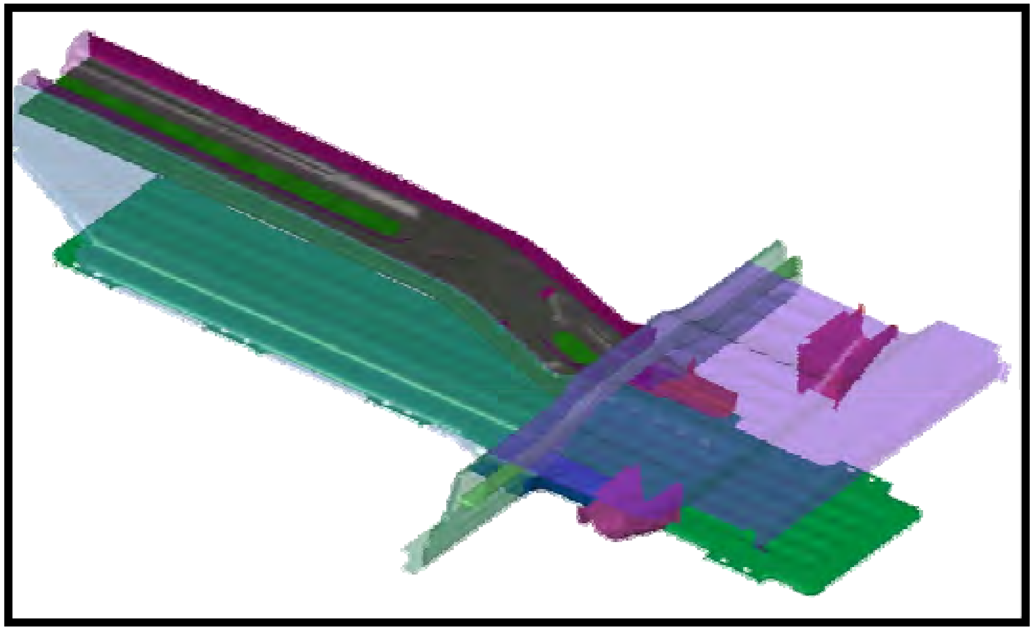
Grade Changes

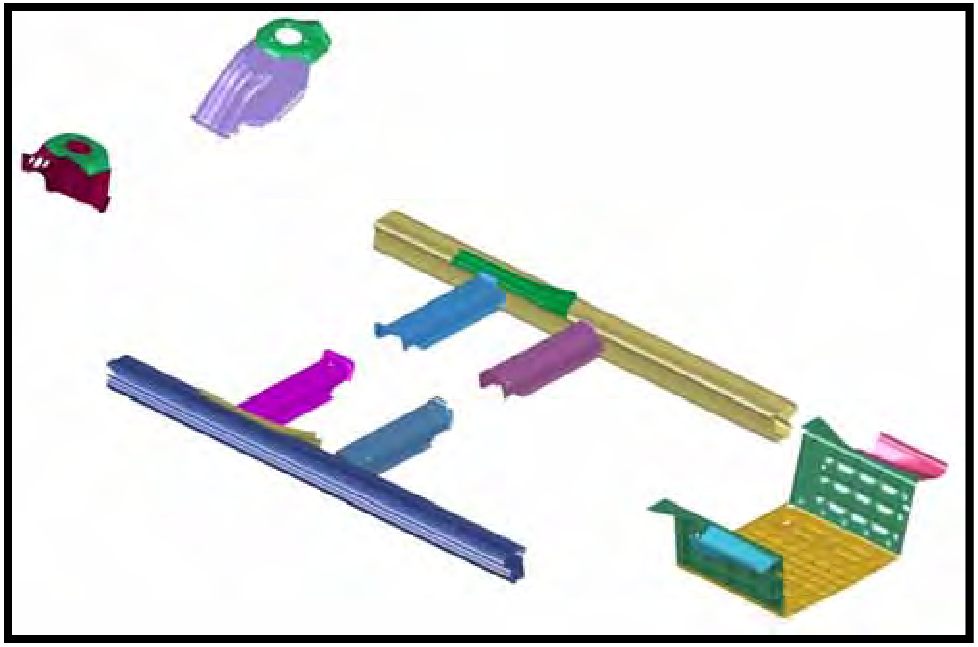


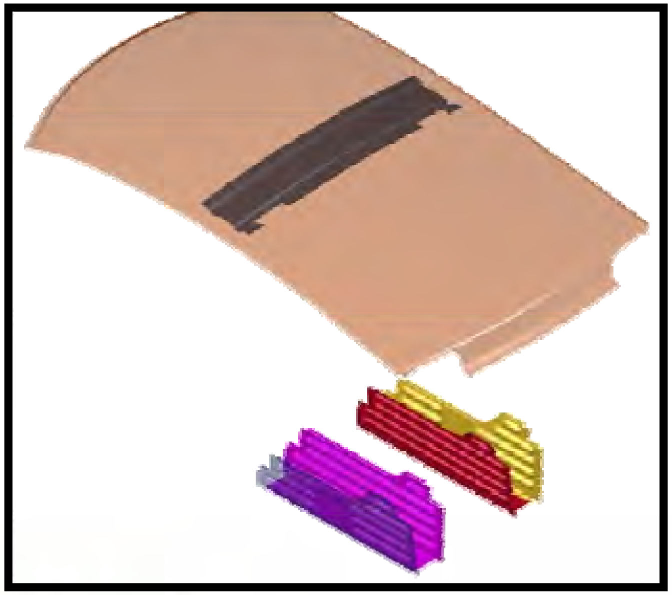
Gauge Changes

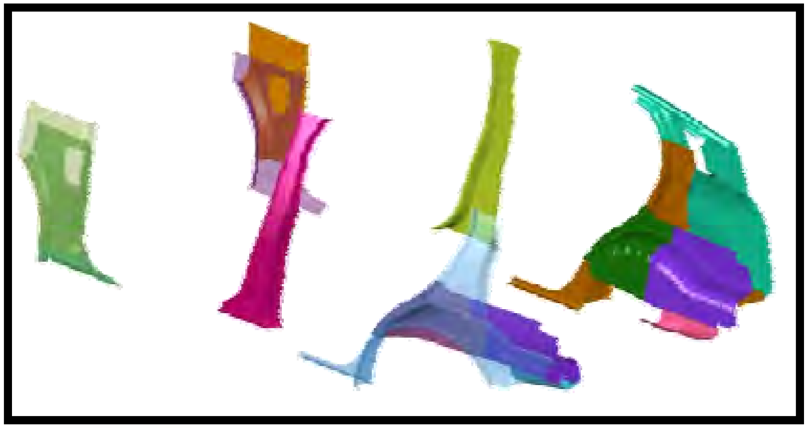


T6 Baseline Material Upgrade

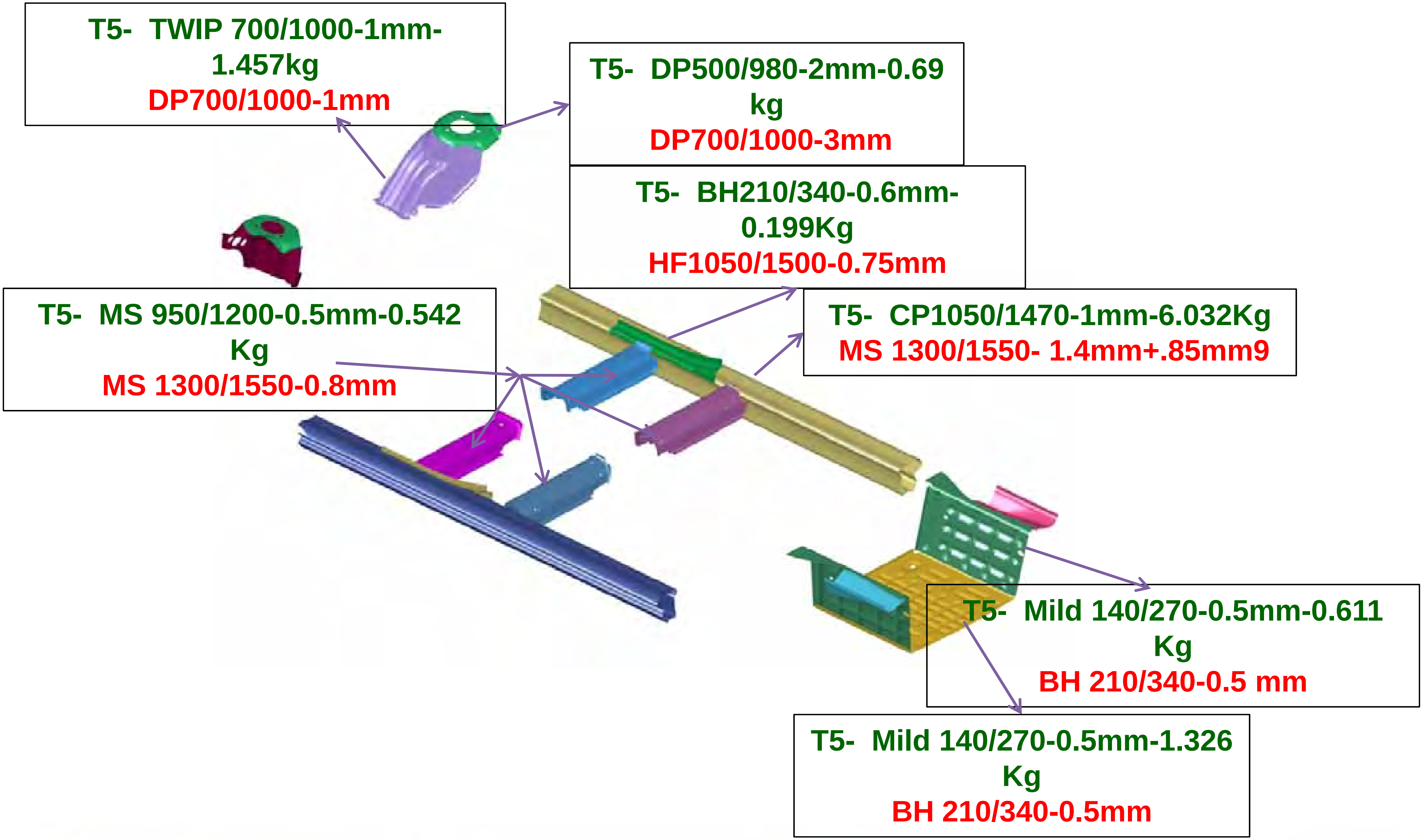




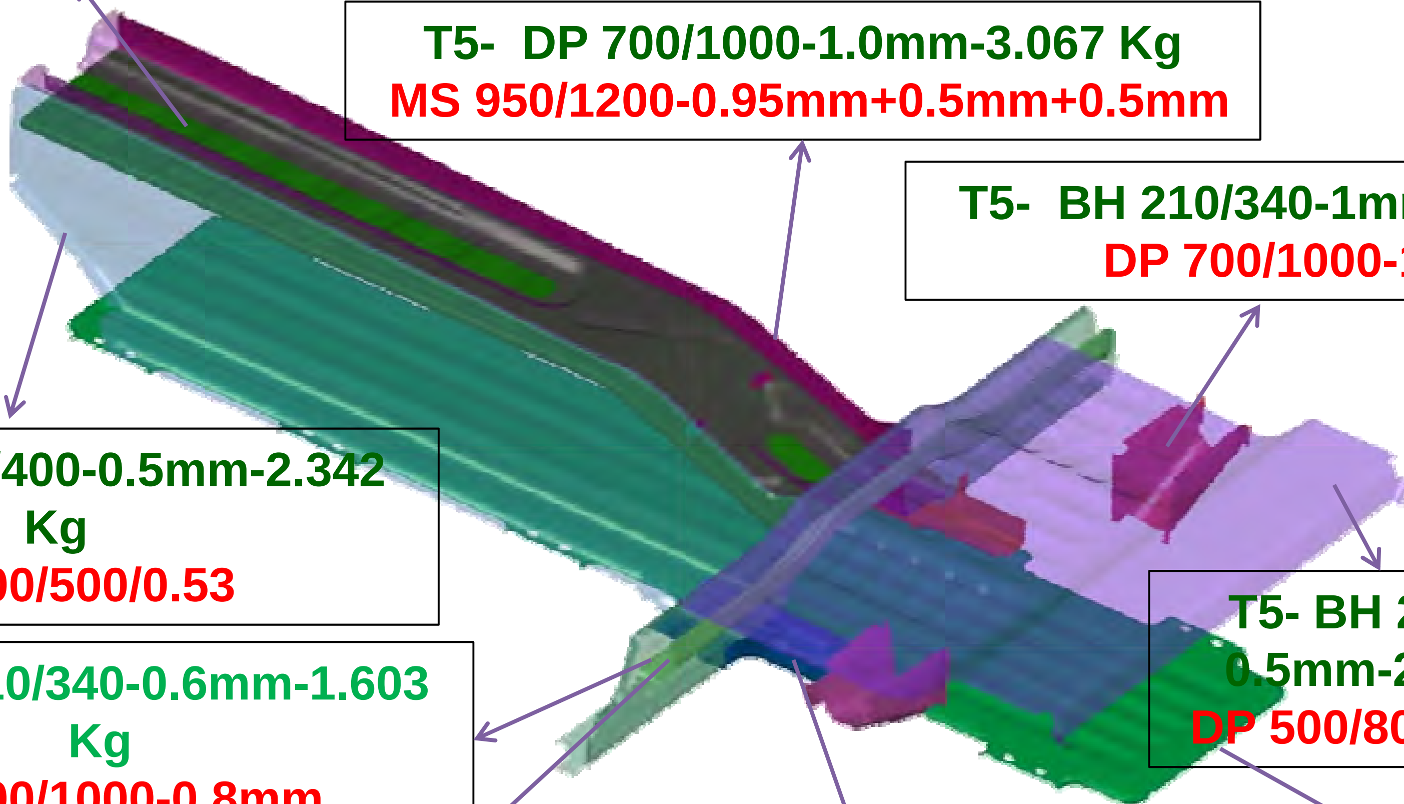




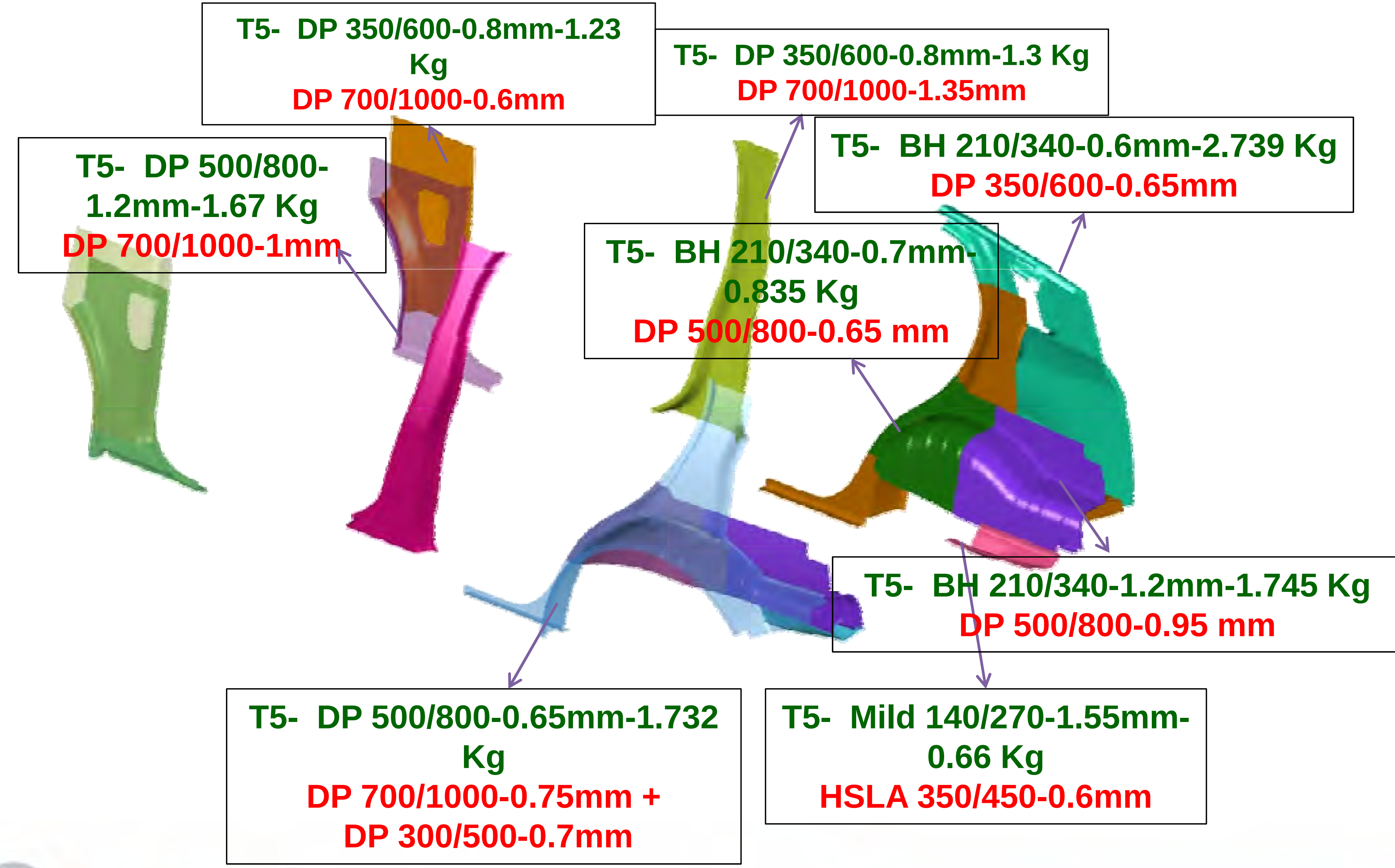
T5-Final to D336 Material Upgrade



T5 to D336 Material Upgrade



T5 to D336 Material Upgrade



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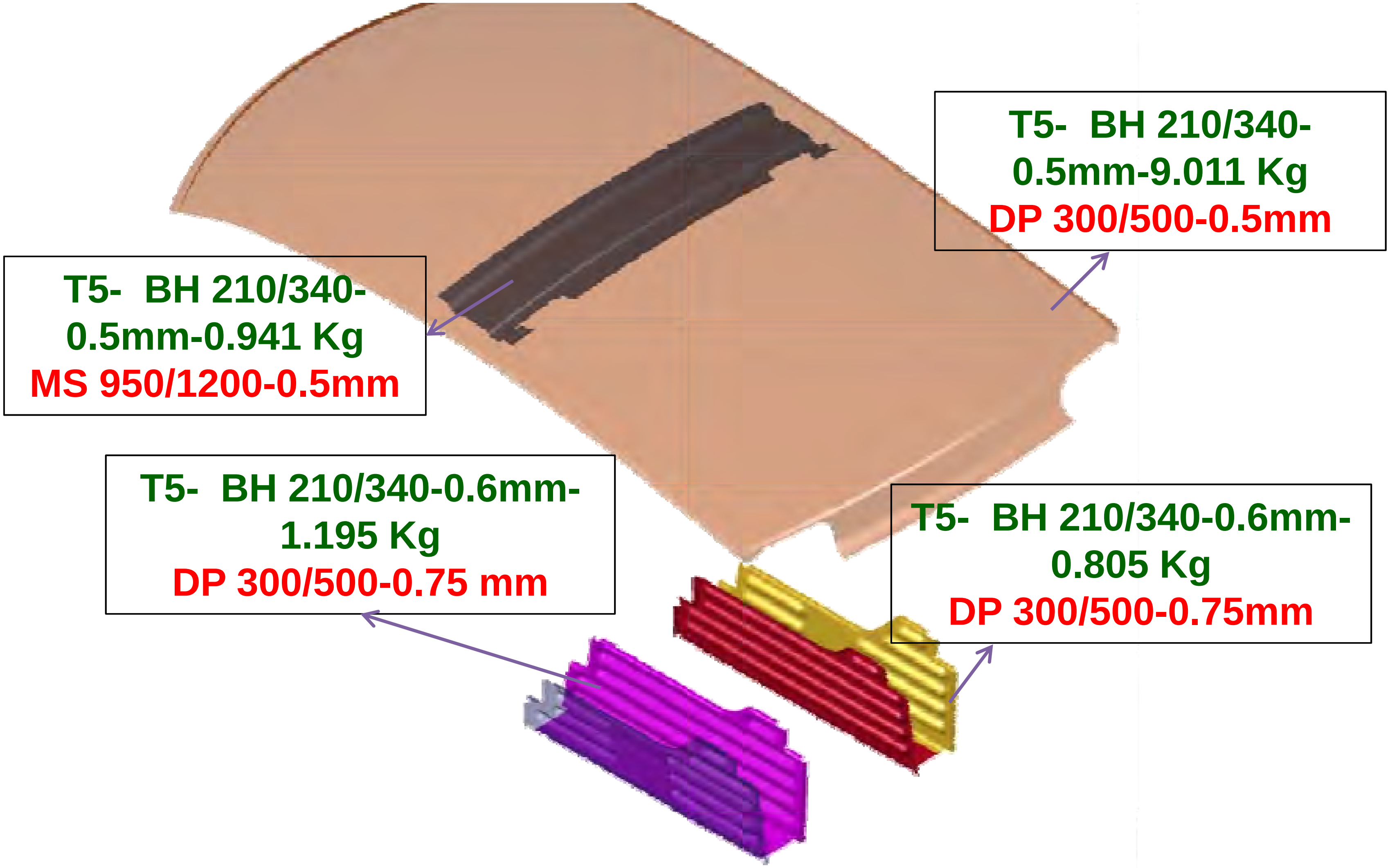
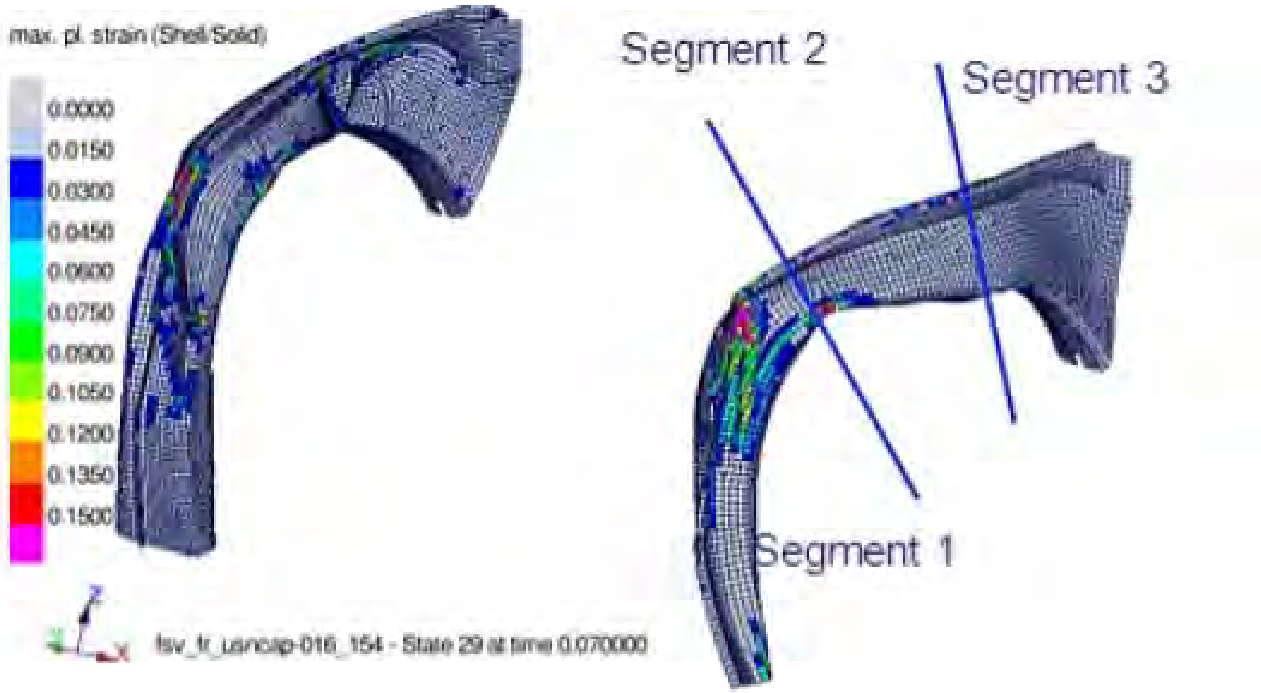
T5 to D336 Material Upgrade



Shotgun Material Model Update

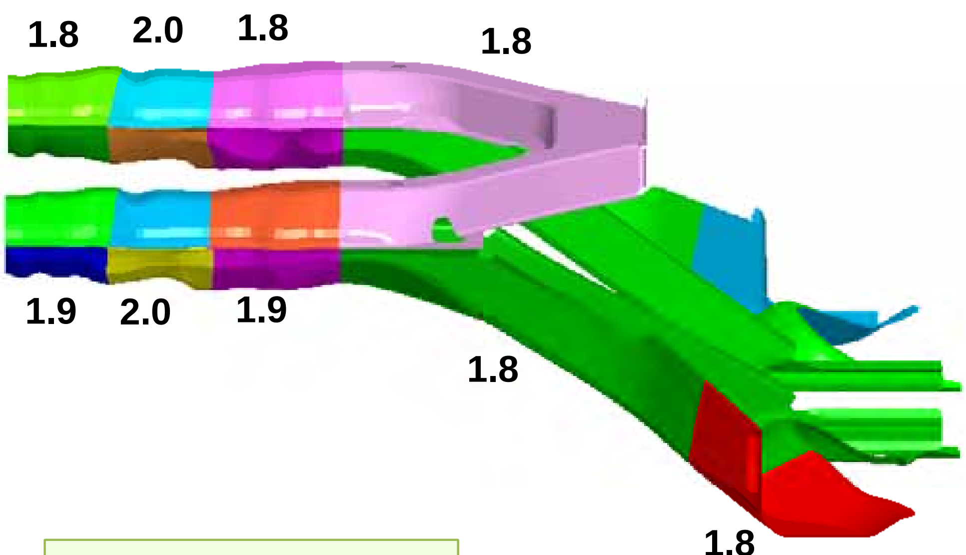


1. Segment 1 – Minimum required elongation 12% **Use DP980**
2. Segment 2 – Minimum required elongation 10% **DP 1200**
3. Segment 3 – Minimum required elongation 7% **Full Hot Stamp**

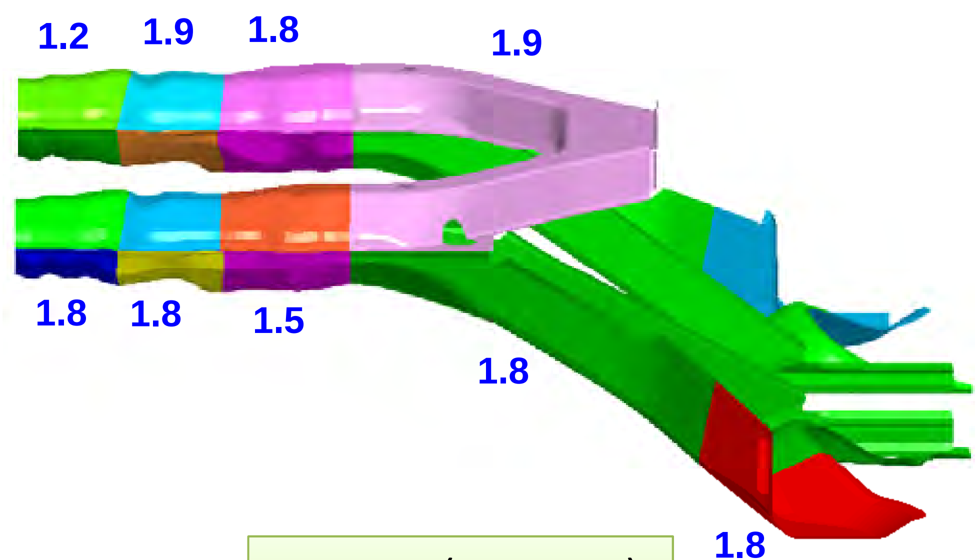
Figure 15.4: *Front shotgun members - Minimum required elongation*

3.0 Project Scope: T6 Baseline - TRIP800 Rails Forming Results

- Front End of T6 Baseline was kept as final design of 3B forming optimization (D63) for consistency
- Used T5-D336 variables for all components of front end system for T6 optimization
- 0.5 Kg mass reduction



T5 (TRIP 980)
Mass =17.7 kg



Opt D63 (TRIP 800)
Mass = 17.2 kg

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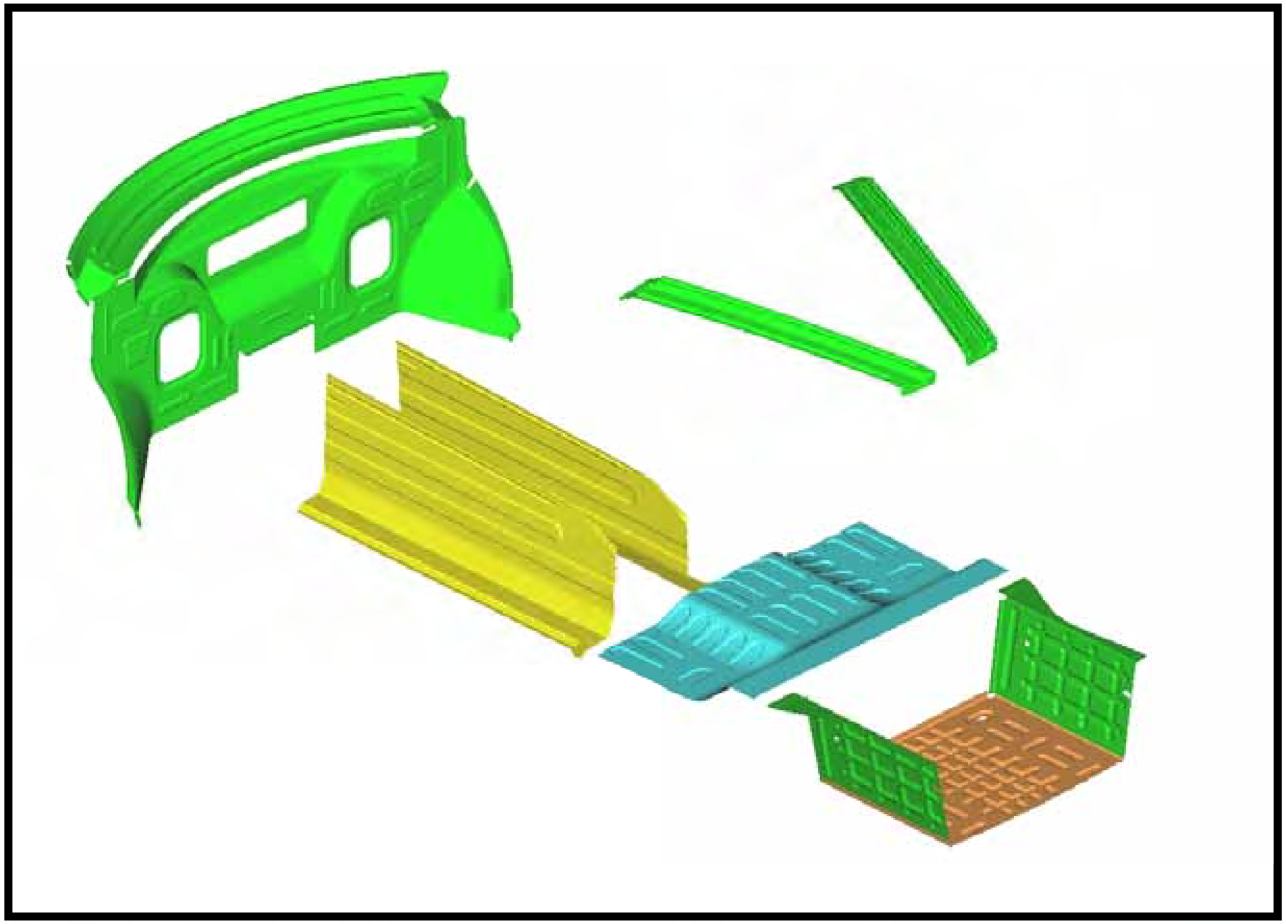
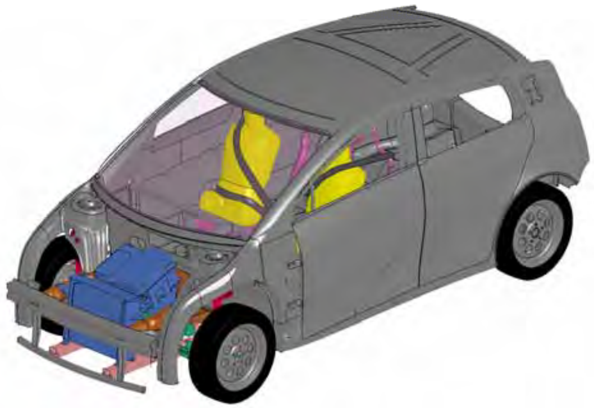
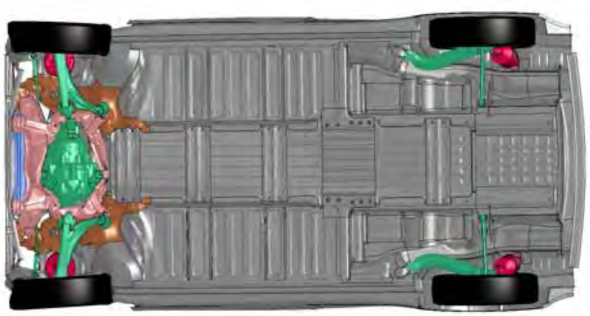
3.0 Project Scope: T6 Baseline – Up-gauged to 0.5

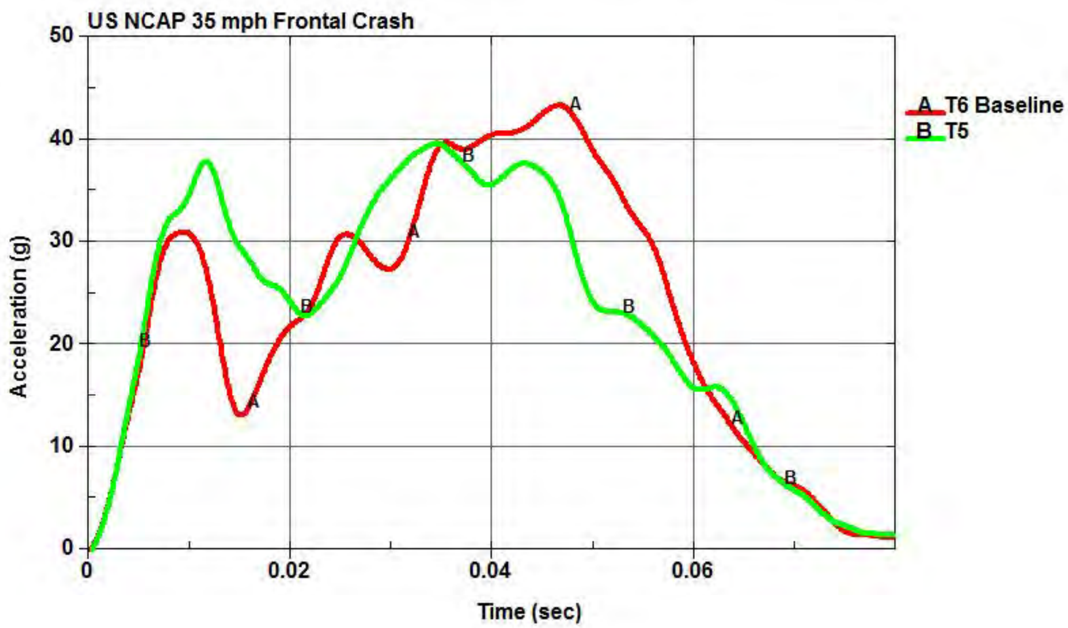
- D336 optimized parts had some gages lower than 0.5 mm. However, based on practicality, all of these parts were upgaged to 0.5 mm



3. Project Scope - T6 Baseline Results NCAP Frontal Impact

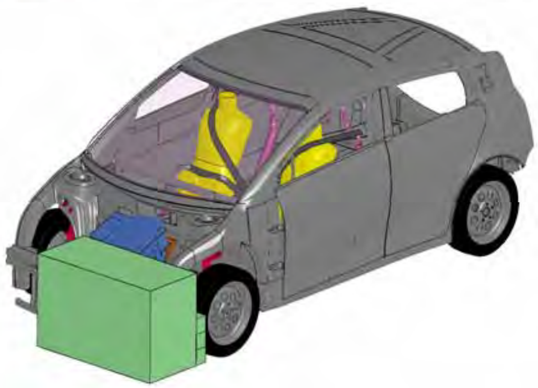


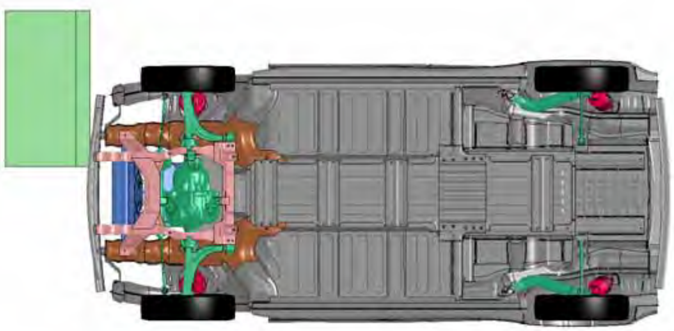


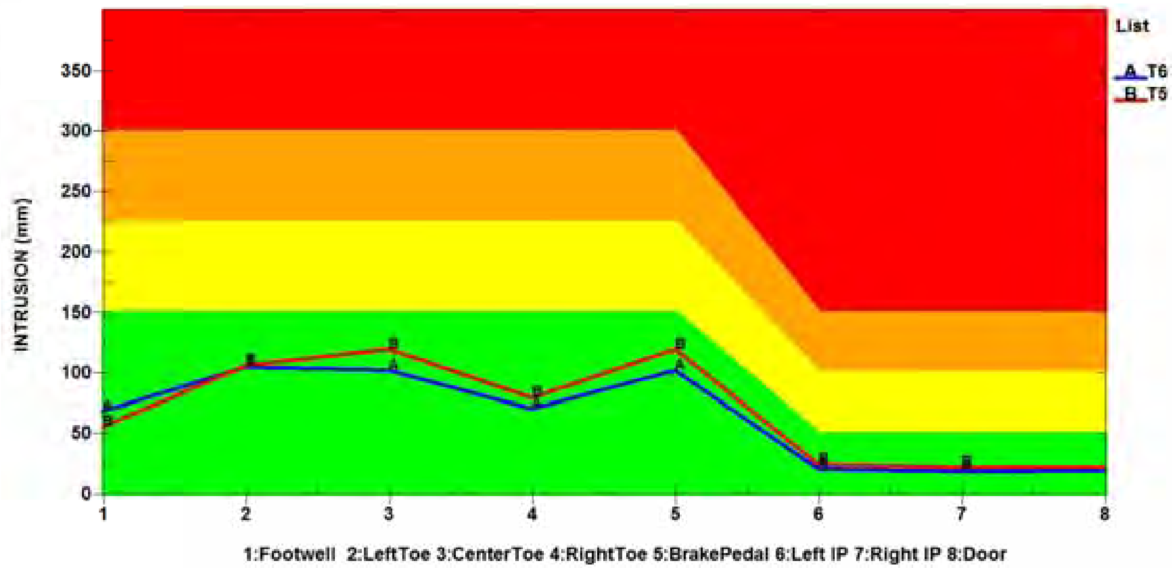


- Vehicle pulse is not meeting the targets of 39.7g at 40-50 msec. Based on vehicle pulse, TRIP 800 in T6 baseline has a different buckling mode. Therefore energy absorption in 1st 20 msec is less, which causes a higher pulse later.
- Since D336 optimization gages were used in the vehicle body, which was not optimized with new TRIP800 front end, this result could be expected.
- These results will be fixed by T6 gage optimization.

3. Project Scope- T6 Baseline Results -40%ODB Frontal Impact

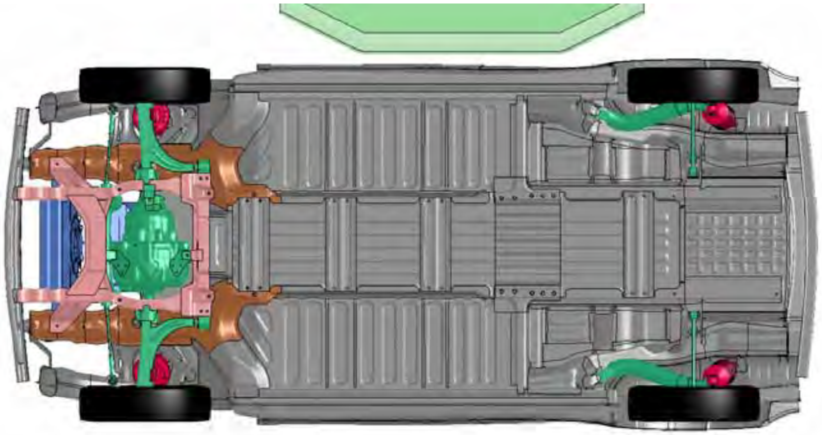


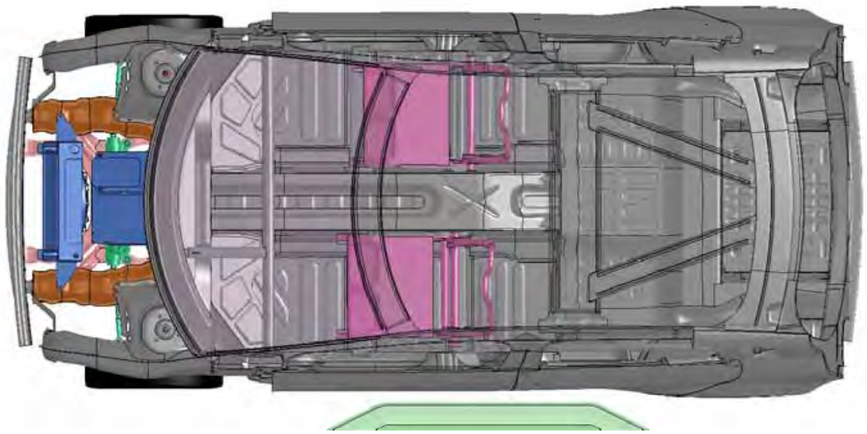


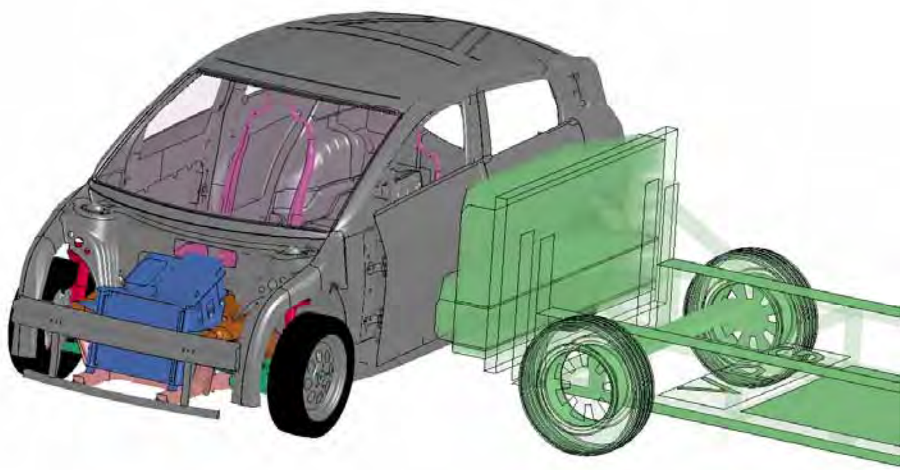


- IIHS 40% ODB frontal impact results are in good range in all areas of IIHS measurements.

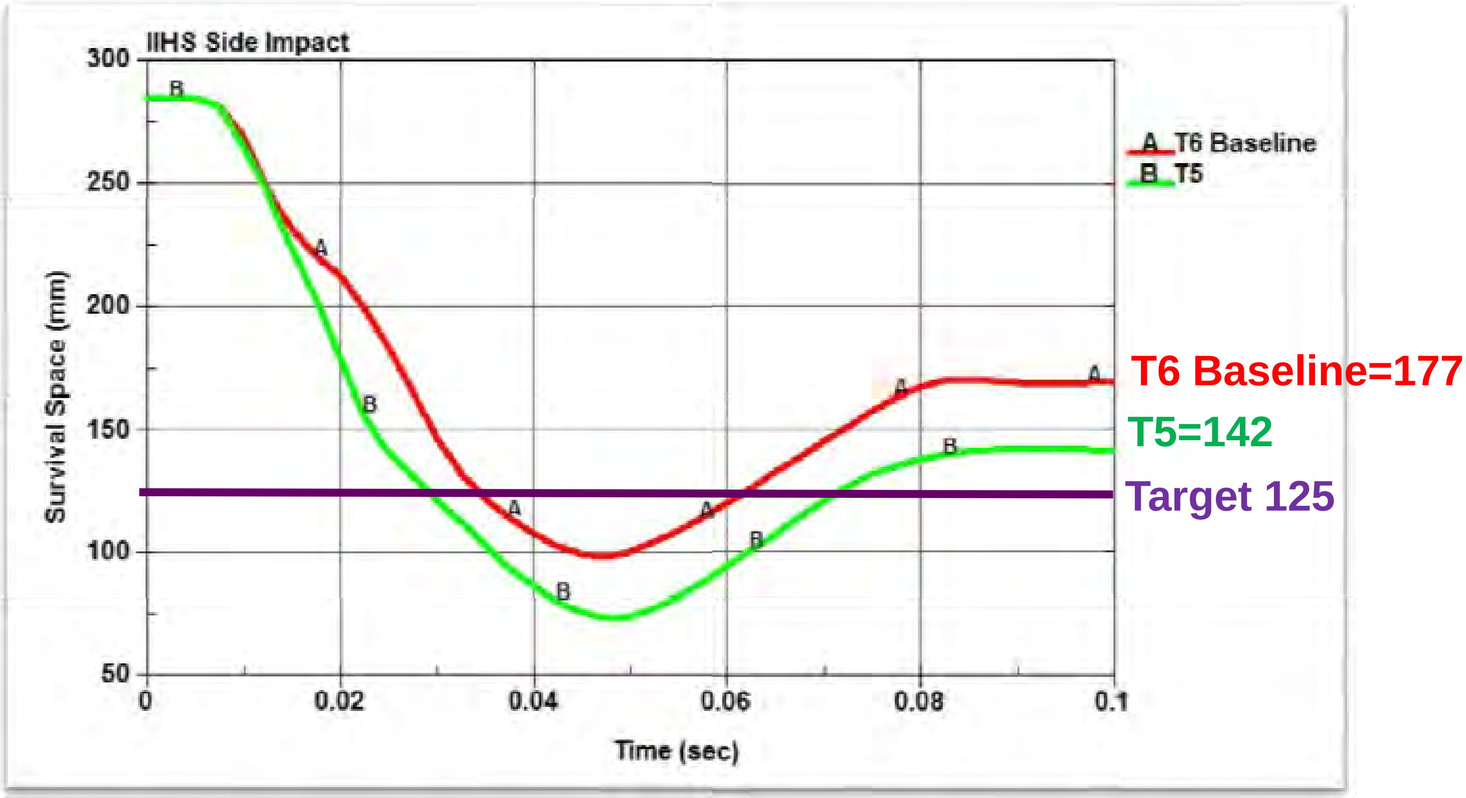
3.0 Project Scope- T6 Baseline Results- IIHS Side Impact





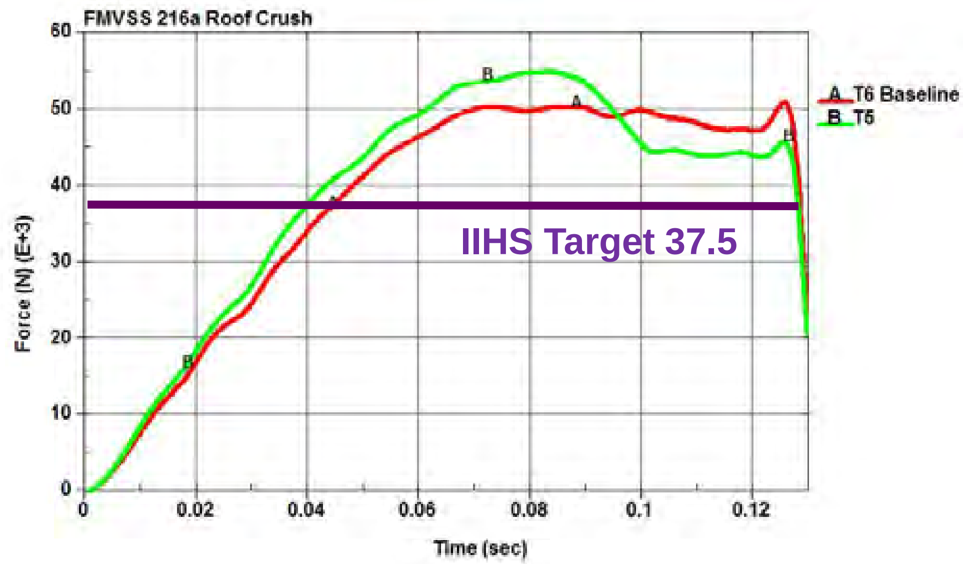


3.0 Project Scope- T6 Baseline Results- IIHS Side Impact



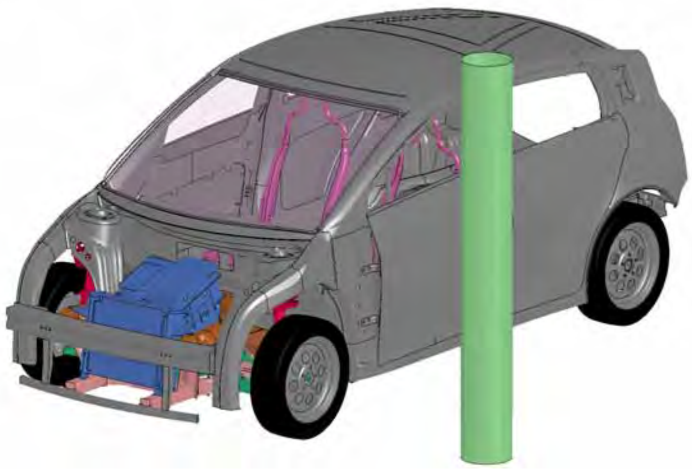
- T6 baseline with D336 (T5 optimization) gages show more survival space compared to T5 results and Targets.
- The key component and reason for this better result is that the side impact load path was maintained even though the gages of the T6 body were lowered.

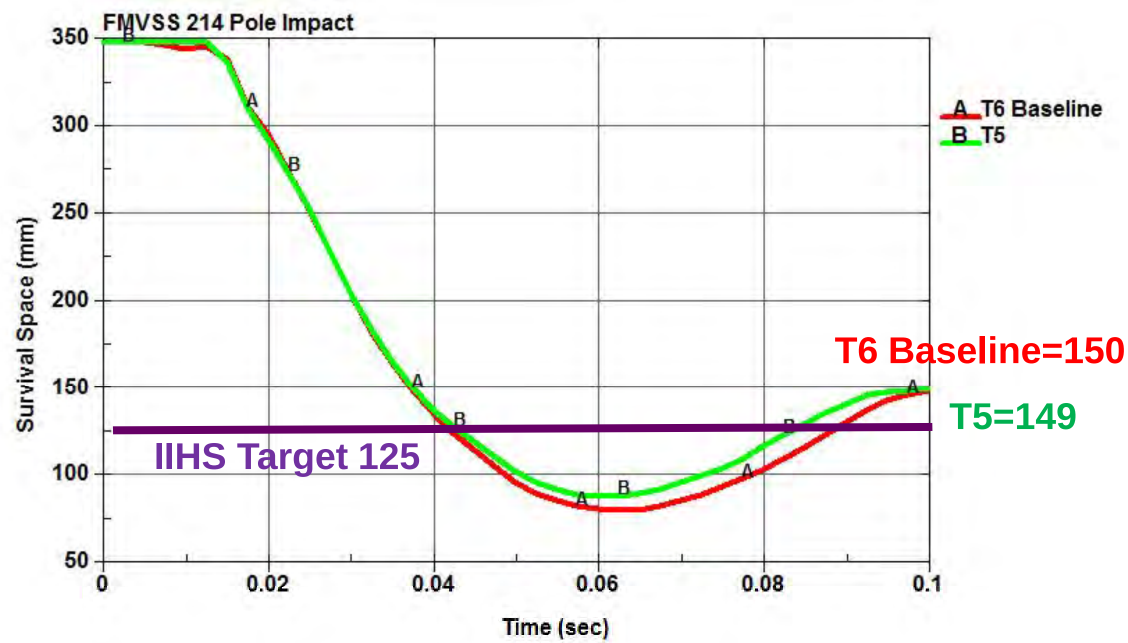
3.0 Project Scope- Baseline Results- IIHS Roof Crush

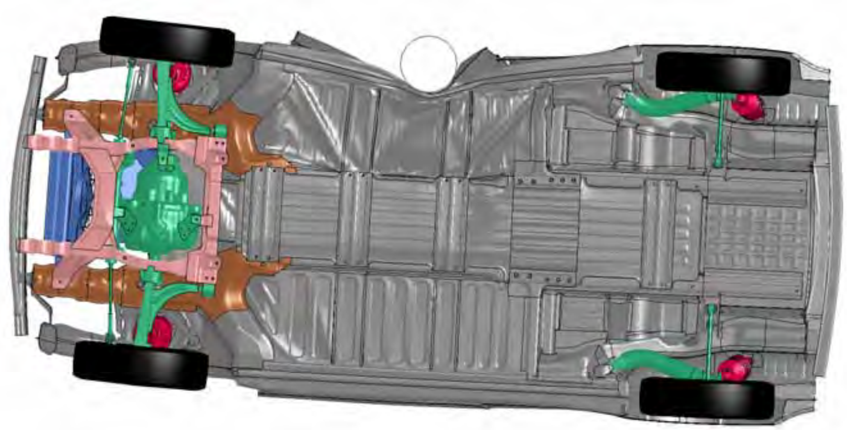


- FSV will meet IIHS and FMVSS 216 roof crush requirements. This result is achieved by taking advantage of AHSS with a good load path.

3.0 Project Scope- Baseline Results- IIHS Pole Impact







- FSV will meet IIHS and FMVSS 214 (U) Pole Impact requirements. This result is achieved by taking advantage of AHSS with a good load path.

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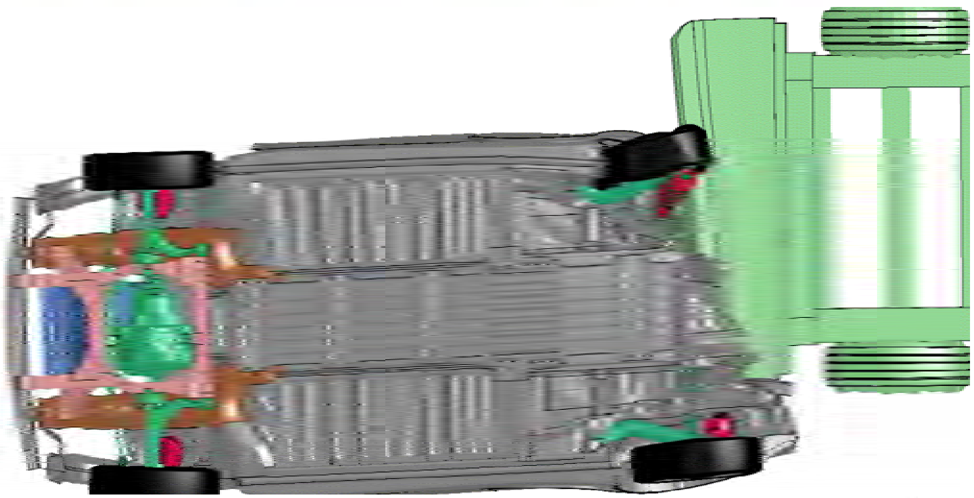
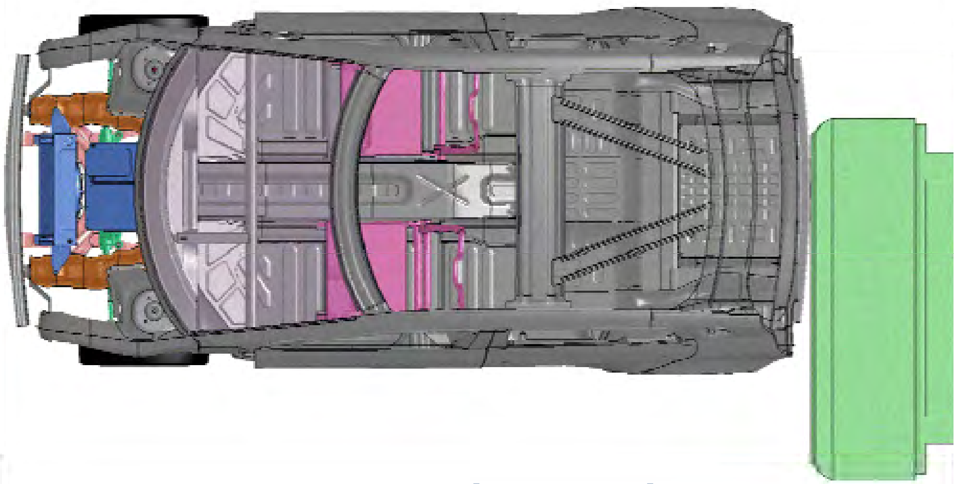
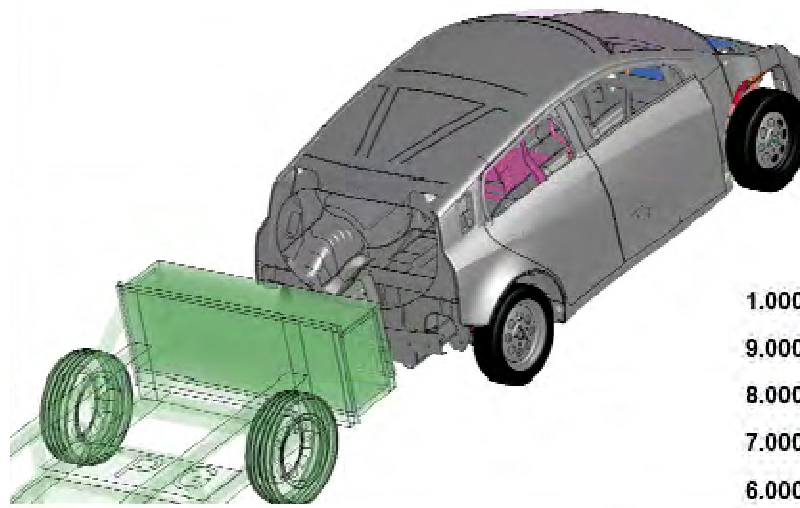
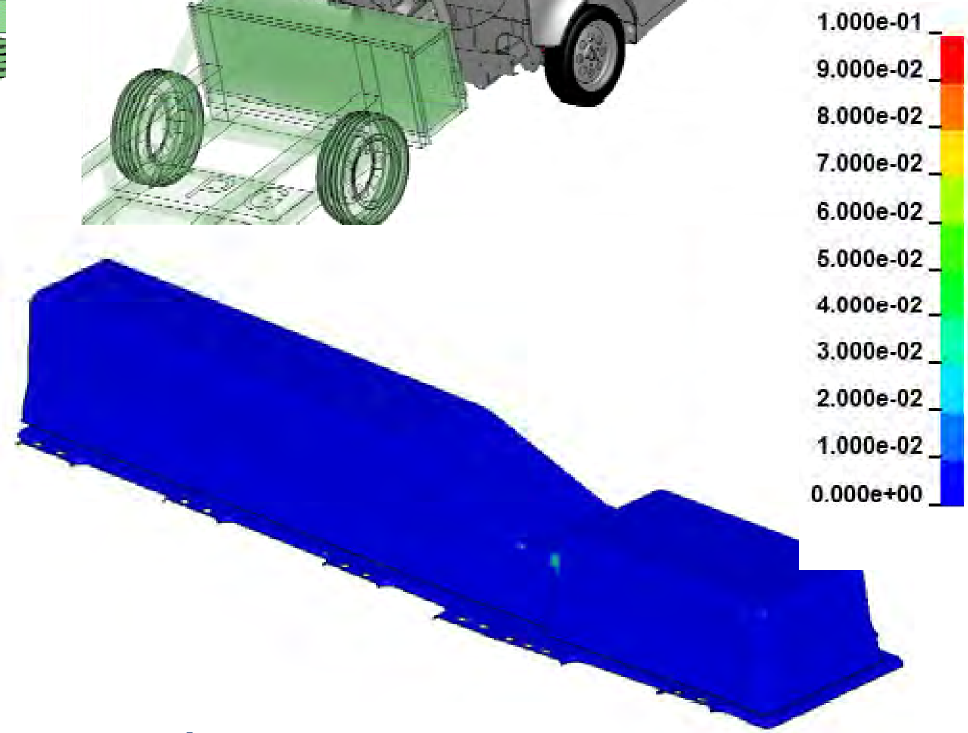
3.0 Project Scope- Baseline Results- FMVSS301 Rear Impact





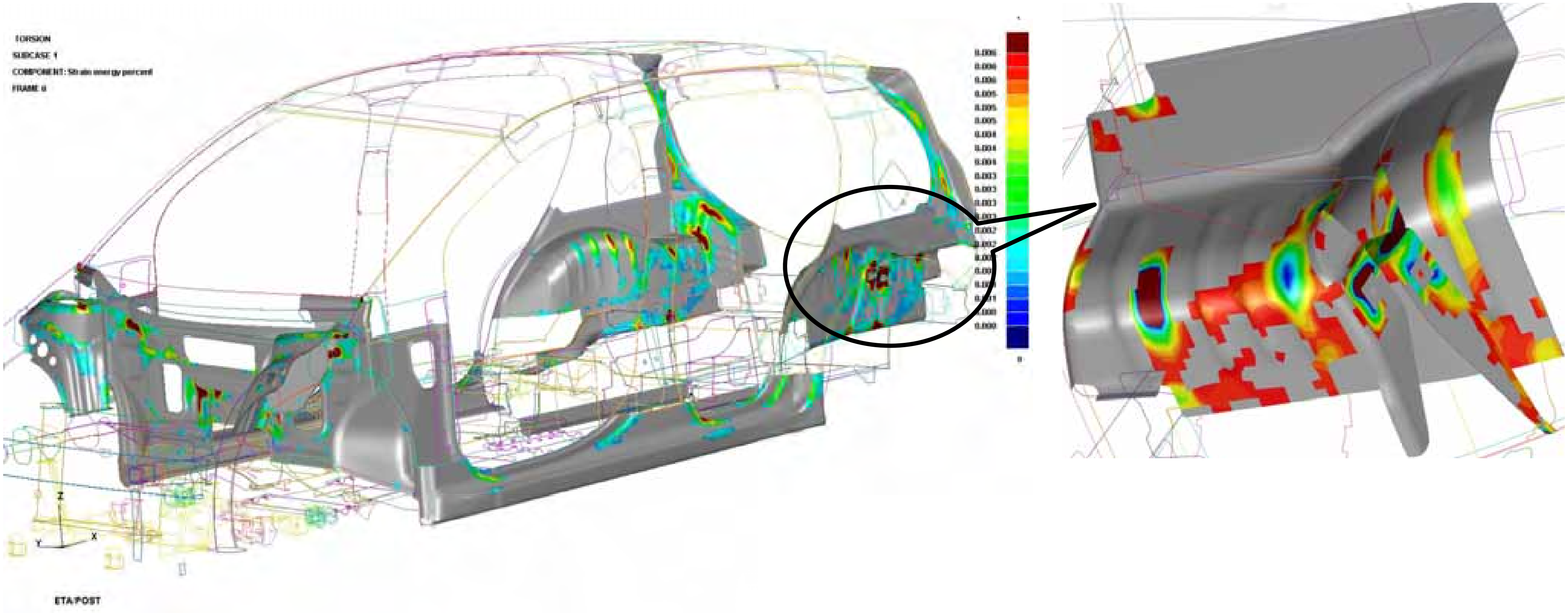




- Battery package does not contact other parts
- Small amount of strain in the battery structure outer cover

3.0 Project Scope: Baseline Results Static Torsional Stiffness

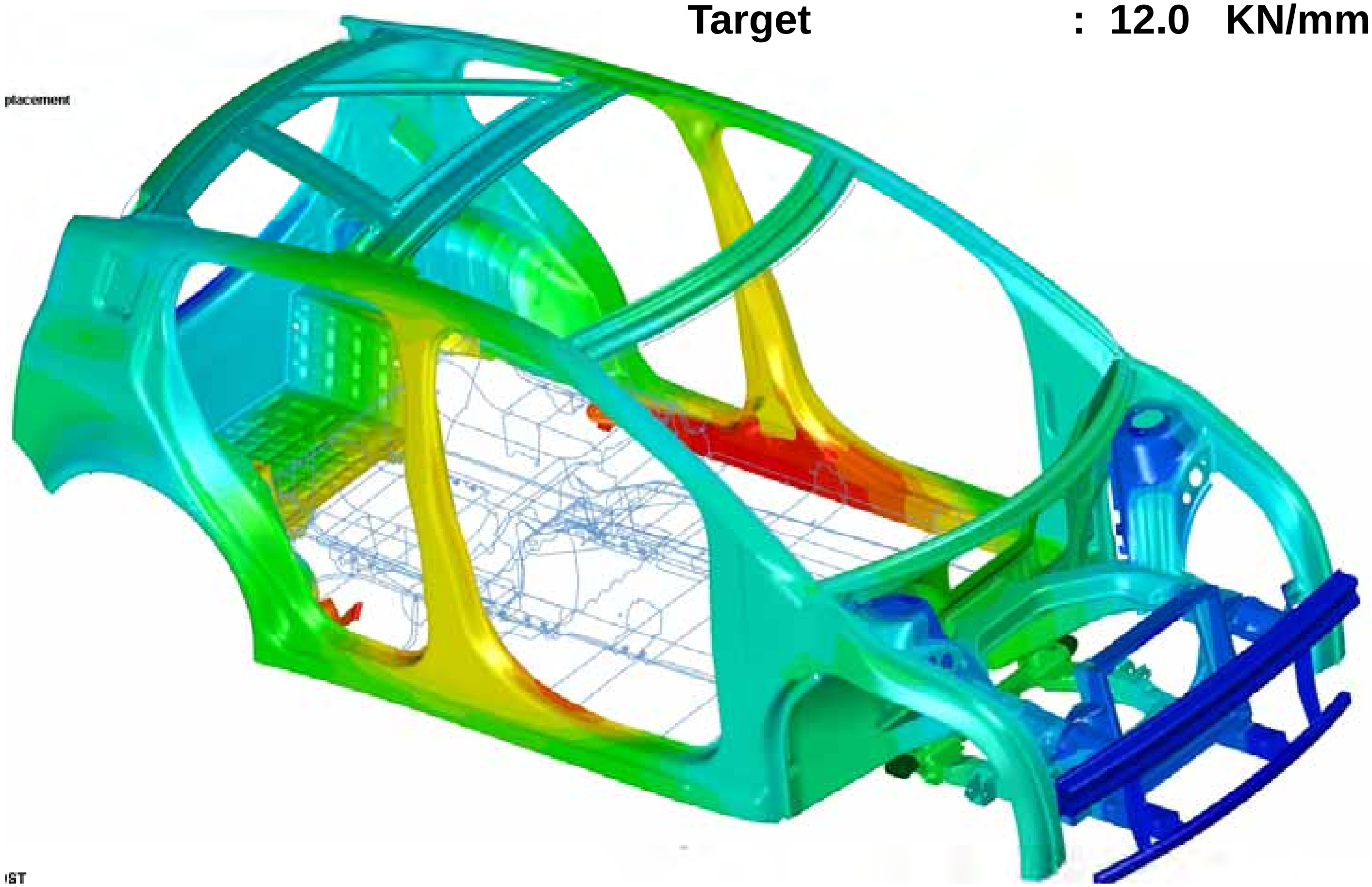
T5	**:19.6 KN-m/deg**
T6 Baseline	**:18.3 KN-m/deg ; - 6.6%**



- T6 baseline shows lower torsional stiffness, which can caused by lowering gages in rear portion of vehicle .
- Torsion will be a critical load case, since AHSS does not effect performance unless it is up-gaged locally

3.0 Project Scope:T6 Baseline Results Static Bending Stiffness

T5	**: 15.5 KN/mm**
T6 Baseline	**: 14.50 KN/mm ; - 6.0%**
Target	**: 12.0 KN/mm**



- T6 baseline shows lower bending stiffness, which can caused by lowering gages in rocker area. However, it is well over the vehicle target.

3.0 Baseline Results Summary

Design	Mass kg	NCAP	Front ODB	IIHS Side	Side Pole	IIHS Rear	IIHS Roof	Bend.	Torsion
Targets	<188	38 g	Good	125mm	125mm	Pass	37.5kN	12	20
T5-Final	188.4	39.7	Good	142	150	Good	55	15.5	19.6
T6-Baseline	179.0 **9.4 kg Lighter**	43.0	5-6% Better	170 (16.5% Better)	150	Good	51 %23> IIHS	14.5	18.3

- T6 Baseline BIW is reduced to **179 Kg mass, by applying T5 Optimization (D336 gage and grades).**
- **T6 Baseline has** better performance in several of the load cases, which could allow potential additional mass saving.
- Task 2 is to improve NCAP and Torsion results by balancing the gages
  - Provide additional mass reduction

T6 Optimization Study
Task2a – Forming Feasibility using eta/DynaForm

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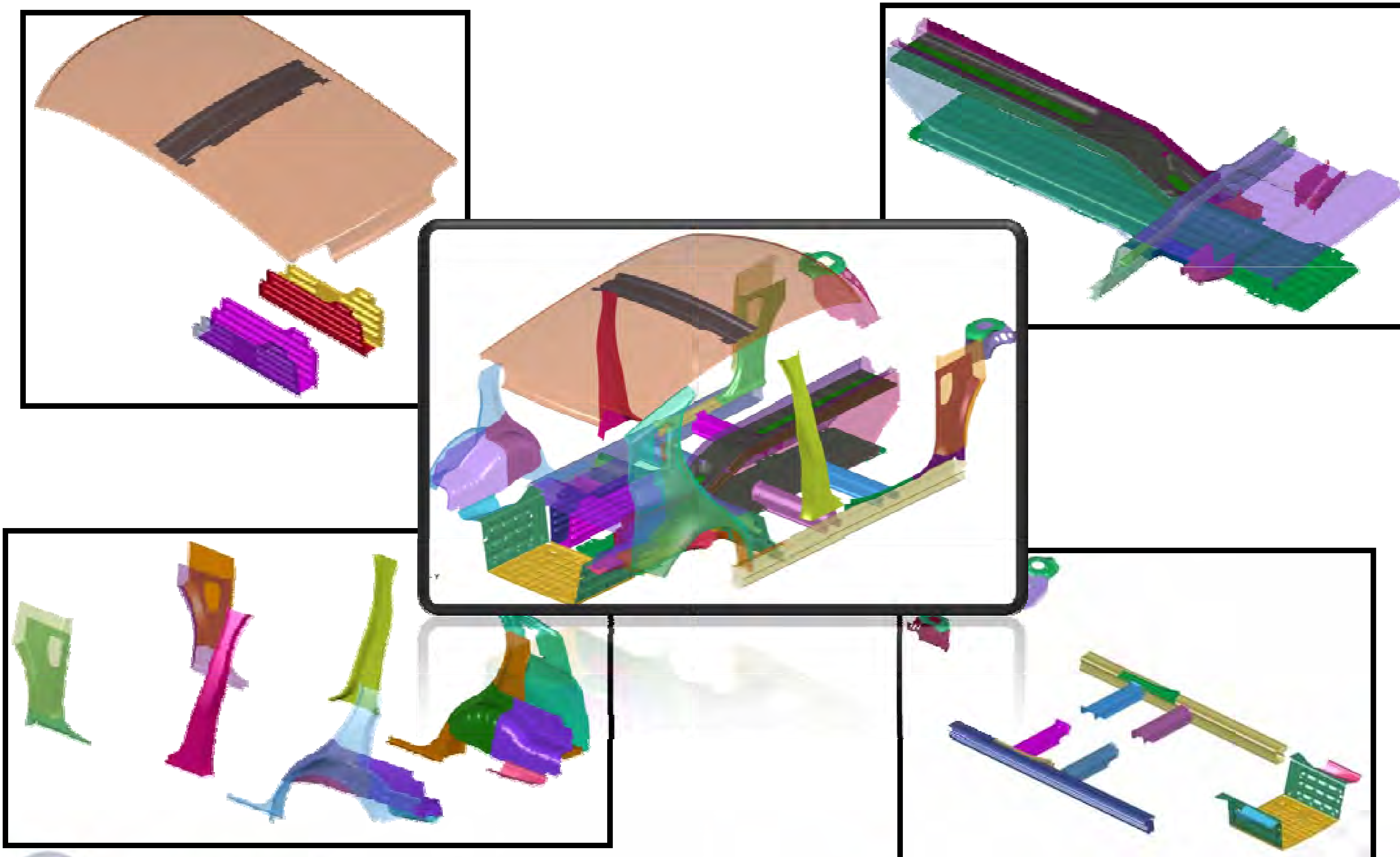
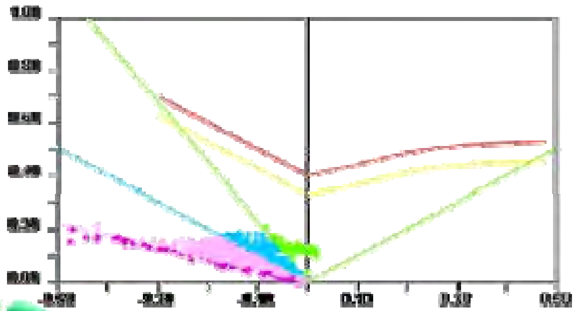
Task2a :Objectives

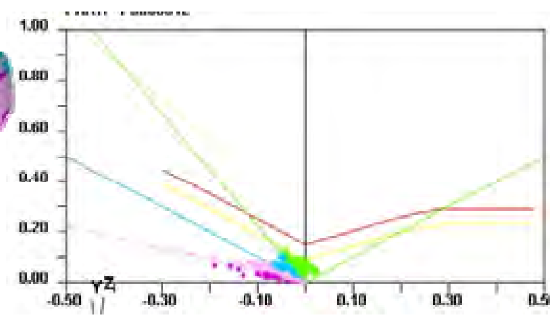
- One step forming analysis is performed on all of the upgraded parts using eta/DYNAFORM to establish baseline for formability.
- In order to select the right grade of material for manufacturability, we have A to B comparison of one step results between T5-Final grades and T5-D336.
- For consistency, one step analysis is performed for the components upgraded from T5-Final to T5-D336 by eta/DynaForm.
- All component grades selected to go forward are highlighted by Green.

Task 2a: Material Changes from T5-Final to T5-D336

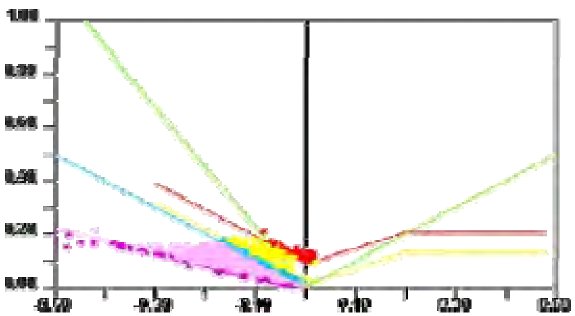


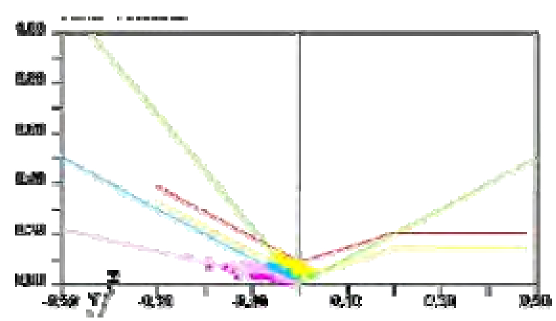
Task2a: Shock Tower- T5-Final Vs D336

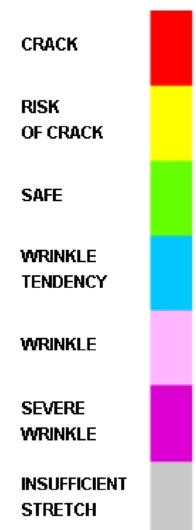




T5- DP500/800-3mm+TWIP 700/1000-1mm

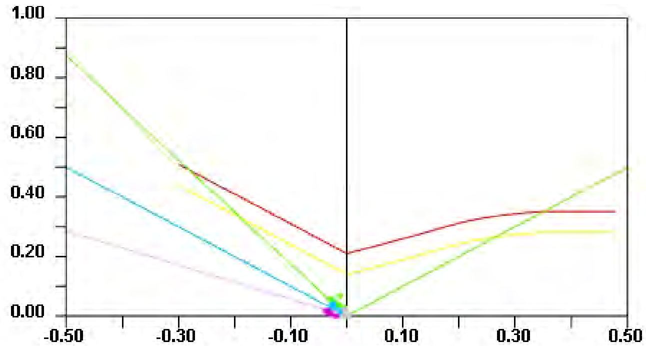


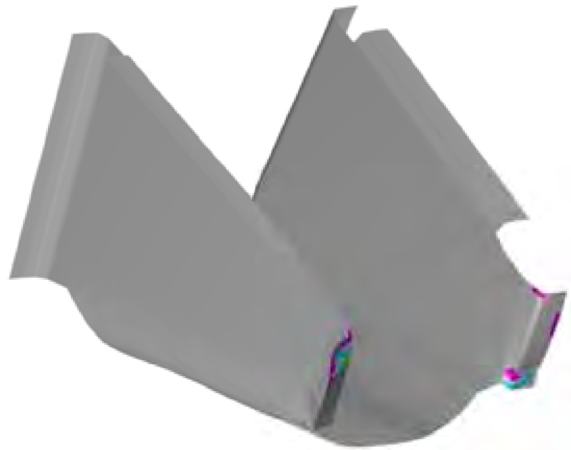


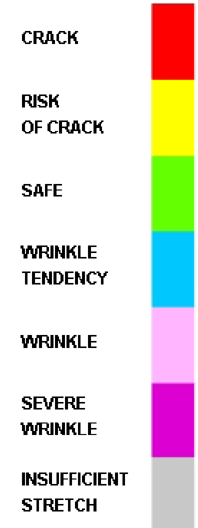


D336- DP700/1000-3mm+DP 700/1000-1mm

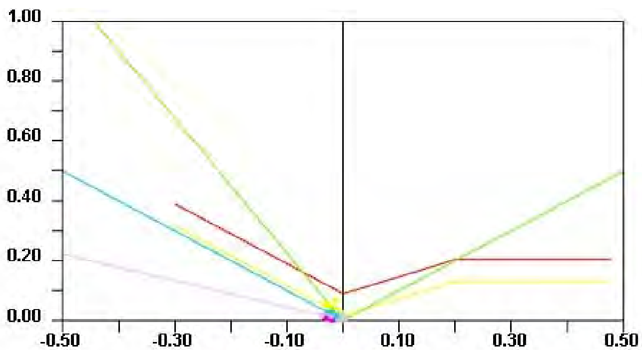
Task2a:Rear Gusset - T5-Final Vs D336

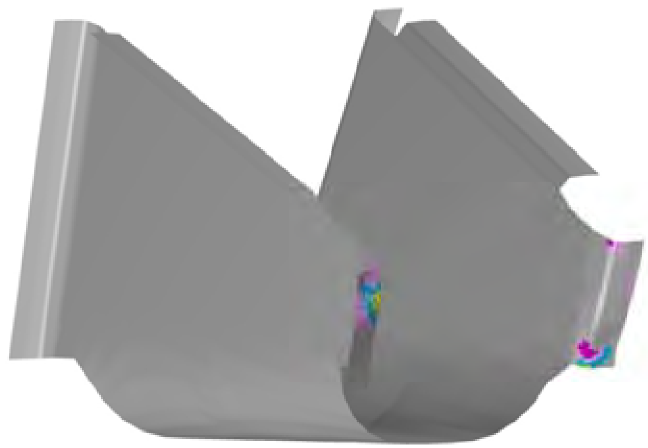


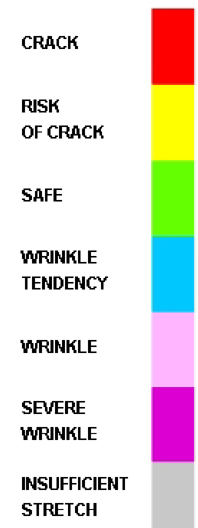




T5- BH 210/340-1mm







✓D336 - DP700/1000-1mm

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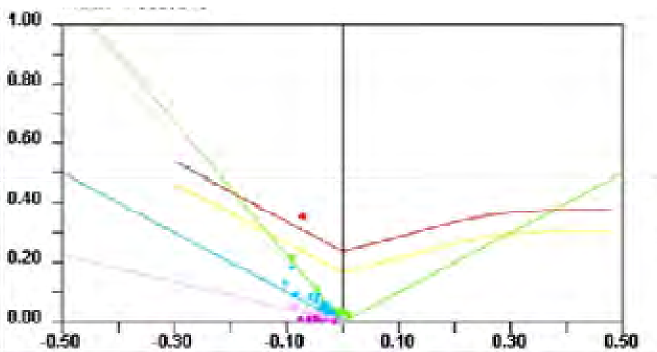
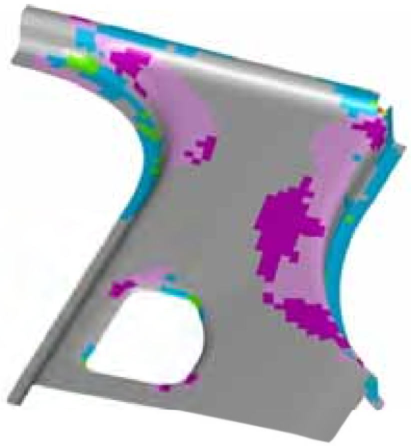
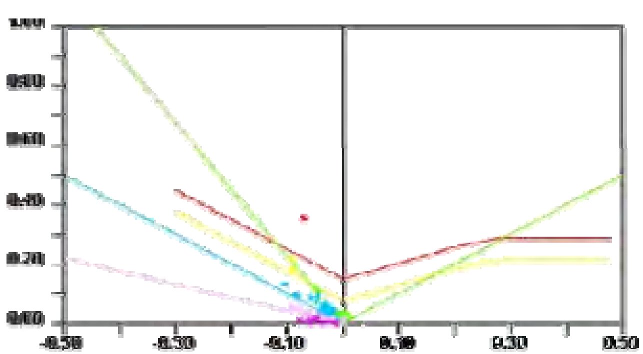
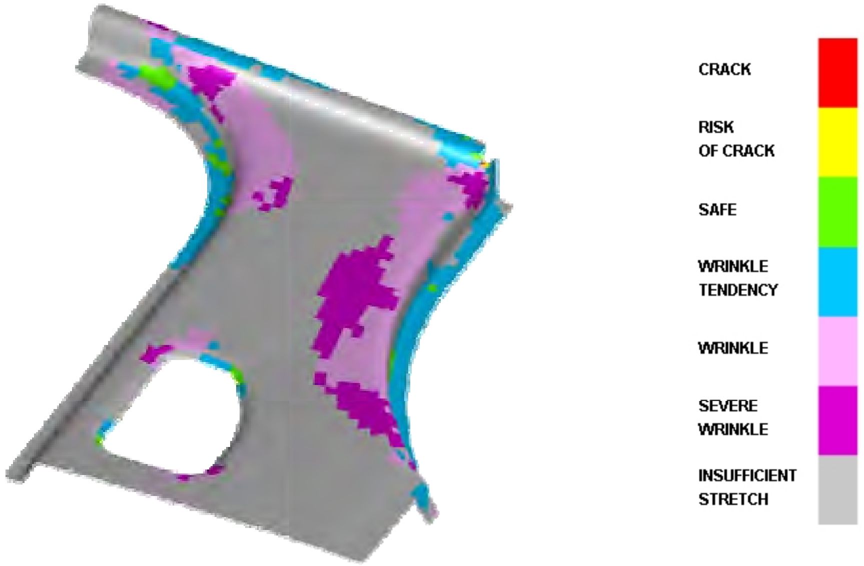
Task2a:Hinge Pillar- T5-Final Vs D336





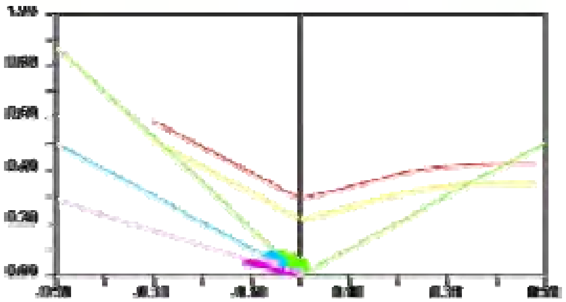
T5- DP 500/800-1.2mm

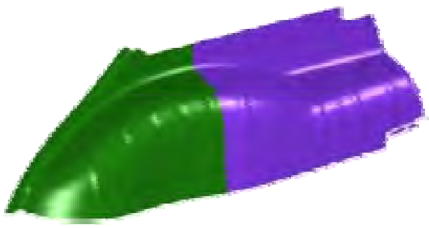


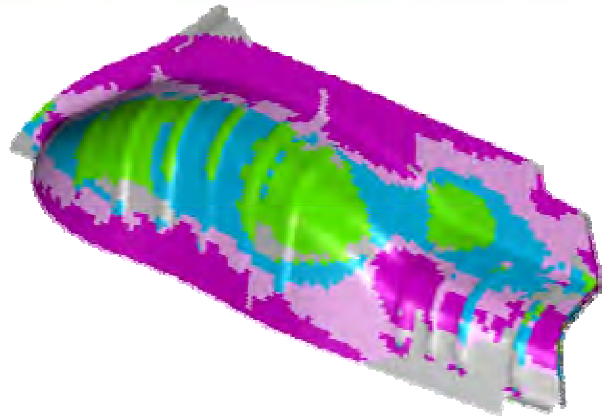


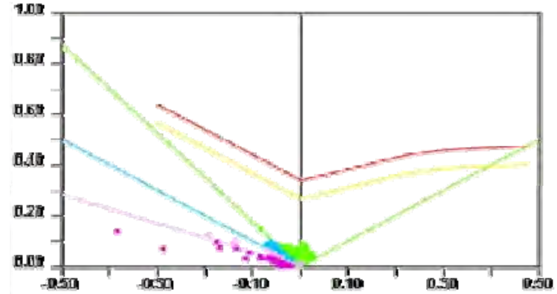
D336- DP 700/1000-1mm

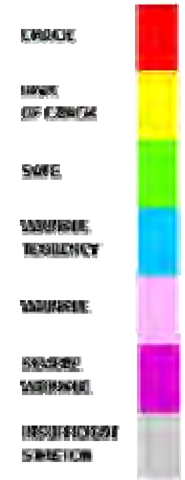
Task2a:Wheel House- T5-Final Vs D336



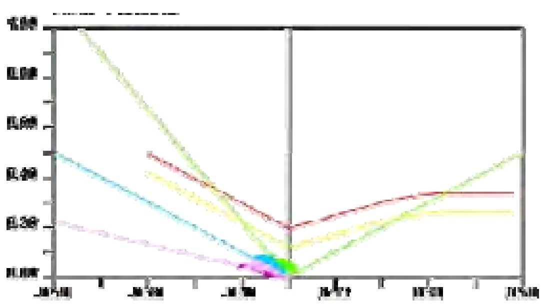


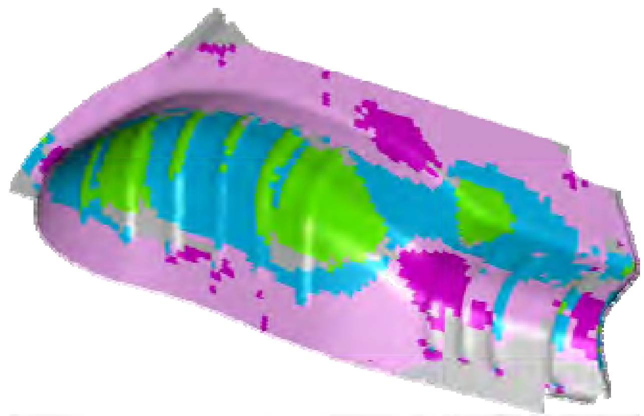


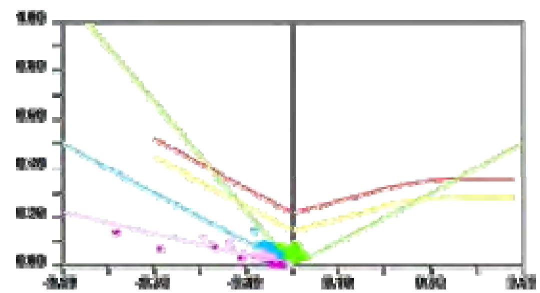




T5- BH 210/340-(1.2mm+0.7mm)

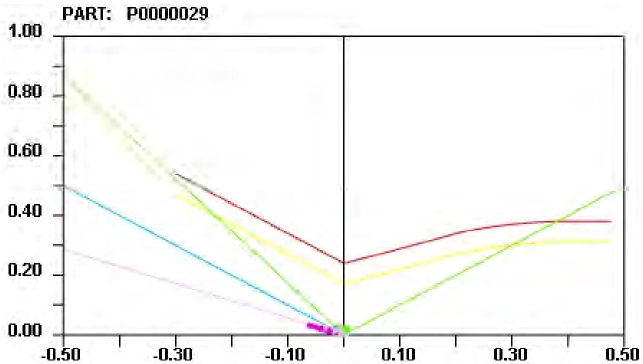




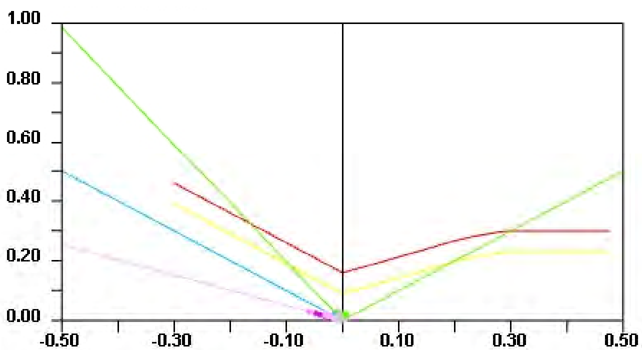


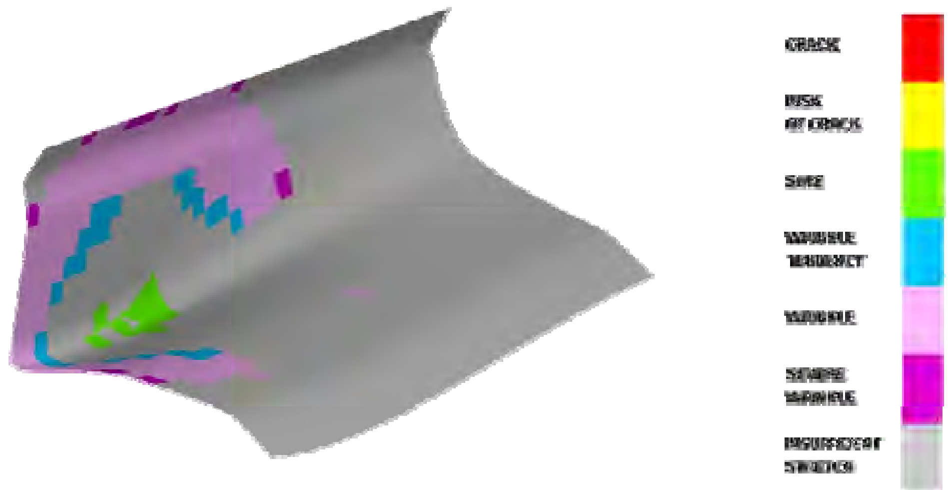
D336- DP 500/800-(0.65 mm+0.7mm)

Task2a:Reinf- Frame Rail Rear- T5-Final Vs D336



T5- Mild 140/270-1.55mm





✓D336- HSLA 350/450-0.6mm

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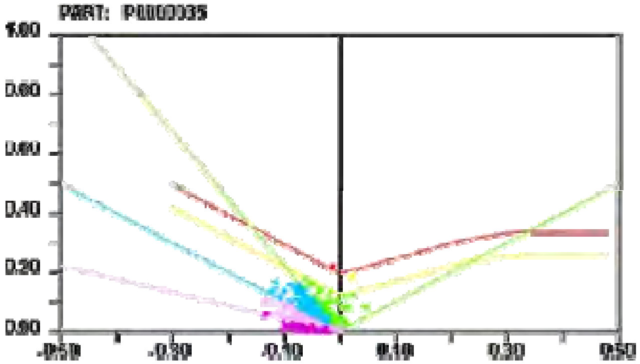
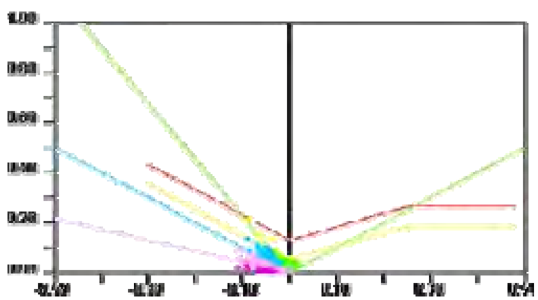
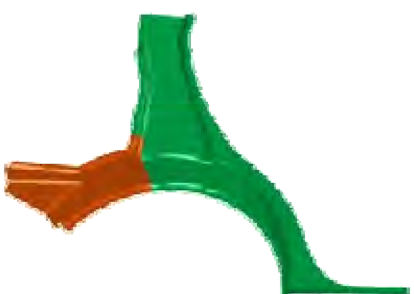
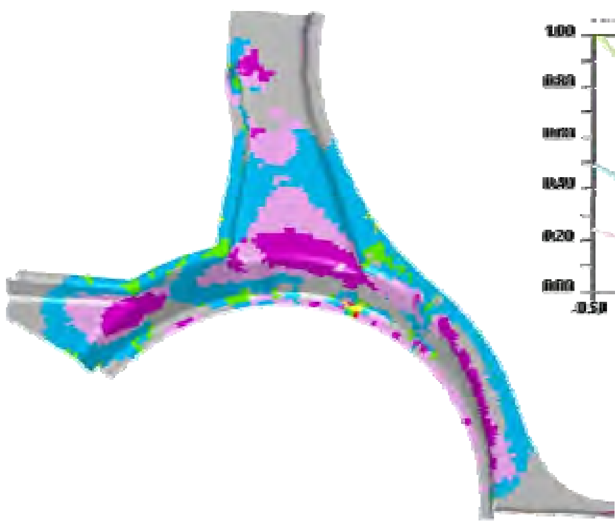
Task2a: Wheel House Outer- T5-Final Vs D336

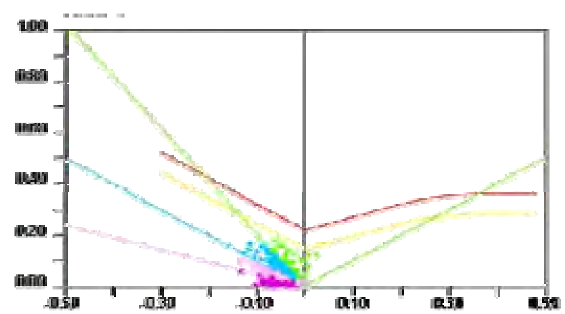


✓ T5- DP 500/800-0.65mm



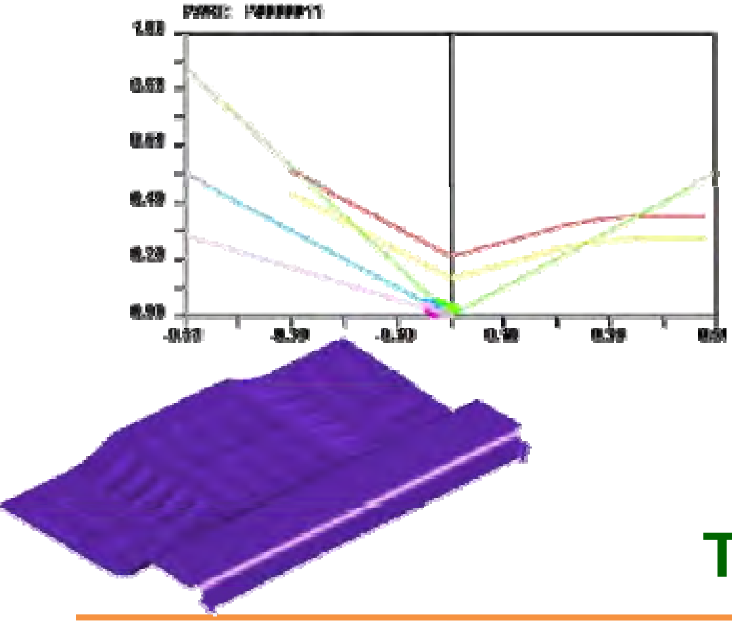


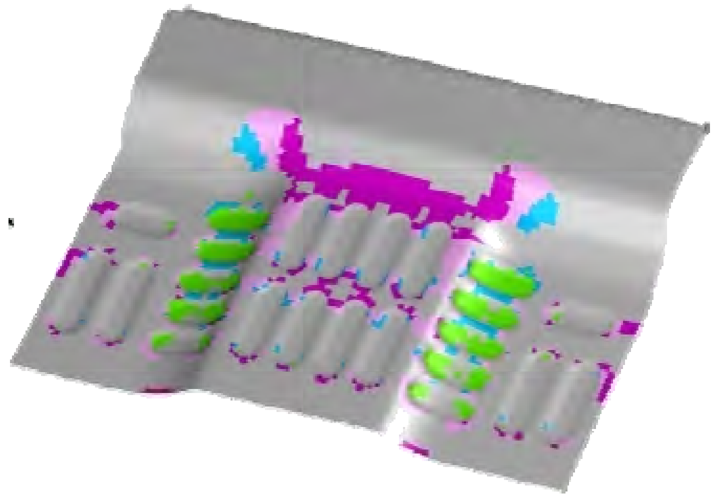




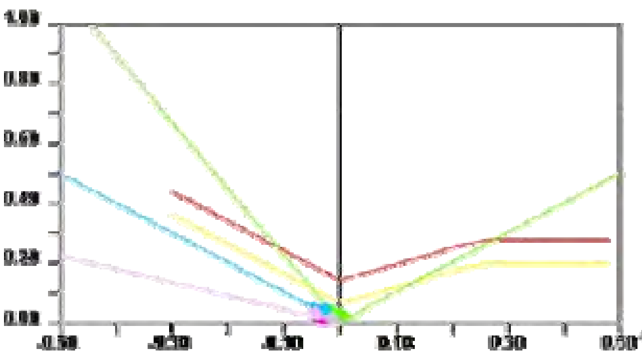
D336- (DP 300/500-0.65mm+ DP 700/1000-0.65mm)

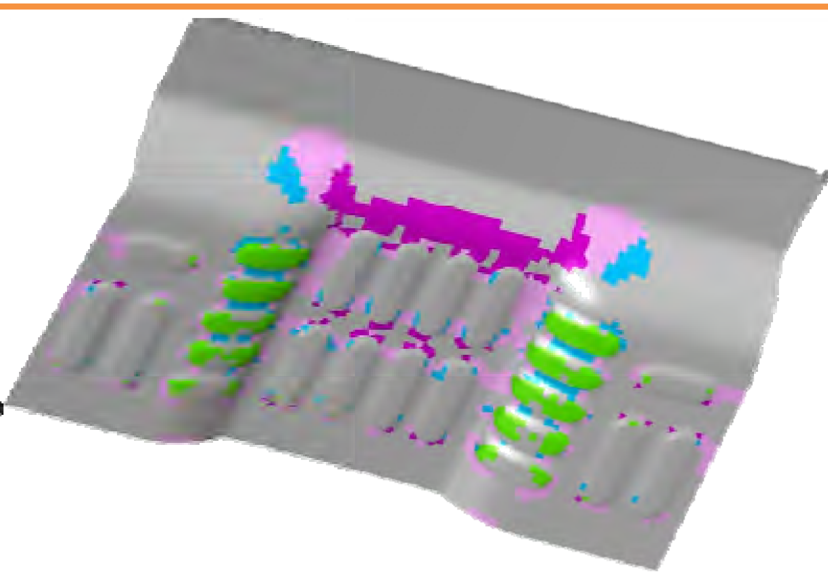
Task2a:Rear Floor- T5-Final Vs D336





T5- BH 210/340-0.5mm





✓D336- DP 500/800- 0.5mm

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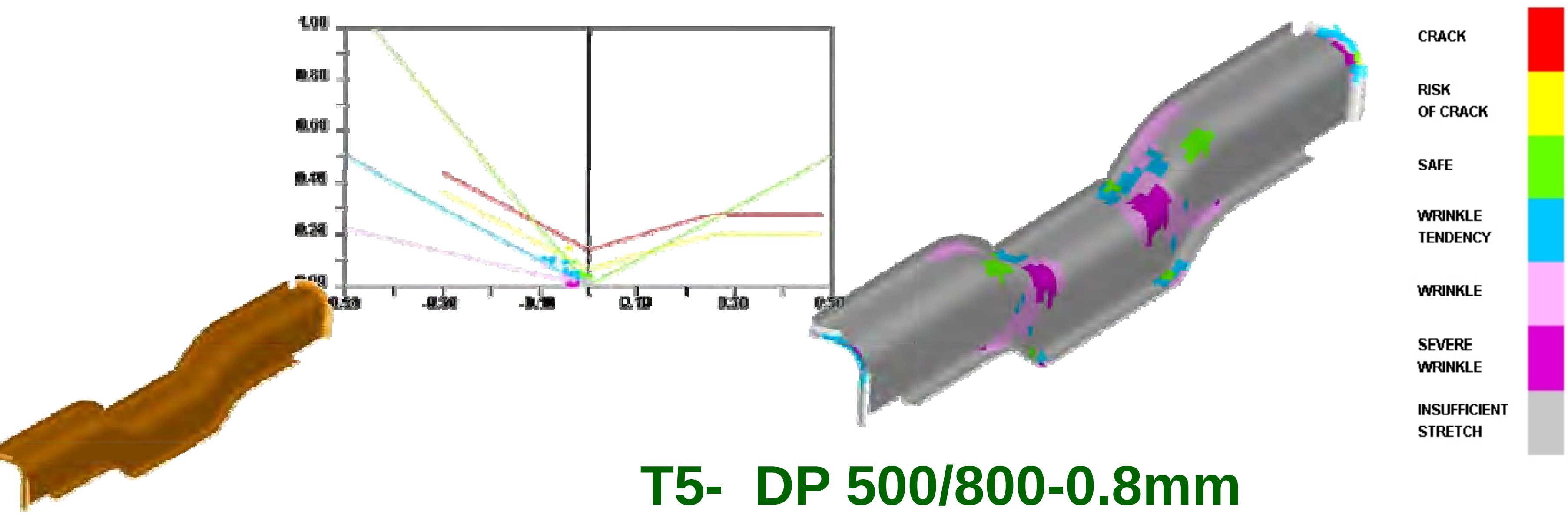
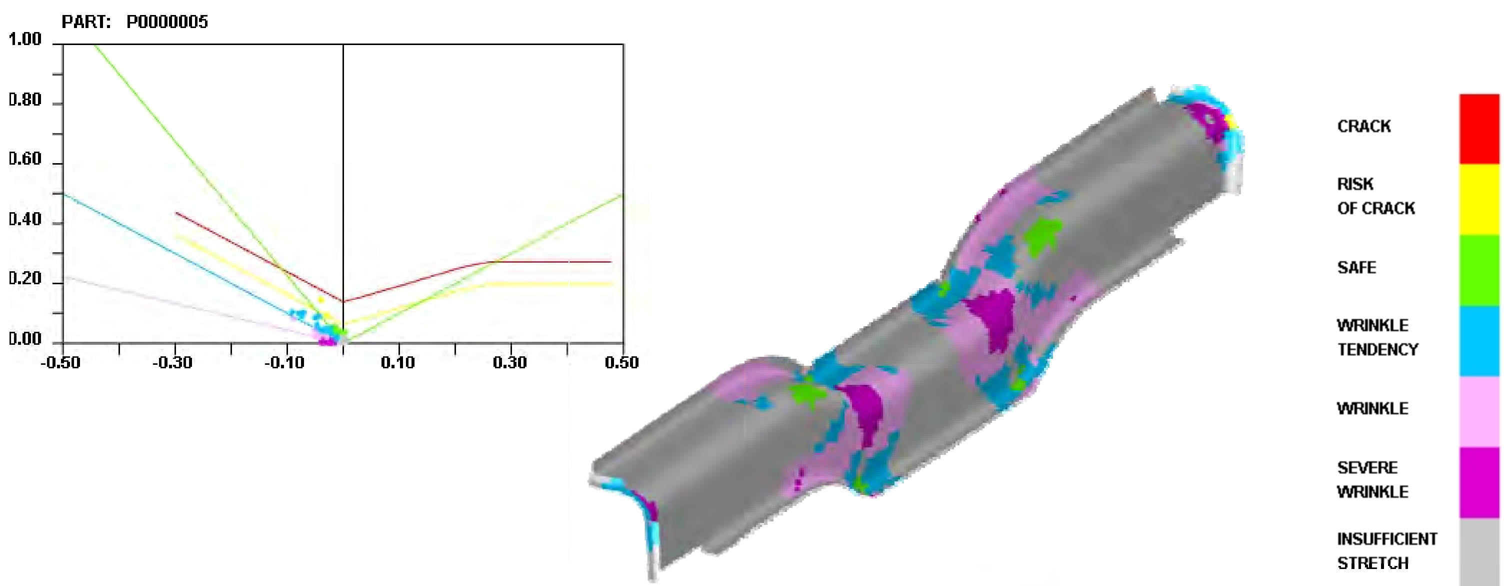
Task2a:Frame Rail Side to Side- T5-Final Vs D336



T5- DP 500/800-0.8mm



✓D336- DP 700/1000-0.8mm

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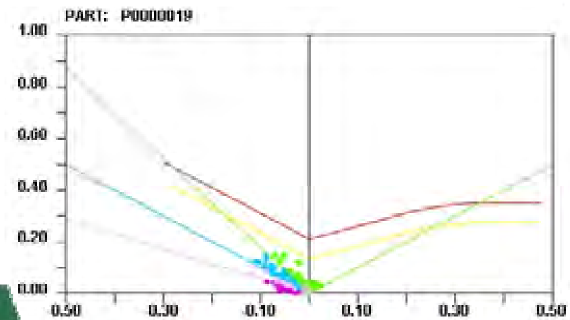
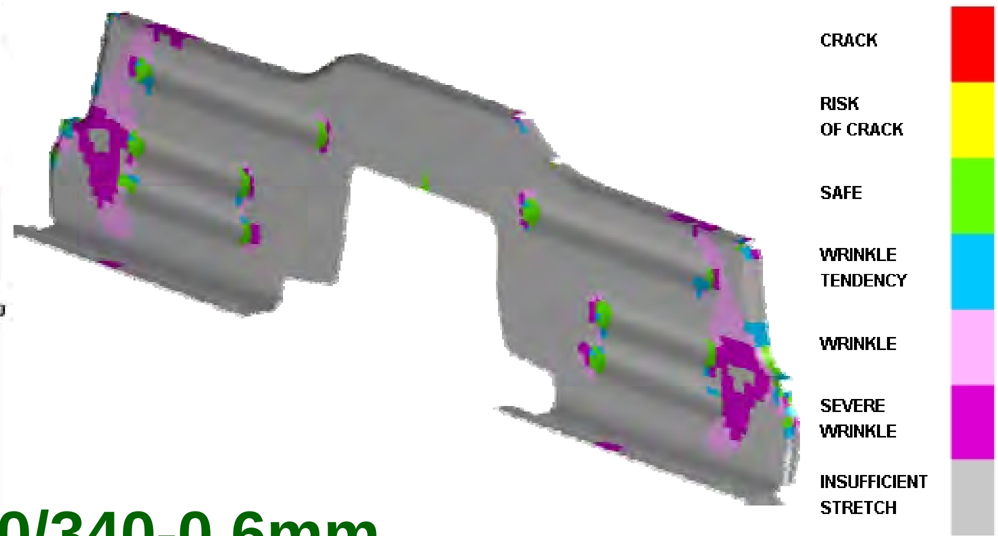
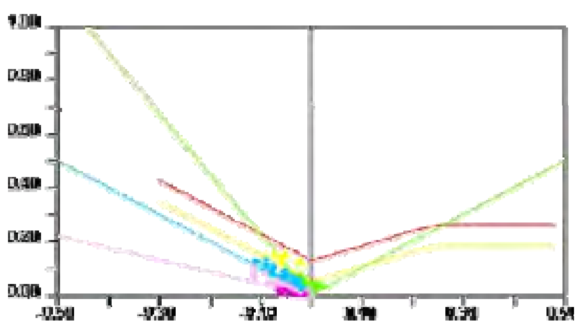
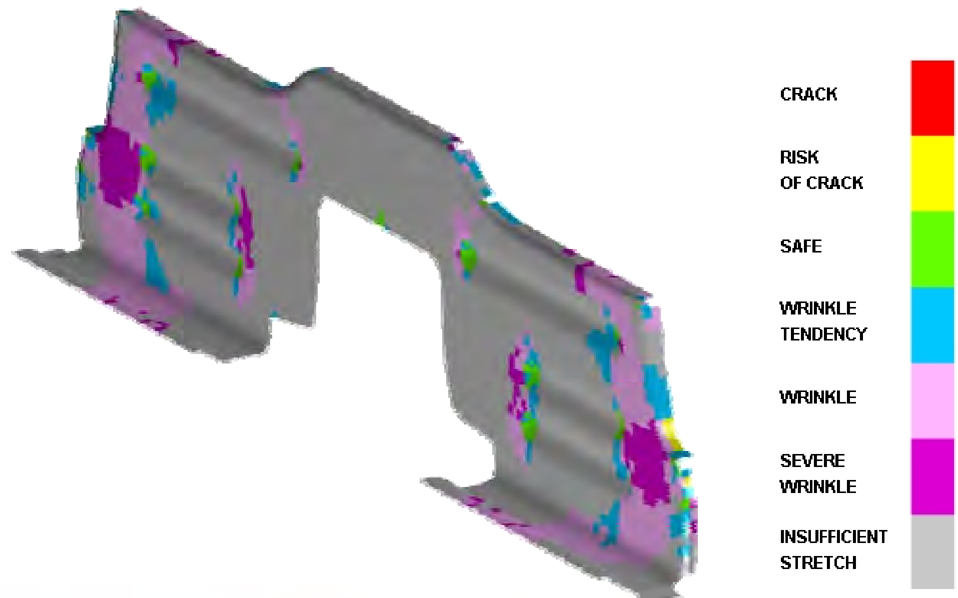
Task2a:Heel Board- T5-Final Vs D336





T5- BH 210/340-0.6mm





✓D336- DP 700/1000-0.6mm

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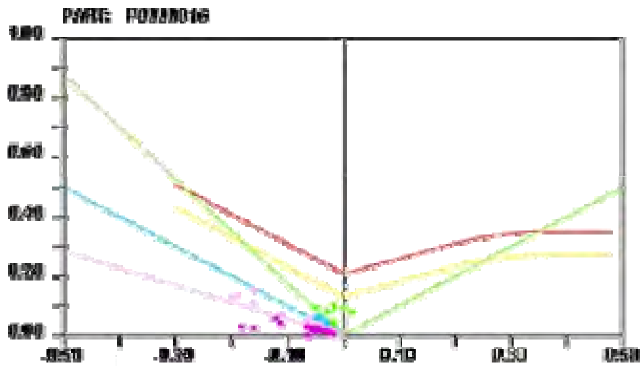
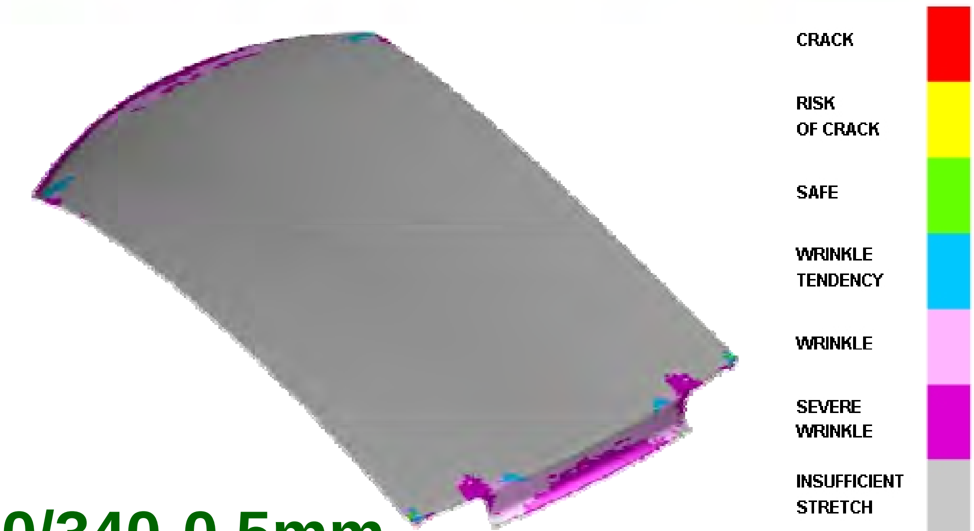
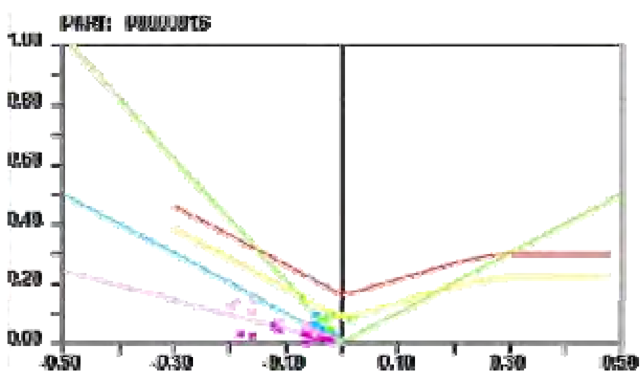
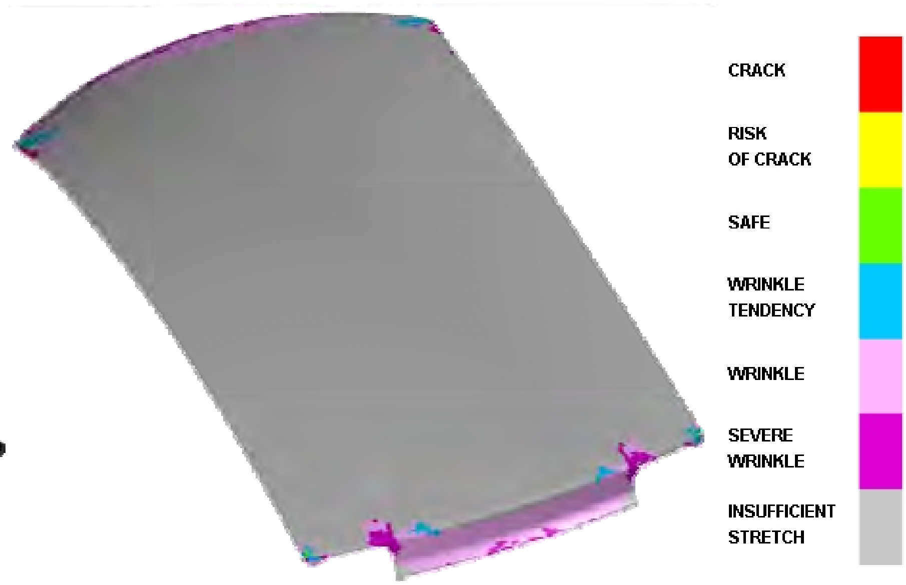
Task2a:Roof Panel- T5-Final Vs D336





T5- BH 210/340-0.5mm





✓D336- DP 300/500-0.5mm

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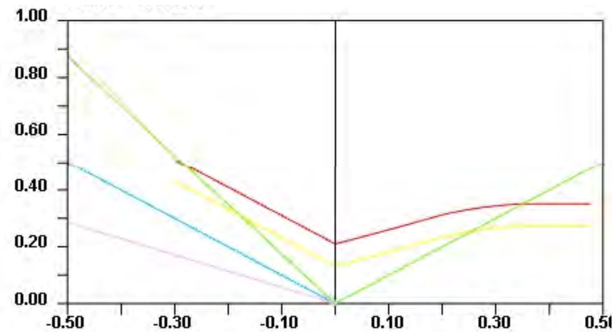
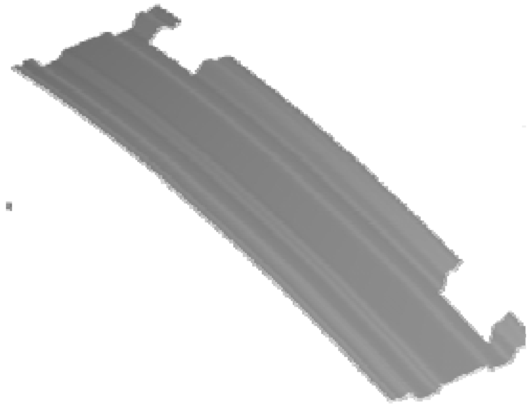
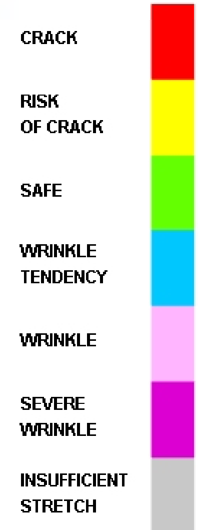
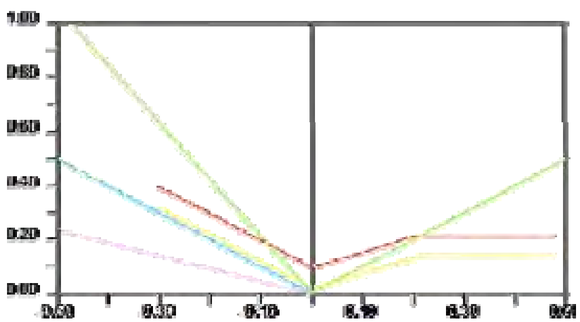
Task2a:Roof Bow- T5-Final Vs D336

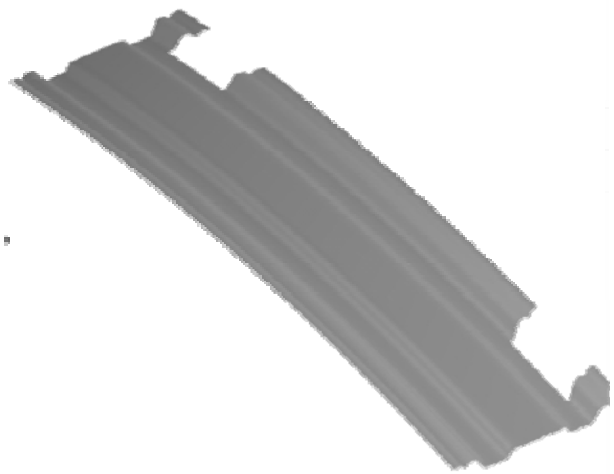






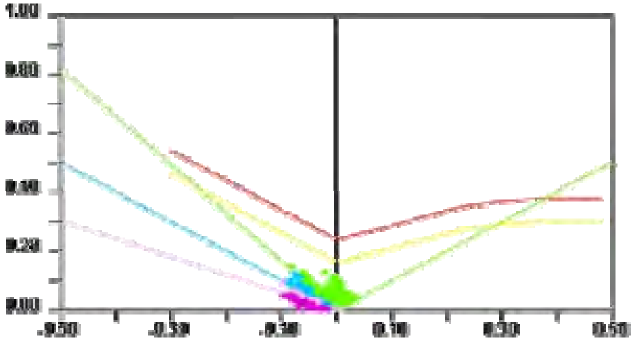
T5- BH 210/340-0.5mm

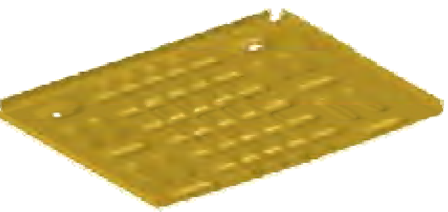


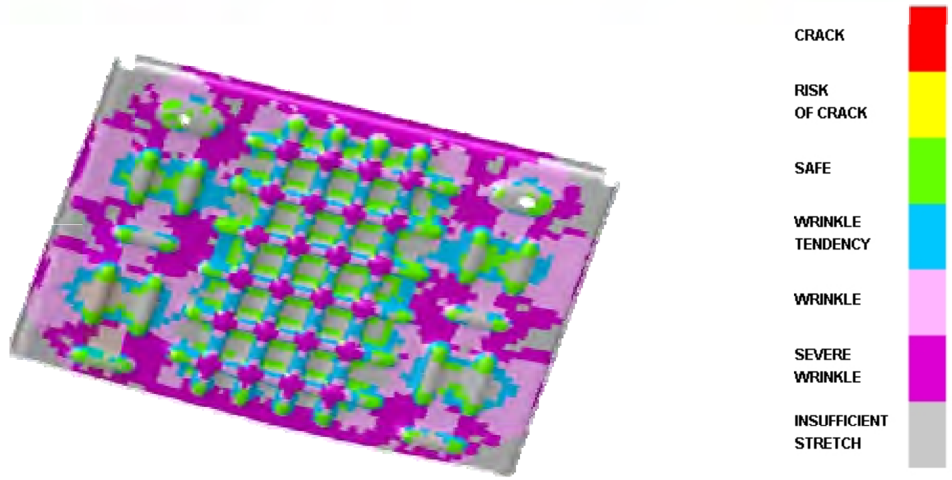


✓D336- MS950/1200-0.5mm

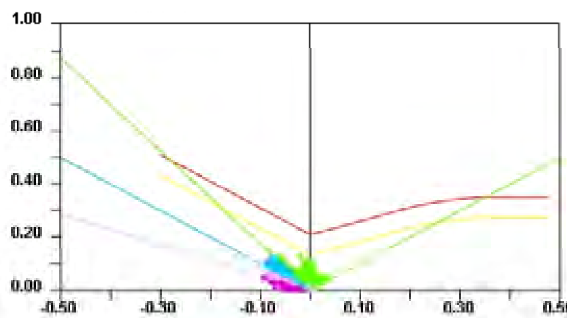
Task2a:Cargo Box Floor- T5-Final Vs D336

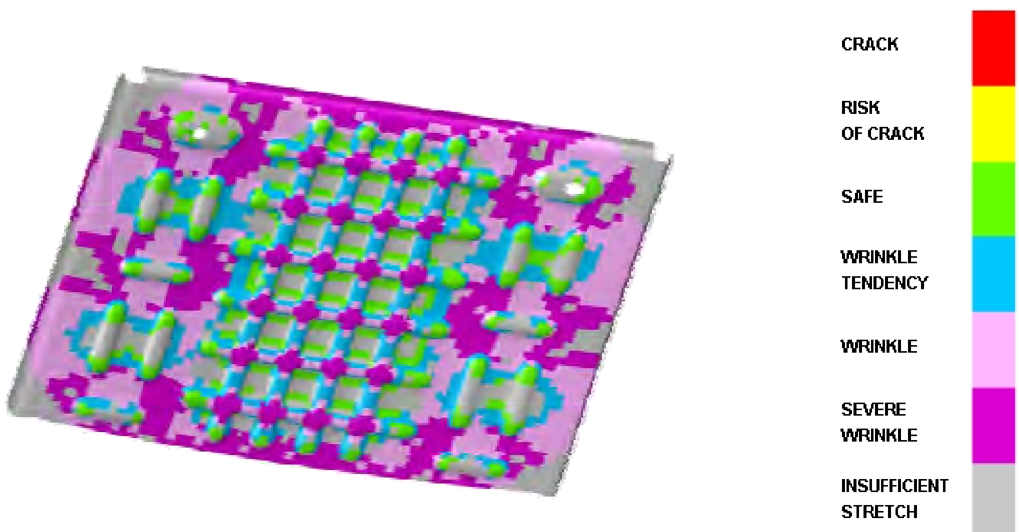






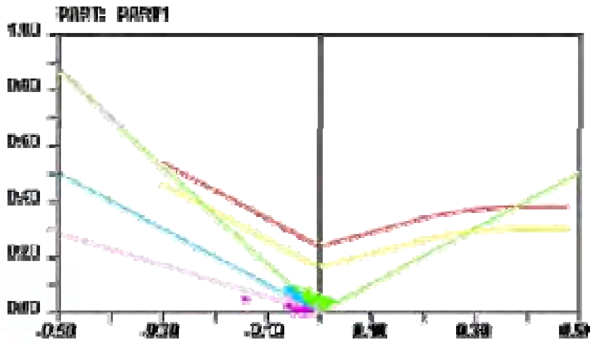
T5- Mild 140/270-0.5mm

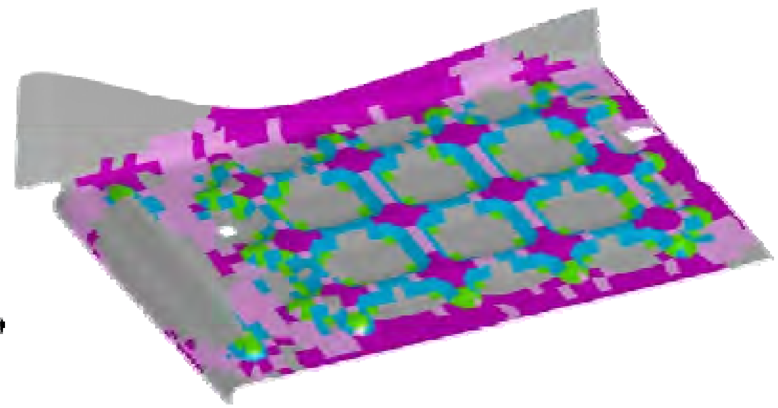


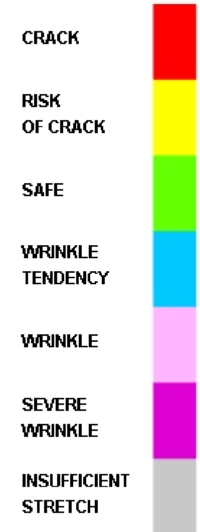


✓D336- BH 210/340-0.5mm

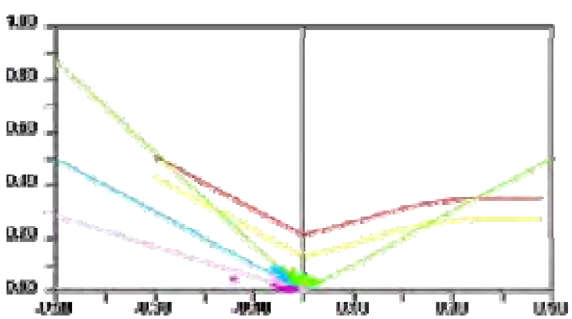
Task2a:Cargo Box Side- T5-Final Vs D336

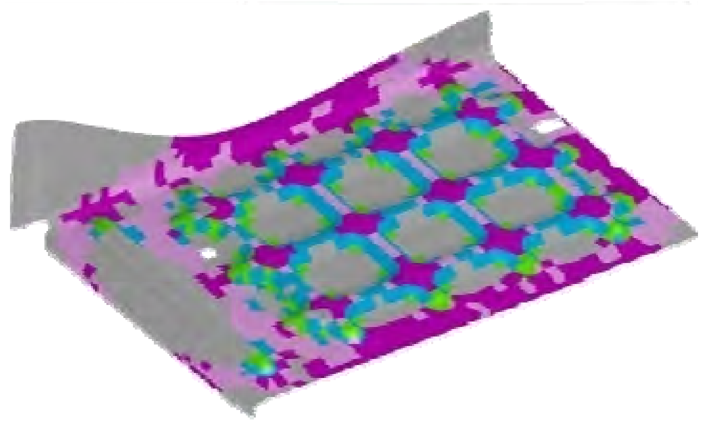






T5- Mild 140/270-0.5mm





✓D336- BH 210/340-0.5mm

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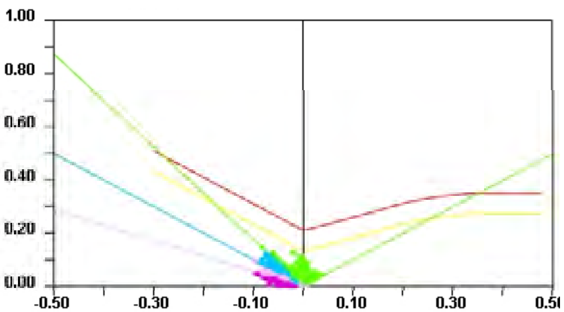
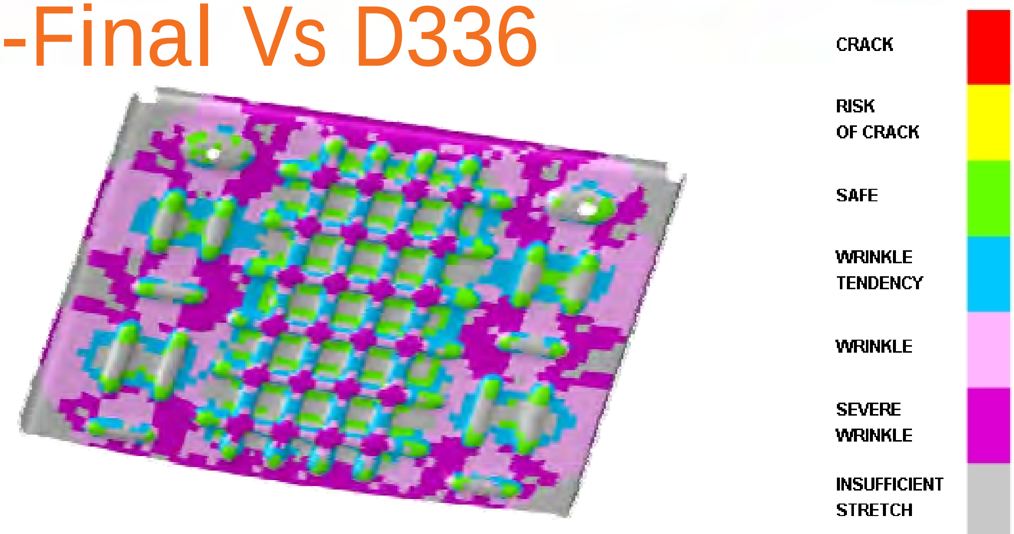
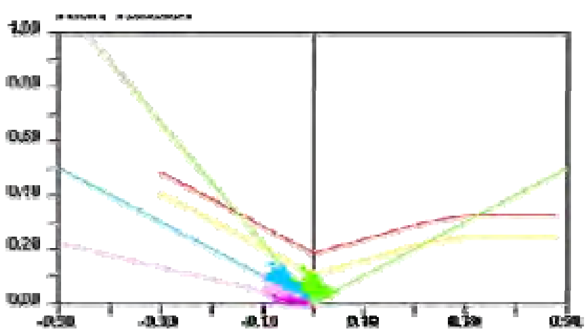
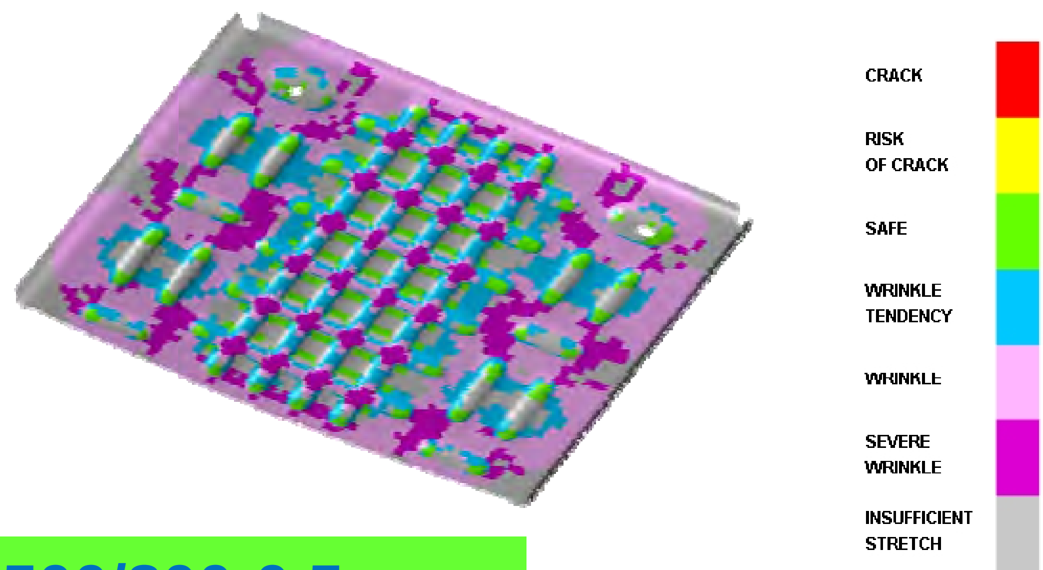
Task2a:Cargo Box Floor-T5-Final Vs D336





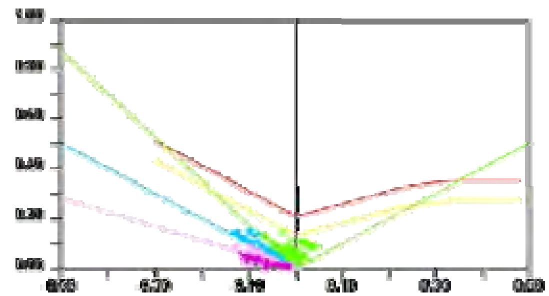
D336- BH 210/340-0.5mm

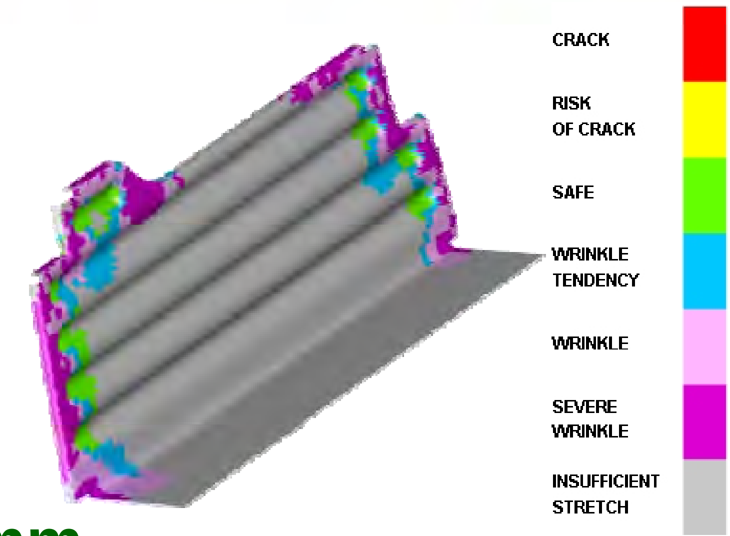




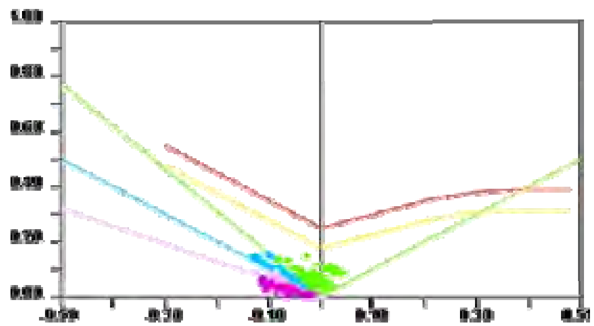
✓DP 500/800-0.5mm

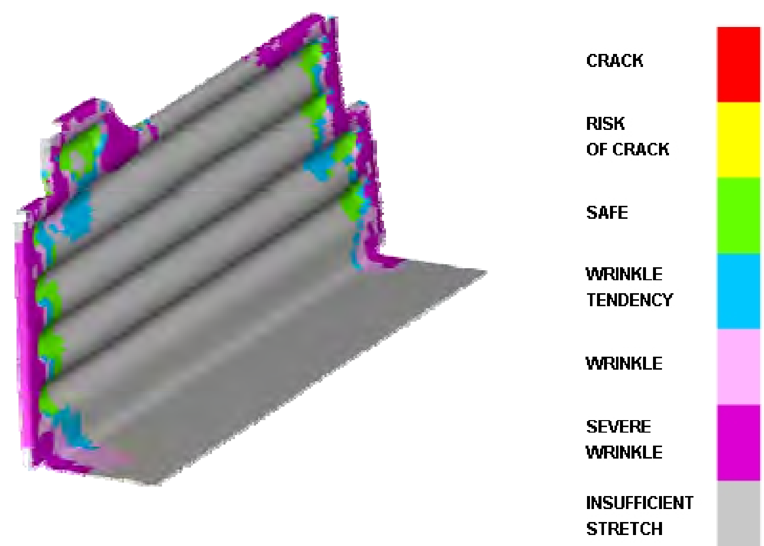
Task2a:Close Off- Battery Outer- T5-Final Vs D336





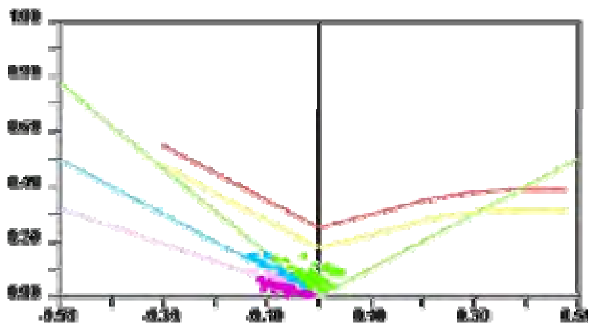
T5- BH 210/340-0.6mm



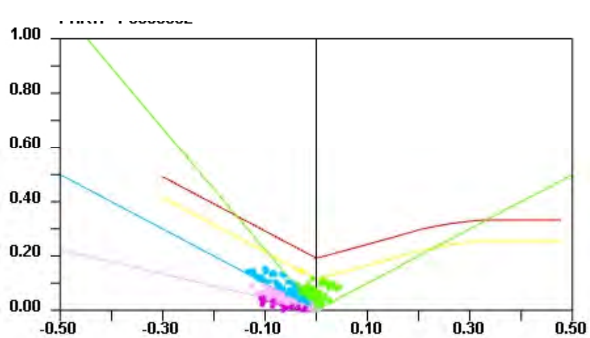


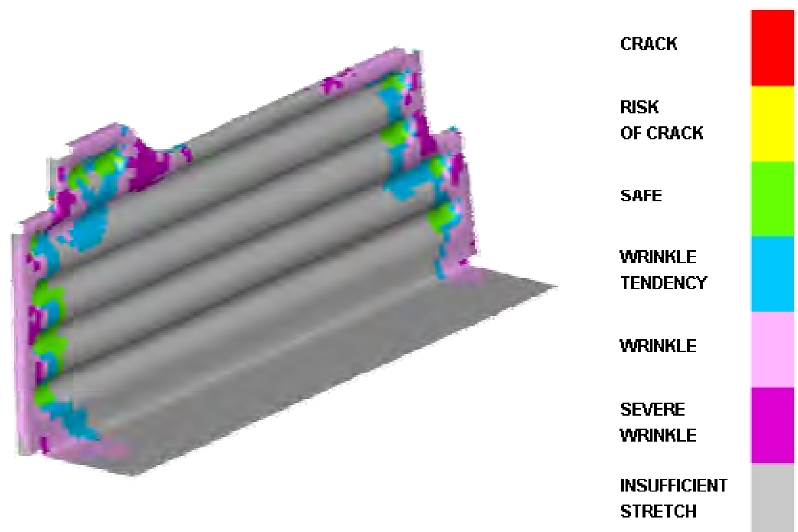
✓D336- DP 300/500-0.6 mm

Close Off- Battery Outer- DP 300/500 Vs **DP 500/800 (recommended)**



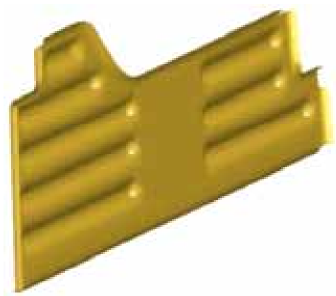
D336- DP 300/500-0.6 mm

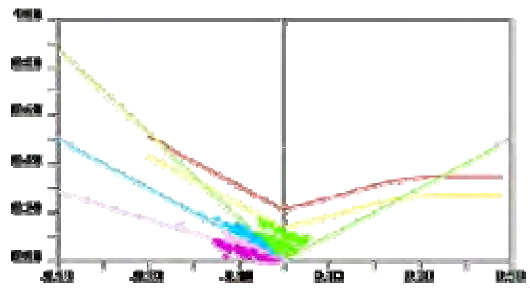


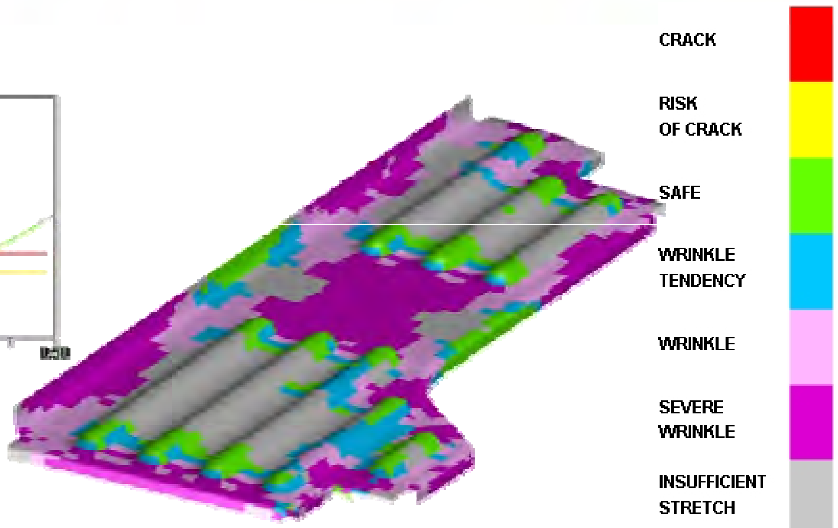


✓DP 500/800-0.6 mm

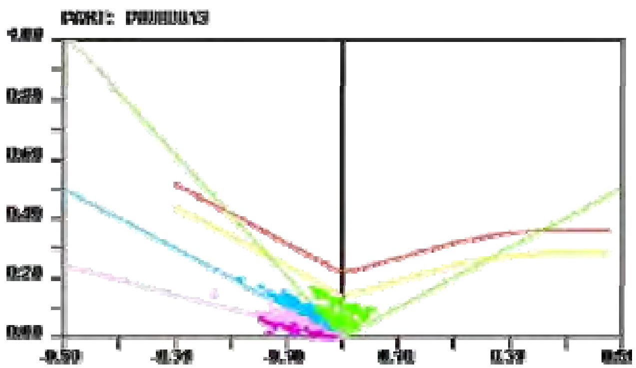
Task2a:Close Off- Battery Inner- T5-Final Vs D336

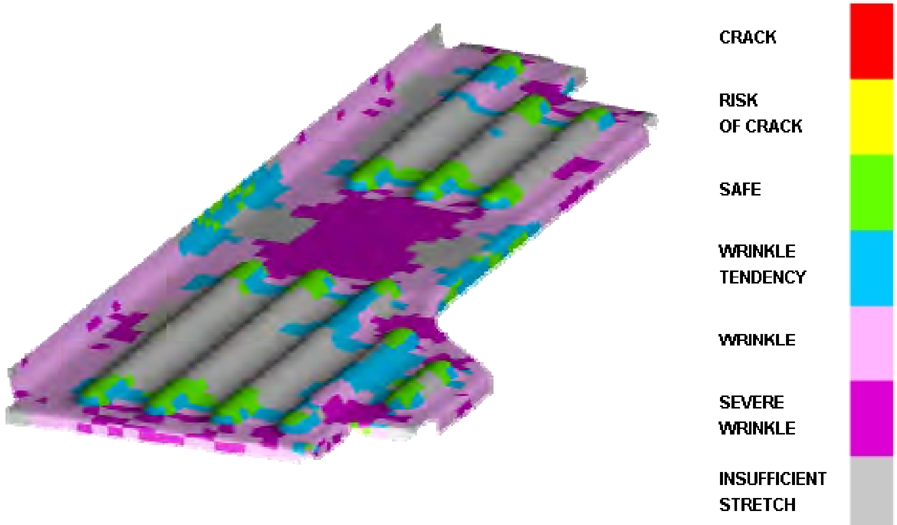






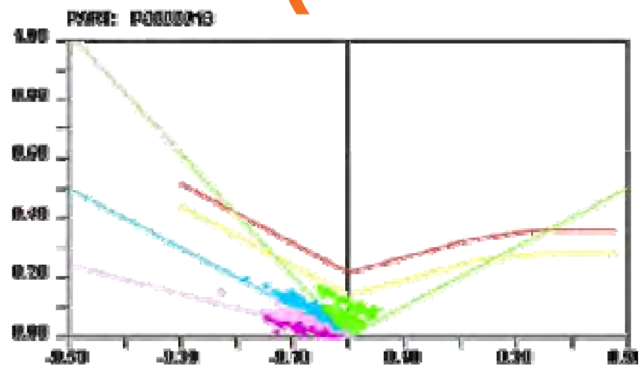
T5- BH 210/340-0.6mm

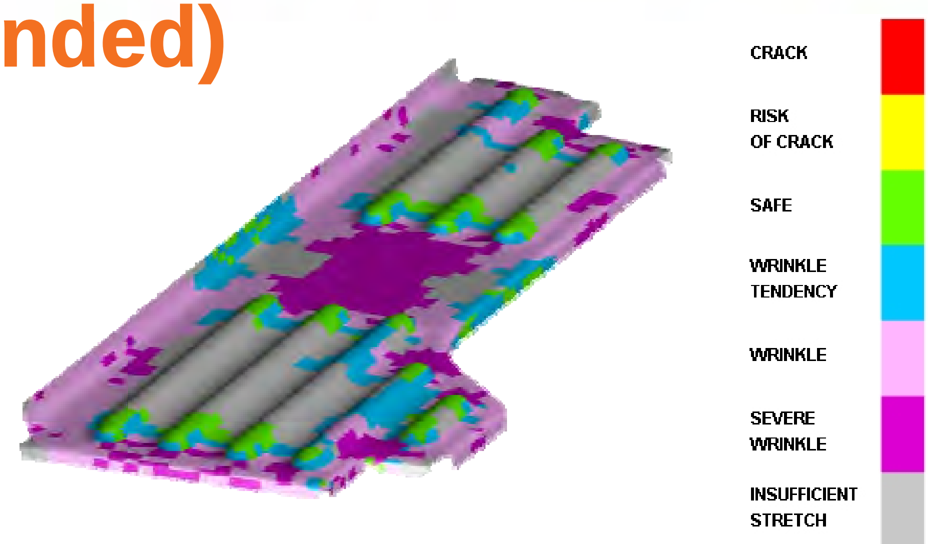




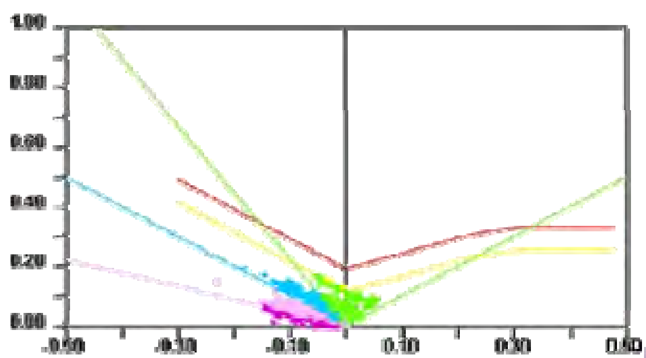
✓D336- DP 300/500-0.6 mm

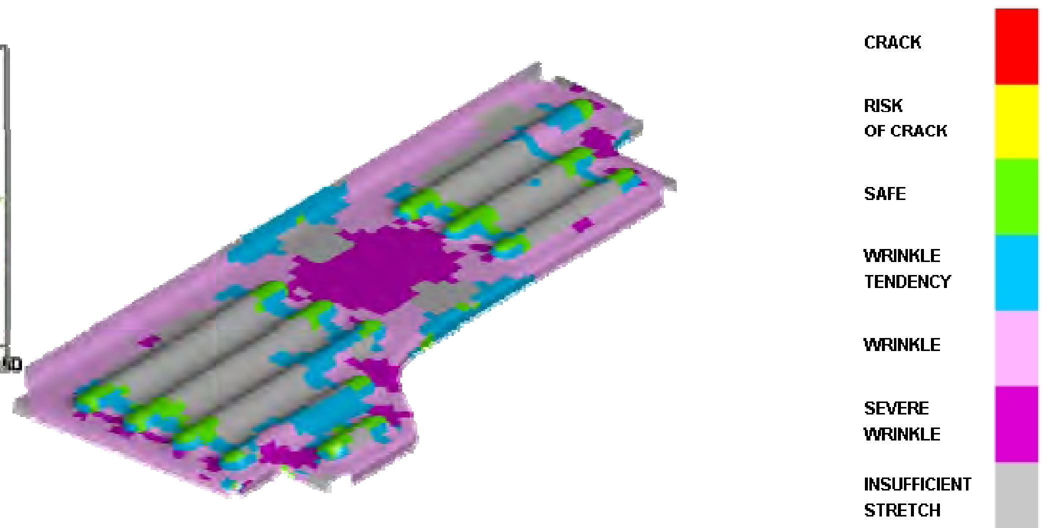
Close Off- Battery Inner- D336- DP300/500 Vs **DP 500/800 (recommended)**





D336- DP 300/500-0.6 mm





✓DP 500/800-0.6 mm

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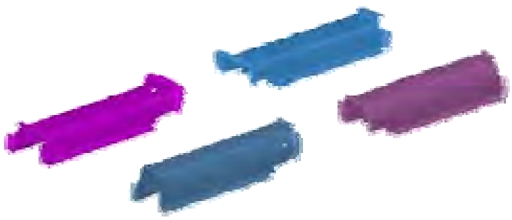
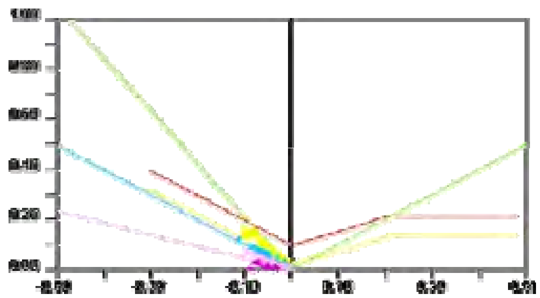
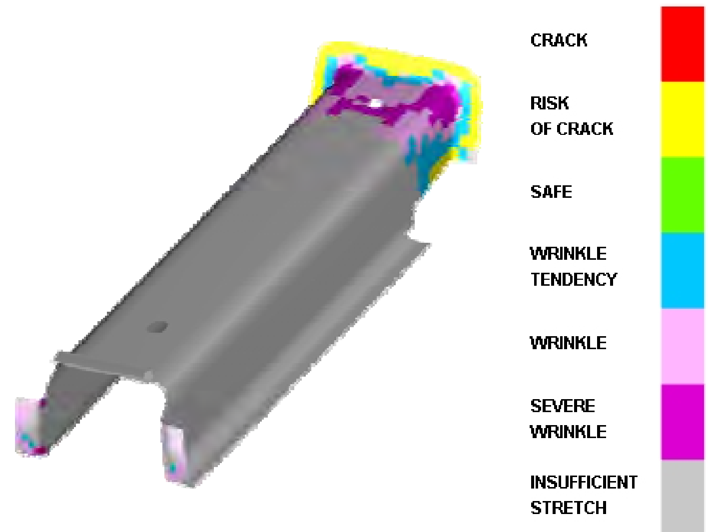
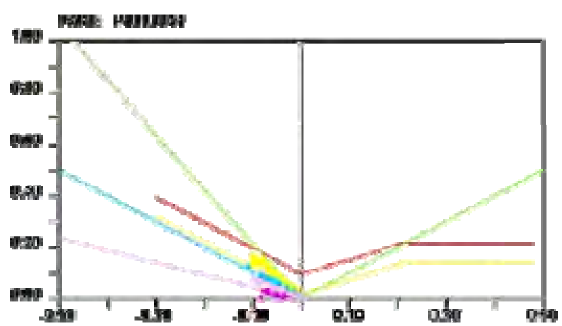
Task2a:Seat Brackets- T5-Final Vs D336

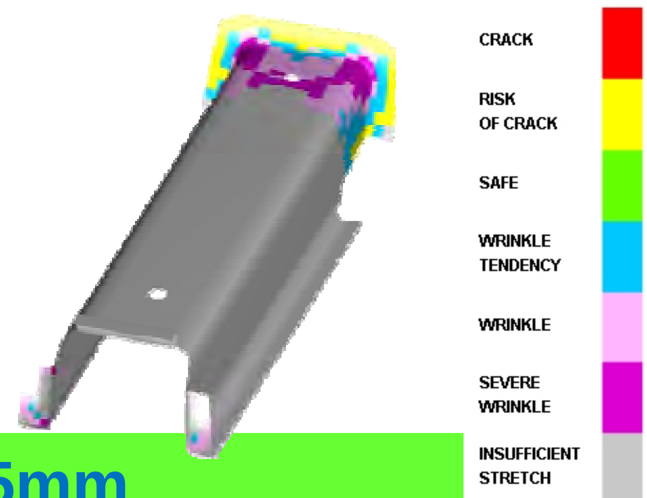






T5- MS 950/1200-0.5mm





- ✓**D336- MS 1300/1550-0.5mm**
- ✓**Might require minor design change in flanges**

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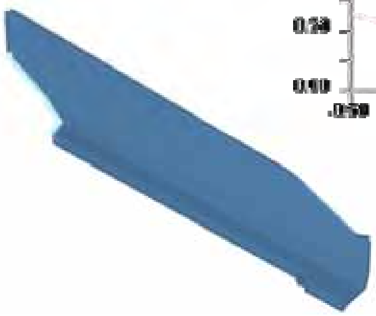
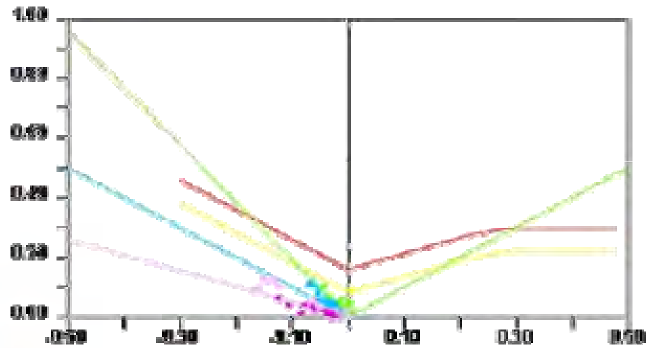
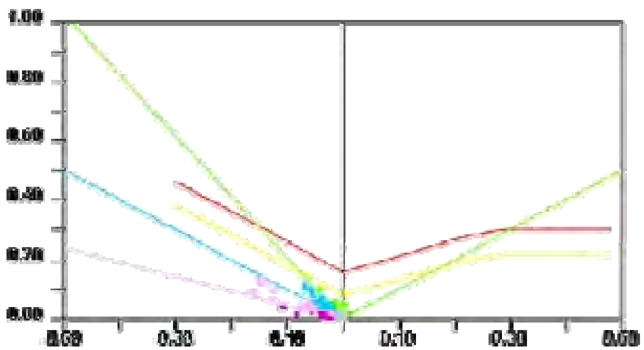
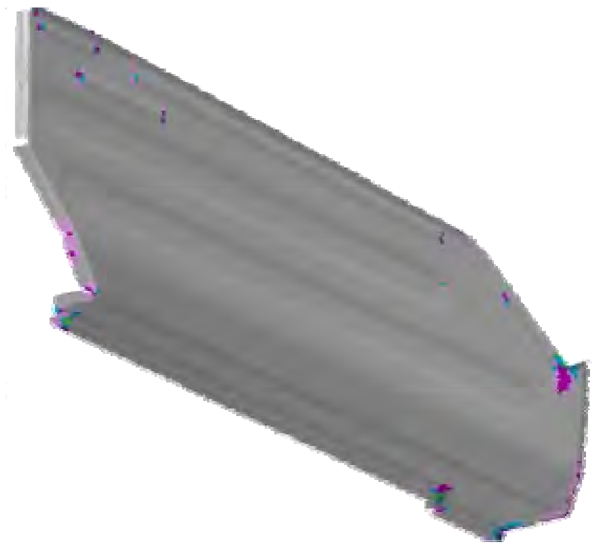
Task2a:Tunnel Side- T5-Final Vs D336

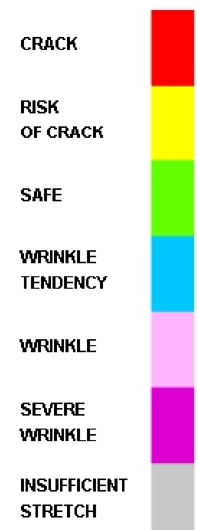




T5- BH 280/400-0.5mm

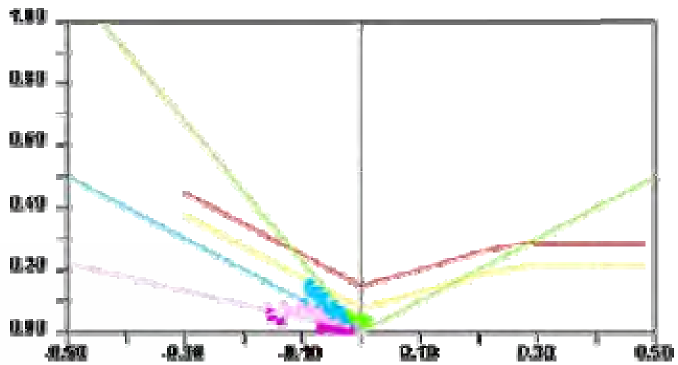


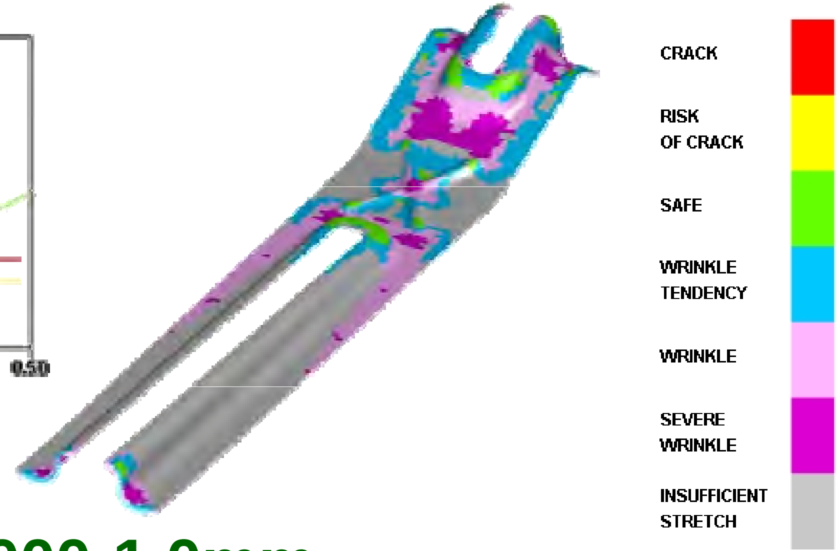




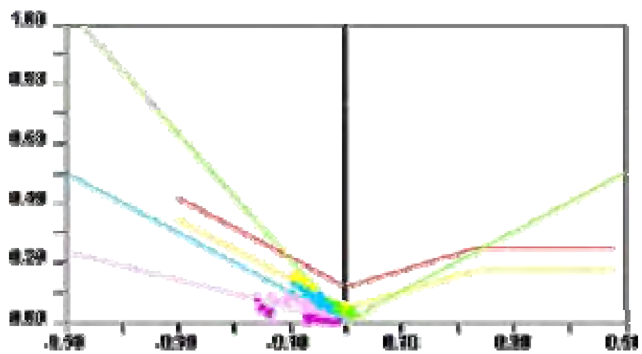
✓D336- DP 300/500-0.5mm

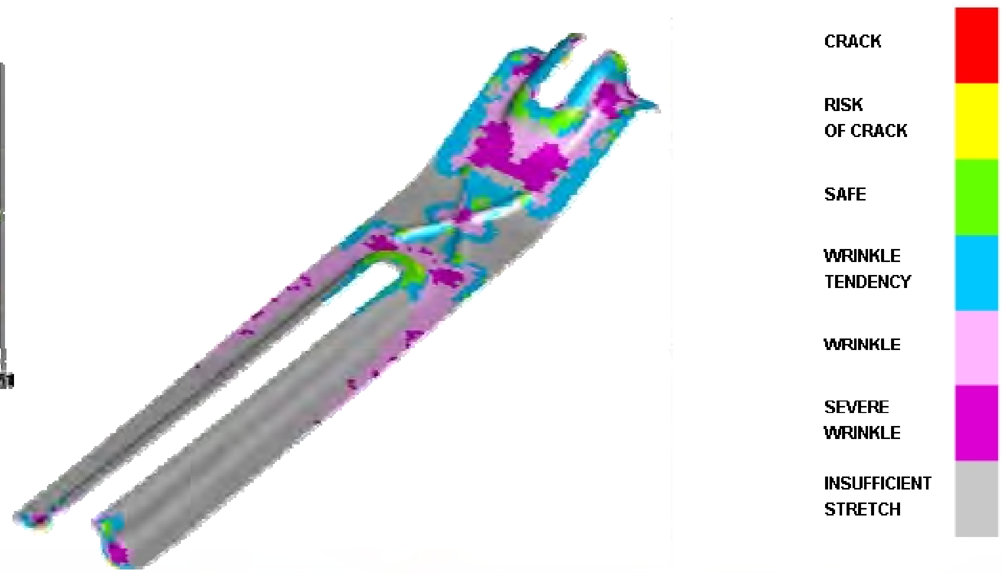
Task2a:Tunnel- Top Panel- T5-Final Vs D336





T5- DP 700/1000-1.0mm





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✓D336-MS 950/1200-1.0mm

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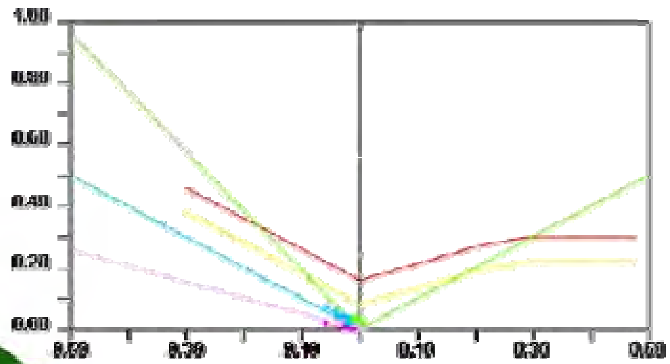
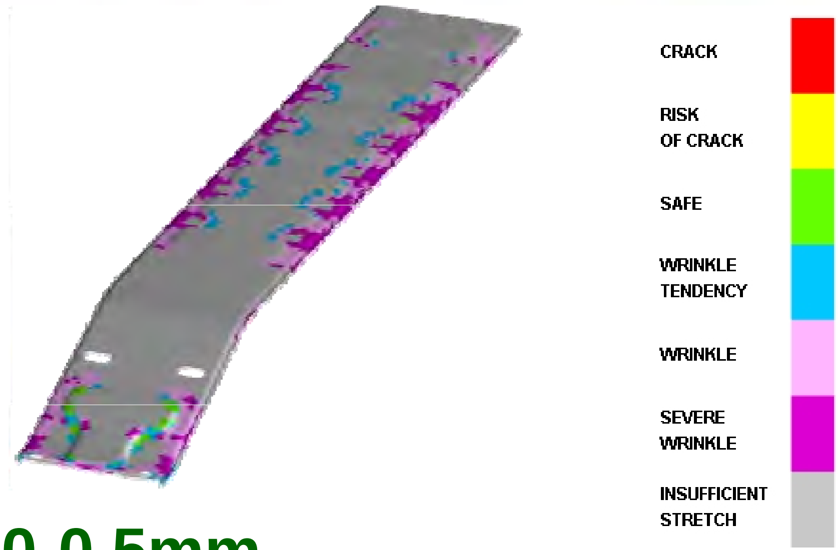
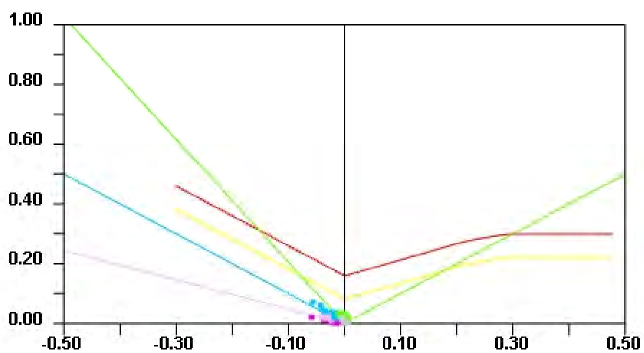
Task2a:Tunnel- Top Reinf.- T5-Final Vs D336





T5- BH 280/400-0.5mm



✓D336-DP 300/500-0.5mm

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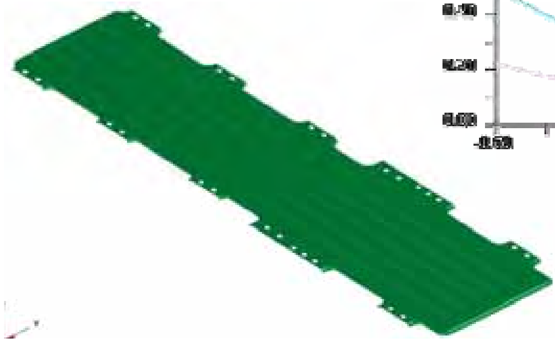
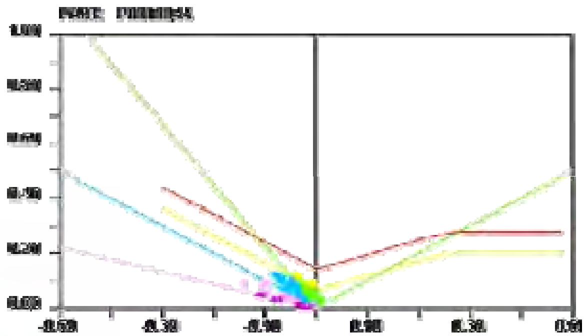
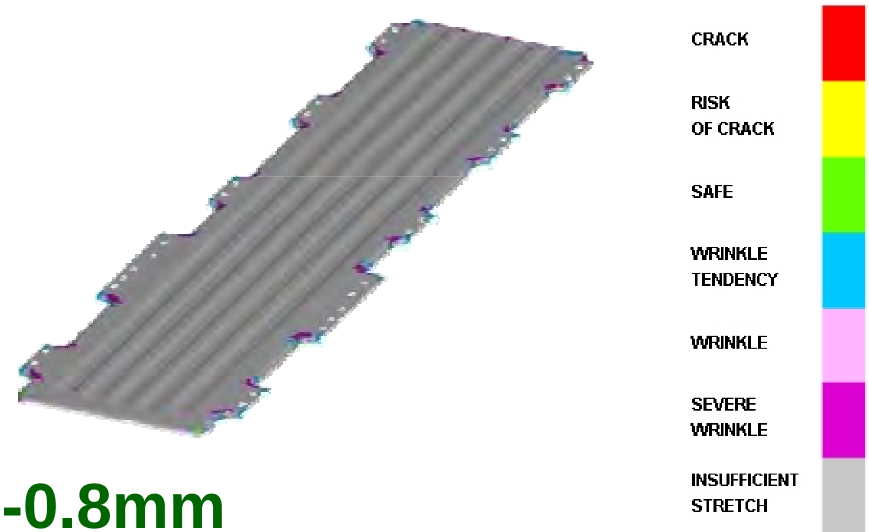
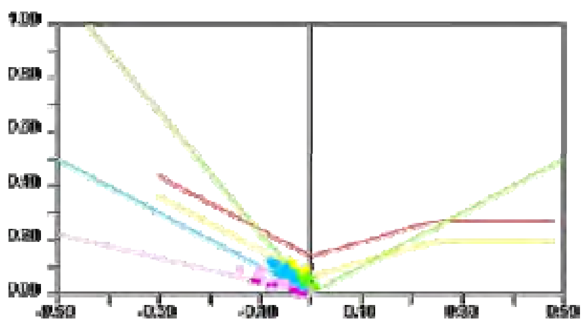
Task2a:Battery Tray- T5-Final Vs D336

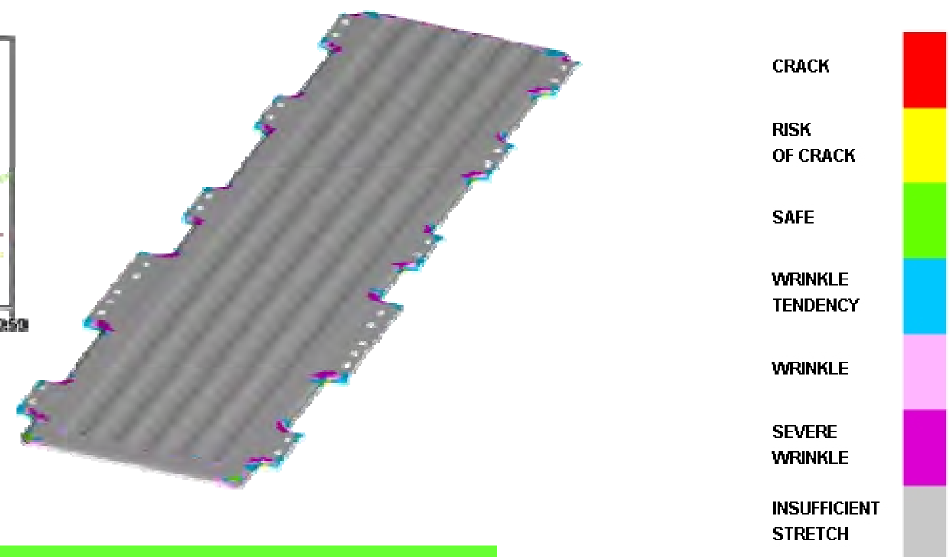






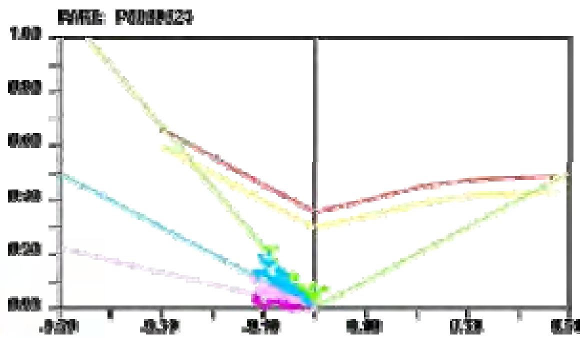
T5- DP 500/800-0.8mm

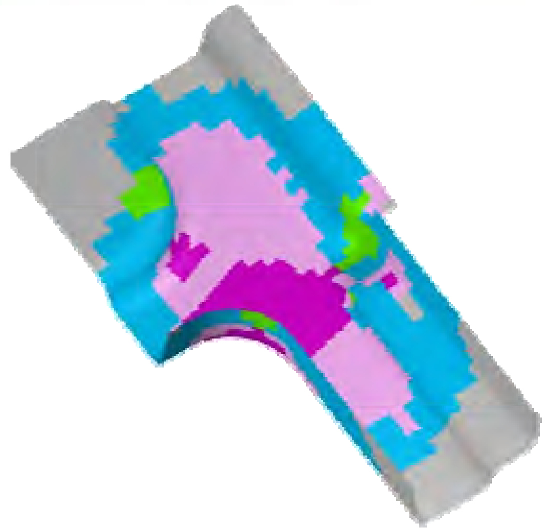


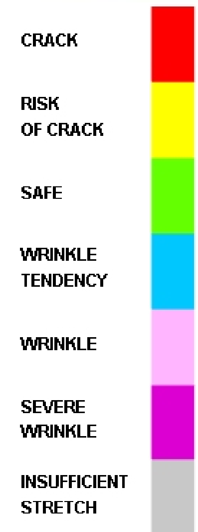


✓D336-DP 700/1000-0.8mm

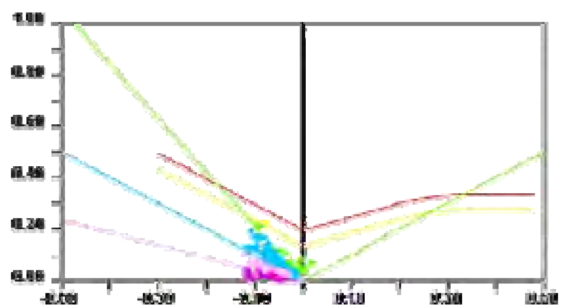
Task2a:Tunnel Rail Bulkhead- T5-Final Vs D336

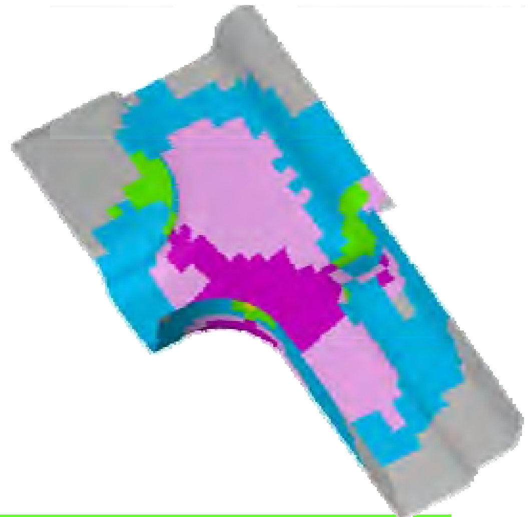






T5- DP 500/800-3mm-from Dynaform





✓D336-MS 950/1200-3mm

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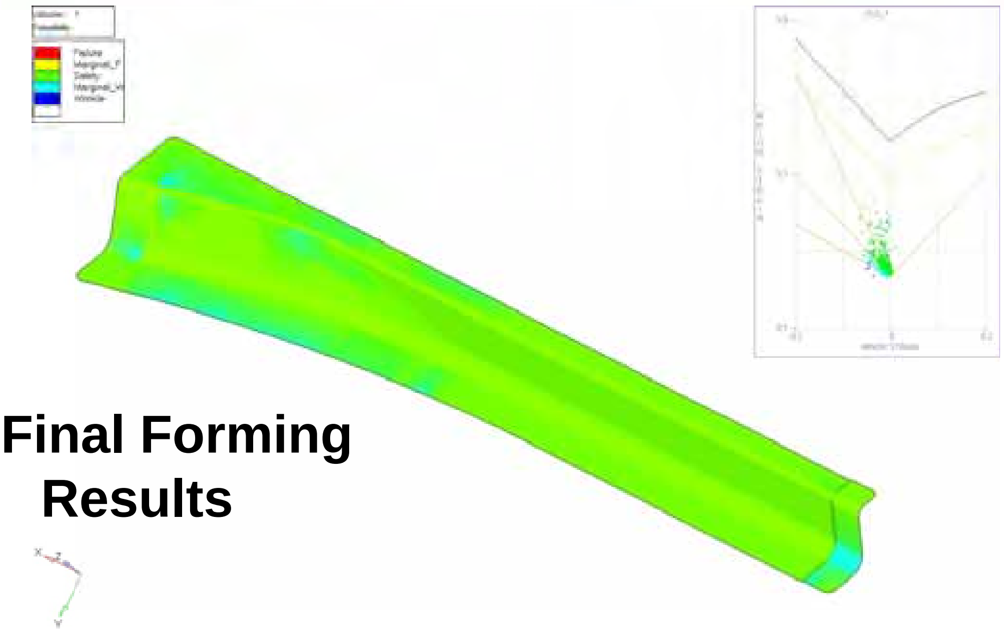
Task2a:Rocker Filler Front- Gusset Rear

T5- **BH210/340-0.6mm-0.199Kg**
D336-HF1050/1500-0.6mm



T5-Final Forming Results

Hot Stamping

Rocker

Roller Forming

T5- **CP1050/1470-1mm-6.032Kg**
D336- MS 1300/1550-1mm+.85mm

Task2a:T6 Optimization Gauges used

Item #	Steel Grade	FSV Portfolio/Steel Capabilities (mm)		D336 (T5) Optimization Gage Recommendation - (mm)		T6 Optimization Range (mm)	
		Min t	Max t	Min t	Max t	Min t	Max t
1	Mild 140/270	0.35	4.60	0.50	0.50	0.50	4.60
2	BH 210/340	0.45	3.40	0.50	1.20	0.50	3.40
3	BH 260/370	0.45	2.80	0.50	0.50	0.50	2.80
4	BH 280/400	0.45	2.80	0.50	0.50	0.50	2.80
8	HSLA 350/450	0.50	5.00	0.50	1.00	0.50	5.00
9	DP 300/500	0.50	2.50	0.50	0.65	0.50	2.50
13	DP 350/600	0.60	5.00	0.60	1.00	0.60	5.00
21	DP 500/800	0.60	4.00	0.50	2.00	0.50	4.00
22	TRIP 450/800	0.60	2.20	1.20	1.90	0.60	2.20
25	TRIP 600/980	0.90	2.00	1.80	2.00	0.90	2.00
27	DP 700/1000	0.60	2.30	0.60	1.00	0.60	2.30
30	MS 950/1200	0.50	3.20	0.50	2.40	0.50	3.20
31	CP 1000/1200	0.80	2.30	1.00	1.00	0.80	2.30
33	MS 1150/1400	0.50	2.00	0.65	0.65	0.50	2.00
35	HF 1050/1500	0.60	4.50	0.60	1.50	0.60	4.50

T6- Optimization
Task2b

Task2b:T6-Optimization Strategy

- Our strategy at this stage of the project is to meet the design targets and optimize the mass of the FSV BIW. Our design space has become much smaller and more sensitive, however, since the vehicle has been optimized several times at different stages of vehicle development. We therefore develop a new strategy to streamline the ACP optimization process . This strategy enhances the normal ACP process with manual process separation, so that we can have a much more detailed search within our design spaces.
    1. Sensitivity optimization process.
    2. Meet the design targets with sensitive load cases and reduce mass.

Task2b: T6 Optimization Process

- Phase 1: All of the loadcases with pre-identified parts
- Phase 2: Front crash (NCAP and ODB) with relevant parts
- Phase 3: Use results from frontal crash optimization to reduce mass in body for other load cases
- Phase 4: Torsion load case only
- Verifications

Task2b: T6 Overall Summary of Results

- Total number of designs run = **865**
- Optimization was performed in four phases
- Phase 1 Optimization : Sensitivity Phase ~**155 designs**
  - Implement T5 Optimization results into T6- Baseline.
  - **Mass savings = 9.4 Kg.**
  - NCAP not meeting the performance target.
  - All 6 load cases were considered.
  - Only one feasible design (#12) which was heavier than the baseline. NCAP Frontal and Torsion were controlling load cases.
- Phase 2 Optimization : Performance Targets ~ **140 designs**
  - Load Case: NCAP and ODB Frontal crash load cases.
  - Consider all parts in frontal crash only, keep body parts the same.
  - Design #54 met performance targets but with **no mass saving**.

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Task2b: T6 Overall Summary of Results

- Phase 3 Optimization: Mass Reduction: **~ 60 designs**
  - Started with Design #54 from Phase 2
  - All 6 load cases were applied
  - Design variables focused on body side
  - **Design #147 provides additional 6.3 kg for a total 15.7 kg mass saving, 8.3% lighter than T5-Final**
  - Design #147 meets targets for all load cases, with the exception of a torsion performance of 17.8 kN-m/deg
- Phase 4 Optimization: Mass Reduction for Torsion Stiffness that provides 3 solutions **~ 500 Design**
  - Start with Design #147 from Phase 2
  - Torsional Load case
    a) Design #147- Mass **15.7 (8.33%)** lighter than T5 and Torsion **:17.8 KN-m/deg**
    b) Design #159- Mass **12.3 kg (6.5%)** lighter than T5 and torsion: **18.66 kN-m/deg**
    c) Design #225- Mass **11.6 kg (6.2%)** lighter than T5 and torsion : **19 kN-m/deg**

Design 225 with 11.6Kg (6.2%) T6 mass reduction is selected

Task2b-T6 Summary Table

Design	Mass kg	NCAP	Front ODB	IIHS Side	IIHS Rear	IIHS Roof	Torsion
Targets	<188	39.6 g	Good	125mm	Pass	37.5kN	19
T5-Final	188.4	39.7	Good	142	Good	55	19.6
T6-Baseline	179 **(-9.4 kg)**	43.0	Good	170	Good	51	18.3
T6-Final	176.8 **(-11.6 kg)**	37.8	Good	152	Good	44.5	19

Phase 1
T6 Optimization- Sensitivity Analysis
All Loadcases

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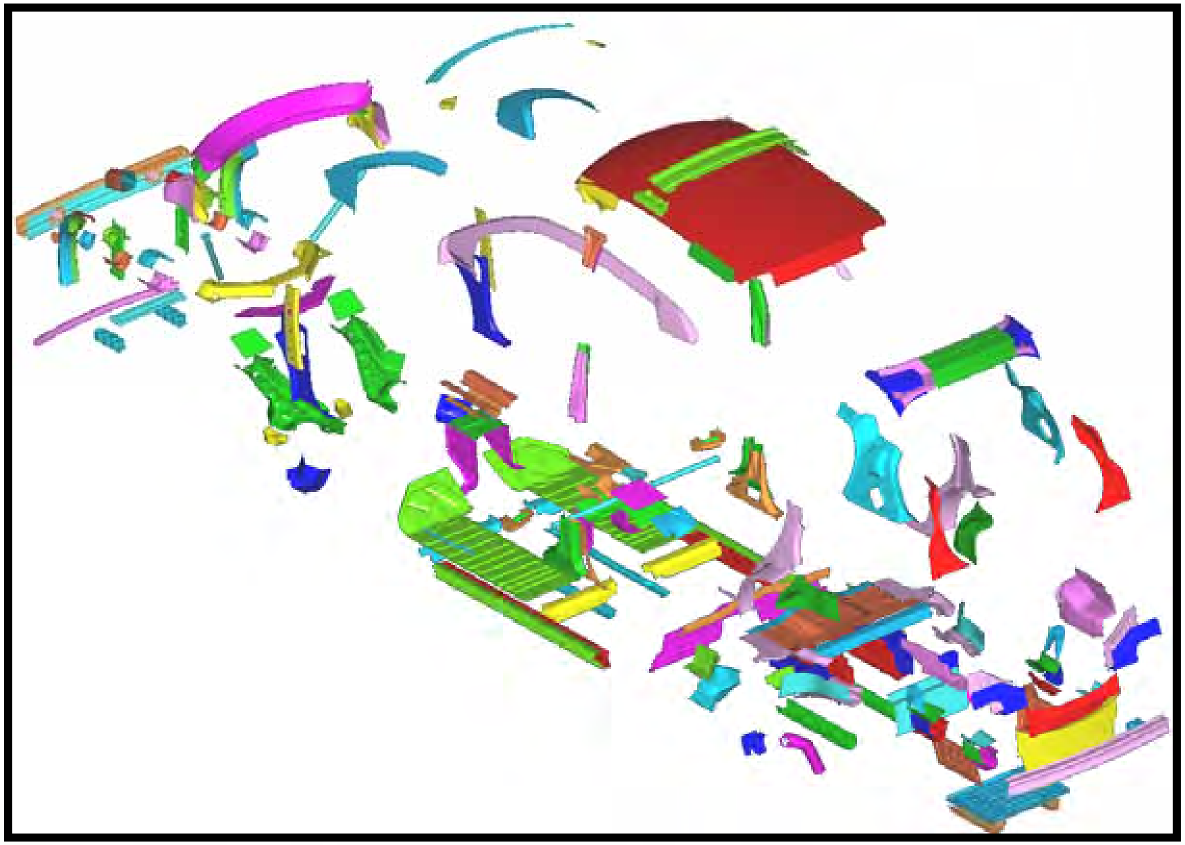
Task2b : T6 Optimization Phase 1 Setup

- Total number of Design variables = 99
- Load cases : US NCAP, IIHS Front ODB, IIHS Side Impact, ODB Rear impact, IIHS Roof Crush and Torsion
- Total of 107 parts, Gage Optimization
- Large panels are 0.5 mm



Task2b : T6 Optimization Phase 1- Design Variables

	Name	Min	Baseline	Max
▶	Dash_Driver_Toepan_400	0.5	0.5	0.6
2	Frt_Floor_Trans_Rail_404	0.6	1.5	1.6
3	Rr_Liftgate_Low_Top_405	0.5	0.6	0.8
4	Fram_Rail_Rr_Outer_406	0.5	0.75	1.0
5	Fram_Rail_Rr_Mid2_408	0.6	0.6	1.0
6	Seat_pan_Rr_Sides_409	0.6	0.6	1.2
7	Seat_pan_Rr_Mid_410	0.5	0.5	0.6
8	Wheelhouse_Outer_411	0.6	0.95	1.2
9	Wheelhouse_Inner_412	0.6	0.65	0.7
10	Back_Panel_Corner_Outer_413	0.5	1.0	2.0
11	Back_Panel_Lower_414	0.5	0.5	0.7
12	Shotgun_Inner_Frt_415	0.6	0.8	2.0
13	Shotgun_Inner_Mid_416	0.6	1.2	2.2
14	Shotgun_Inner_Rr_417	0.6	1.5	2.0
15	Tunnel_Frt_and_Back_418	0.5	0.5	0.8
16	Tunnel_Reinf_Frt_and_Back_420	0.5	0.95	1.0
17	Tunnel_Feinf_Mid_407	0.5	0.75	1.0
18	Xmem_Bat_Sus_Inner_421	0.6	0.6	1.0
19	Wheelhouse_Reinf_422	0.6	0.65	0.85
20	Shotgun_Outer_Frt_423	0.6	0.8	2.0
21	Shotgun_Outer_Mid_424	0.6	1	2.2
22	Shotgun_Outer_Rr_425	0.6	1.5	2.0
23	Cowl_Lower_426	0.5	0.5	0.6
24	Battery_Close_Inner_Outer_427	0.5	0.6	2.5
25	Rr_Gusset_428	0.6	1	2.3

	Name	Min	Baseline	Max
26	Xmem_Frt_Seat_Frt_429	0.5	0.5	1.0
27	Xmem_Frt_Seat_Rr_430	0.5	0.6	1.0
28	Heel_Board_431	0.6	0.6	1.0
29	Rail_Exten_Tunnel__Inner_432	0.6	1.2	2.3
30	Rail_Exten_Tunnel_Outer_433	0.6	0.9	1.2
31	Fram_Rail_Rein_Rr_Outer_434	0.5	0.6	1.0
32	Fram_Rail_Rein_Rr_Inner_436	0.6	0.7	1.0
33	Frt_Rail_Lower_Outer_437	0.6	1.8	1.9
34	Frt_Rail_Lower_Mid1_438	0.6	1.8	1.9
35	Frt_Rail_Lower_Mid2_439	0.6	1.5	1.9
36	Frt_Rail_Lower_Rr_Inner_440	0.6	1.8	1.9
37	Frt_Rail_Lower_Rr_Outer_441	0.6	1.8	1.9
38	Frt_Rail_Upper_Outer_442	0.6	1.2	1.9
39	Frt_Rail_Upper_Mid1_443	0.6	1.9	1.9
40	Frt_Rail_Upper_Mid2_444	0.6	1.8	1.9
41	Frt_Rail_Upper_Inner_445	0.6	1.9	1.9
42	Closeout_Upper_Rail_446	0.6	0.8	2.0
43	Closeout_Lower_Rail_447	0.6	1.5	2.0
44	Rail_Side_to_Side_448	0.6	0.8	1.0
45	APill_Brace_449	0.5	1	1.2
46	Back_Panel_Corner_Inner_450	0.5	1	2.0
47	Rear_Cargo_Box_451	0.5	0.5	1.0
48	Rr_Header_452	0.5	0.5	0.6
49	Rr_Header_Main_453	0.5	0.5	0.7
50	Rr_Header_Corners_454	0.5	1.15	2.0

Task2b : T6 Optimization Phase 1- Design Variables

	Name	Min	Baseline	Max
51	Roof_Panel_456	0.5	0.5	0.6
52	Roof_Bow_457	0.5	0.5	0.6
53	CPill_Inner_463	0.6	0.65	0.8
54	BPill_Inner_Top_464	0.6	0.8	1.2
55	BPill_Inner_Mid1_465	0.6	0.6	1.0
56	BPill_Inner_Mid2_466	0.6	0.8	1.5
57	BPill_Inner_Bot_467	0.6	0.6	1.0
58	Roof_Rail_Reinf_468	0.6	0.65	0.7
59	Roof_Rail_Inner_Frt_469	0.6	0.7	0.8
60	BPill_Reinf_Top_470	0.6	0.6	1.0
61	BPill_Reinf_Mid1_471	0.6	0.8	1.3
62	BPill_Reinf_Bot_472	0.6	0.6	1.0
63	Hinge_Pill_Inner_473	0.6	1	1.2
64	Rocker_Inner_474	0.5	0.85	1.4
65	Rocker_Outer_475	0.5	1.1	3
66	Cradle_Frt_476	0.5	1.4	1.9
67	Cradle_Back_477	0.5	1.4	1.4
68	Trailing_Arm_478	0.5	2.4	3.0
69	Door_Reinf_and_Beams_479	0.8	1	2.0
70	Seat_Beam_480	0.5	1.2	3
71	Bumper_Beams_482	0.5	1.2	2
72	Top_Panel_Tunner_Rear_601	0.5	0.5	1
73	Top_Panel_Tunner_Middle_602	0.5	0.75	1
74	Tunnel_Rail_Bulkhead_603	0.5	1	3.2
75	Reinf_Frame_Rail_Rear_Middle_6(	0.6	0.65	2.3
76	Frame_Rail_Outer_Rear_Middle_6(	0.6	1.4	2.3
77	Panel_Sear_Side_606	0.6	0.7	2.3
78	Frame_Rail_Inr_Rear_Front_607	0.6	1.4	2.3
79	Reinf_FBHP_608	0.6	0.8	2.3
80	Bulkhead_Upr_Tunnel_609	0.6	0.8	2.3
81	Bulkhead_Lwr_Tunnel_610	0.6	0.8	2.3
82	Front_Bumper_Otr_611	0.6	1	4
83	Front_Bumper_Inr_612	0.6	1	4
84	Front_Crush_Cans_613	0.6	1.2	4
85	Rear_Crush_Cans_614	0.6	1	5
86	Shotgun_Brace_615	0.5	0.7	3.4
87	Bumper_Cradle_616	0.5	1.2	3.4
88	Roof_Rail_Inr_Rear_617	0.5	1.1	3.4
89	Rocker_Cap_618	0.5	0.85	3.4
90	Panel_Gutter_Rear_619	0.5	0.8	3.4
91	Bracket_Roof_Rail_To_Bow_620	0.5	1	3.4
92	Front_Header_621	0.5	0.8	3.4
93	Bracket_Roof_Rail_To_Header_62	0.5	1	3.4
94	Cowl_Upr_623	0.5	0.6	3.4
95	Radiator_Closure_Side_625	0.5	0.75	3.4
96	Radiator_Closure_Top_626	0.5	0.75	3.4
97	Radiator_Closure_Bottom_627	0.5	0.75	3.4
98	Reinf_Rear_Shock_628	2.0	2.5	4.0
99	Mount_Rear_Shock_629	2.5	3.0	4.0

Task2b : T6 Optimization Phase 1- Performance Criterion

❑Performance Criterion: Minimize Mass

Name	Analysis	Option	Limit
NCAP_MAX_PULSE_0_20_ms	Dyna_NCAP	<=	38
NCAP_MAX_PULSE_20_70_ms	Dyna_NCAP	<=	39
ODB_FOOT_WELL	Dyna_ODB	<=	91
ODB_TOE_PAN_LH	Dyna_ODB	<=	131
ODB_TOE_PAN_CTR	Dyna_ODB	<=	155
ODB_TOE_PAN_RH	Dyna_ODB	<=	139
ODB_IP_LH	Dyna_ODB	<=	35
ODB_IP_RH	Dyna_ODB	<=	35
ODB_DOOR	Dyna_ODB	<=	24
ROOF_FORCE	Dyna_Roof	>=	40000
REAR_MAX_PULSE	Dyna_Rear	<=	40
REAR_DOOR	Dyna_Rear	<=	90
TORSION_AVG	Dyna_Torsion	<=	1.8

Task2b : T6 Optimization Phase 1- Results

- # of Designs run: 155
- Design 12 meets all the targets, but is heavier than the baseline

Design	Mass kg	NCAP	Front ODB	IIHS Side	Side Pole	IIHS Rear	IIHS Roof	Bend.	Torsion
Targets	<188	39.6g	Good	125mm	125mm	Pass	37.5kN	12	20
T5-Final	188.4	39.7	Good	142	150	Good	55kN	15.5	19.6
T6-Baseline	179 **9.4 kg Lighter**	43.0	5-6% Better	170 (16.5% Better)	150	Good	51kN %23> IIHS	14.5	18.3
Design 12	**Heavier**	38.6	Good	196.37		Good	61.2kN		>20

Task2b : T6 Optimization Phase 1- Highlights

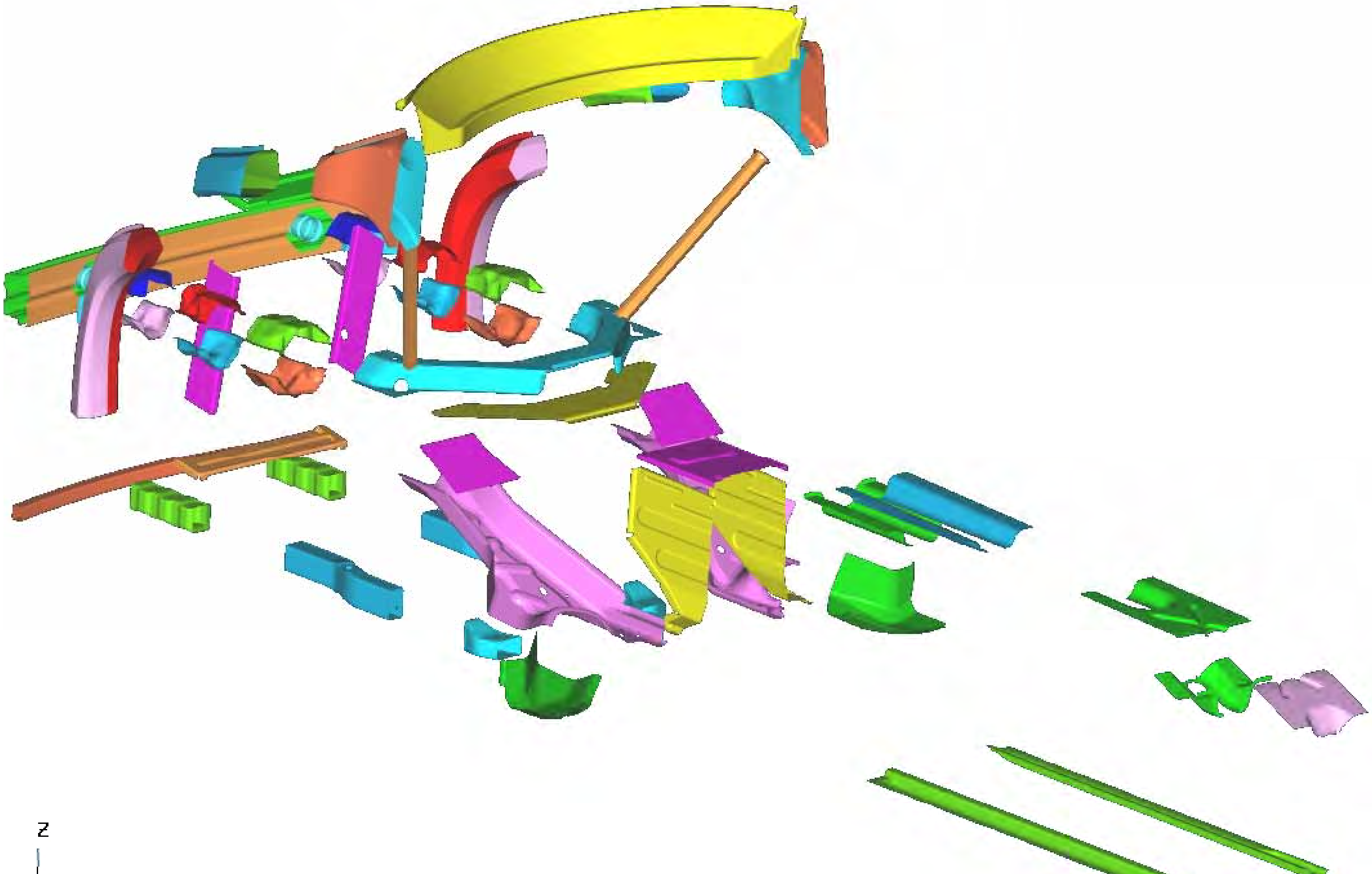
- As usual in this phase, optimization looks to first meet performance, and the results show that the system is sensitive to 2 load cases: NCAP Frontal Crash and Torsional stiffness.
- Frontal NCAP and ODB are controlling loadcases, all other load cases meets the target.
- Frontal NCAP and ODB are conflicting; meaning only one of them meets the target at one time.
- Significant mass goes to Non-BIW parts.
- To improve optimization process speed to meet targets, using Phase 1 results, front crash load cases and torsion stiffness will be optimized individually.

Phase 2
T6 Optimization- Gage Optimization
Load case : Front Crash (NCAP and IIHS/ODB)

Task2b : T6 Optimization Phase 2- Highlights

- Only two loadcases are considered- Frontal NCAP and IIHS/ ODB.
- Only components affecting these loadcases are optimized, so as not to affect performance of other load cases.
- Once the optimization is completed, all load cases will be run to check for the performance.
- # of Design Variables = 36

Task2b : T6 Optimization Phase 2- Components



- The components were consider in front crash gage optimization

Task2b : T6 Optimization Phase 2- Design variables

	Name	Type	Min	Baseline	Max
1	Frt_Floor_Trans_Rail_404	Continuous	0.6	1.5	1.6
2	Tunnel_Feinf_Mid_407	Continuous	0.5	0.75	1.0
3	Shotgun_Inner_Frt_415	Continuous	0.6	0.8	2.0
4	Shotgun_Inner_Mid_416	Continuous	0.6	1.2	2.2
5	Shotgun_Inner_Rr_417	Continuous	0.6	1.5	2.0
6	Tunnel_Frt_and_Back_418	Continuous	0.5	0.5	0.8
7	Tunnel_Reinf_Frt_and_Back_420	Continuous	0.5	0.95	1.0
8	Shotgun_Outer_Frt_423	Continuous	0.6	0.8	2.0
9	Shotgun_Outer_Mid_424	Continuous	0.6	1	2.2
10	Shotgun_Outer_Rr_425	Continuous	0.6	1.5	2.0
11	Frt_Rail_Lower_Outer_437	Continuous	0.6	1.8	2.0
12	Frt_Rail_Lower_Mid1_438	Continuous	0.6	1.8	2.0
13	Frt_Rail_Lower_Mid2_439	Continuous	0.6	1.5	2.0
14	Frt_Rail_Lower_Rr_Inner_440	Continuous	0.6	1.8	2.0
15	Frt_Rail_Lower_Rr_Outer_441	Continuous	0.6	1.8	2.0
16	Frt_Rail_Upper_Outer_442	Continuous	0.6	1.2	2.0
17	Frt_Rail_Upper_Mid1_443	Continuous	0.6	1.9	2.0
18	Frt_Rail_Upper_Mid2_444	Continuous	0.6	1.8	2.0

	Name	Type	Min	Baseline	Max	D
19	Frt_Rail_Upper_Inner_445	Continuous	0.6	1.9	2.0	
20	Closeout_Upper_Rail_446	Continuous	0.6	0.8	2.0	
21	Closeout_Lower_Rail_447	Continuous	0.6	1.5	2.0	
22	APill_Brace_449	Continuous	0.5	1	1.5	
23	Cradle_Frt_476	Continuous	0.5	1.4	1.9	
24	Cradle_Back_477	Continuous	0.5	1.4	1.9	
25	Top_Panel_Tunner_Rear_601	Continuous	0.5	0.5	1	
26	Top_Panel_Tunner_Middle_602	Continuous	0.5	0.75	1	
27	Front_Bumper_Otr_611	Continuous	0.6	1	1	
28	Front_Bumper_Inr_612	Continuous	0.6	1	1	
29	Front_Crush_Cans_613	Continuous	0.6	1.2	2.5	
30	Shotgun_Brace_615	Continuous	0.5	0.7	1.5	
31	Bumper_Cradle_616	Continuous	0.5	1.2	1.2	
32	Cowl_Upr_623	Continuous	0.5	0.6	0.6	
33	Radiator_Closure_Side_625	Continuous	0.5	0.75	0.75	
34	Radiator_Closure_Top_626	Continuous	0.5	0.75	0.75	
35	Radiator_Closure_Bottom_627	Continuous	0.5	0.75	0.75	
36	Cradle_mid_33013	Continuous	1.2	1.4	2.0	

Task2b : T6 Optimization Phase 2- Optimization Targets

Name	Analysis	Option	Limit
NCAP_MAX_PULSE	Dyna_NCAP	<=	39.6
NCAP_MAX_PULSE	Dyna_NCAP	<=	39.6
ODB_FOOT_WELL	Dyna_ODB	<=	91
ODB_TOE_PAN_LH	Dyna_ODB	<=	131
ODB_TOE_PAN_CTF	Dyna_ODB	<=	155
ODB_TOE_PAN_RH	Dyna_ODB	<=	139
ODB_IP_LH	Dyna_ODB	<=	35
ODB_IP_RH	Dyna_ODB	<=	35
ODB_DOOR	Dyna_ODB	<=	24

Task2b : T6 Optimization Phase 2- Results Summary

- Number of Designs: 140
- Best Design: Design #54

Design	Mass kg	NCAP	Front ODB	IIHS Side	Side Pole	IIHS Rear	IIHS Roof	Bend.	Torsion
Targets	<188	39.6g	Good	125mm	125mm	Pass	37.5kN	12	20
T5-EDAG	188.4	39.7	Good	142	Good	Good	55kN	15.5	19.6
T6-Baseline	179 **(-9.4 Kg)**	43.0	5-6% Better	170 (16.5% Better)	Good	Good	51kN %23> IIHS	14.5	18.3
Design # 54	**178.8** **(-9.6 Kg)**	38.9	Good						18

- Phase 2 optimization improved the vehicle pulse from 43 G to 38.9 G, with 9.6 kg mass reduction over T5

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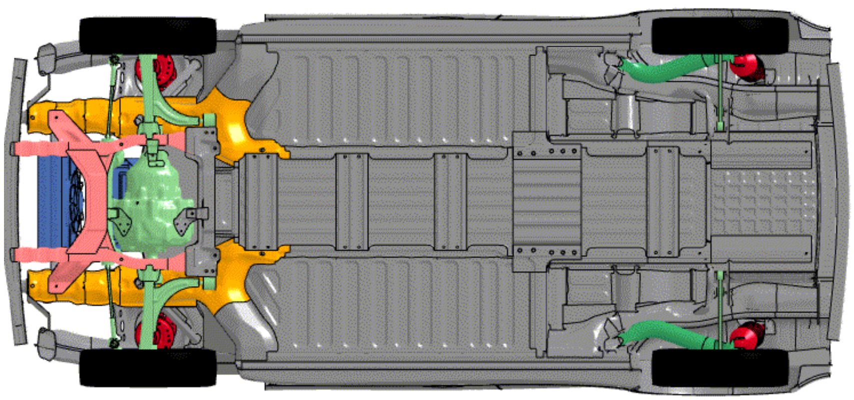
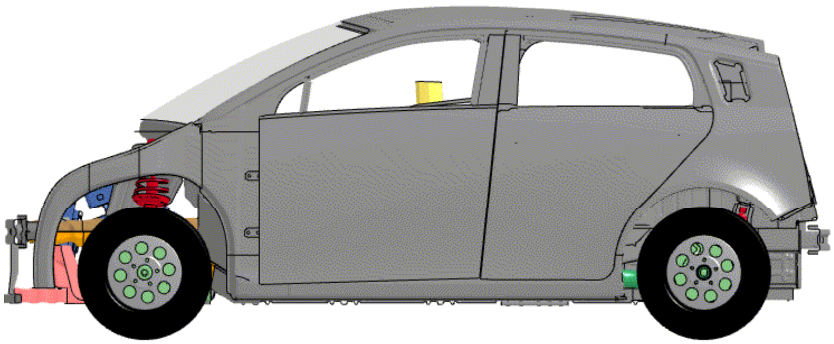
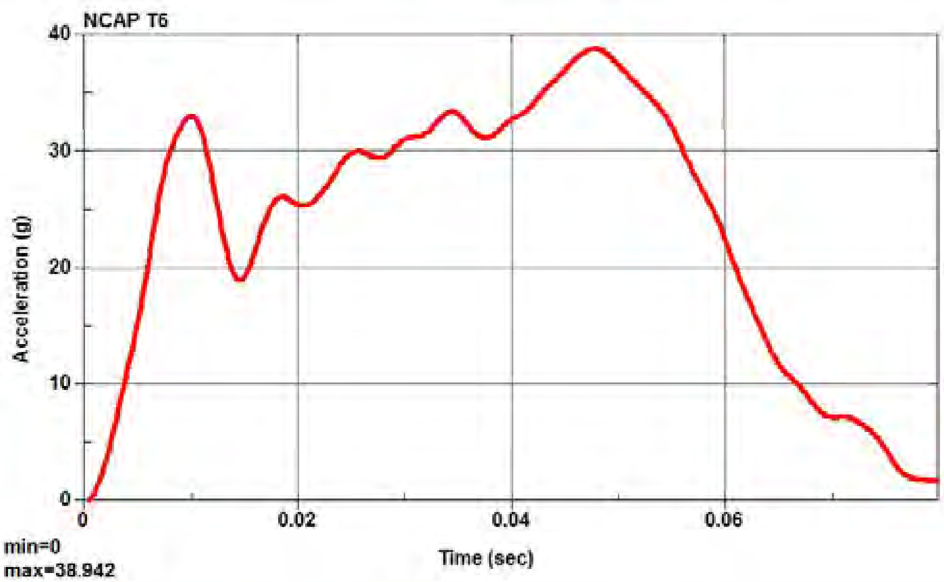
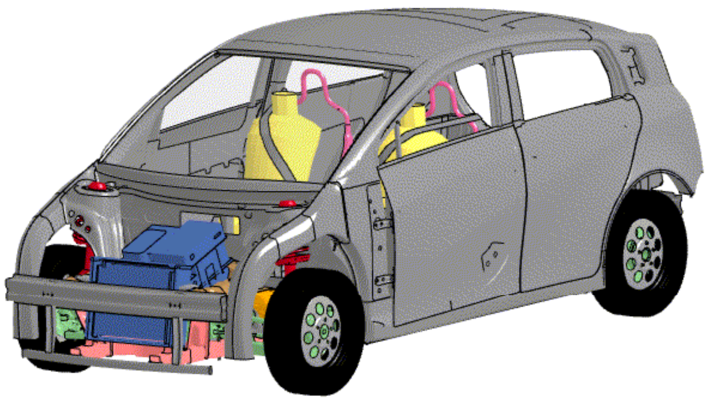
Task2b : T6 Optimization Phase 2- Optimization Results

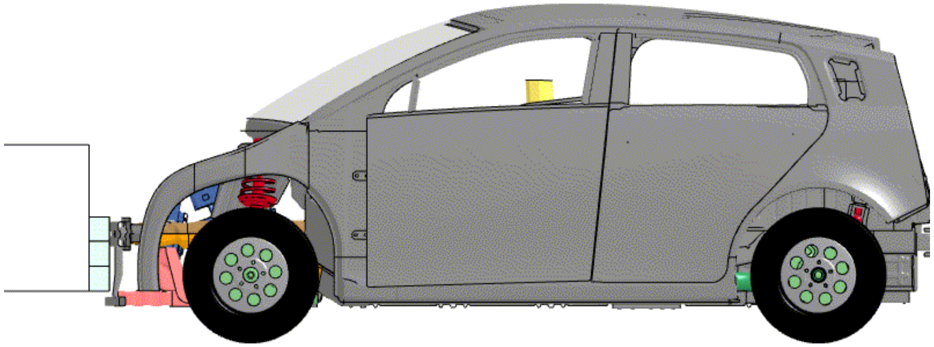


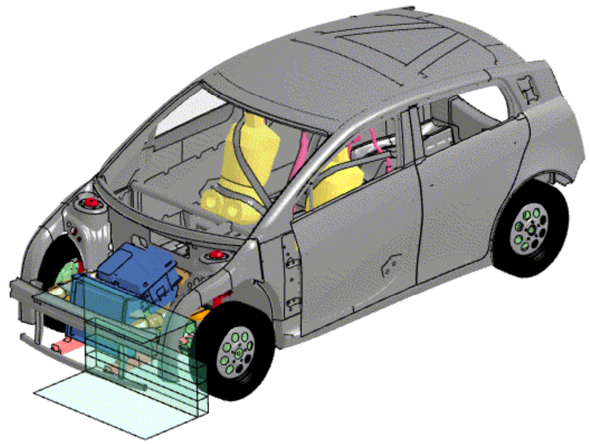


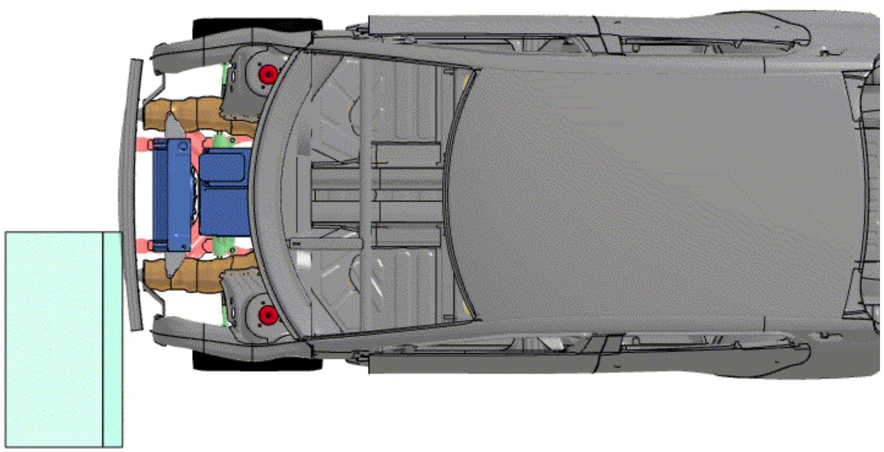




Task2b : T6 Optimization Phase 2- Optimization Results







Phase 3
T6 Optimization- Body Side Optimization
Load case :All Load Cases

Task2b : T6 Optimization Phase 3- Load cases

- Mass reduction from the body side for following load cases
  - Side Impact
  - Rear Impact
  - Roof Strength

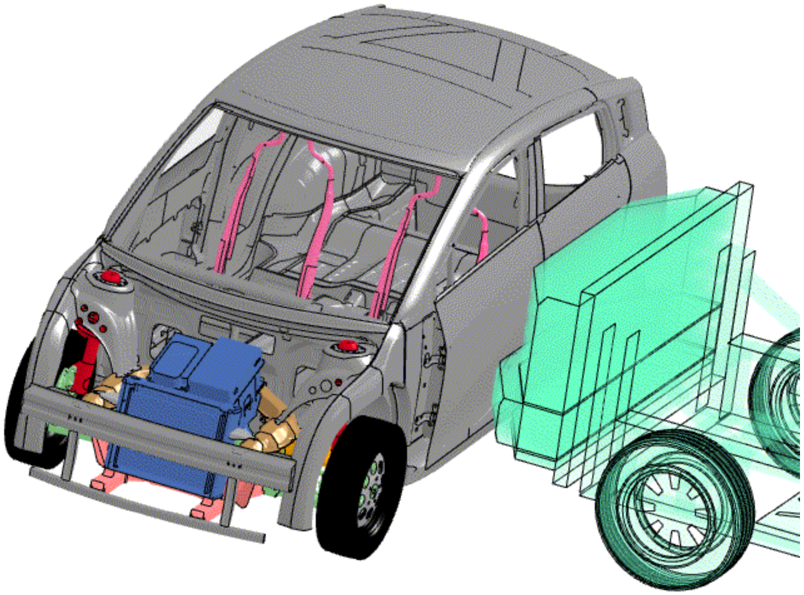
Task2b : T6 Optimization Phase 3- Results Summary

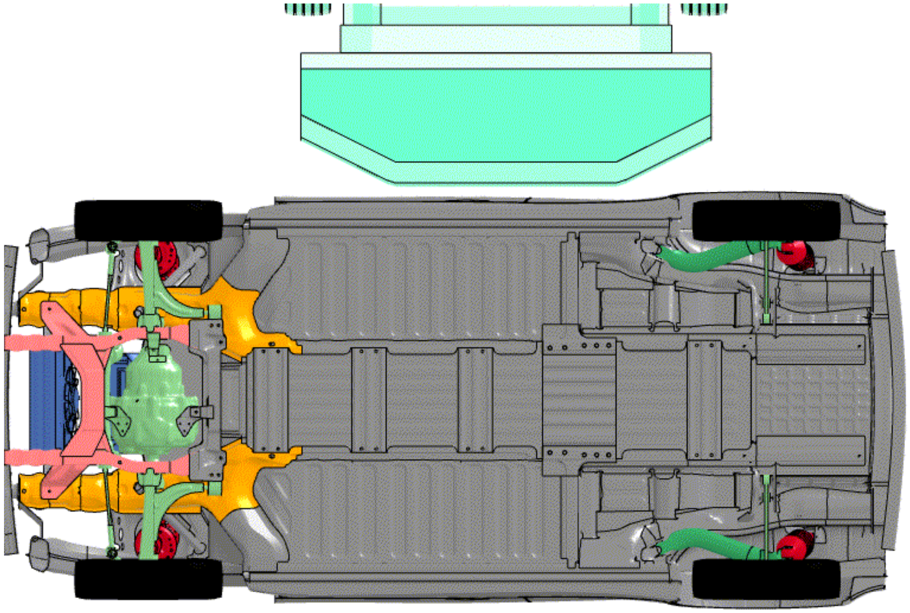
- Number of Designs: 60
- Best Design: Design #147

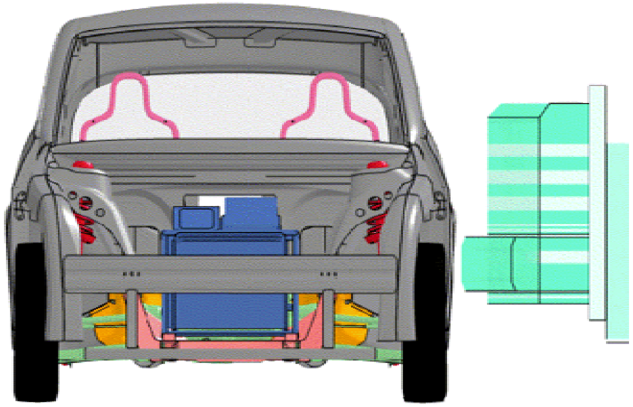
Design	Mass kg	NCAP	Front ODB	IIHS Side	Side Pole	IIHS Rear	IIHS Roof	Torsion
Targets	<188	39.6g	Good	125mm	125mm	Pass	37.5kN	20
T5-Final	188.4	39.7	Good	142	Good	Good	55 kN	19.6
T6-Baseline	179 (-9.4 Kg)	43.0	5-6% Better	170 (16.5% Better)	Good	Good	51 kN %23> IIHS	18.3
Design # 54	**178.8** **(-9.6 Kg)**	38.9	Good	Good				18
Design # 147	**172.7** **(-15.7 Kg)**	39.3	Good	148.7		Good	46.9 kN	17.8

- Phase 3 optimization improved the weight reduction to 15.7 Kg over T5-Final

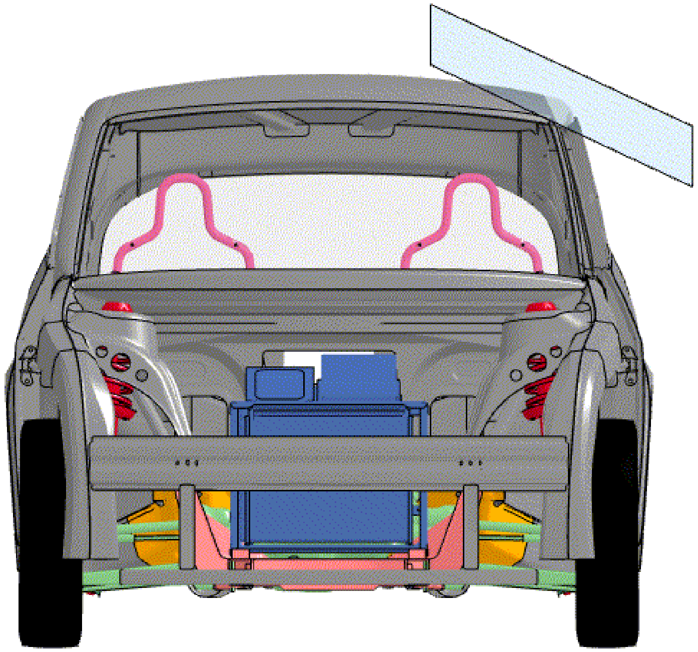
Task2b : T6 Optimization Phase 3- IIHS Side Impact

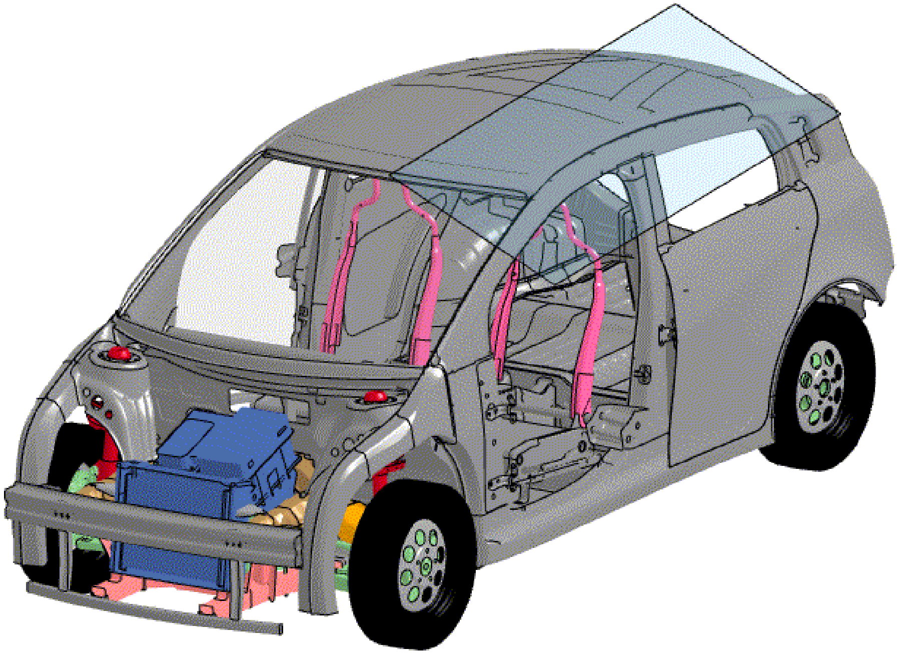




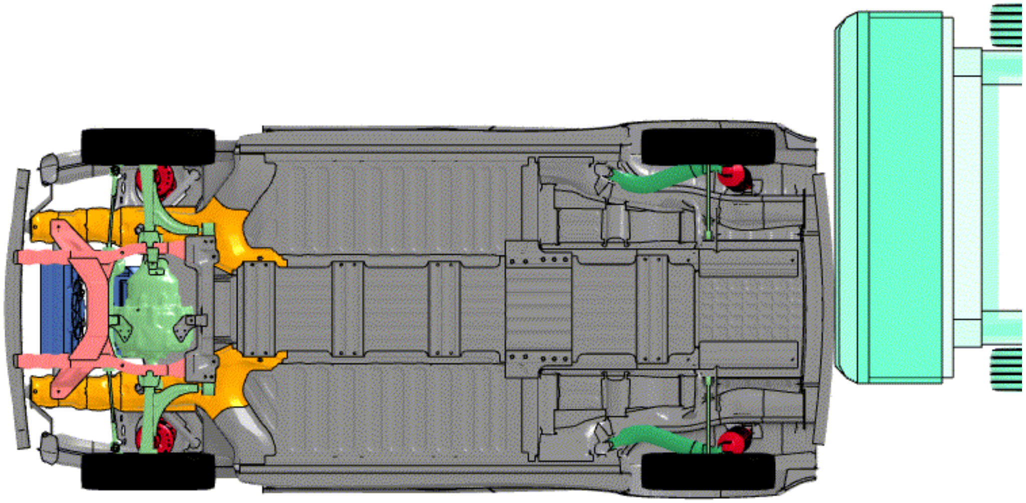


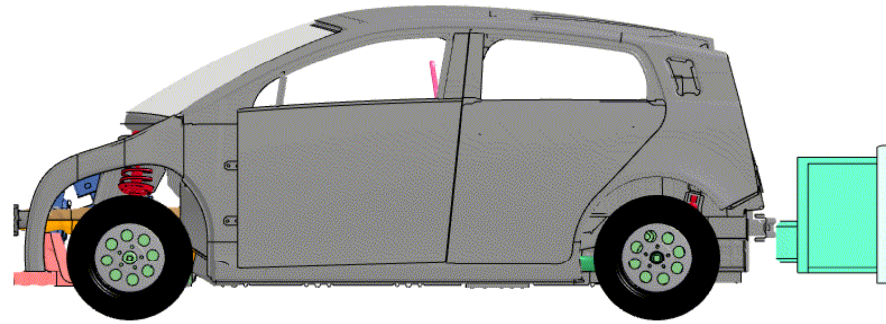
Task2b : T6 Optimization Phase 3- IIHS Roof Crush

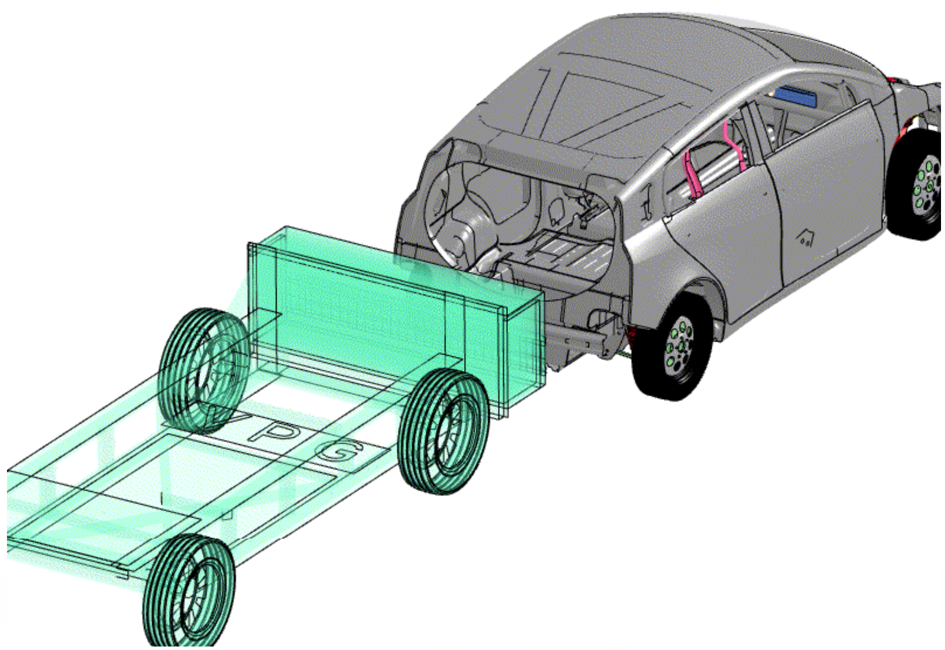




Task2b : T6 Optimization Phase 3- Rear Impact







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Task2b : T6 Optimization Phase 3- Results Summary

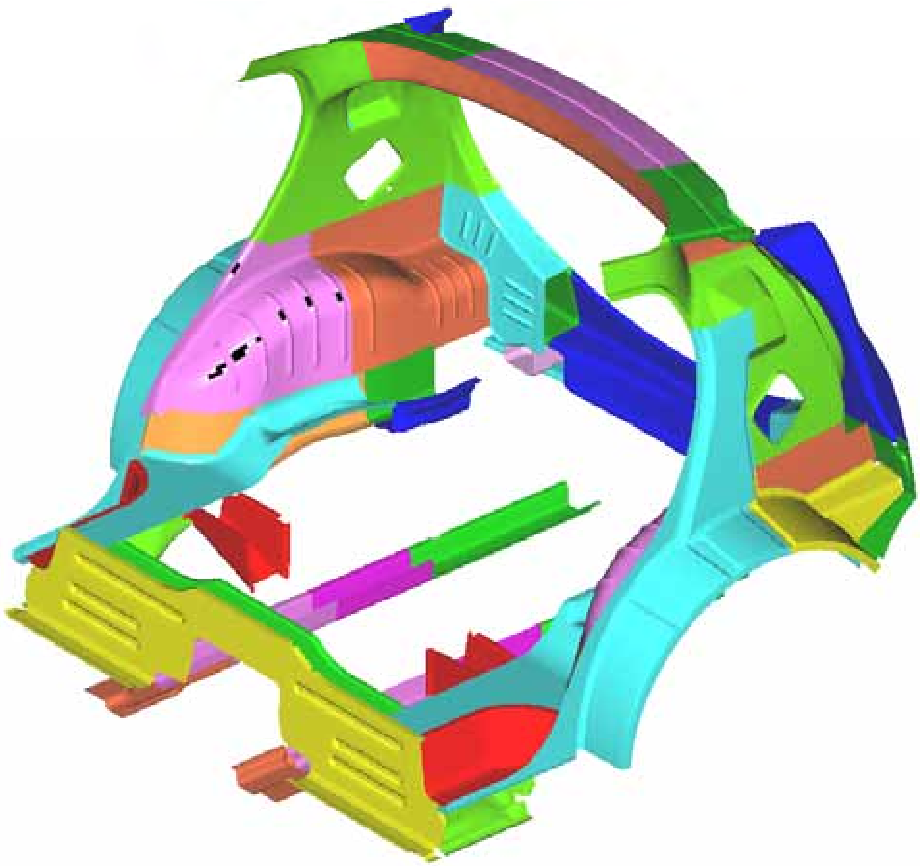
- Total of 15.7 Kg mass savings over T5-Final.
- Torsion still not meeting the target, all other load cases are meeting targets.

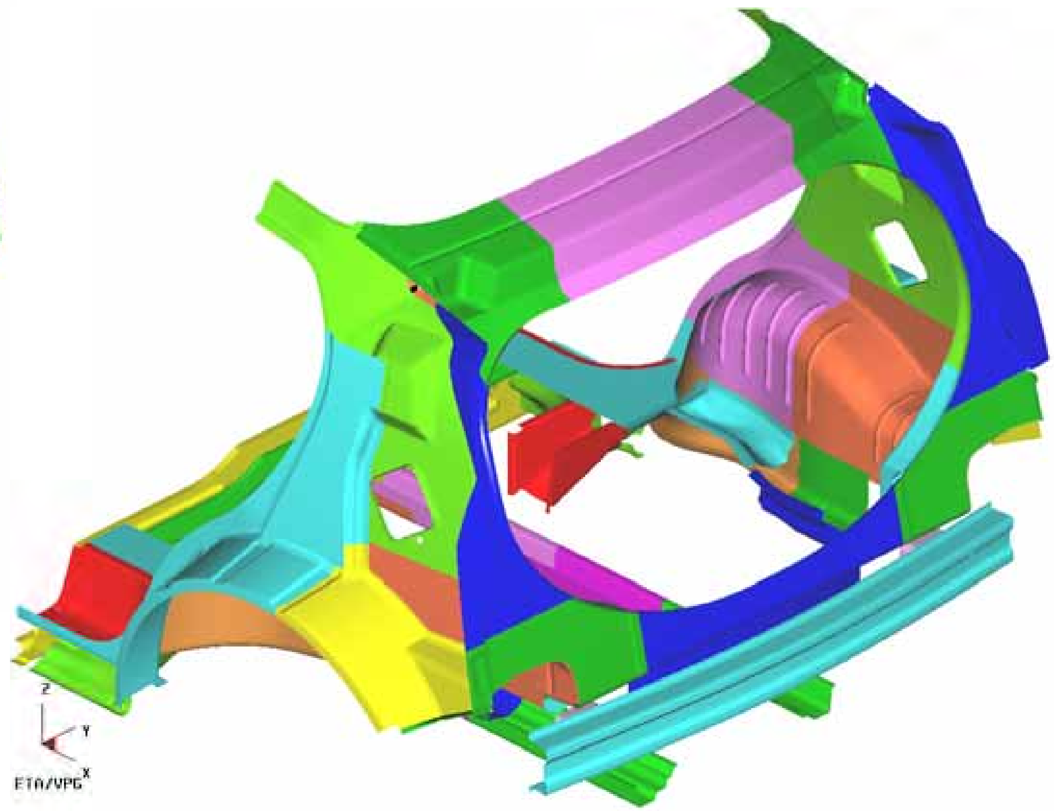
Phase 4
T6 Optimization- Gage Optimization
Load case : Torsion

Task2b : T6 Optimization Phase 4- Strategy

- Based on past experience in FSV BIW mass reduction tasks, the vehicle is very sensitive to Torsional Stiffness. This leads that stiffness can not be improve by AHSS but requires higher gage at critical locations
- Parts to be optimized were selected so as not to disrupt any other load case performances.
- The starting point for optimization is Phase 3 final results (Design #147 ,mass=172.7 Kg).

Task2b : T6 Optimization Phase 4- Components





Task2b : T6 Optimization Phase 4- Design Variables

	Name	Min	Baseline	Max
1	Fram_Rail_Rr_Mid2_408	0.6	0.6	1.0
2	Wheelhouse_Outer_411	0.6	0.95	2.5
3	Wheelhouse_outer_twb_4111	0.6	0.95	2.5
4	Wheelhouse_Inner_412	0.6	0.65	0.7
5	Back_Panel_Corner_Outer_413	0.5	1.0	2.5
6	Back_Panel_Lower_414	0.5	0.5	1.5
7	Wheelhouse_Reinf_422	0.6	0.65	0.85
8	Rr_Gusset_428	0.6	1	2.3
9	Heel_Board_431	0.6	0.6	1.0
10	Rail_Exten_Tunnel__Inner_432	0.6	1.2	2.3
11	Battery_Rail_inr_twb_4321	0.6	1.2	2.3
12	Rail_Exten_Tunnel_Outer_433	0.6	0.9	1.2
13	Wheelhouse_Reinf_twb_435	0.5	0.65	1
14	Fram_Rail_Rein_Rr_Inner_436	0.6	0.7	1.0

	Name	Min	Baseline	Max
15	Rail_Side_to_Side_448	0.6	0.8	1.0
16	Back_Panel_Corner_Inner_450	0.5	1	3.4
17	Rr_Header_452	0.5	0.5	1.2
18	Rr_Header_Main_453	0.5	0.5	1.2
19	Rr_Header_corner_454	0.5	1.15	1.5
20	CPill_Inner_463	0.6	0.65	0.8
21	Bumper_Beams_482	0.5	1.2	2
22	Tunnel_Rail_Bulkhead_603	0.5	1	2.5
23	Frame_Rail_Outer_Rear_Middle_605	0.6	1.4	2.3
24	Panel_Sear_Side_606	0.6	0.7	2.3
25	Frame_Rail_Inr_Rear_Front_607	0.6	1.4	2.3
26	Rear_Crush_Cans_614	0.6	1	3
27	Panel_Gutter_Rear_619	0.5	0.8	3.4
28	Reinf_Rear_Shock_628	2.0	2.5	4.0
29	Mount_Rear_Shock_629	2.5	3.0	4.0

Task2b : T6 Optimization Phase 4- Results summary

- Total number of designs run: 500
- Torsion stiffness is a function of mass. ACP could not find a lighter design while meeting the target.
- There are many designs which meet the targets but are heavier. The following scenarios are possibilities:

Design	Mass kg	Torsion	Comments
Torsion Optimization Baseline (Design 147 from previous optimization)	**172.7 kg** **(-15.7 Kg)**	17.8	Meets all other targets and is the lightest design with **15.7kg or 8.33%** mass savings compared to T5-Final.
Design 143	**176.1** **(-12.3 Kg)**	18.66	Meets all other targets and is **12.3 kg or 6.5%** lighter than the T5-Final.
Design 225 -	**176.8** **(-11.6 Kg)**	19. 1	Meets all other targets and is **11.6 kg or 6.2%** lighter than the T5-Final.

Task2b : T6 Optimization Phase 4-Final Results

Design 225 was selected as final T6 Optimized design with Mass of **176.8** kg **11.6 kg** or **6.2%** mass reduction over T5 design and **39%** overall mass reduction over FSV Benchmark

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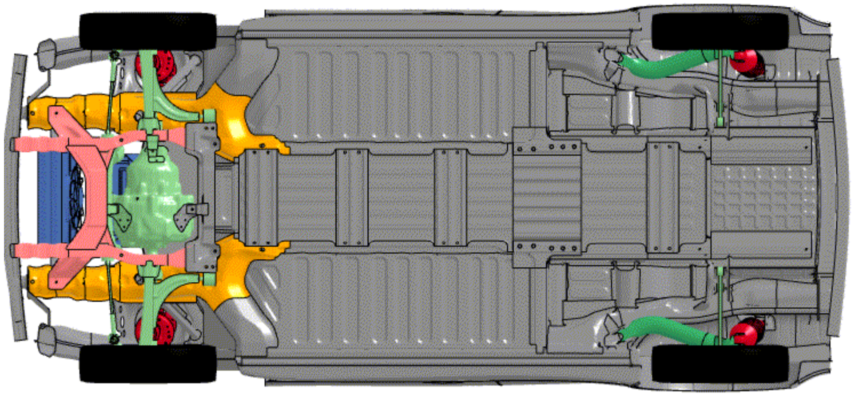
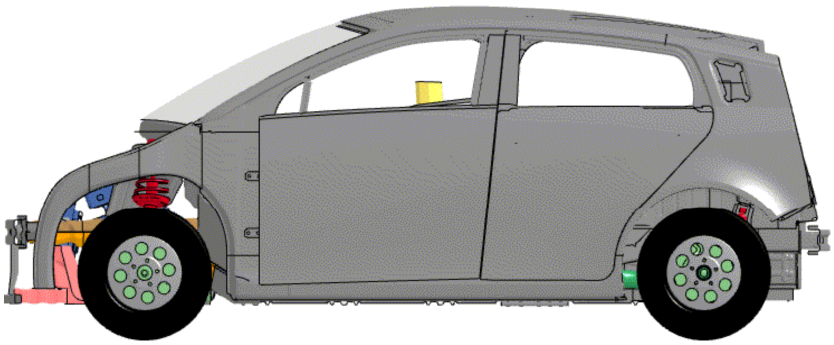
T6 Final Verification
Design 225

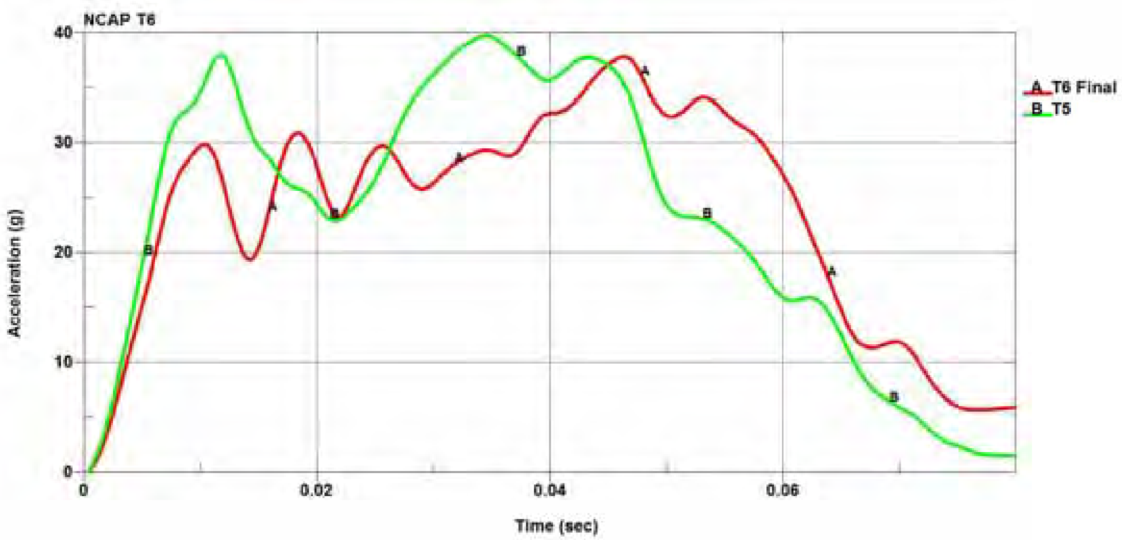
Task2b : T6 Optimization Verification

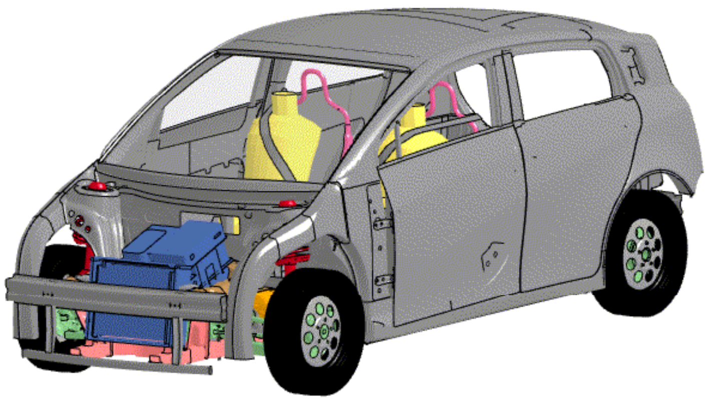
- Run all load cases with Design 225 gages and grades to ensure that the final design meets all targets.

Task2c : T6 Verification –Front NCAP









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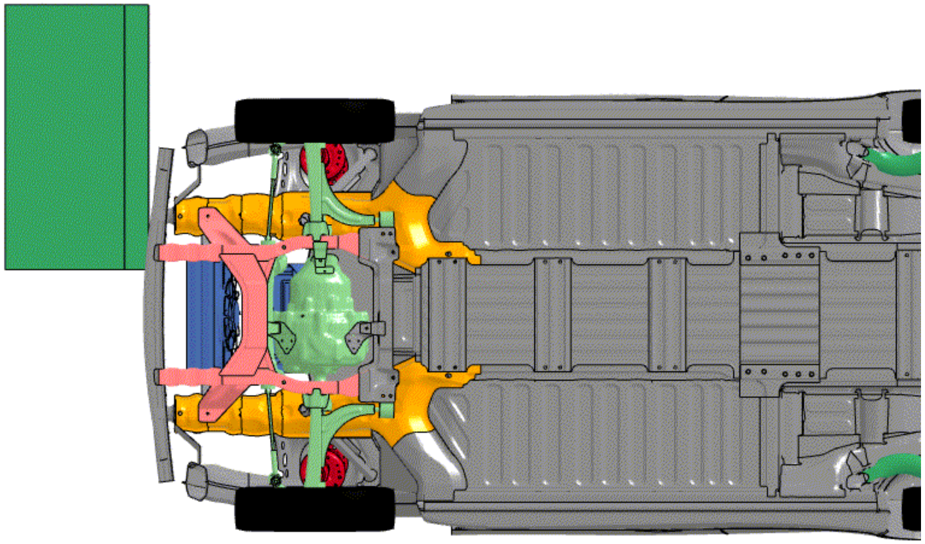
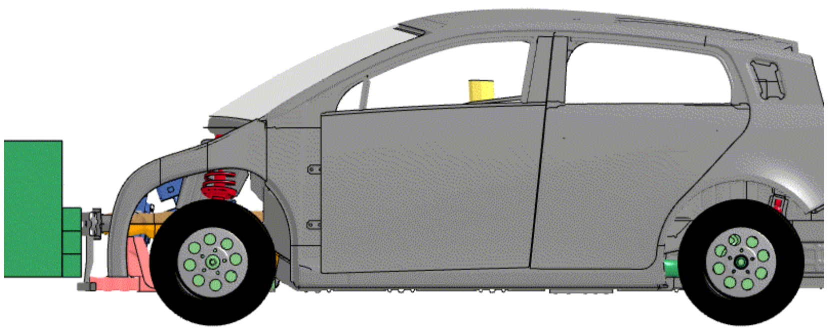
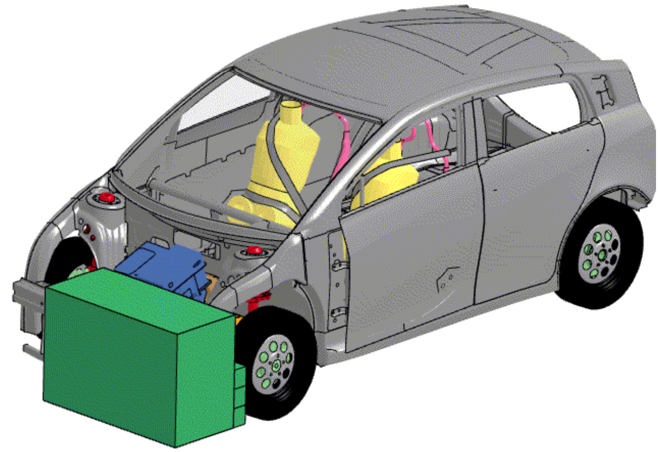
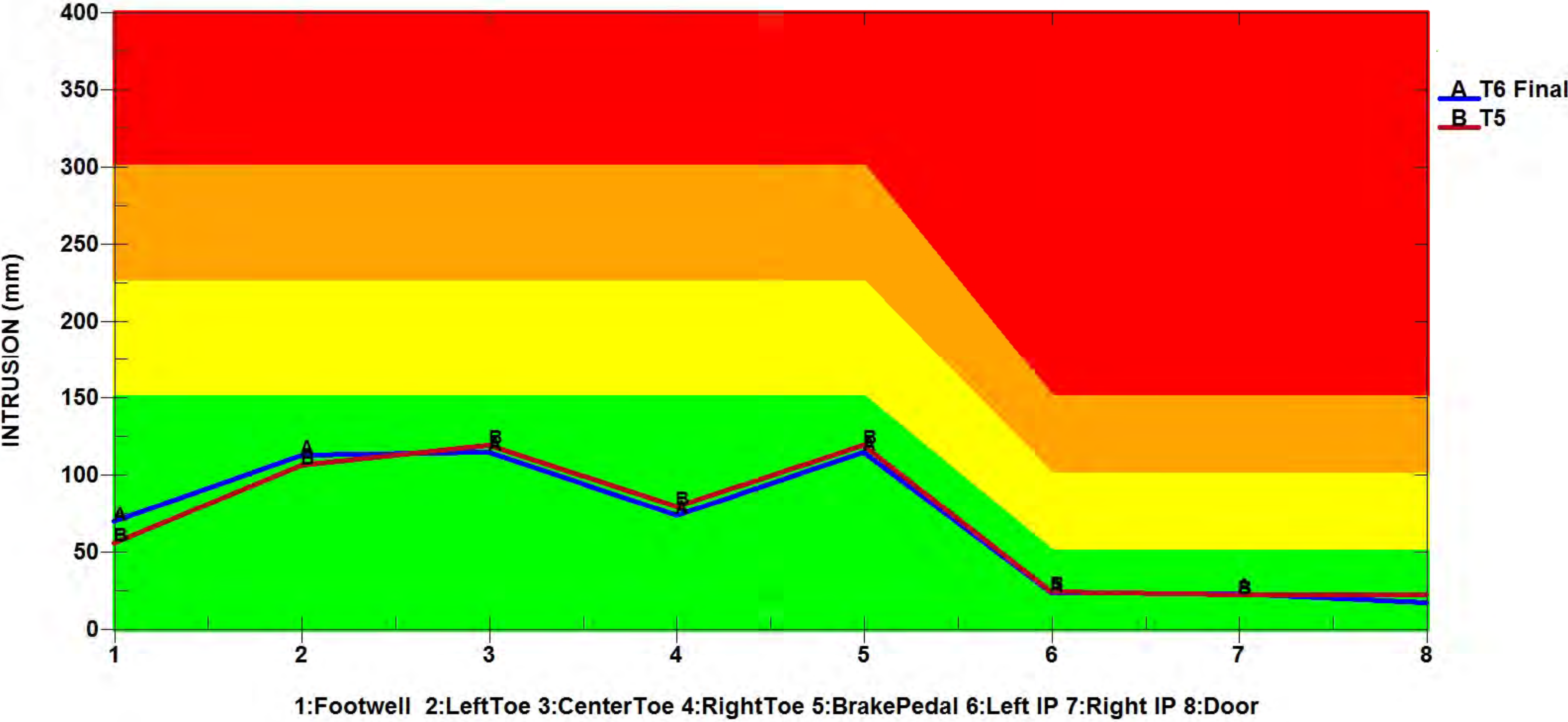
Task2c : T6 Verification –Front IIHS/ODB



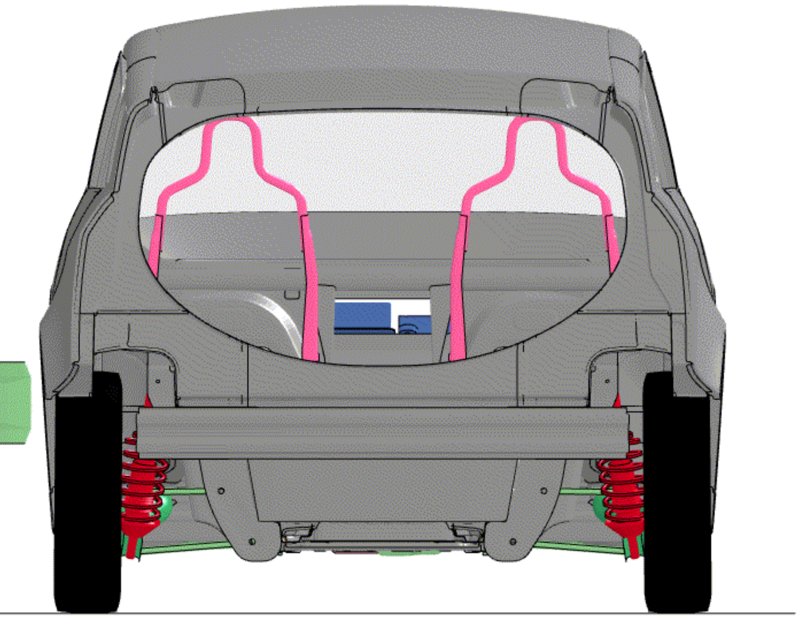


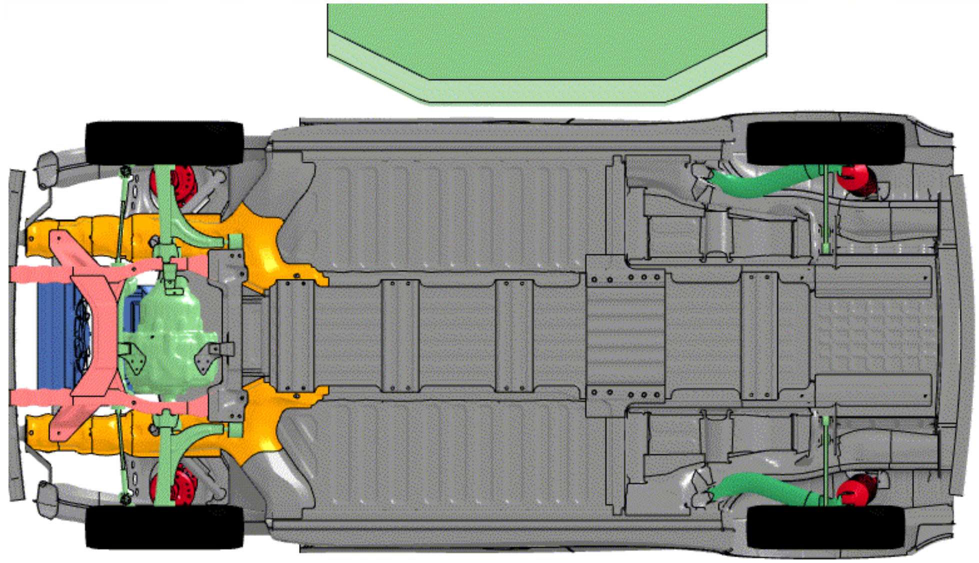


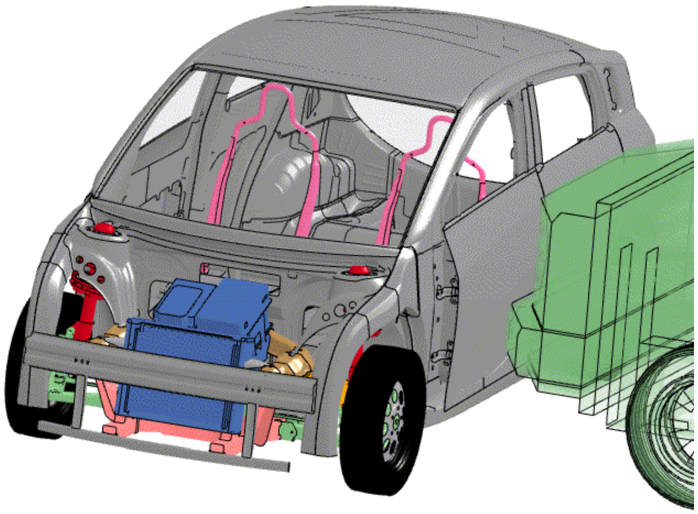
Task2c : T6 Verification –Front IIHS/ODB



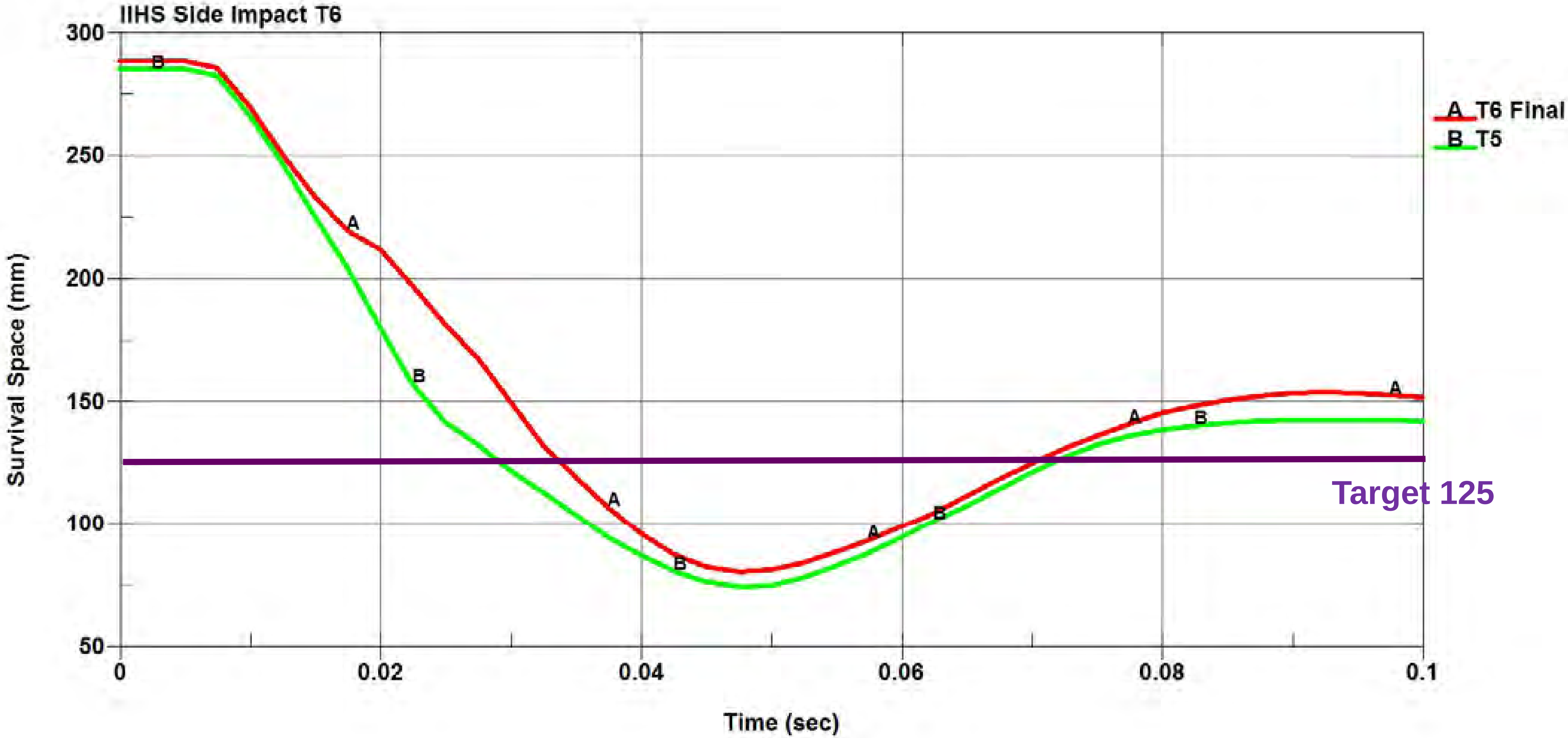
Task2c : T6 Verification –IIHS Side Impact



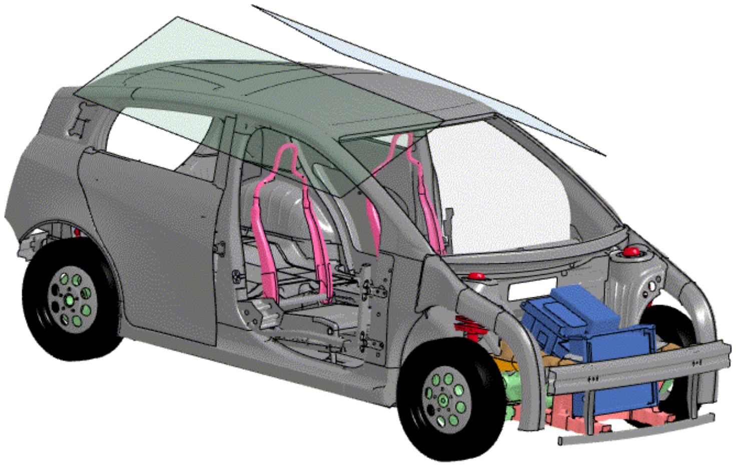


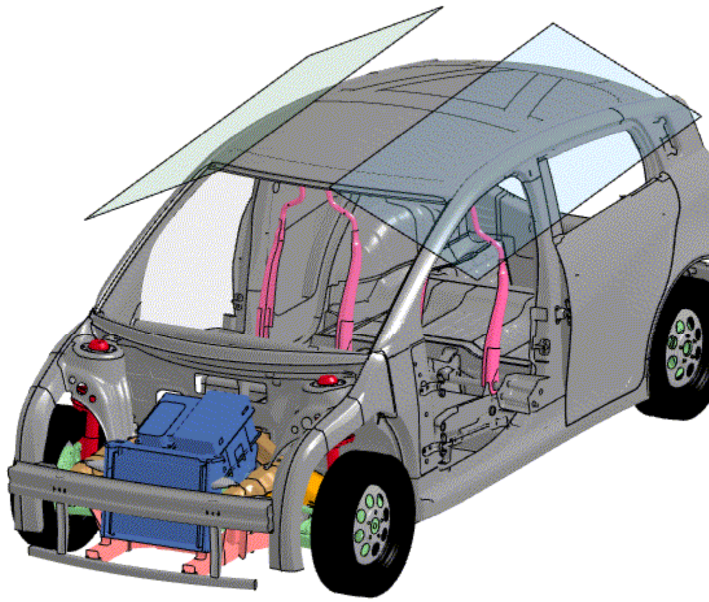


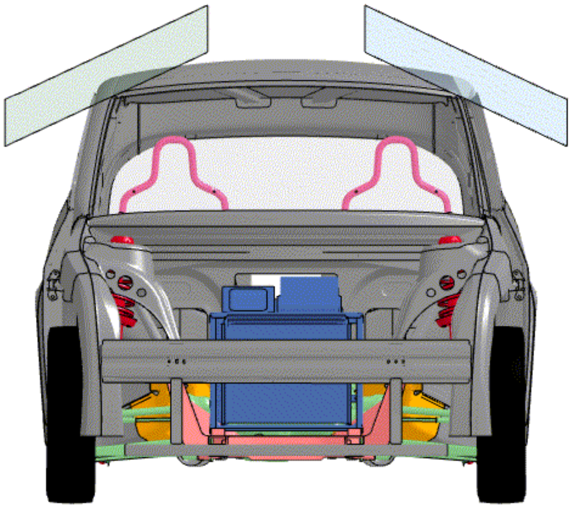
Task2c : T6 Verification –IIHS side Impact



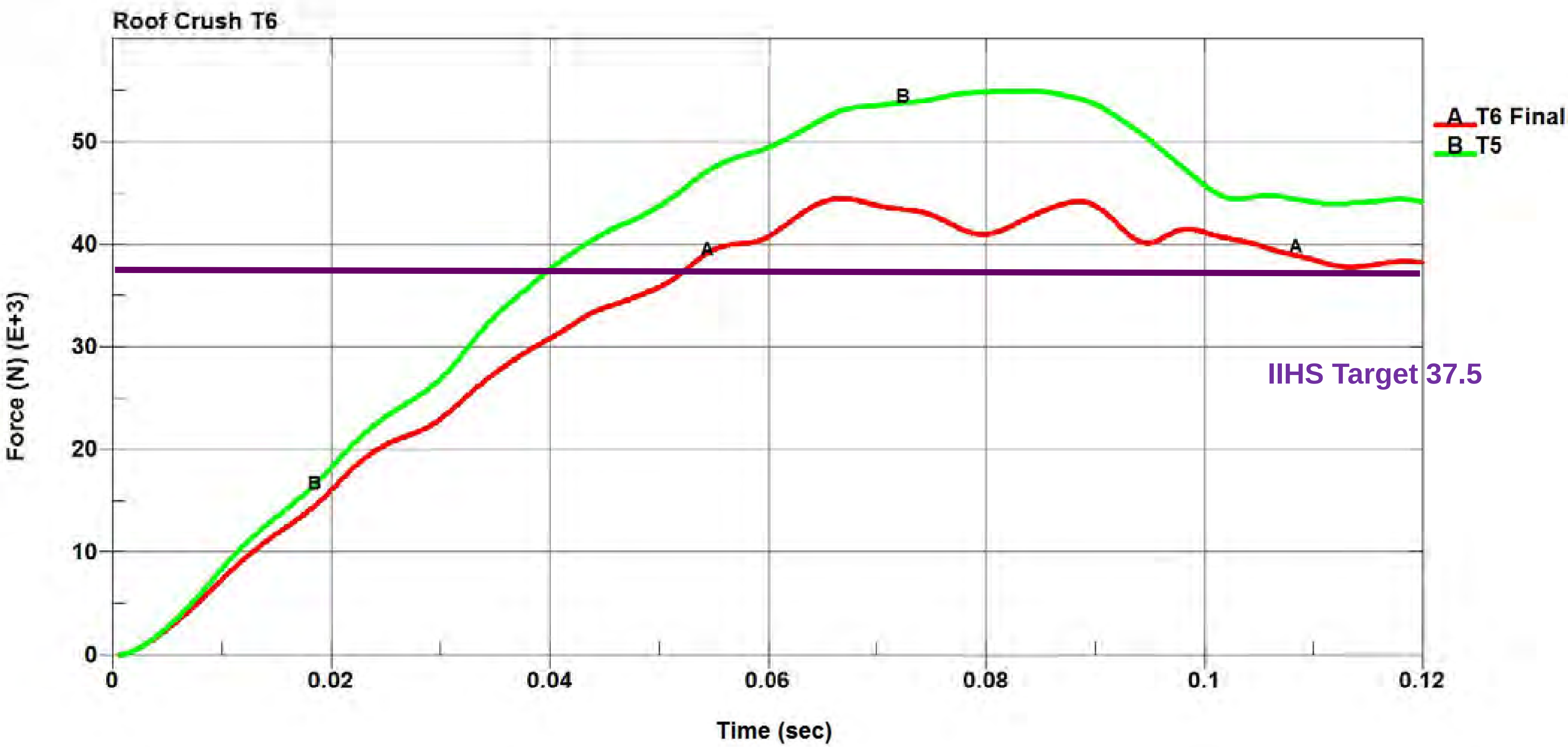
Task2c : T6 Verification –IIHS Roof Crush



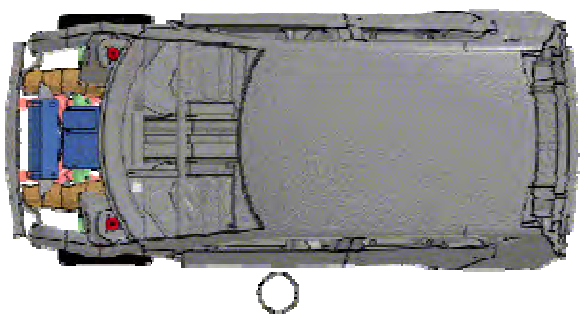


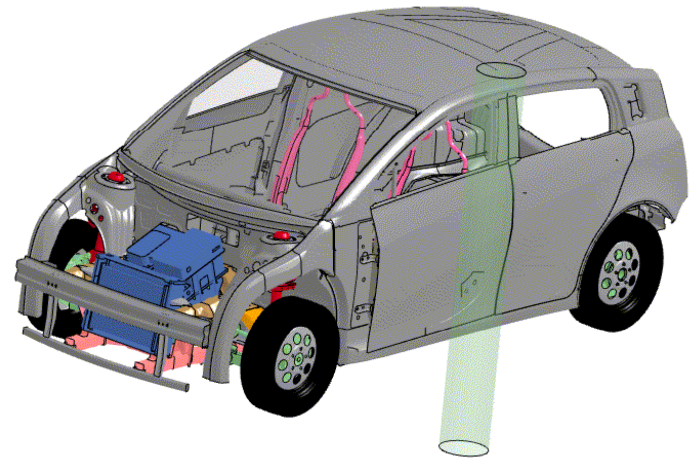


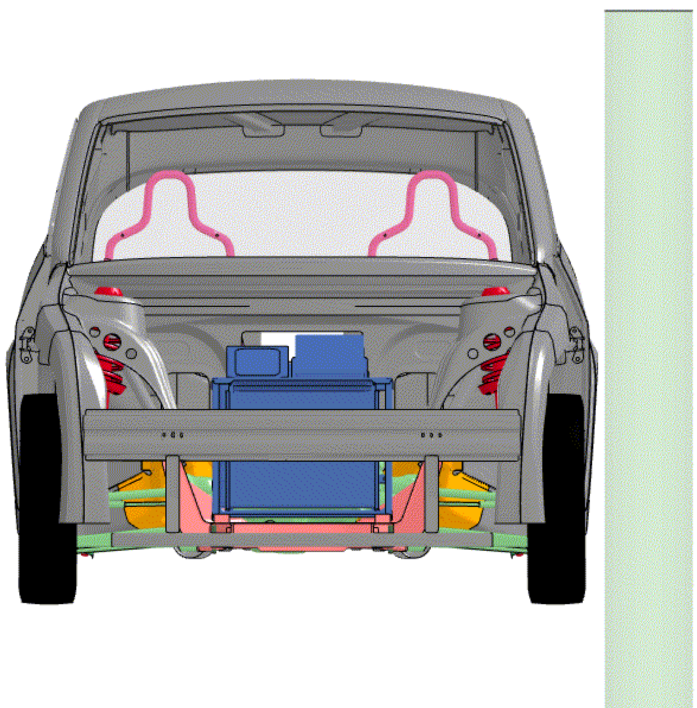
Task2c : T6 Verification –Roof Crush



Final T6 Design – Pole Impact Result







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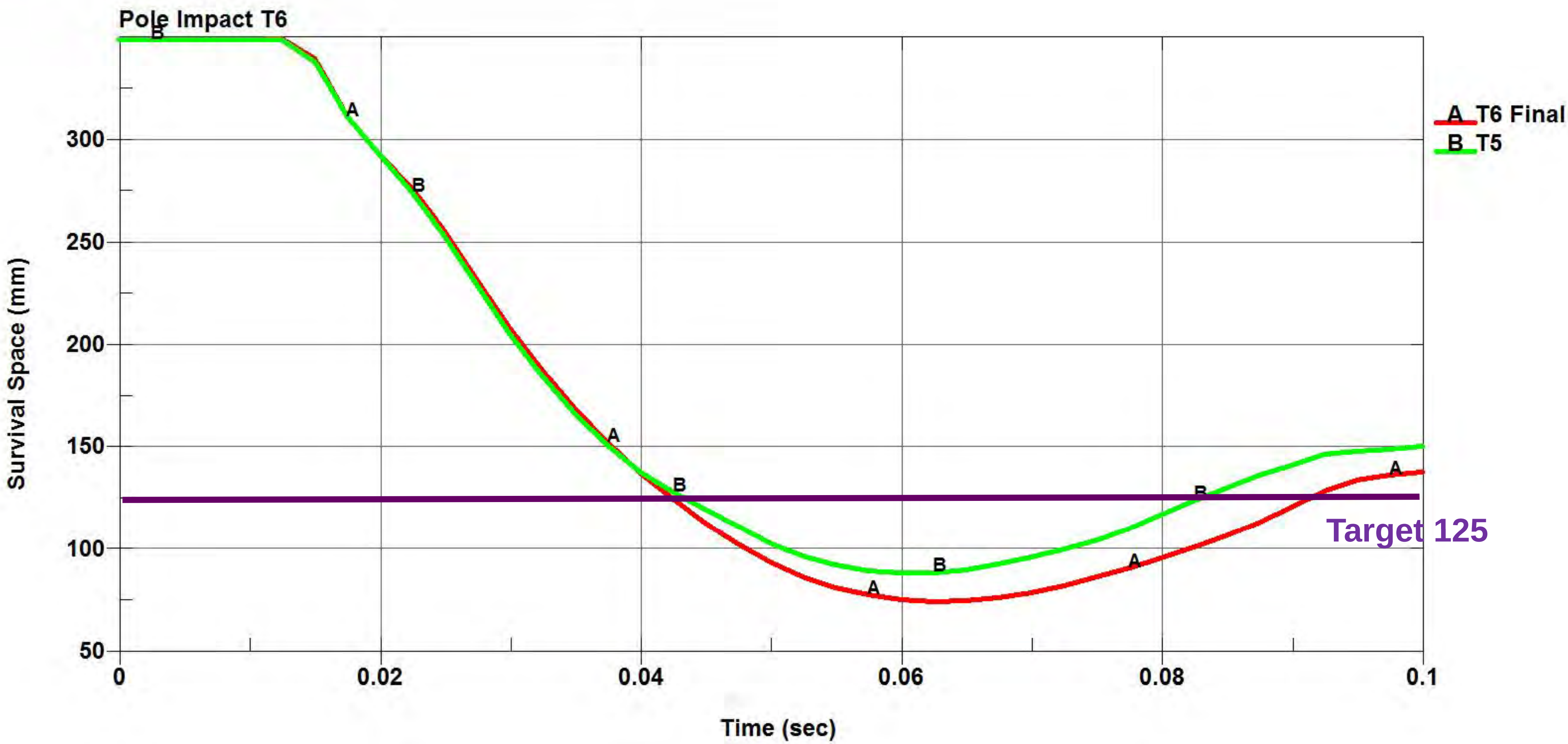
Task2c : T6 Verification –Pole Impact



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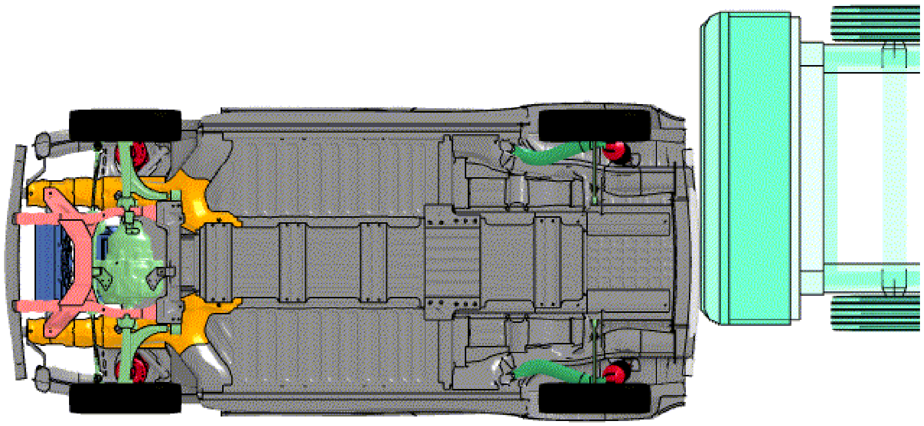
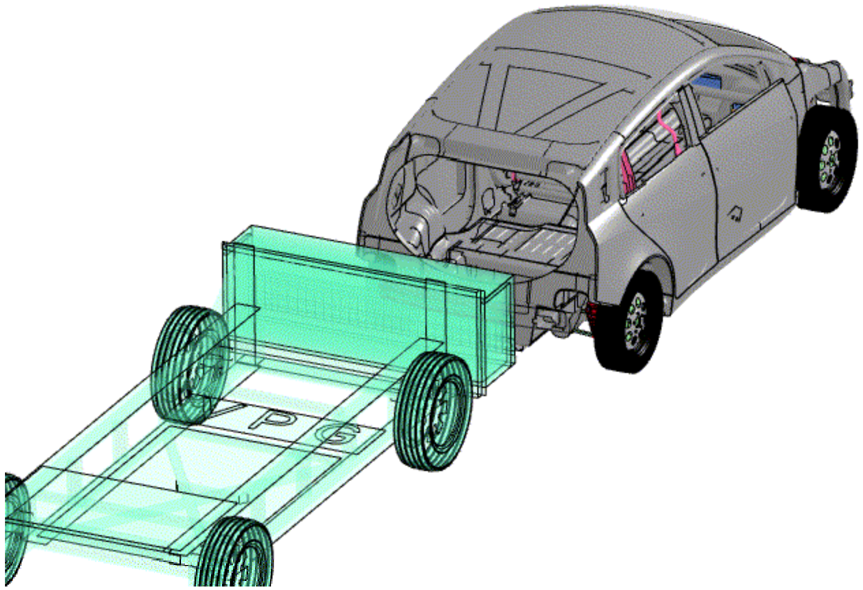
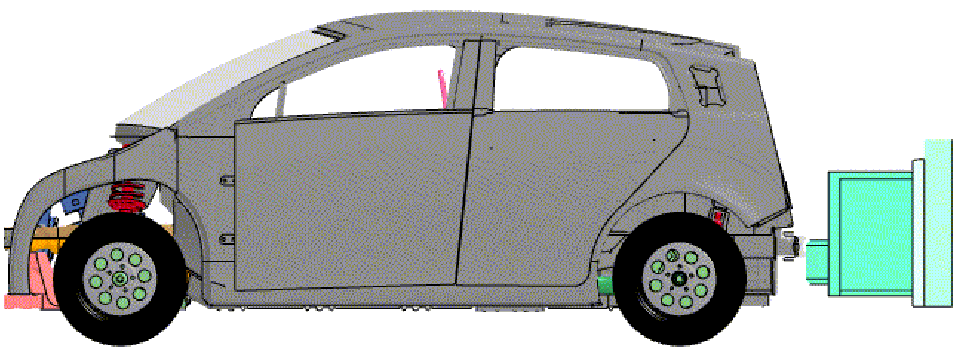
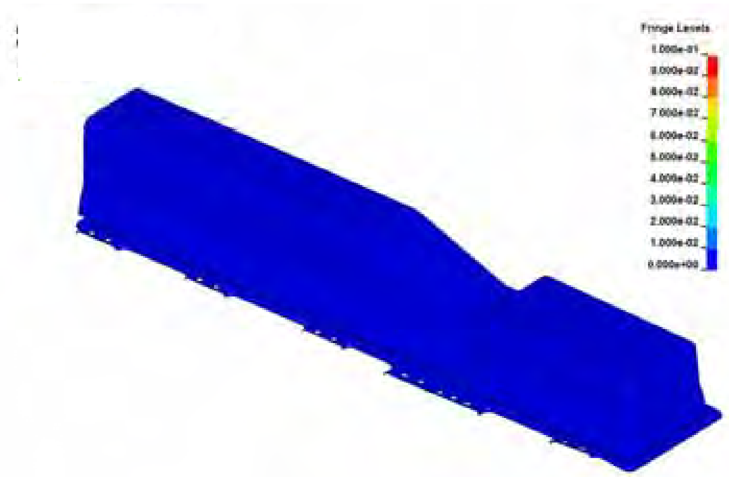
Task2c : T6 Verification –IIHS Rear Crash









- Small amount of strain in the battery structure outer cover

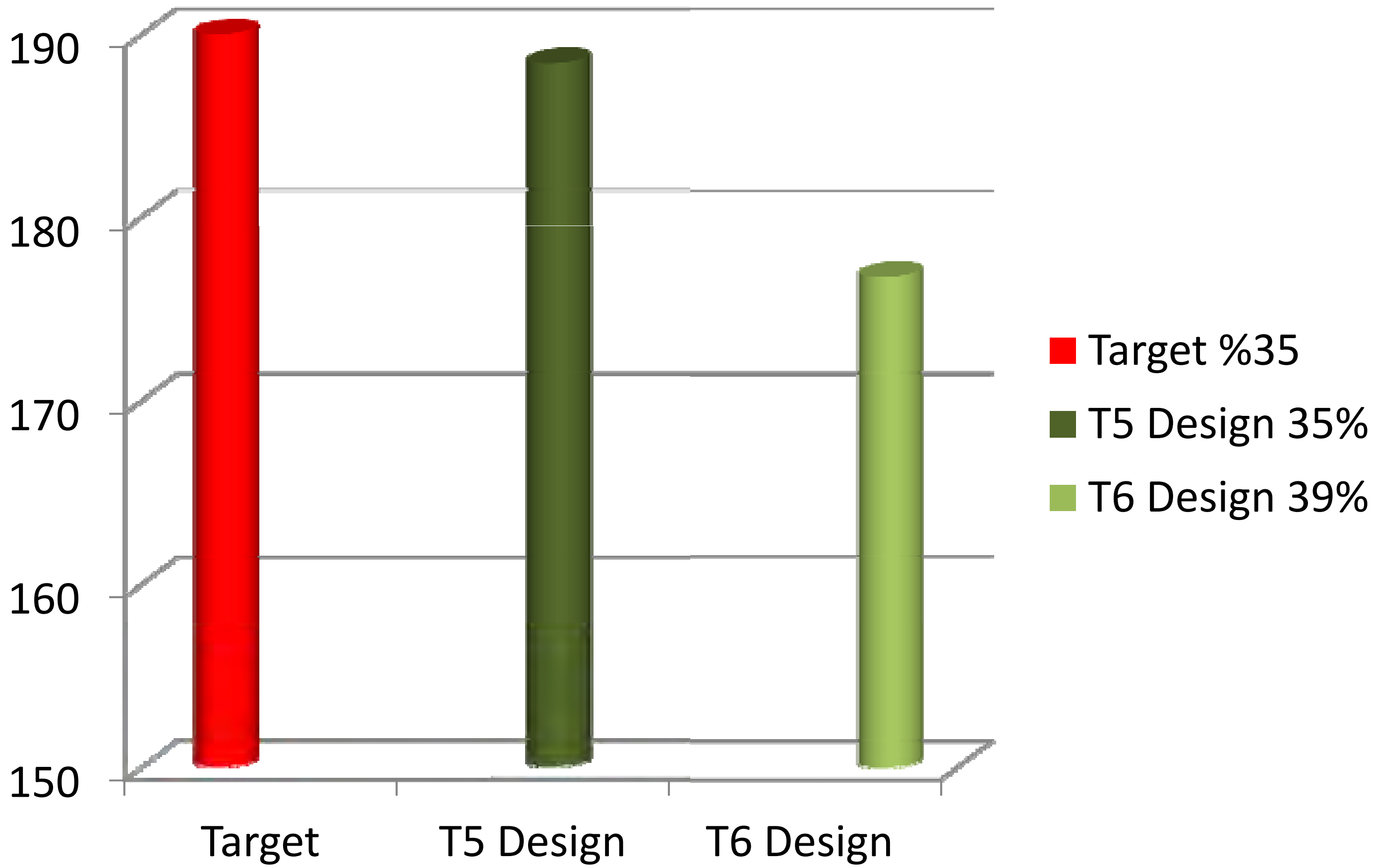
Task 2c- T6-FInal Design Results Summary

Design	Mass kg	NCAP	Front ODB	IIHS Side	Side Pole	IIHS Rear	IIHS Roof	Bend.	Torsion
Targets	<188	38 g	Good	125mm	125mm	Pass	37.5kN	12	20
T5-Final Design	188.4	39.7	Good	142	150	Good	55	15.5	19.6
T6-Final	176.8 **11.6 kg Lighter**	37.8	Good	152	138	Good	44.5	14.2	19

- T6 Final BIW is mass is reduced 11.6kg (6.2%) from T5.
- T6 Final Design meets targets for all load cases, with better front crash pulse.
- **Final MASS Reduction of 39%**

FSV Project Results

Benchmark BIW = 290 Kg



Nature's Way to Mobility

FutureSteelVehicle

Near Term Front Longitudinal Rail Shape Study

November 14, 2012

ACP™
Accelerated Concept
—› to Product Process

eta

Design Project Overview

1. Background
   – Near term front longitudinal shape
2. Objective
3. Project scope:
   – Task 1a: Near Term Initial Longitudinal Design and Performance
   – Task 1b: Baseline Design Evaluation (Crash and Formability)
   – Task 2a: Full Vehicle System (NACP, ODB) Gage Optimization
   – Task 2b: Formability Feasibility
   – Task 3 : Final validation
   – Task 4 : Final report

FSV Design Process Strategy

- The current FSV Front End is based on New Optimization Process founded on 3 distinct key design processes:
  - Load Path Optimization
  - 3G Optimization
  - Designing Nature's Way
- This methodology shows it is very efficient and introduced a new direction for product design and development. However, the design process has introduced new geometry and shapes that are not used traditionally in product design for automotive structures. These new geometry and shapes for some components introduce new challenges to auto industry.

Objective

- Design and optimize conventional shape longitudinal rail and crush-can based on T6 final design and provide comparison of mass and performance for T6 and Near Term design.

3.0 Project Scope :
Task1a: Near Term Initial Rail Design

- Use the T6 final design model which is, in essence, the same design geometry as the T5 model. The assumptions are:
  - Use initial longitudinal design based on initial T6 design shown in Figure 1 below.
  - The same topology (load path) to top and bottom of the tunnel and to rocker will maintain.
  - keep tip section straight-only allow diameter at front and back to move so it remains conic. Allow diameter change to stay within package space (engine, tire flop, suspension travel, etc.)
  - Keep the welding flanges and connections as close to original T6 design

Near Term Initial Design Concept

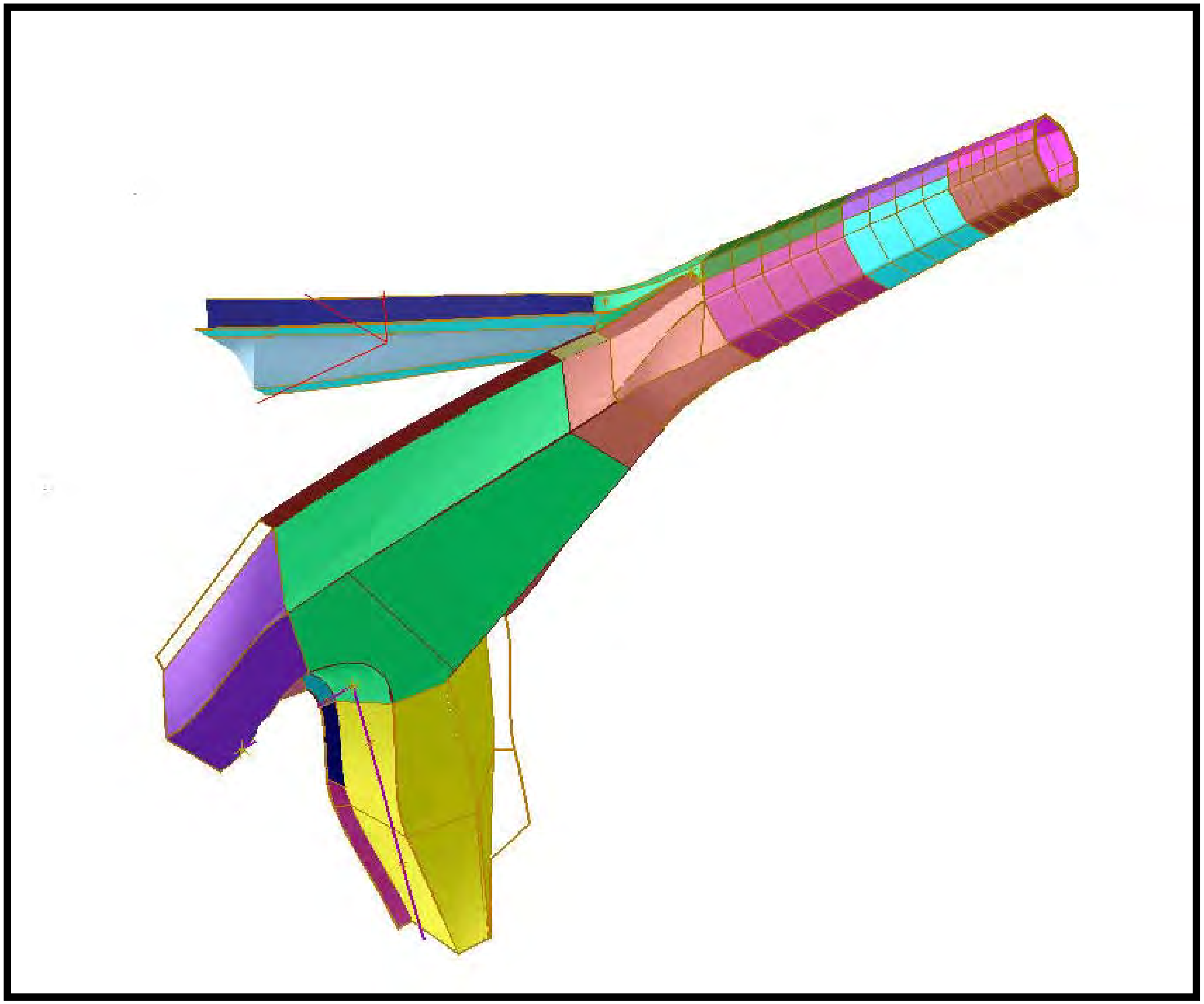
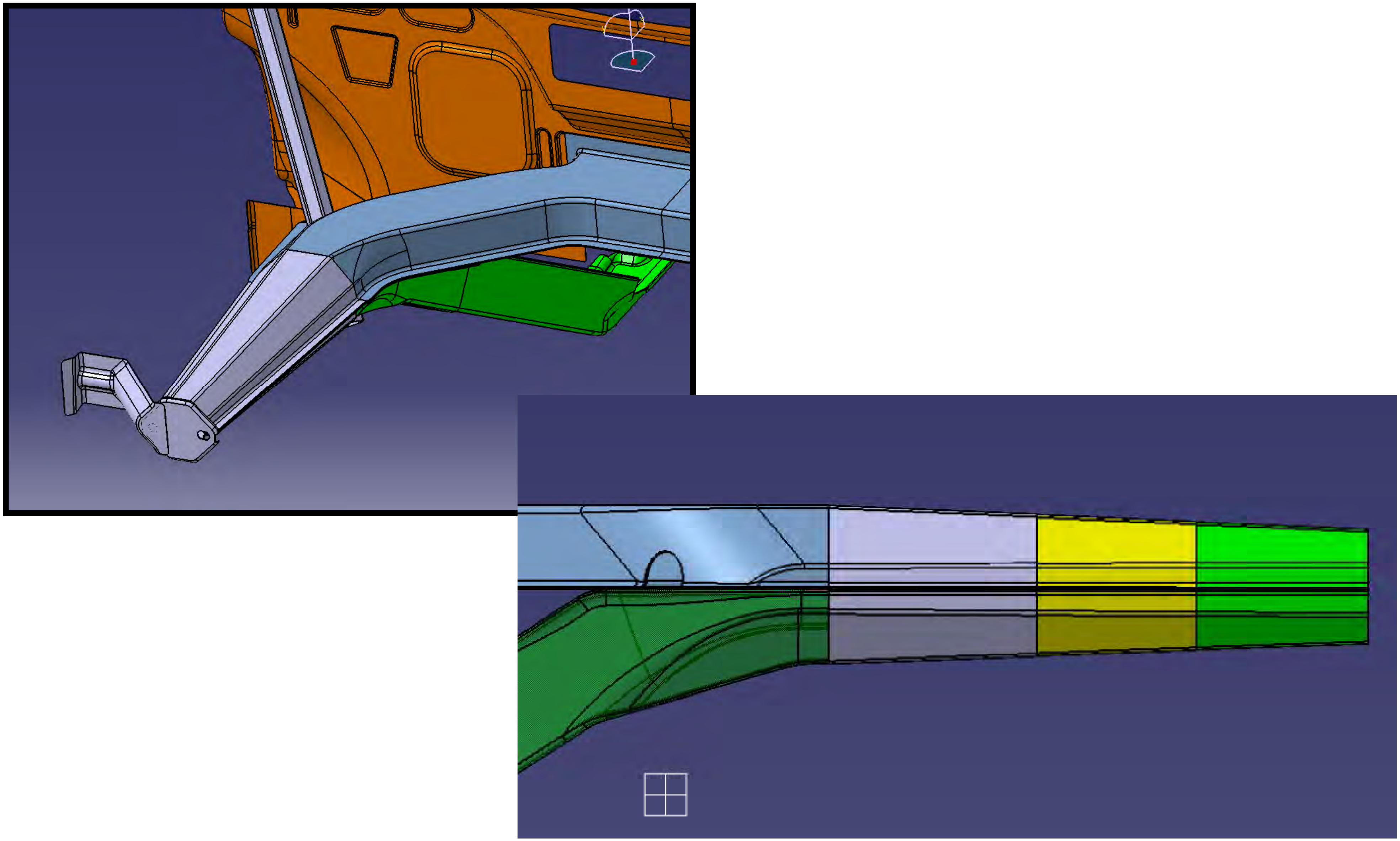
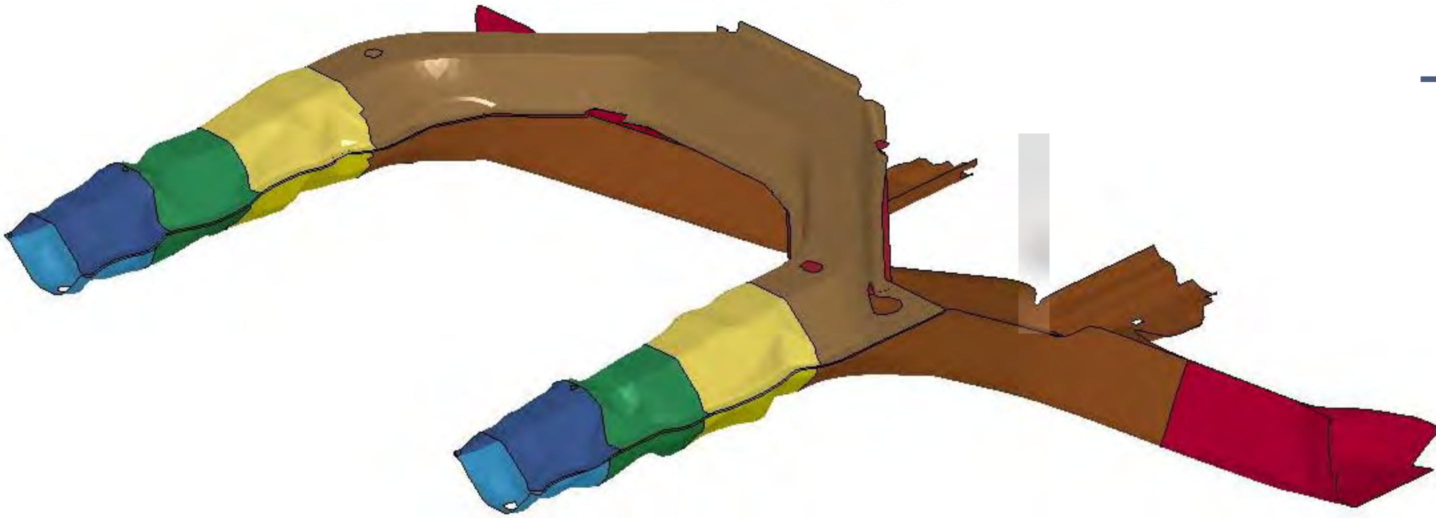


Figure 1

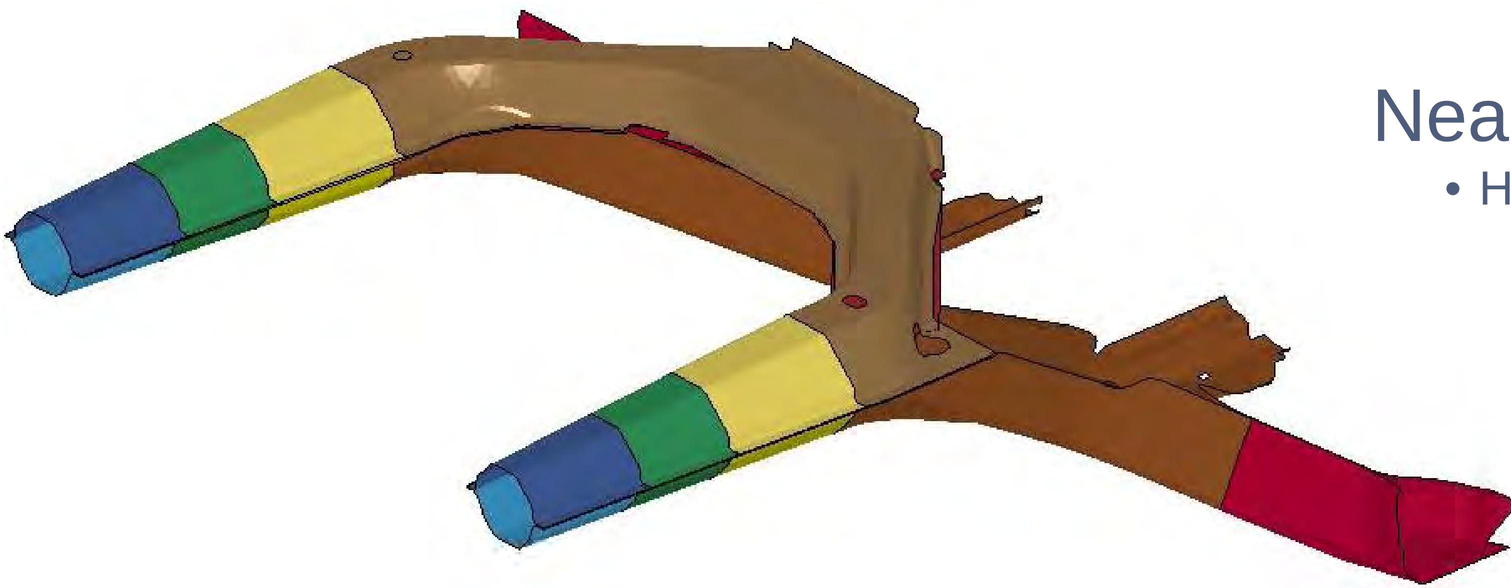
Near Term Initial Longitudinal - **Design-Concept**



T6 and Near Term Initial Rails Design



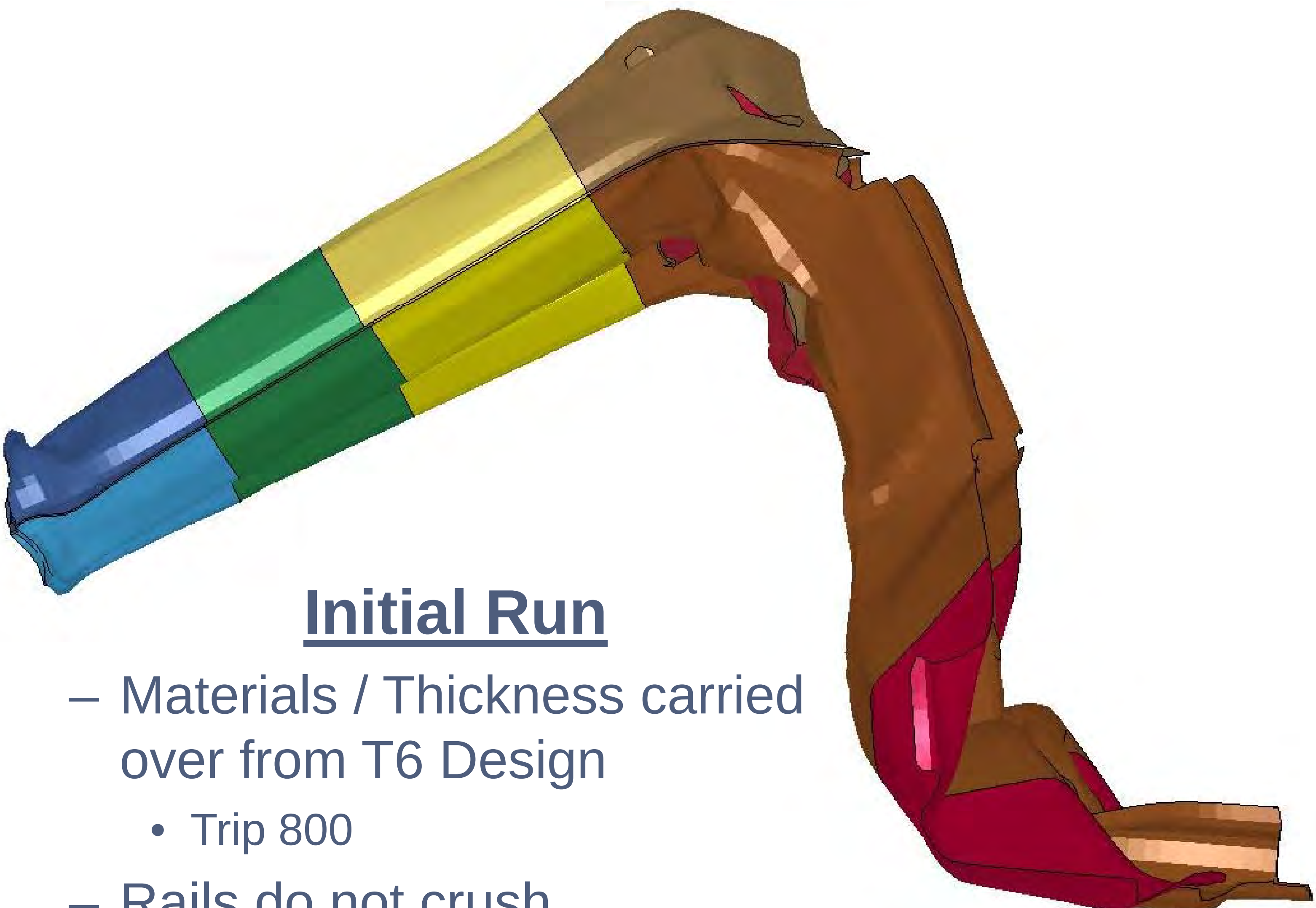
T6 Design



Near Term

- Hexagonal Shape

Near Term Initial Longitudinal - **Design-Concept**

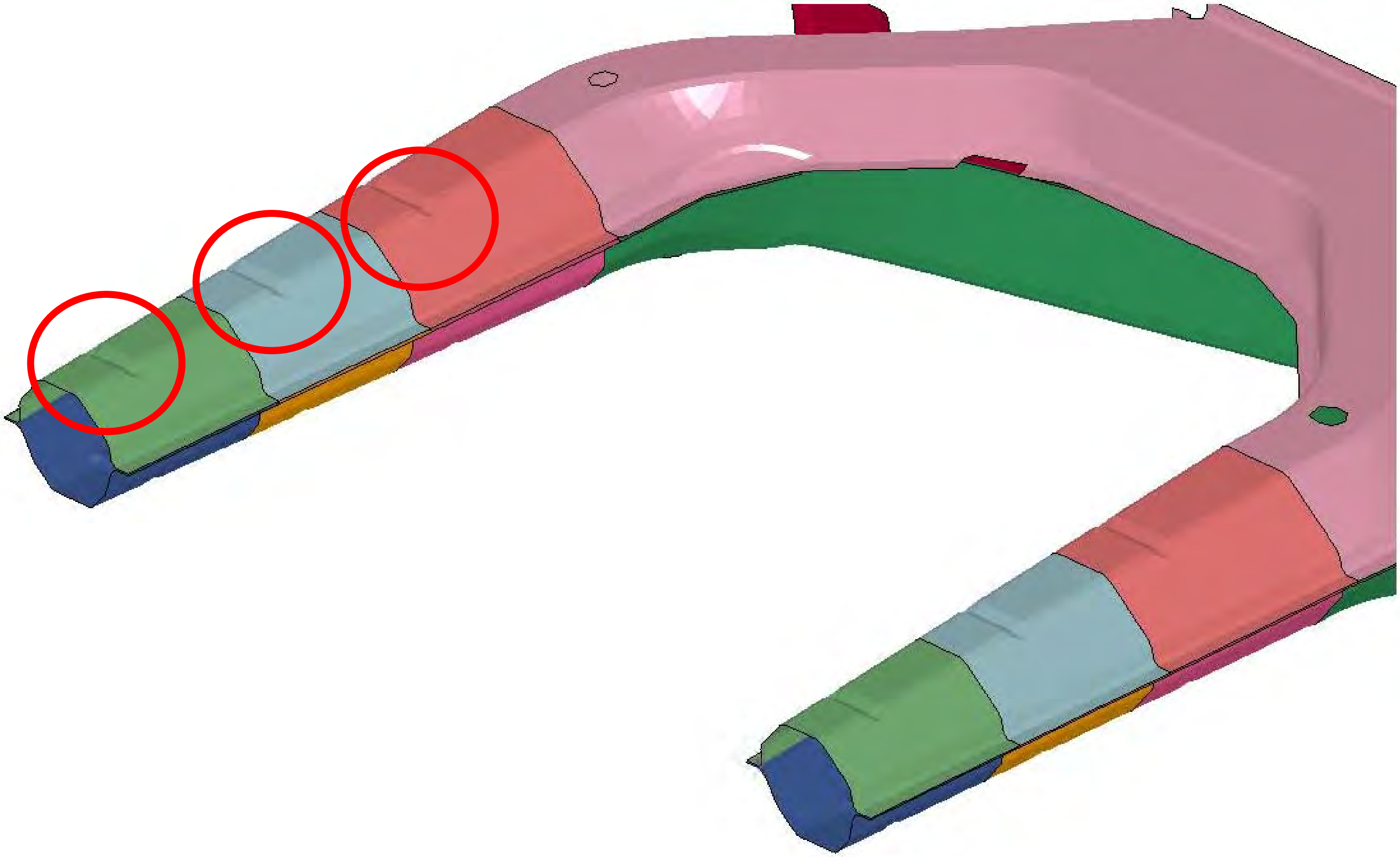


Initial Run

- Materials / Thickness carried over from T6 Design
  - Trip 800
- Rails do not crush
- Very high ODB crash intrusion

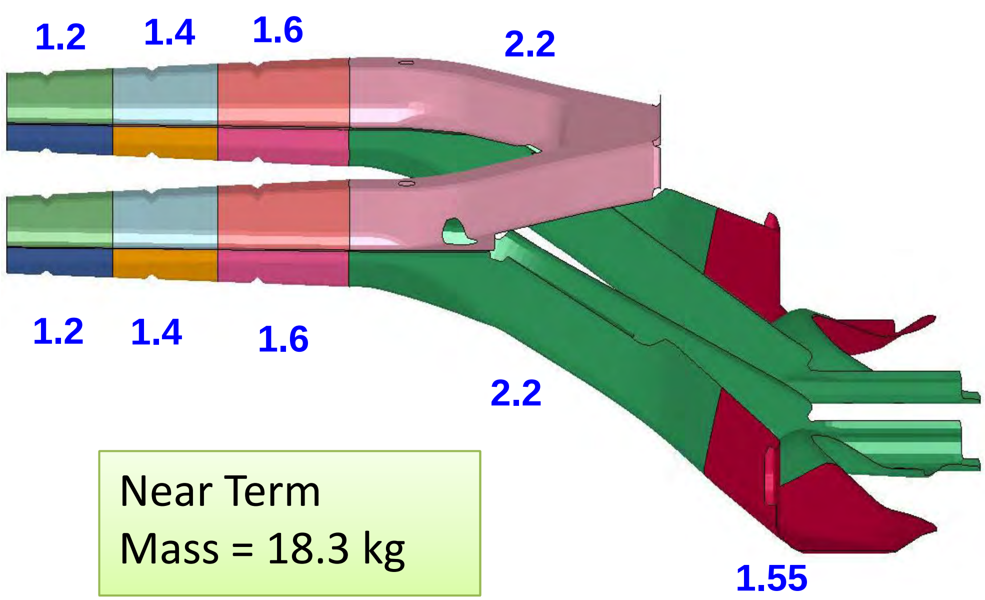
Near Term Design Rails with Crush Initiation's

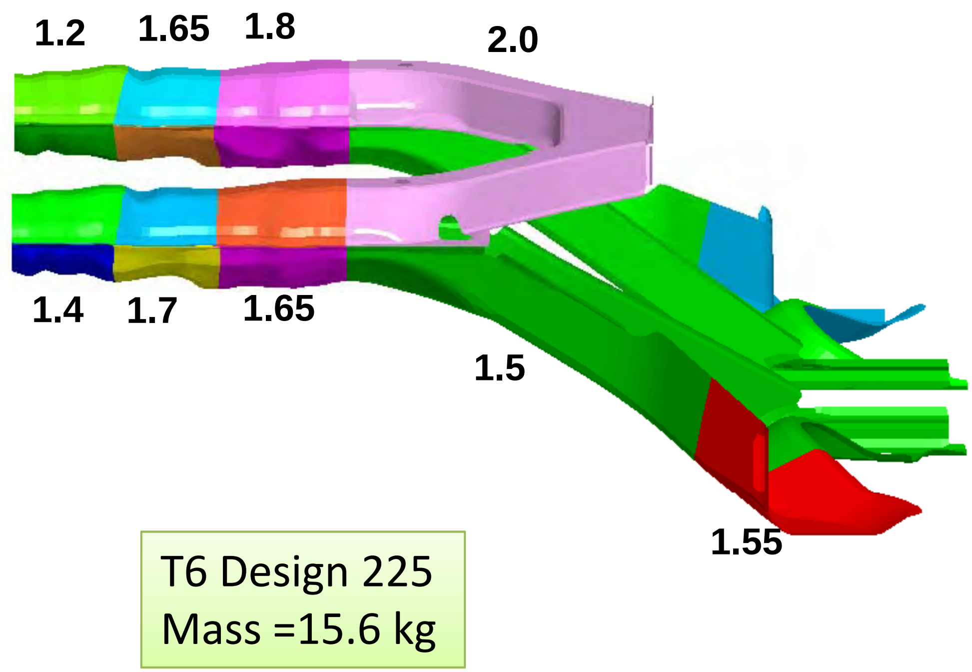
- Crush initiators 5 mm deep x 15.6 mm wide
- Hexagonal Shape



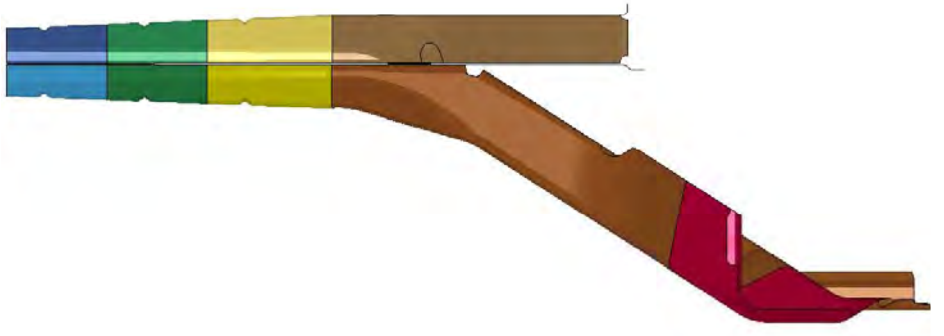
Near Term Baseline Rail Front Crash Performance

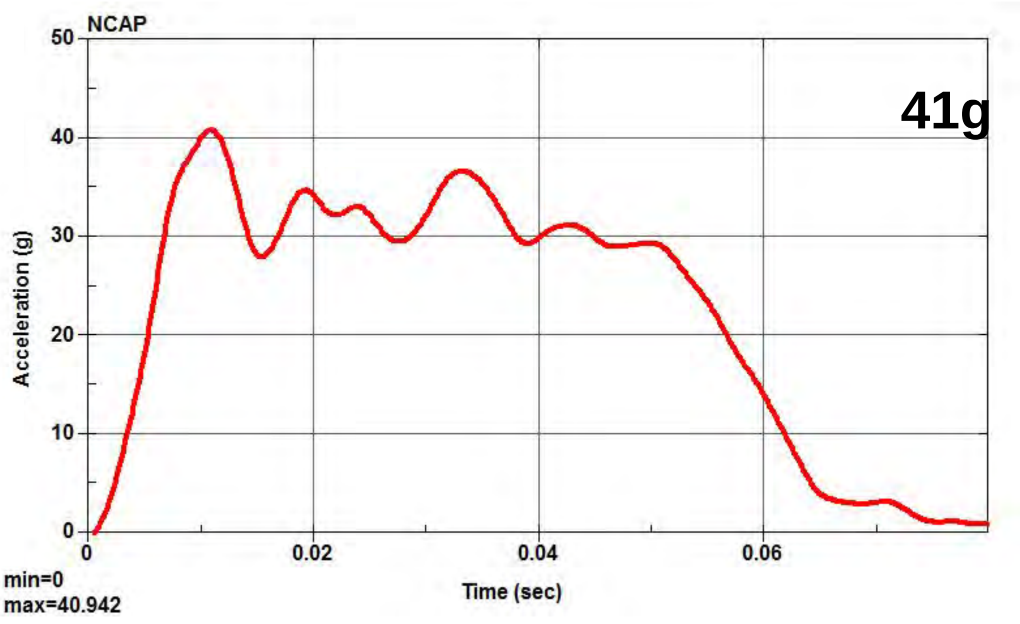
- Crush Initiators Added Front End of T6 Baseline was kept as final design From T6 optimization for consistency
- Trip 800 is used
- Gauges estimated based on experience, to get acceptable pulse and ODB performance
- Current design performance more after 15 design iterations with mass of 2.61 kg mass increase

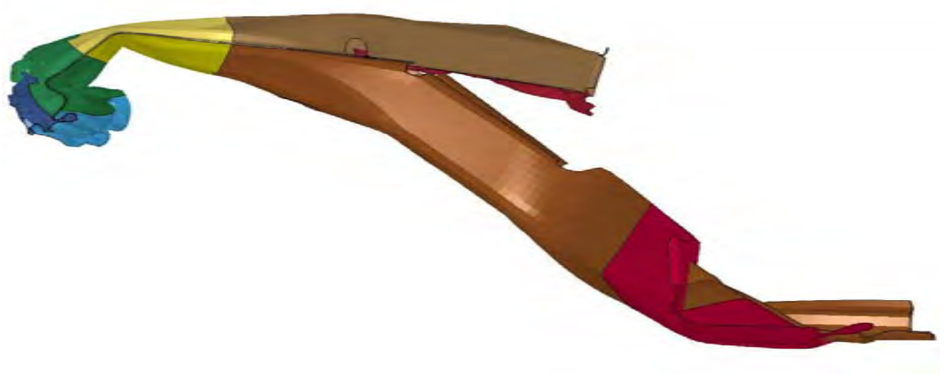


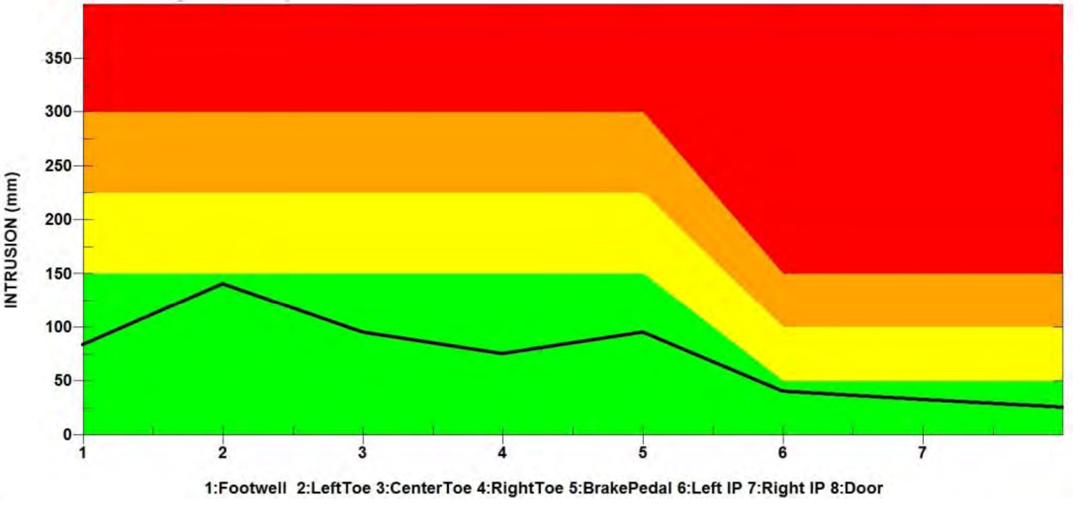


Near Term Baseline Rail Front Crash Performance

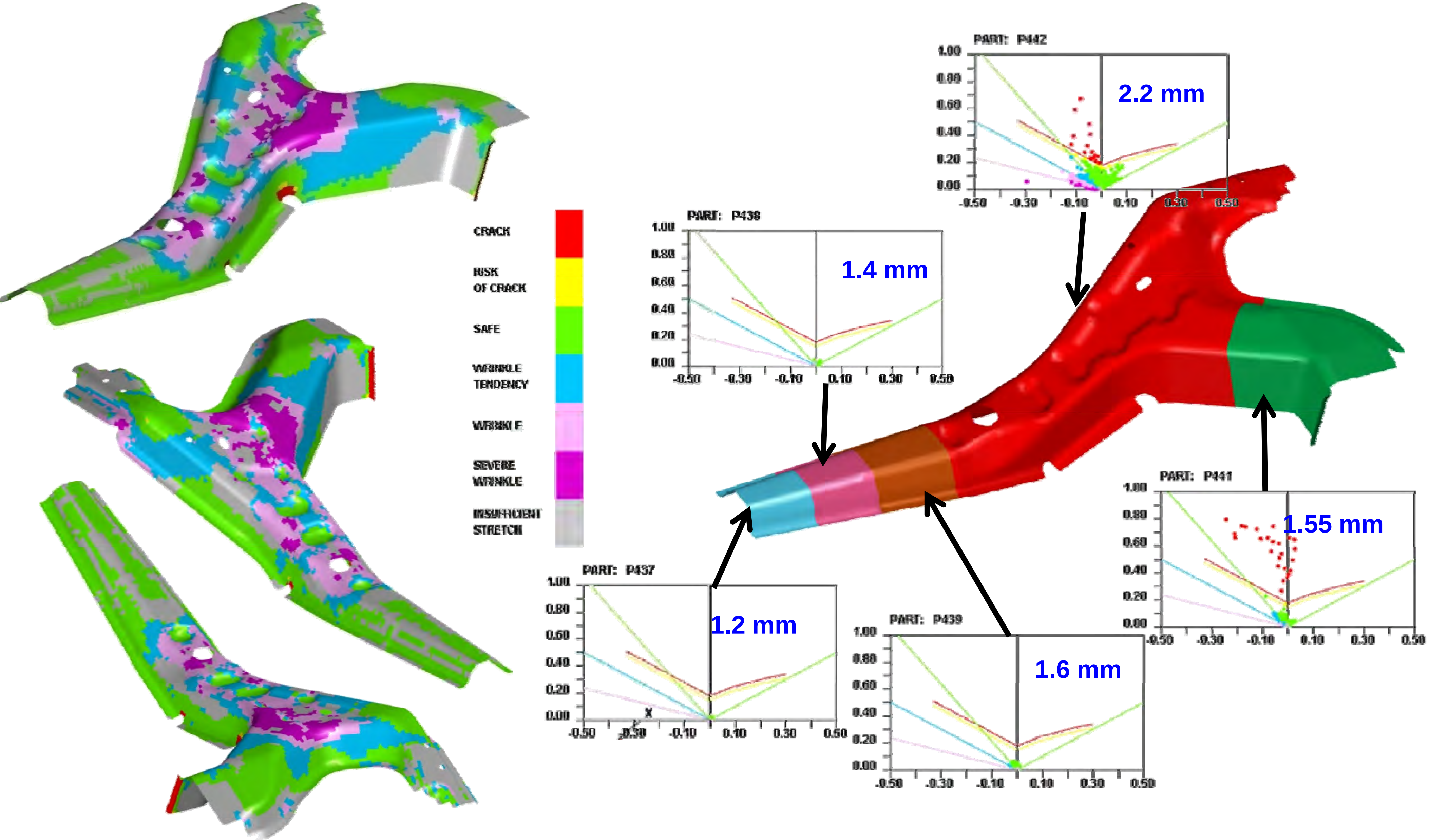






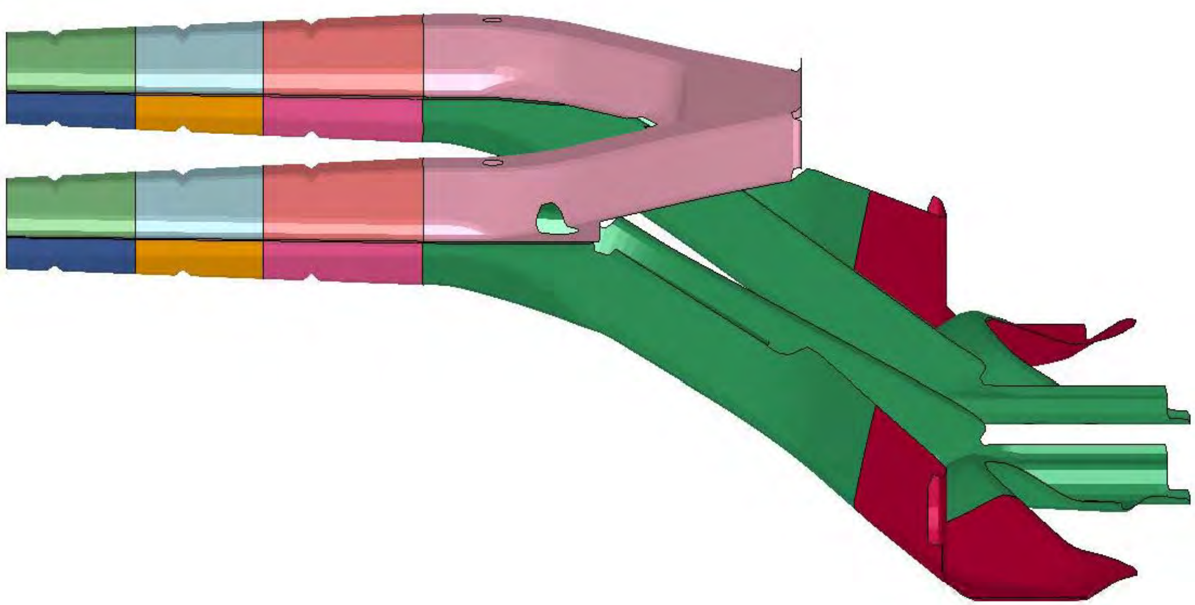


Near Term Baseline Formability Results



Optimization Study

- Optimize Longitudinal Front Rail Subsystem for Near Term Solution
- TWB was maintained
- Thickness is varied between the minimum and maximum (as used for T6)

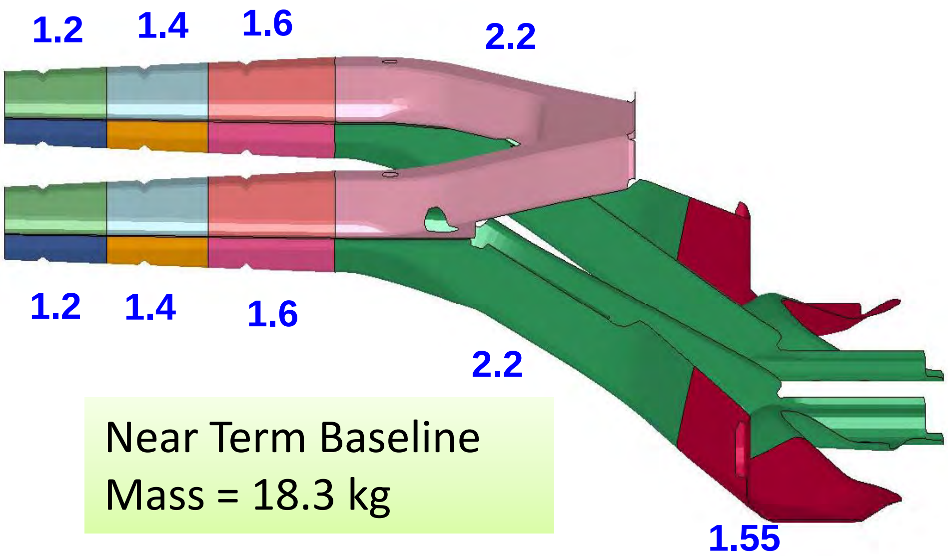


Optimization Details

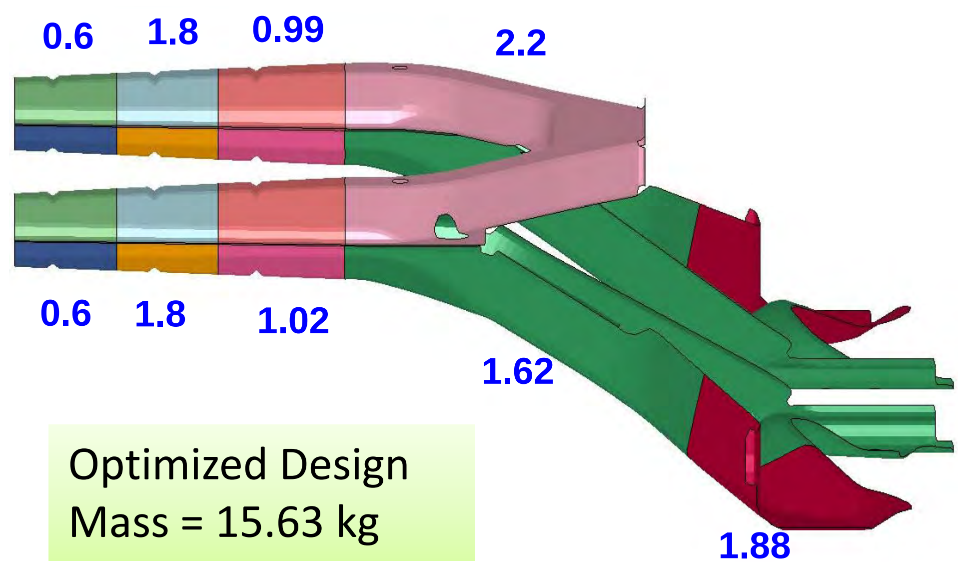
- Objective: Minimum Mass
- Performance Criterion
  - NCAP Max Pulse < 38.6g
  - ODB Footwell Deflection < 91 mm
  - ODB Left Toe Pan Deflection < 131 mm
  - ODB CenterToe Pan Deflection < 155 mm
  - ODB Right Toe IP Pan Deflection < 35 mm
  - ODB Right IP Deflection < 35 mm
  - ODB Door Deflection < 24 mm

Optimization Results

- Total # of designs evaluated = 92
- Best Design: Design # 73

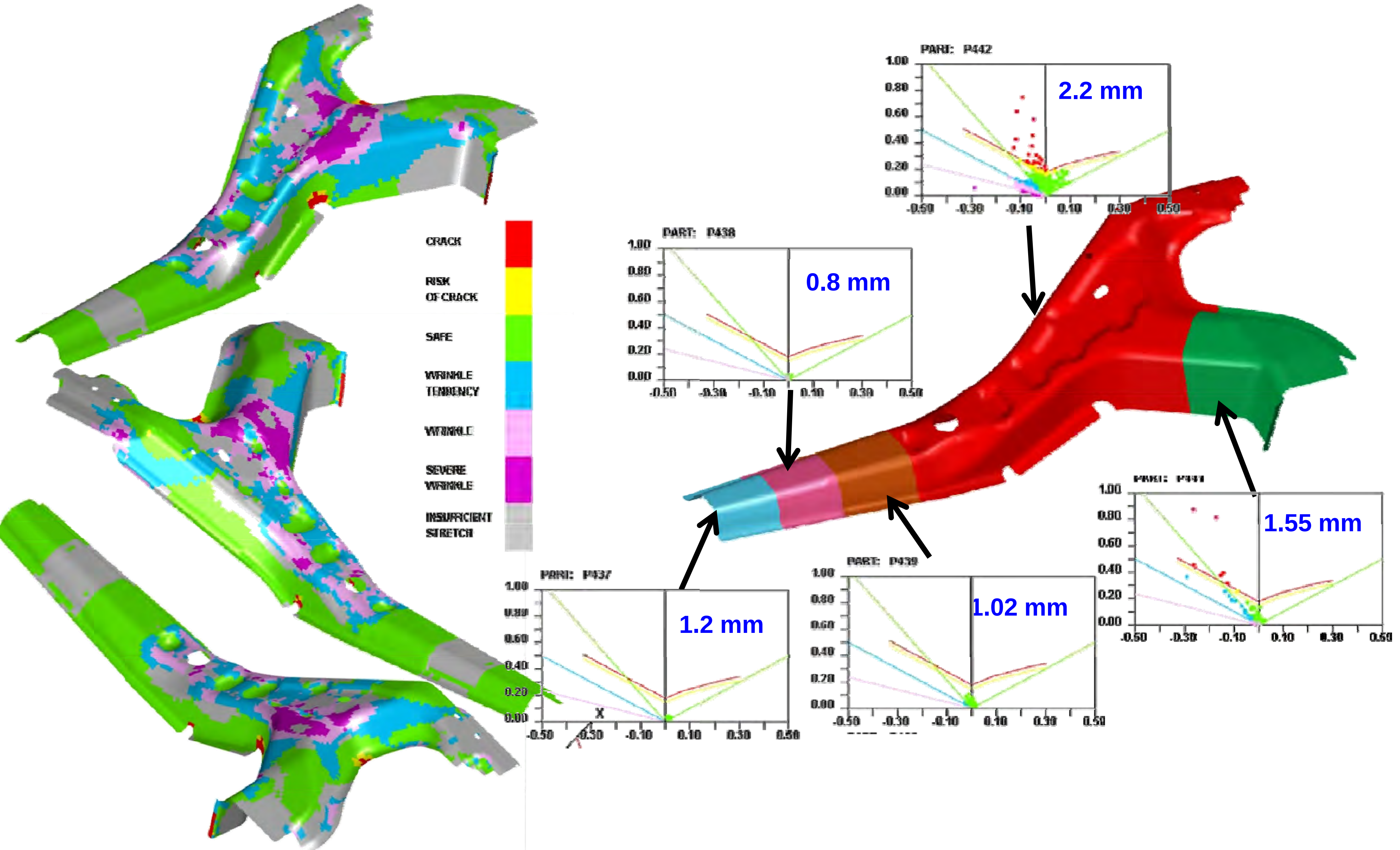


Near Term Baseline
Mass = 18.3 kg

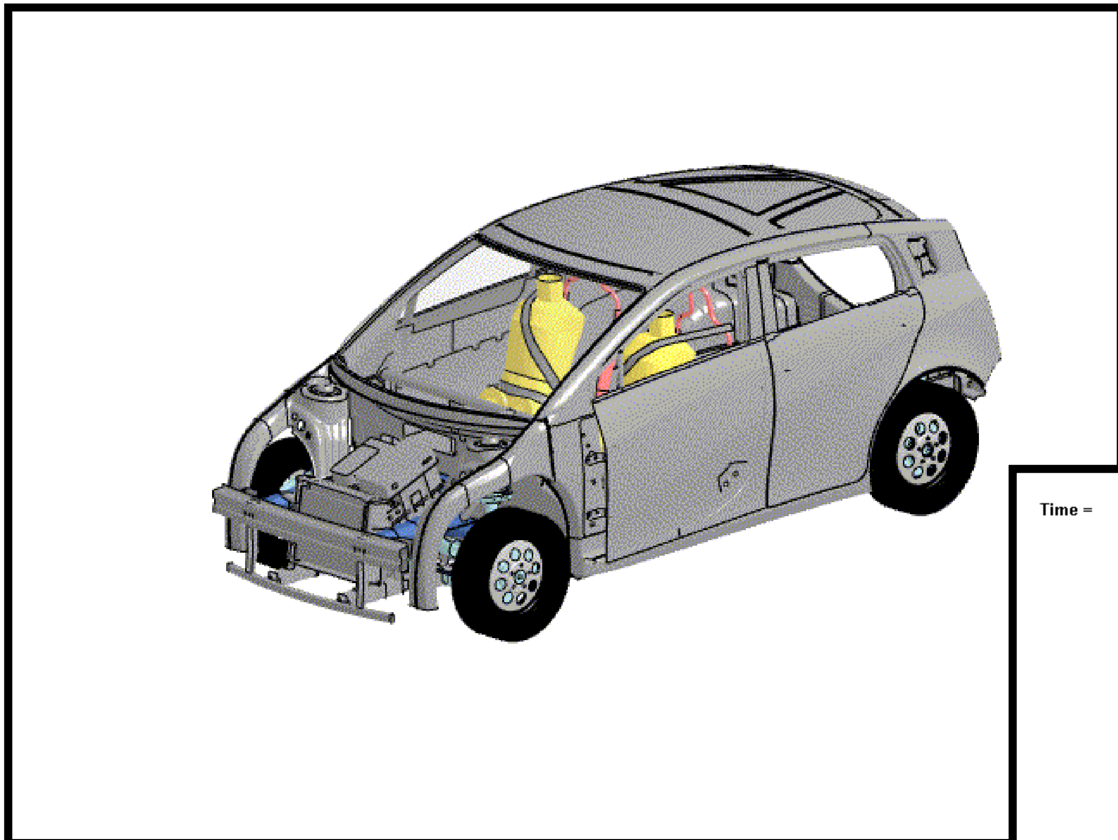


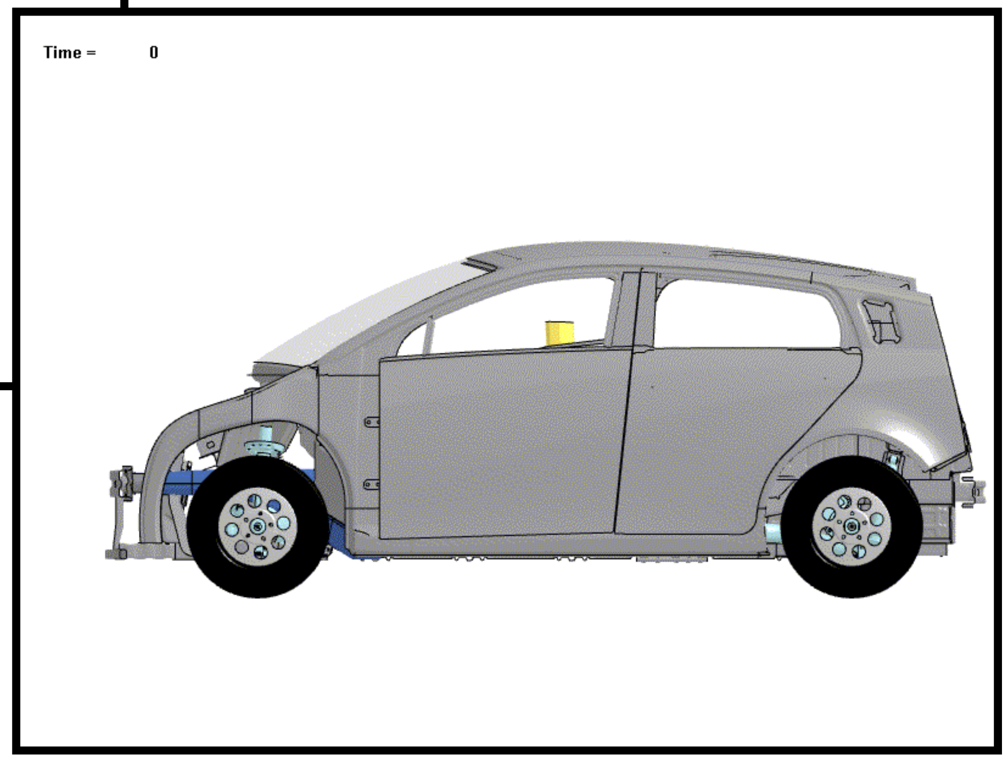
Optimized Design
Mass = 15.63 kg

Formability-Near Term Optimized Design # 73

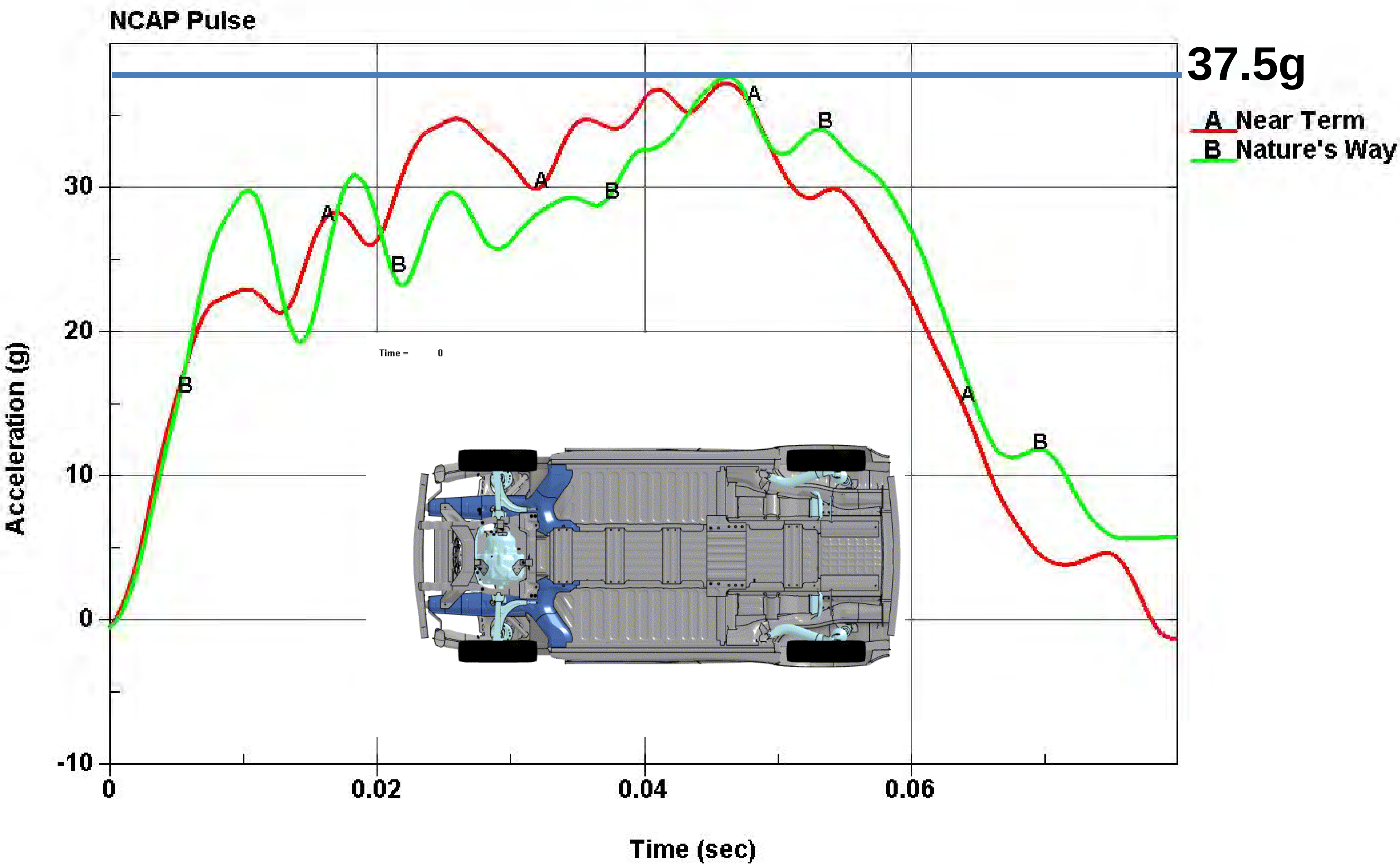


Design # 73 - NCAP Results

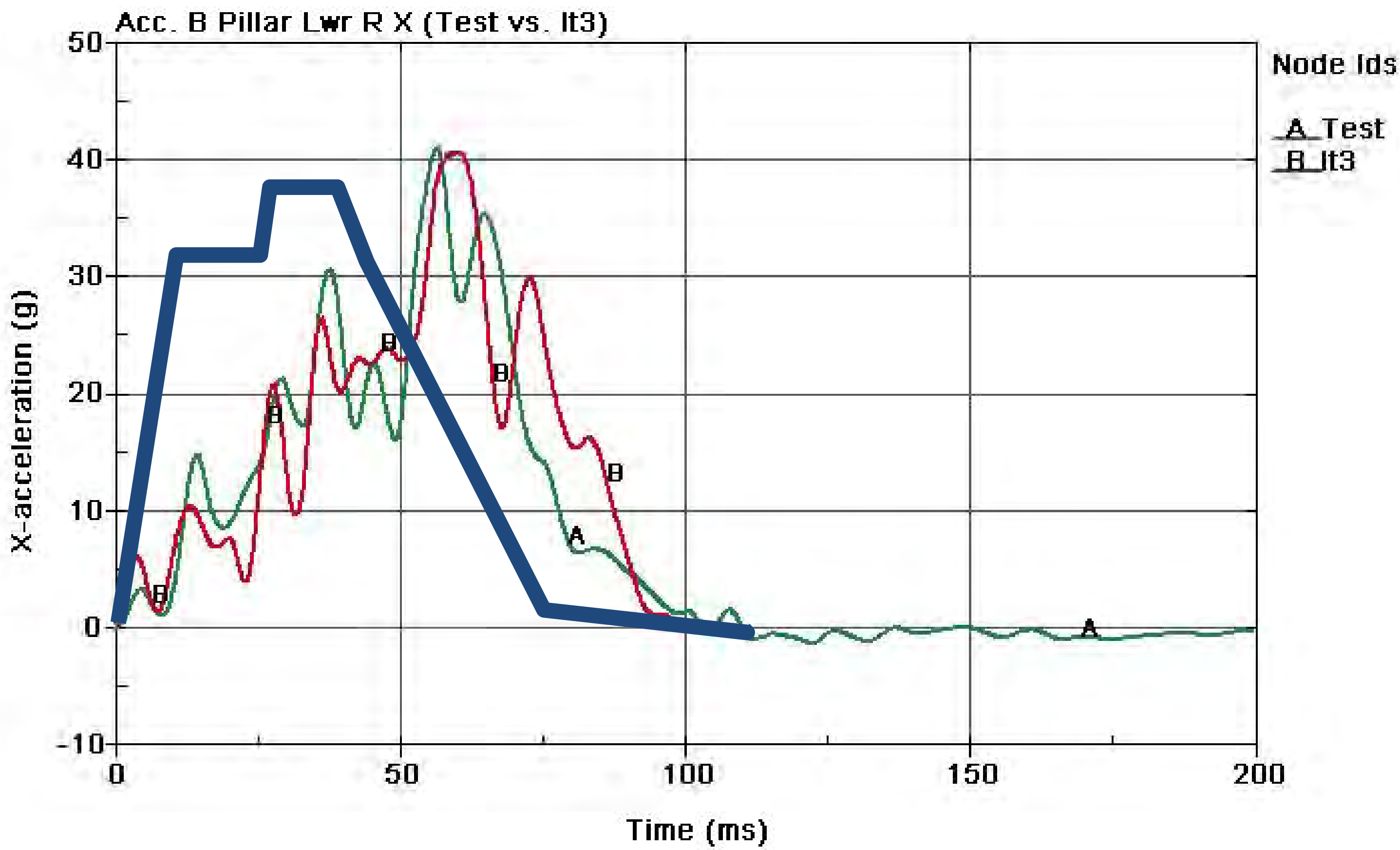




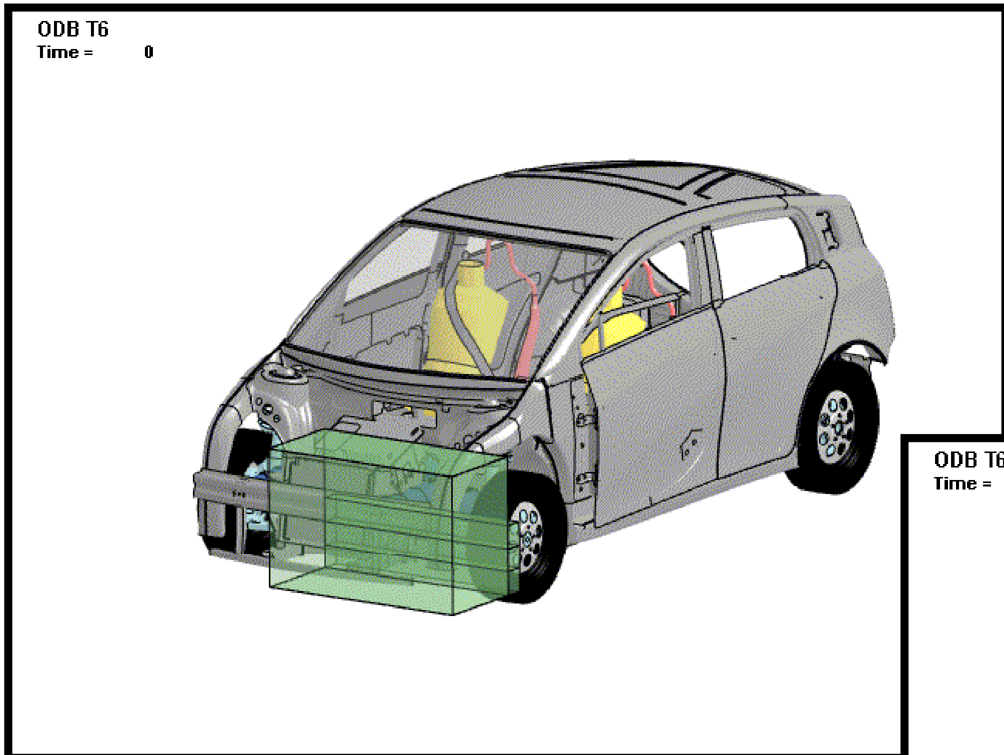
Design # 73 - NCAP Results

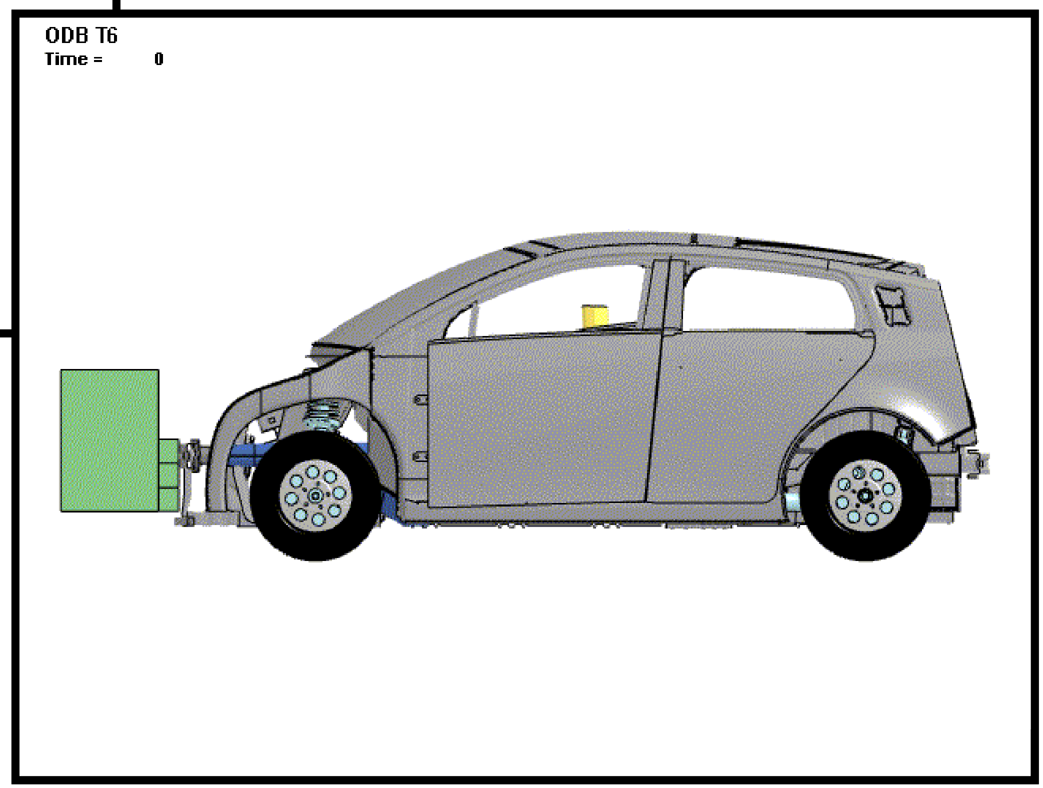


Typical Midsize Vehicle Pulse comparison with FSV

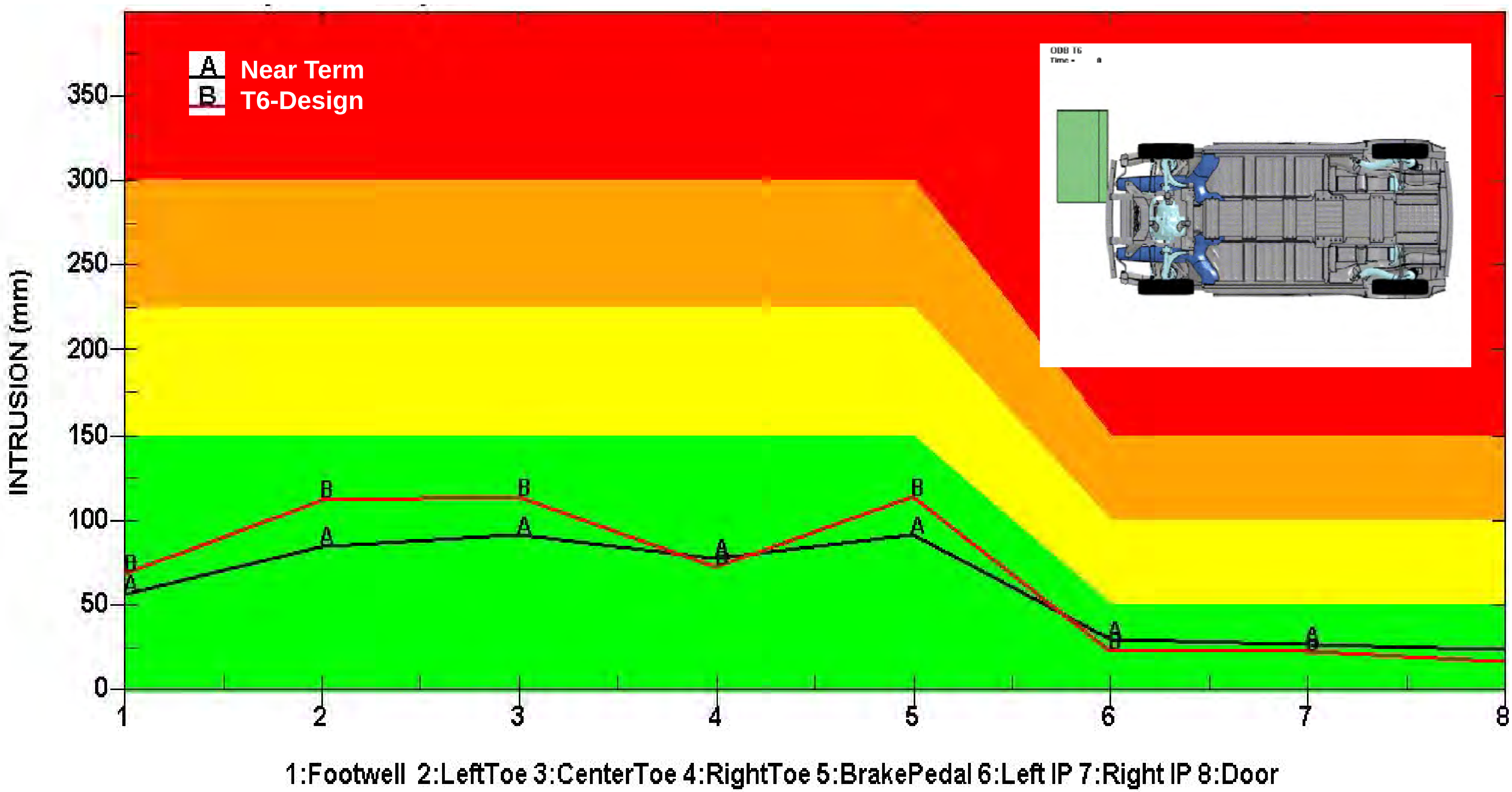


Design # 73 – Front ODB Results



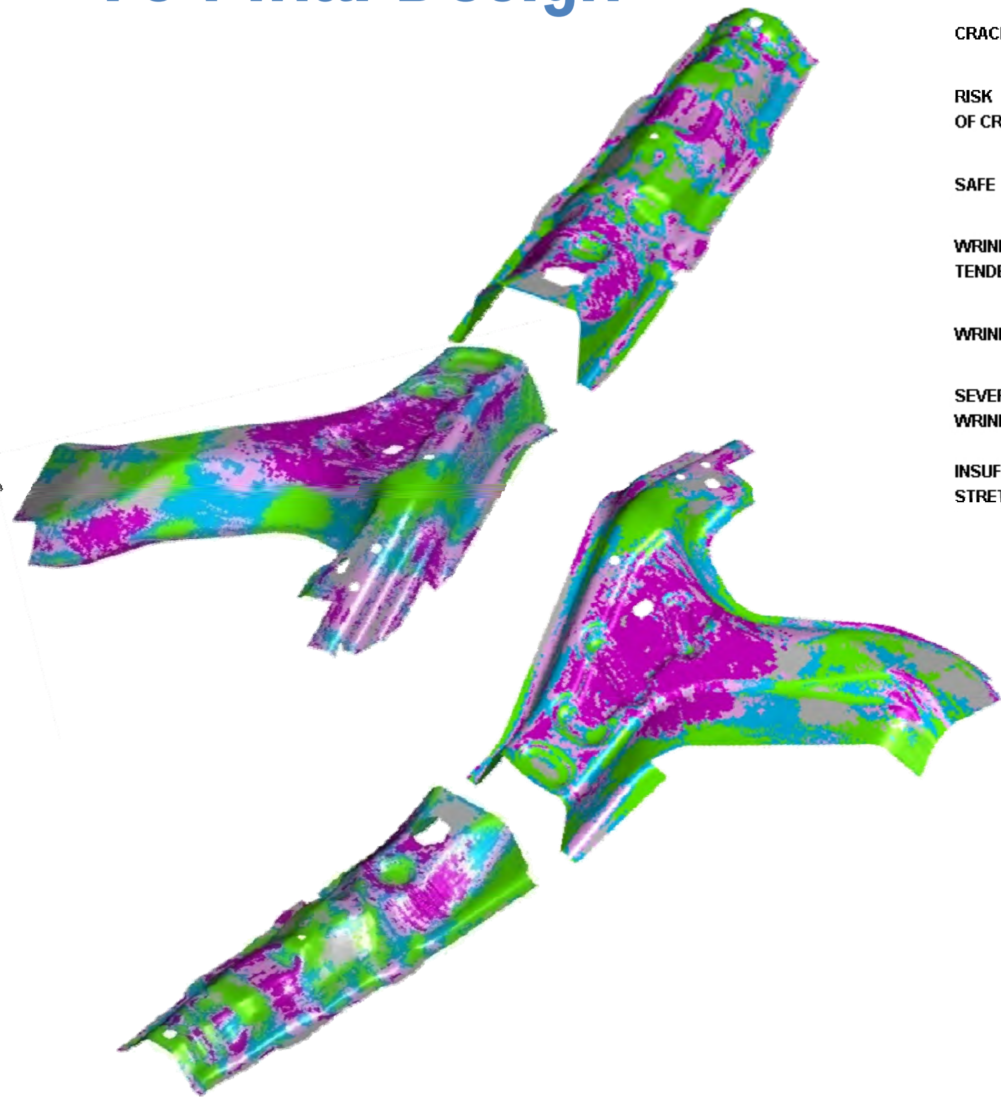


Design # 73 - ODB Results

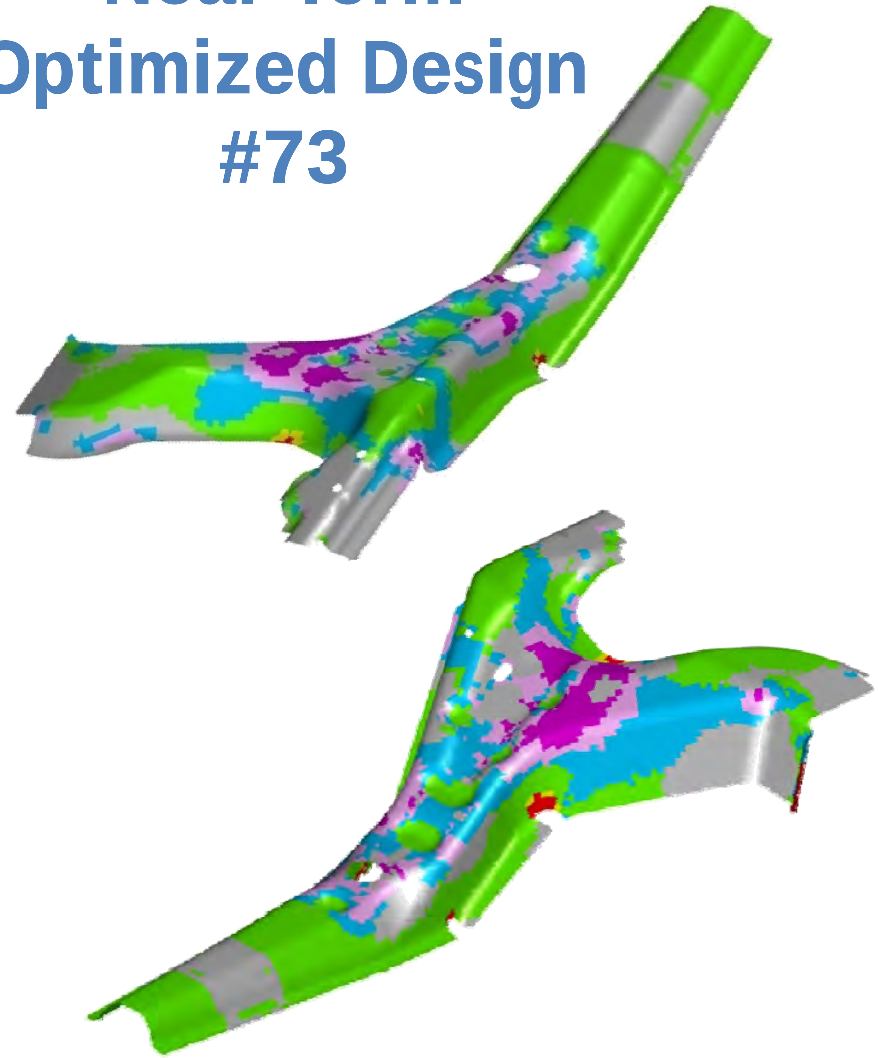


Formability Comparison

T6 Final Design

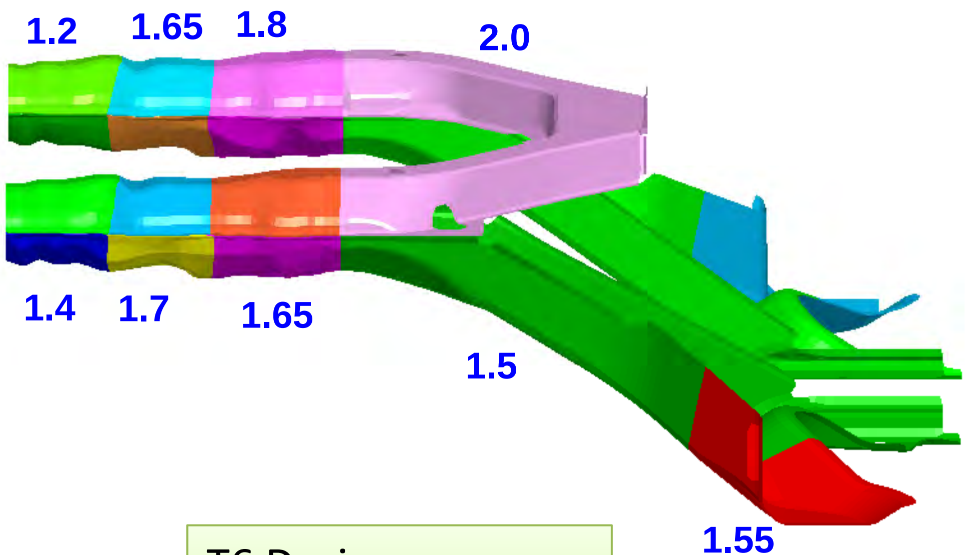


Near Term Optimized Design #73



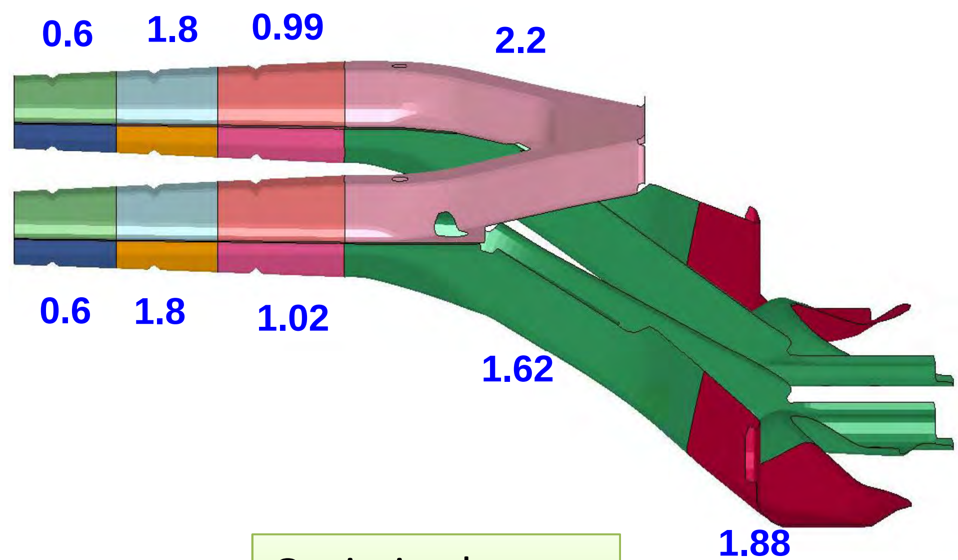
Mass Comparison

T6 Design



T6 Design
Mass = 15.6 kg

Hexa Shape

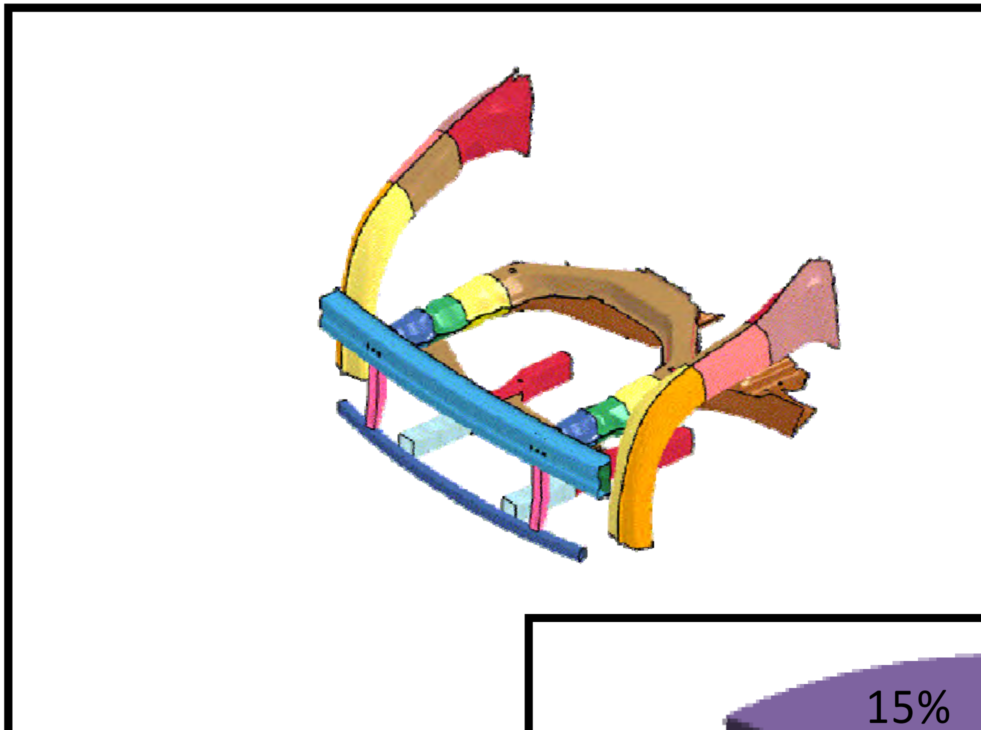


Optimized
Mass = 15.63 kg

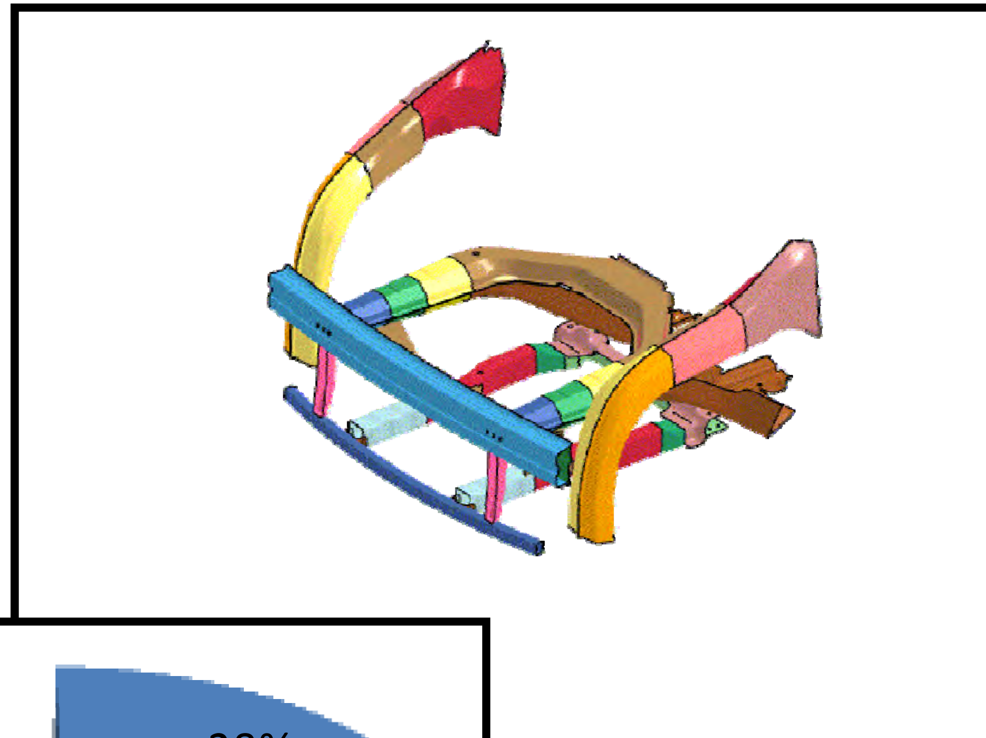
- ❑ BIW mass are the same in both design

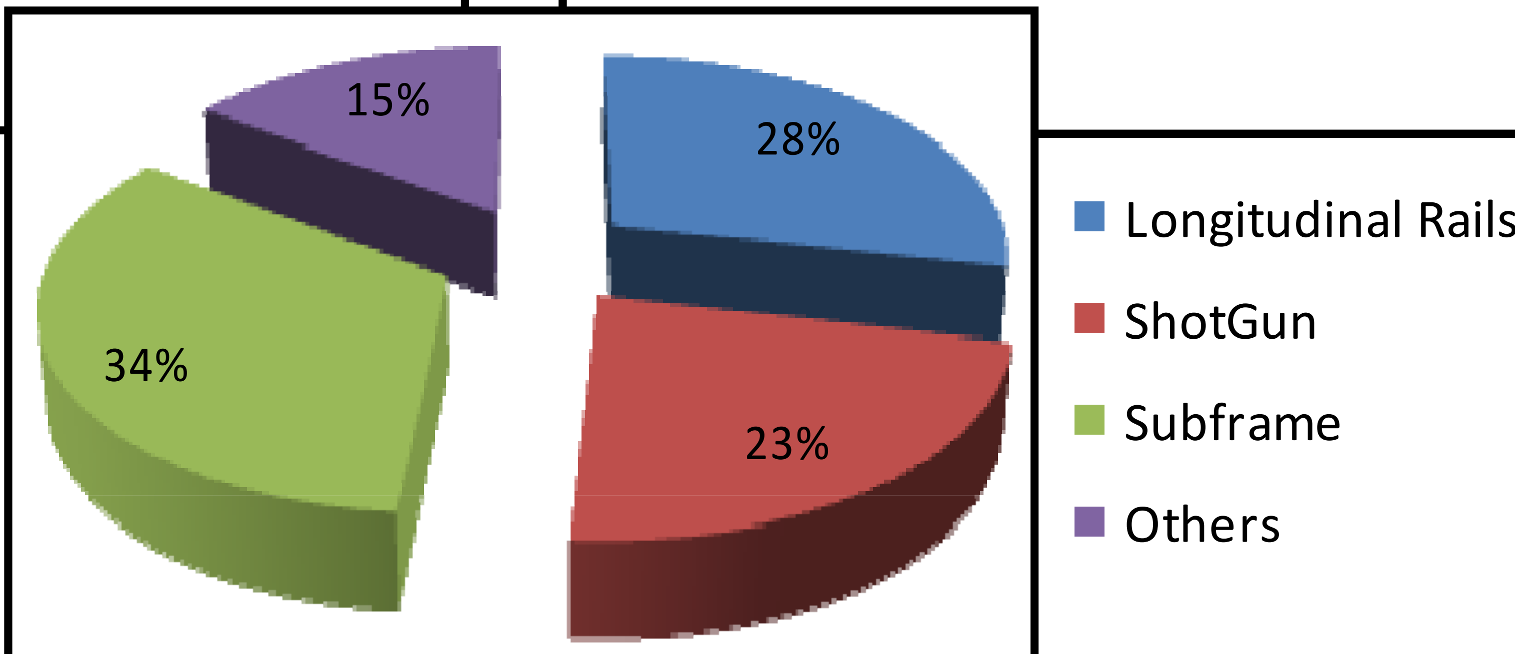
Front Subsystem Key Components Load Management

T6 Design



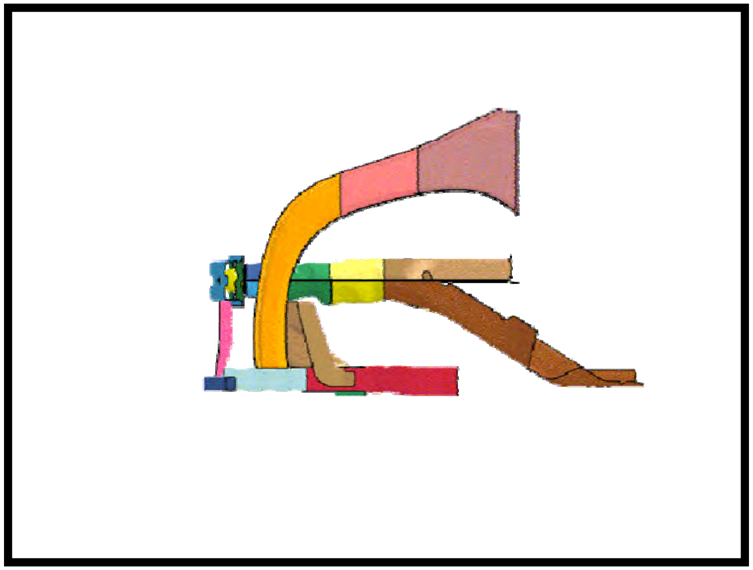
Hexa Shape

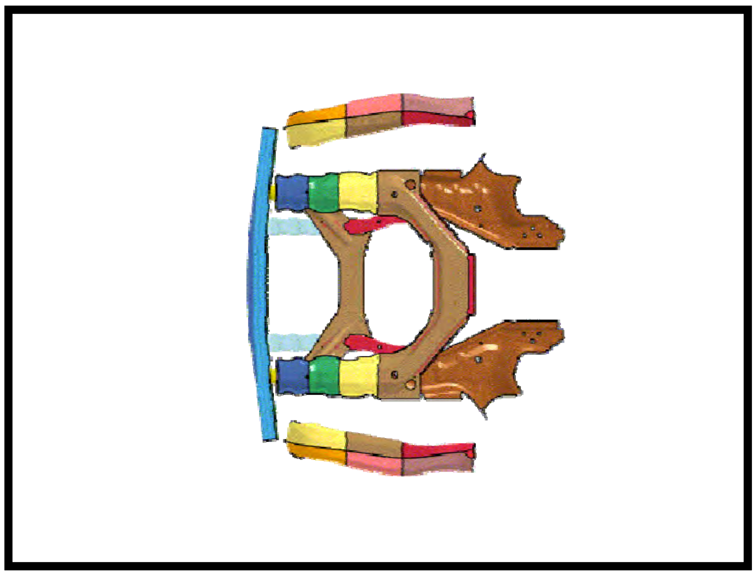




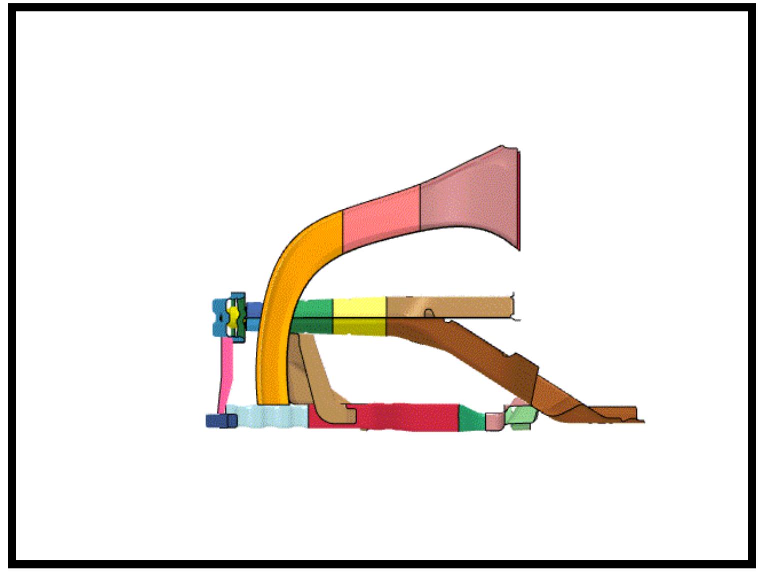
Front Subsystem

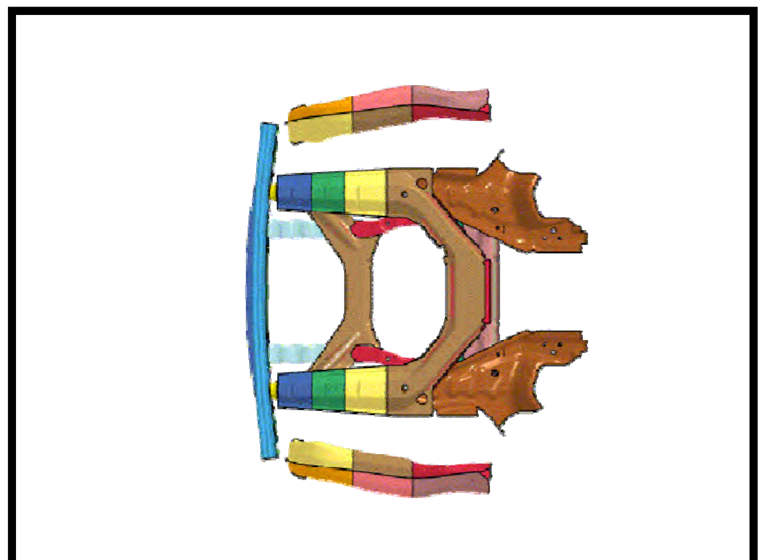
T6-Design





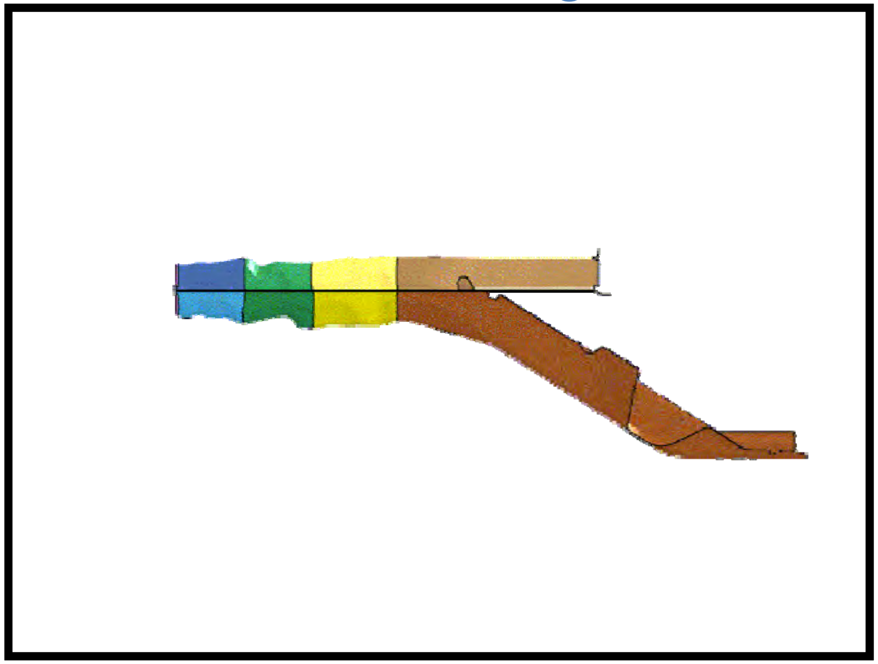
Hexa Shape

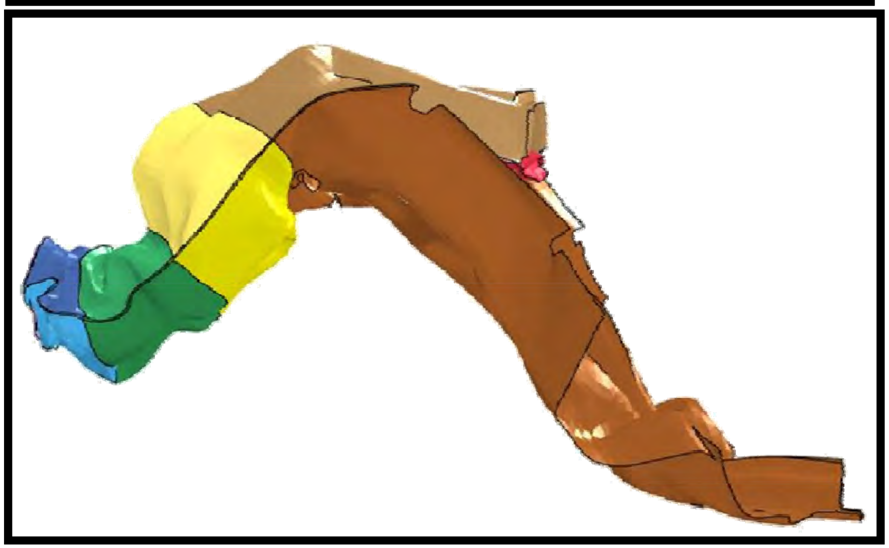




Longitudinal Rails

T6-Design





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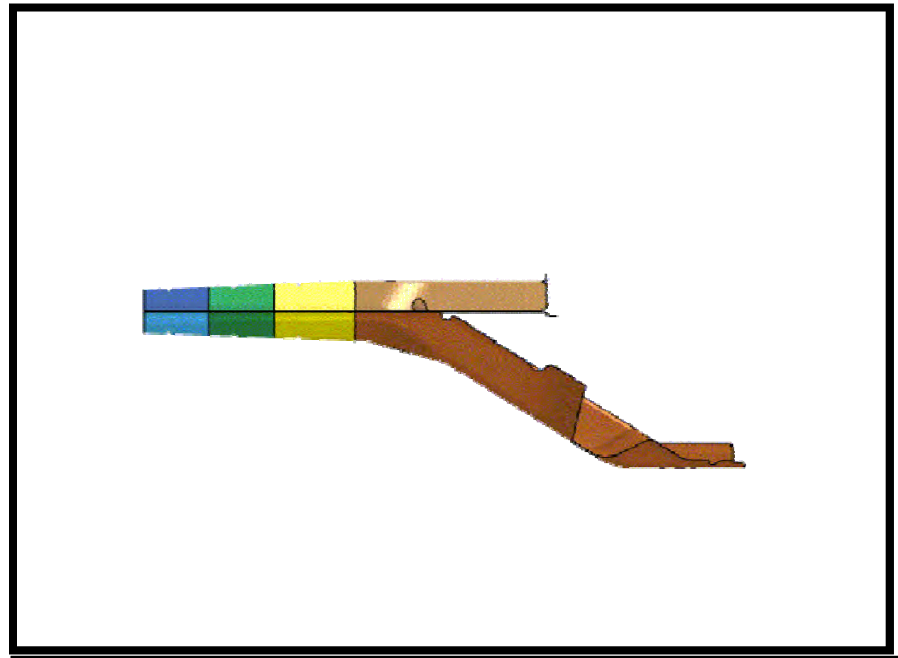
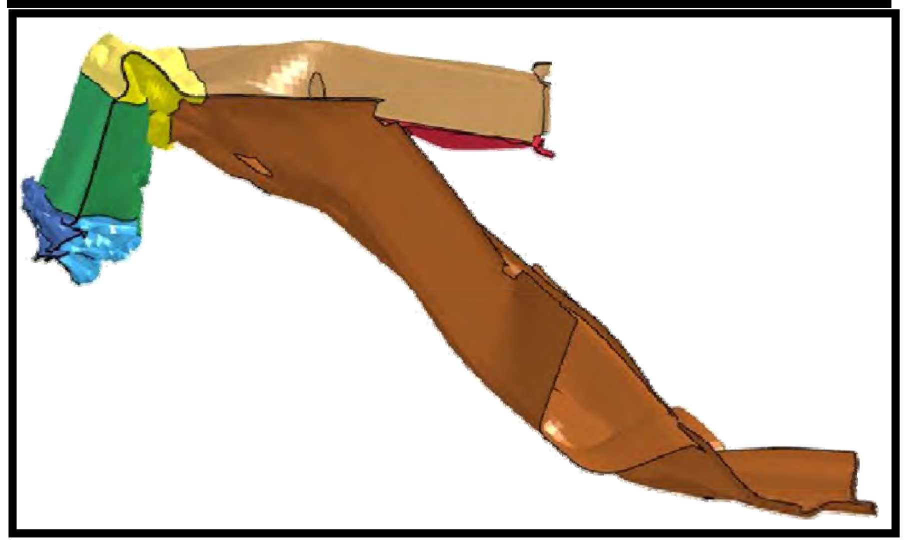
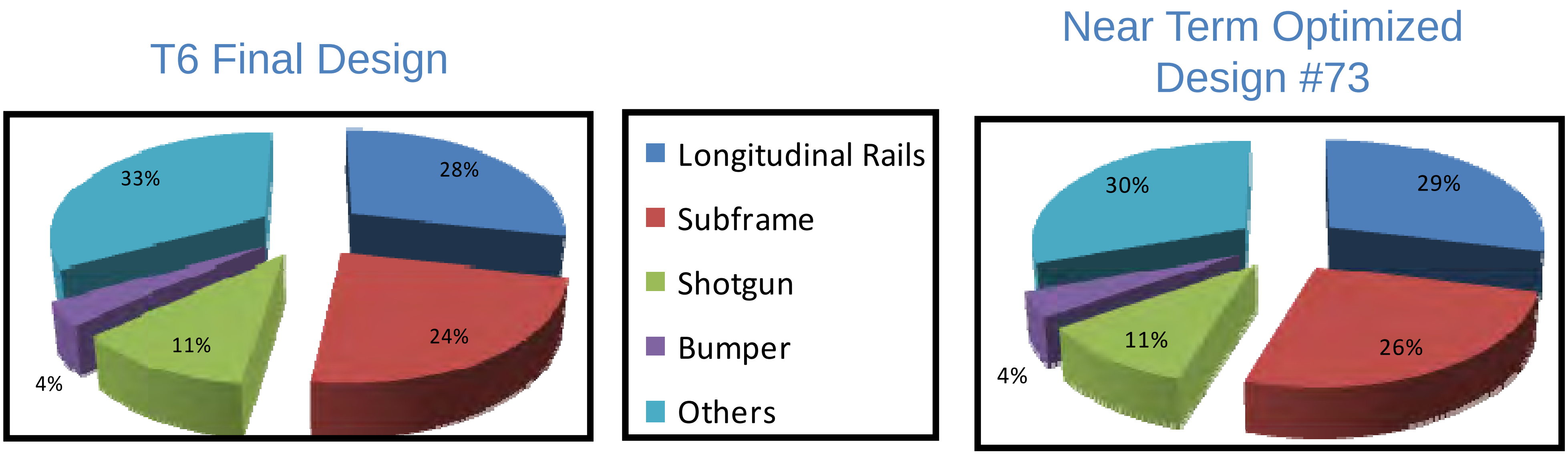




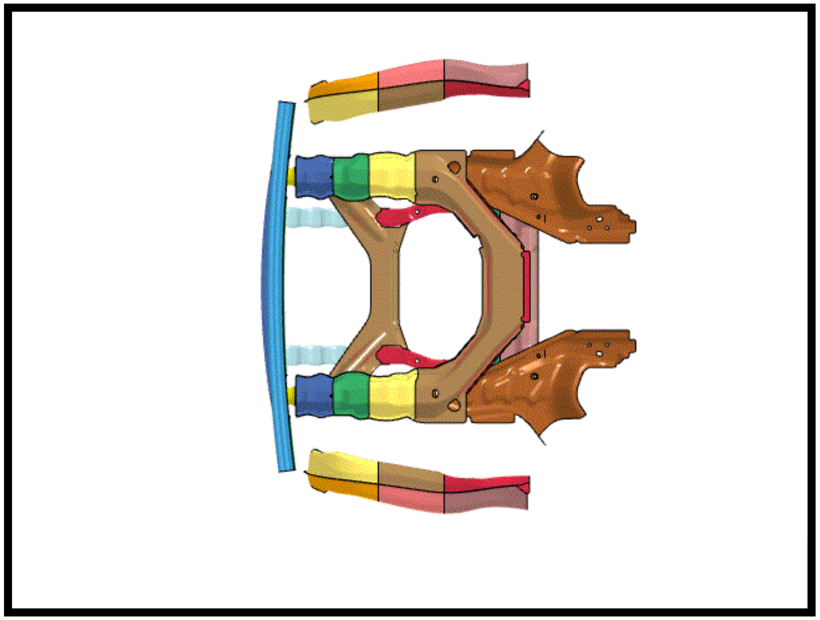
Energy Absorption Comparison- NCAP

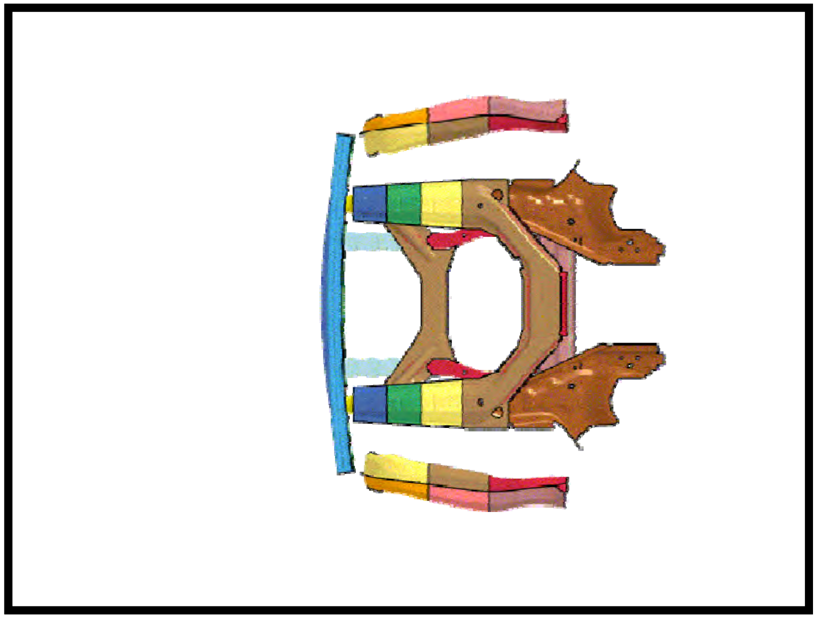


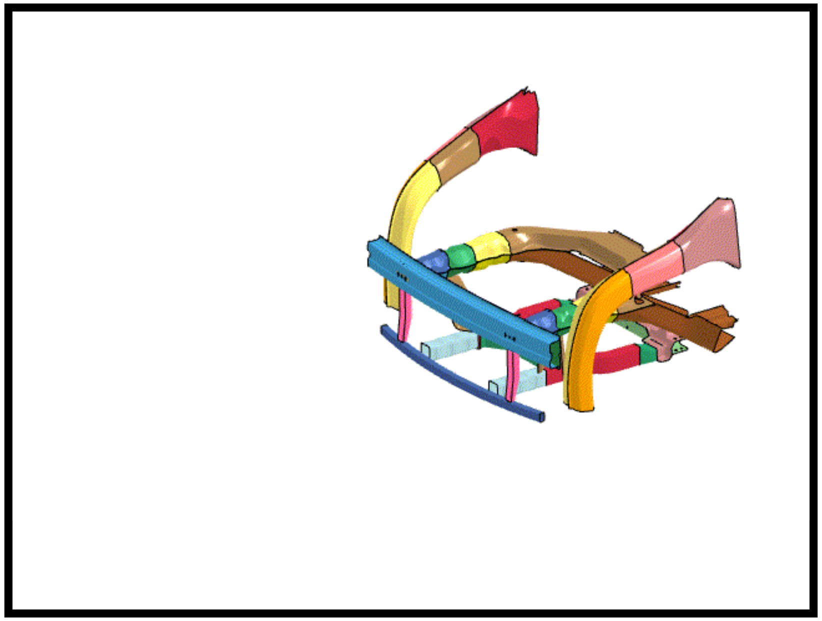
Front Subsystem

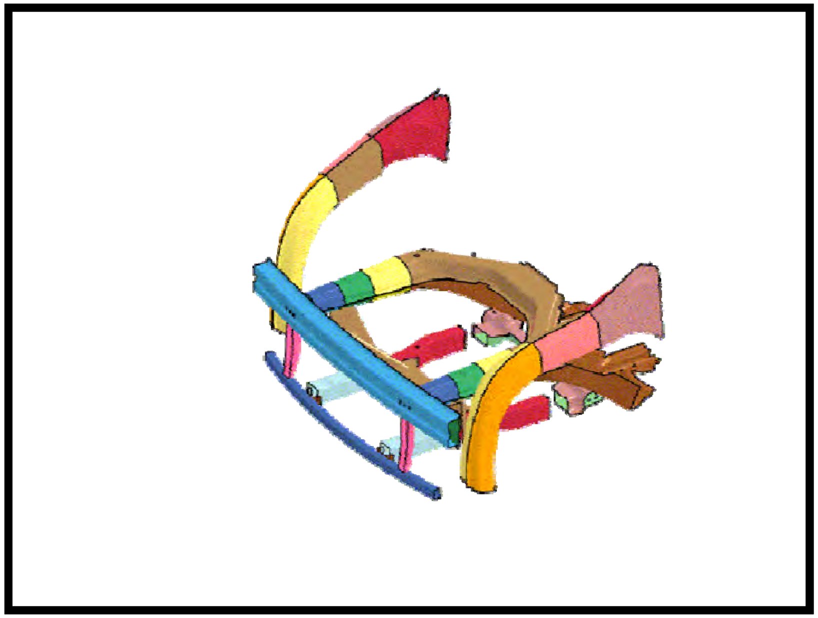
T6-Design

Hexa Shape





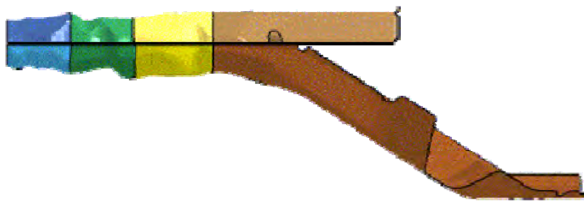


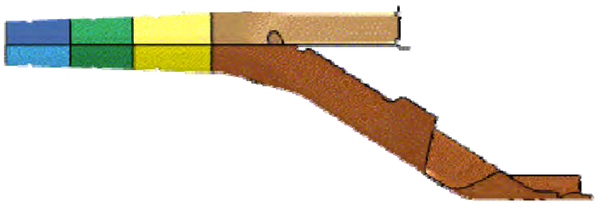


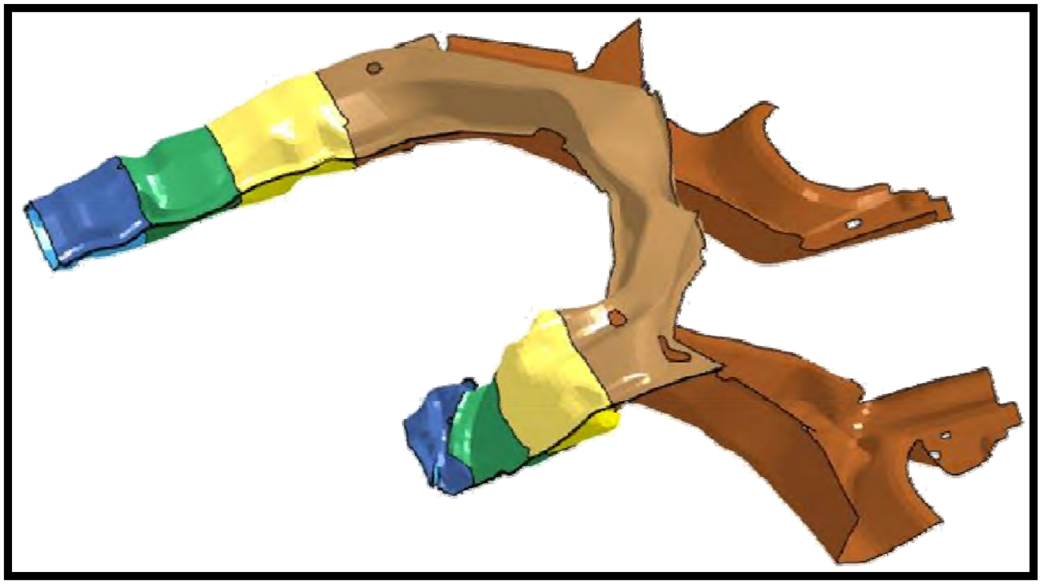
Longitudinal Rails

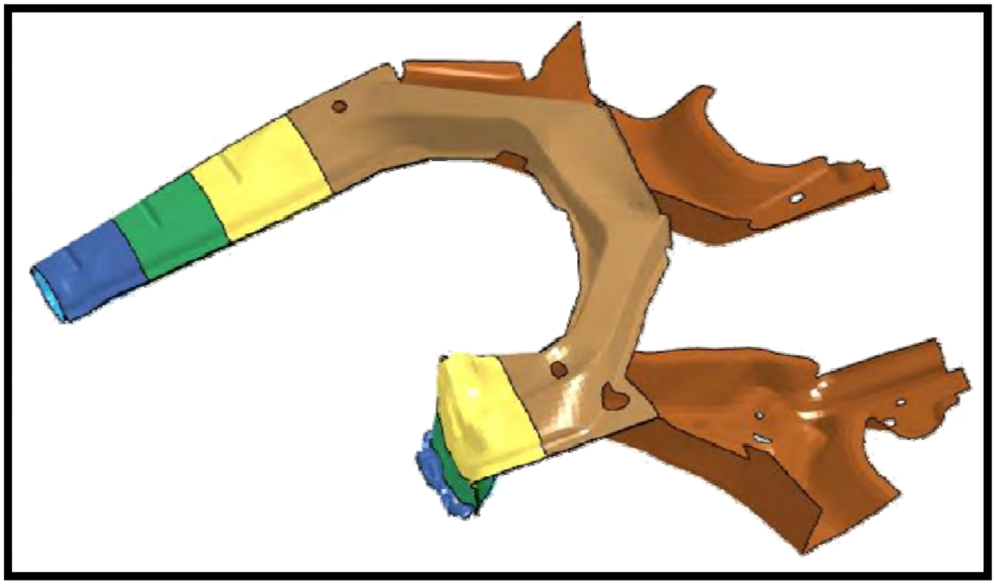
T6-Design

Hexa Shape









Energy Absorption Comparison- ODB

T6-Design

Hexa Shape

Results Comparison

Design	Mass kg	NCAP	Front ODB	IIHS Side	Side Pole	IIHS Rear	IIHS Roof	Bend.	Torsion
Targets	<188	39.6 g	Good	125mm	125mm	Pass	37.5kN	12	20
T6 Design	176.8	37.5	Good	152	138	Good	44.5	14.2	19
Near Term-Hexa Shape	176.83	37.3	Good	Same	Same	Same	Same	Same	19

Conclusions

- The Near Term Longitudinal Rail design shape such as Hexagonal is following Nature's Way design strategy.
- Over all performance and mass comparison is the same as T6 Design
- Buckling modes of two designs concept are different based on their own design strategies.
- NCAP's vehicle pulse and ODB's Intrusion of both design rail shapes are very close
- In NCAP case, 28% of total energy is absorbed by rails and 72% by other components , therefore, the shape of tip of front rail does not play a major role in front crash performance.
- Near Term Hexagonal design shape provides fewer challenges for forming in the front tip of the rails.
- The effect of non- intuitive shapes design on other components could be different (such as rocker or B-pillar, etc..). This needs to be studied separately.
- Load path and effect of AHSS in combination are dominant in defining vehicle front crash performance using "Natures Way Design" Strategy.
- 70% and 50% energy absorption by 3 systems (Front rail, Shotgun and Sub-frame).shows the most effective strategy for load management to design vehicle front-end structure

12.0 FSV Structure Design Methodology

12.1 Overview

12.1.1 FSV Development Process

The design and development process used for the Future Steel Vehicle program is shown in Figure 12.1. The Auto/Steel Partnership (A/SP) projects, Future Generation Passenger Compartment(FGPC) Phases 1 & 2, have previously validated the major portions of this design and development process for an existing structure. This form of optimization is referred to as 3G Optimization, representing full shape, material and gauge (geometry, grade and gauge) optimization. Building on this work, the FSV program will first define the optimum load path of a clean sheet design by blocking out the initial structure. This type of optimization is called Topology Optimization. It will then continue with the previous proven methods developed by FGPC Phases 1 & 2.

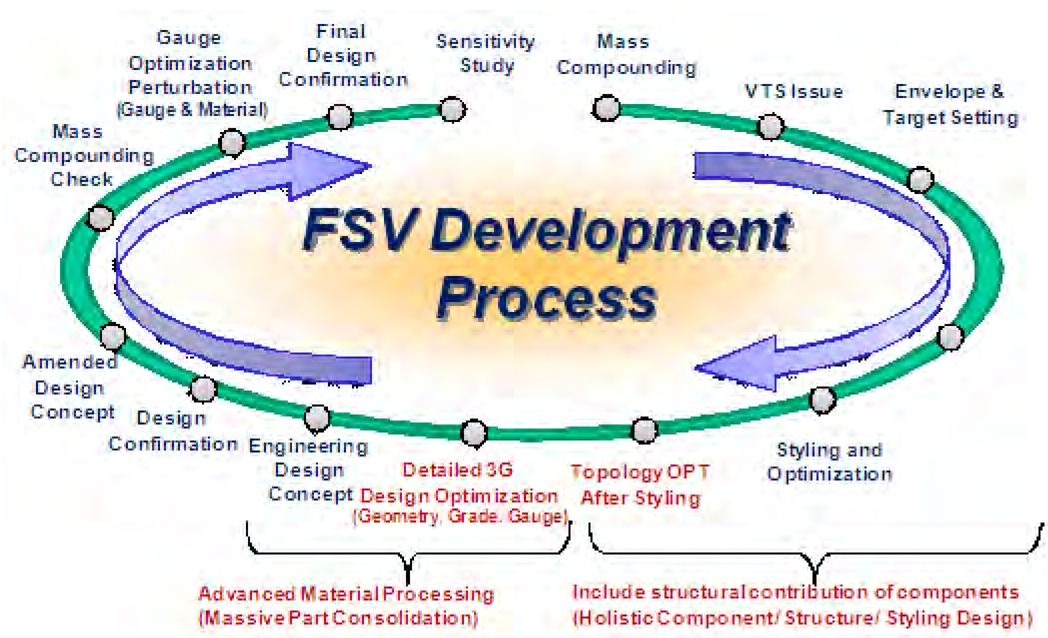


Figure 12.1: *Detailed FSV development process*

12.1.2 FSV Pilot Project Development Process

The FSV pilot project development process is shown in Figure 12.2. The complete FSV development process is significantly more detailed than the pilot project. But, a majority of the tasks within the FSV Development process have already been proven by both FGPC projects. It is only the integration of Topology Optimization into the whole process that has not previously been considered. Hence, the focus of the FSV pilot project was Topology Optimization and its integration to the overall development process.

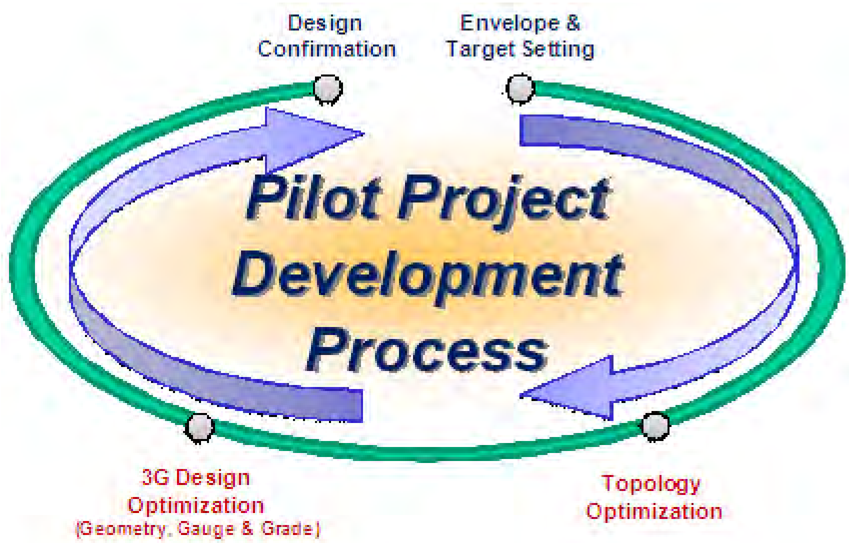


Figure 12.2: *Pilot project development process*

12.1.3 Objective

The first objective of FSV pilot project was to validate the proposed optimization methodology that will be used in the FSV program.

The second objective was to apply the same optimization methodology to the A/SP Lightweight Front End (LWFE) front rail to establish any additional mass savings. Figure 12.3 illustrates a summary of the LWFE program. The project started with the donor vehicle front rail and created three optimized concepts: a Laser Welded Blank (LWB) and two Tailor Welded Tube (TWT) concepts. The LWB concept was the baseline geometry for the pilot project.

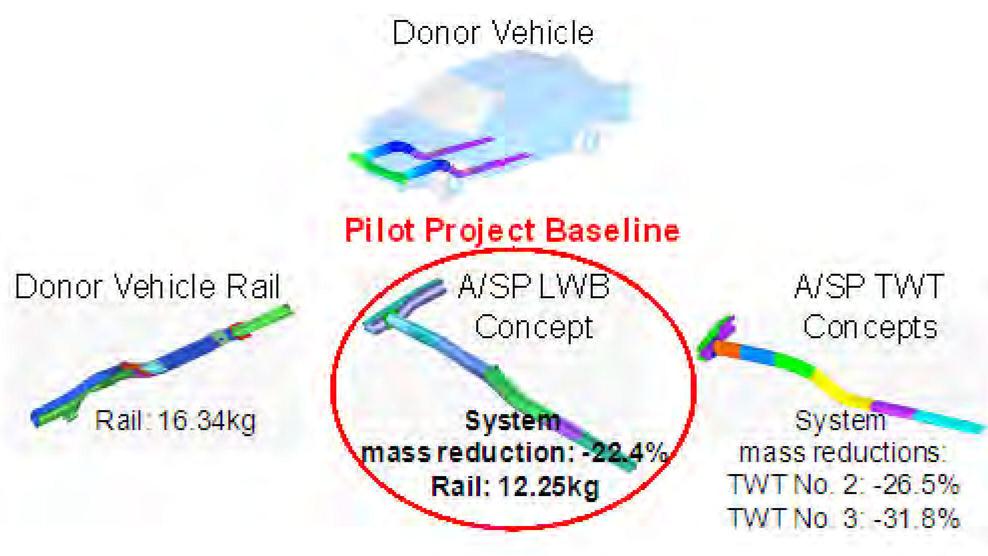


Figure 12.3: *LWB concept - pilot project baseline*

12.1.4 Optimization Methodology

As shown in Figure 12.4 the optimization methodology involved the following steps:

- Block out design envelope
- Topology Optimization
- Parameterize Geometry
- Detailed 3G Optimization: Geometry (Shape), Grade (material) & Gauge

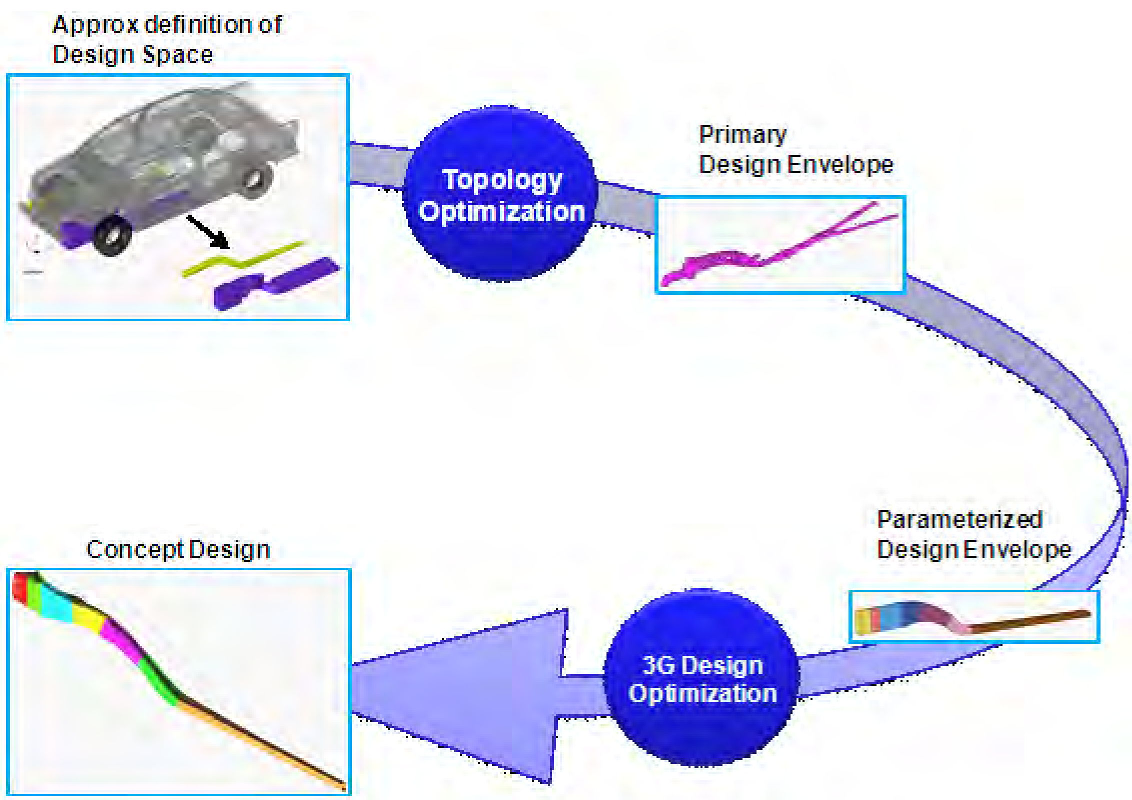


Figure 12.4: *Optimization methodology overview*

Following were the optimization load cases considered:

- US-NCAP zero degree front crash
- IIHS Front Impact 40% Offset Deformable Barrier (ODB)
- Static stiffness
    - Torsion
    - Bending

12.2 Baseline Model

The donor vehicle model as received was a full LS-Dyna crash model of approximately 310,000 elements. The donor vehicle model and front rail model are shown in Figure 12.5.

Front rail mass = 12.25 kg (A/SP LWFE-LWB)

Figure 12.5: *Model as received (front rails shown for clarity)*

In order to assess the baseline model performance, CAE analysis was conducted on the donor vehicle model for the following test procedures:

- US-NCAP zero degree front crash
- IIHS front crash 40% ODB

Also, the following static stiffnesses were calculated for the baseline model.

- Torsion
- Bending

12.2.1 Baseline Performance

12.2.1.1 US-NCAP Zero Degree Front Crash

Boundary Conditions

The impact barrier is represented as a fixed rigid wall positioned so that it almost contacts the front tip of the front bumper at the start of the simulation. The ground is also represented as a rigid wall positioned at the very lowest points of the tires. The performance of the vehicle structure was verified under NCAP loading. The vehicle is impacted into a rigid wall at an initial velocity of 35 mph.

Results

The CAE test setup and results are shown in Figure 12.6.

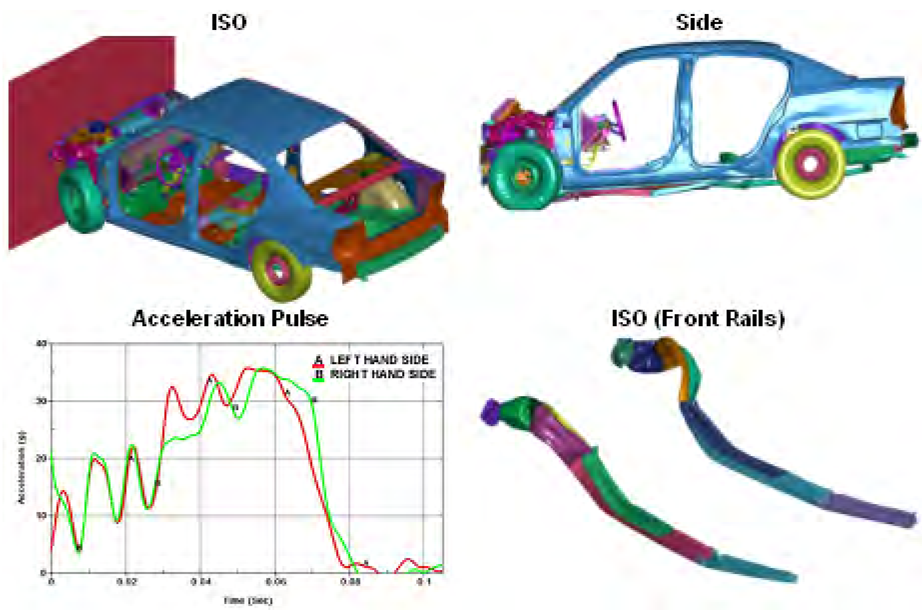


Figure 12.6: *NCAP - deformed plots & acceleration*

Maximum B-Pillar Pulse

The maximum B-pillar pulses were the following:

- Left hand side: 36 g
- Right hand side: 36 g

12.2.1.2 IIHS Front Crash 40% ODB

Boundary Conditions

The vehicle impacts a deformable barrier, offset 10% from centerline (40% overlap), at 40 mph.

Results

The CAE test results are shown in Figure 12.7 and Figure 12.8[1].

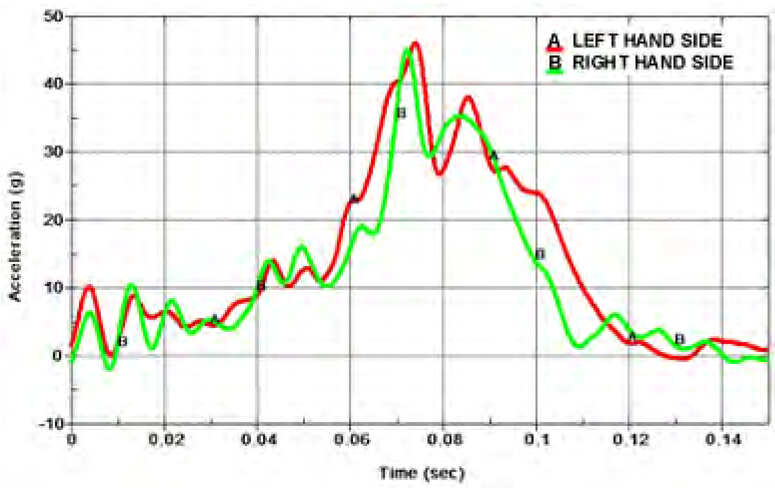


Figure 12.7: *Rocker acceleration pulse*

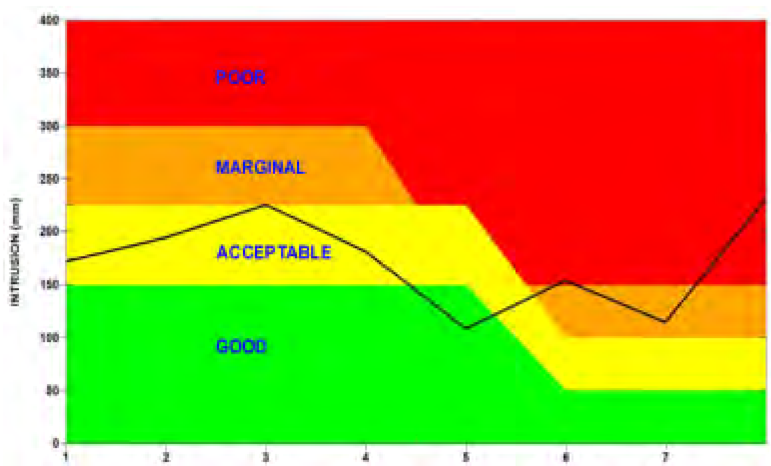


Figure 12.8: *IIHS intrusion performance*

[1] 1: Footwell, 2:Left Toe, 3:Center Toe, 4:Right Toe, 5:Brake Pedal, 6:Left IP, 7:Right IP, 8:Door

12.2.1.3 Static Stiffness

Boundary Conditions

Following were the boundary conditions:

- Torsion: Vehicle is held at the rear stock towers and front bumper. A couple is applied to the front shock towers.
- Bending: Vehicle is supported at all four shock towers, a load is applied in the vertical (negative z-direction) to the rocker at the front door opening.

Results

The CAE test results are shown in Figure 12.9.

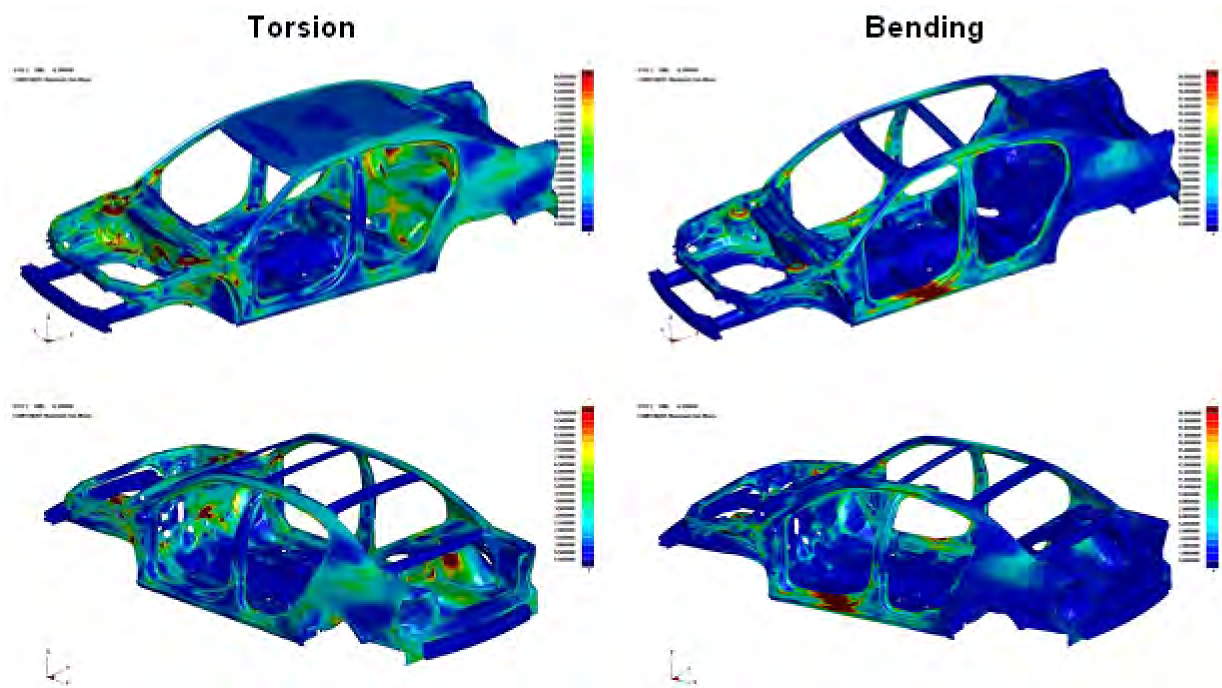


Figure 12.9: *Static stiffness*

Following were the stiffness values attained from CAE analysis results (shown in Figure 12.9):

- Torsion: 17,788 $\frac{\text{Nm}}{\text{deg}}$
- Bending: 12,122 $\frac{\text{N}}{\text{mm}}$

12.2.1.4 Performance Summary

The performance summary of the baseline model is shown in Table 12.1.

LOADCASE	PERFORMANCE	
NCAP Front Impact	**Max B-Pillar Pulse**	
	Left Hand Side	36g
	Right Hand Side	36g
IIHS Front Impact 40% ODB	**IIHS Peak Intrusion**	
	Left Toepan	15 cm
	Center Toepan	20 cm
	Right Toepan	24 cm
	A-B Pillar Closure	19 cm
Static Stiffness	Torsion	17,788 Nm/deg
	Bending	12,122 N/mm

Table 12.1: *Baseline model performance summary*

12.3 Topology Optimization

The Topology Optimization began by defining the design space available to the optimization as shown in Figure 12.10. This represented the extreme packaging volume that the optimization can use. The new front rail must fit within this space.

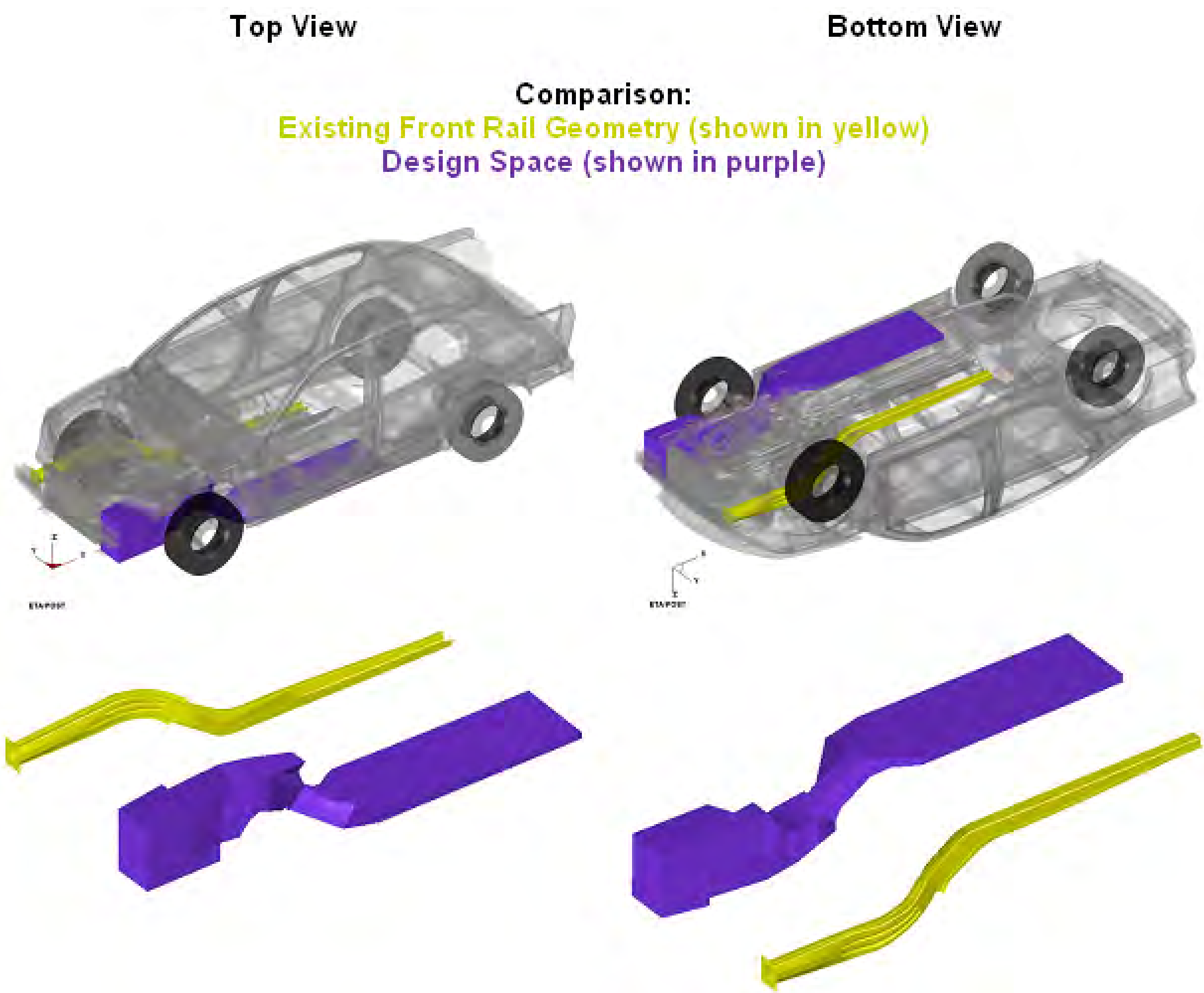


Figure 12.10: *Design space*

Calibration of the Donor Vehicle used a full vehicle dynamic crash model. However, Topology Optimization is based on static analysis and so an analogous static loading of the dynamic impact was applied to a de-coupled sub-model of the front rail. Figure 12.11 shows a direct comparison of the front rail deformed shapes for both the full vehicle dynamic analysis and the de-coupled static analysis.

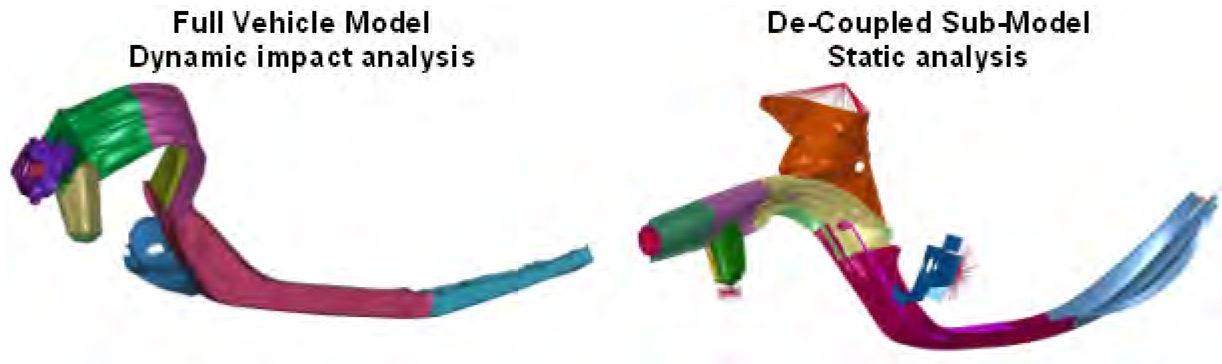


Figure 12.11: *Comparison between full-vehicle dynamic & de-coupled static deformed shapes*

Figure 12.12 shows the results of the Topology Optimization in combination with the Design Space (in light red) & original rail (in green). The Topology Optimization provided an insight into what the structure desires, free from the traditional design thought process. The optimal load path could now be used as the base for the 3G (Geometry, Grade & Gauge) Optimization. However, it should be noted that although Topology Optimization may seem quite straight forward, it is in fact a subtle iterative process.

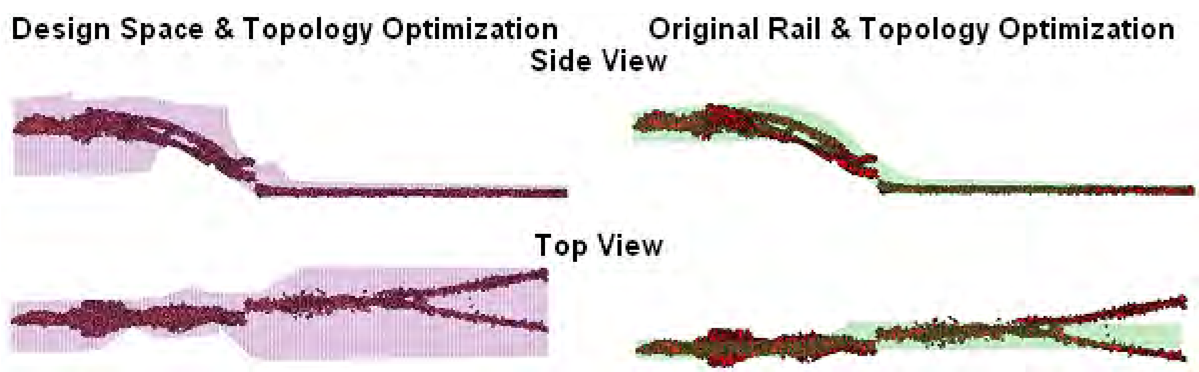


Figure 12.12: *Topology Optimization results shown in combination with the design space (in light red) & original rail (in green)*

12.4 3G Optimization

12.4.1 Background

3G Optimization represents full shape, material and gauge (Geometry, Grade & Gauge) optimization. At its core the process is the fully automated interface between the multi-dimensional optimization, simulation and parametric modeling. The multi-dimensional optimization controls the process as it conducts its search through the design space. It creates a design iteration which it submits to the simulation software for analysis. It then reviews the analysis results, compares these to the design objectives and the previous search history to develop a new design proposal. Any geometry changes it deems necessary are created by the parametric modeler. Once the new design proposal is complete, the optimization submits it for analysis to begin the next cycle of optimization. Figure 12.13 illustrates the 3G Optimization interface.

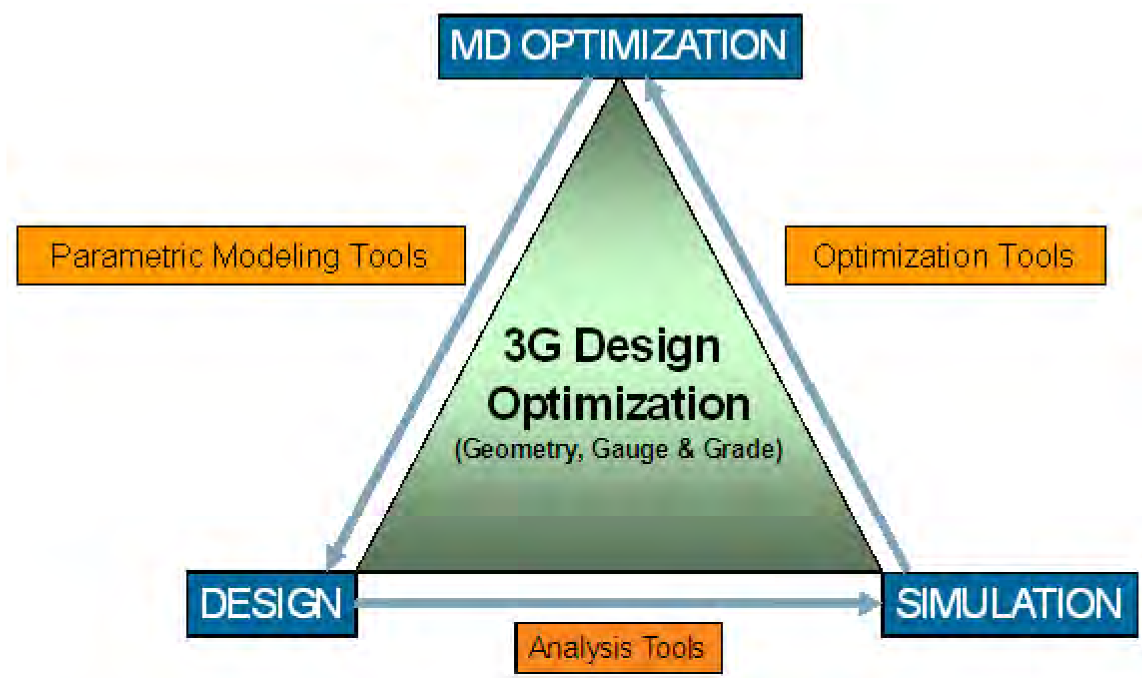


Figure 12.13: *3G Optimization - key interfaces*

12.4.2 Load Path Parameterization

The first step to setting up the 3G Optimization was to parameterize the load path by defining a series of cross-sections through the load path. At each section, the optimization will be able to vary its dimensions, thus locally defining its shape. It was therefore necessary to define not only the location and number of cross-sections but also the boundary parameters that the optimization can control.

Figure 12.14 shows sections cut through both the load path and design space. For reference, Figure 12.15 includes the original front rail in place.

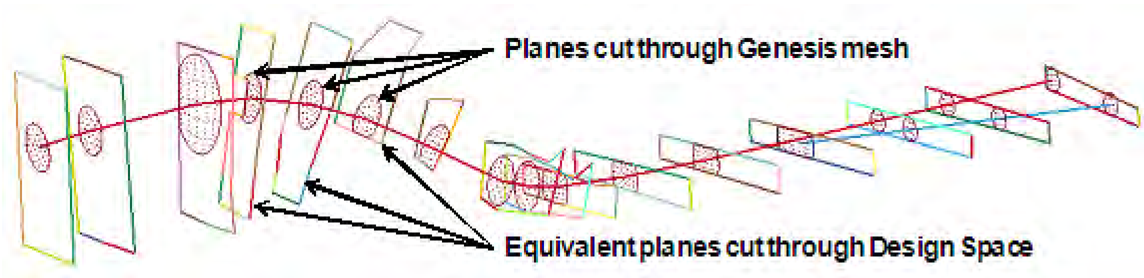


Figure 12.14: *Cross-sections through the Topology Optimization's load path mesh & design space*

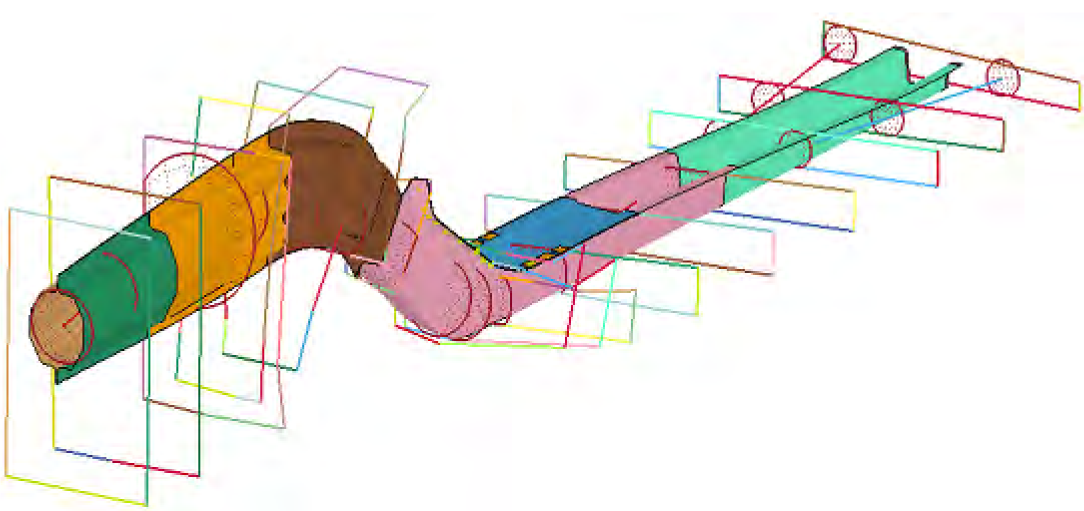


Figure 12.15: *Original front rail shown in combination with cross-sections through the design space*

After reviewing the deformed shapes from the initial calibration NCAP and IIHS Front Crash analysis, it was decided to add additional cross-sections at the front of the rail, cross-sections 1→12 and use fewer cross-sections for the rear portion, sections 13→15 (as shown in Figure 12.16 & Figure 12.17).

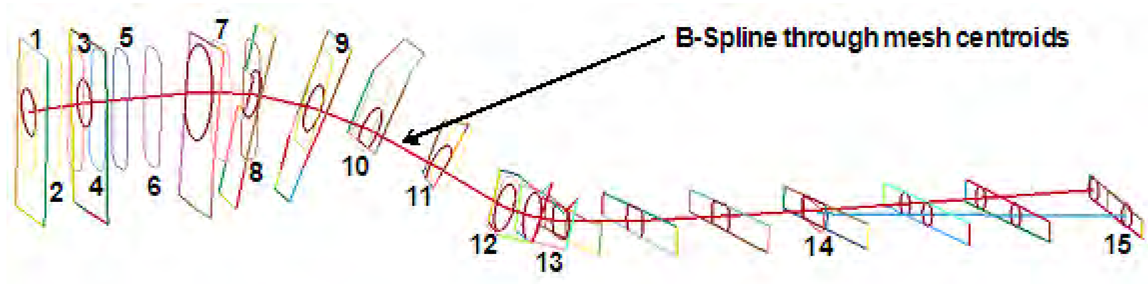


Figure 12.16: *Finalized cross-sections through the Topology Optimization's loadpath mesh & design space*

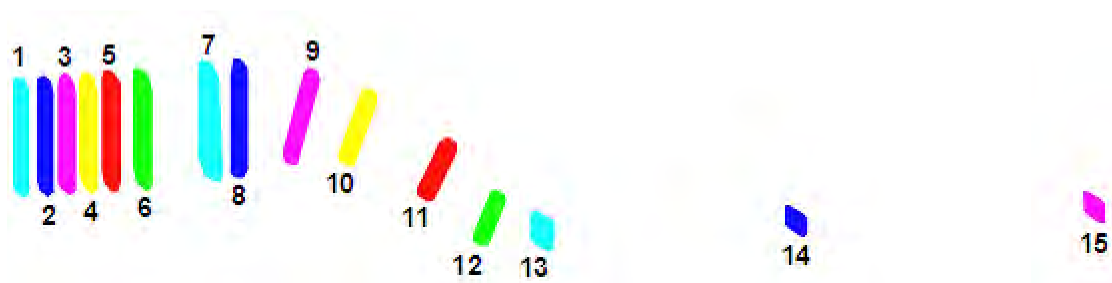


Figure 12.17: *Finalized cross-sections*

Once the number and location of the cross-sections were defined, the parameterization continued with the definition of the control points for each section, as shown in Figure 12.18.

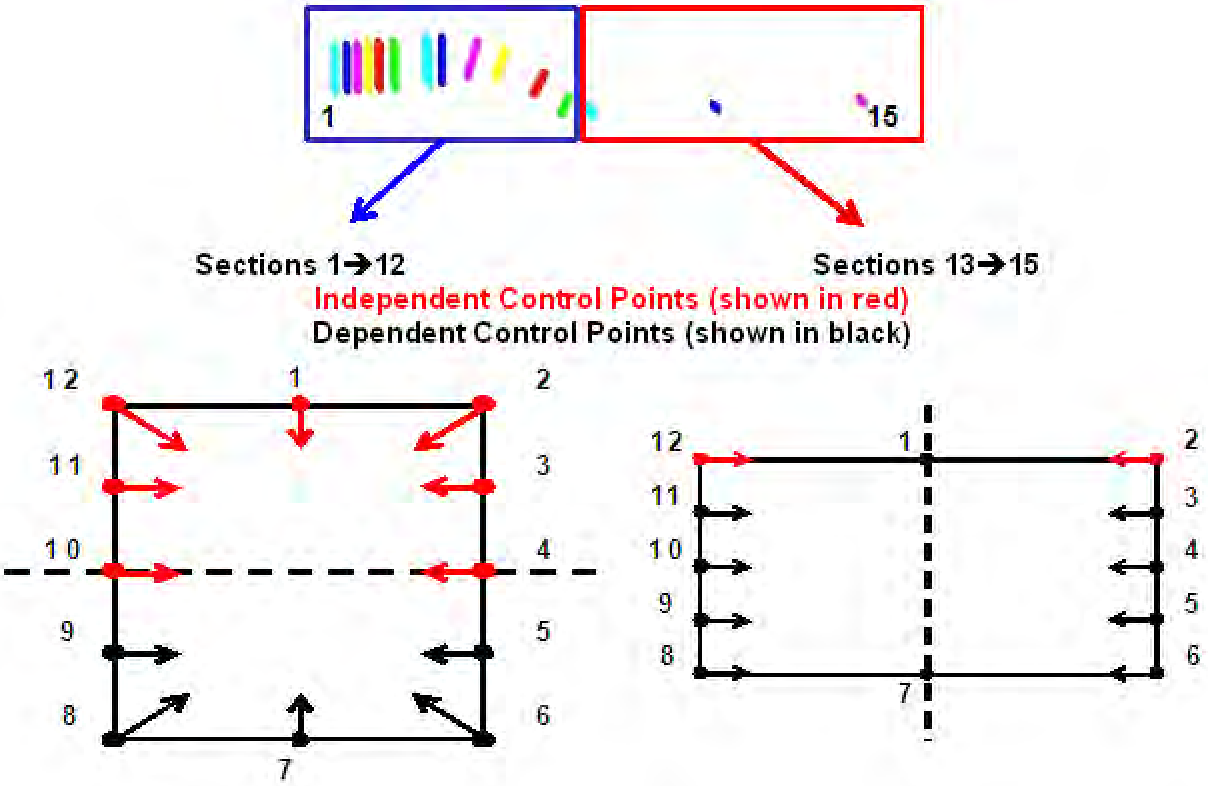


Figure 12.18: *Parameterization of cross-sections*

The shape of each cross-section is defined by twelve control points, as shown in Table 12.2. The independent control points are free to move within the plane of the cross-section. A dependent control point must follow its corresponding independent point's movement. Limits to a cross-section's shape change were set so that the maximum size of the section was the outer limit of the design space, from here the optimization was free to reduce the perimeter by up to 40% or 60% of the outer boundary.

CROSS-SECTION	CONTROL POINTS	
01→12	Independent	1, 2, 3, 4, 10, 11, 12
	Dependent	5, 6, 7, 8, 9
13→15	Independent	2, 12
	Dependent	1, 3, 4, 5, 6, 7, 8, 9, 10, 11

Table 12.2: *Control points*

In addition to shape changes, the optimization was able to independently select both material and gauge along the length of the rail. Table 12.3 lists the material and allowable gauge range available to the optimization. Figure 12.19 shows the regions in which this choice was available (Note: The rail's shape variables are shown at the maximum size for each section, the outer limit of the design space).

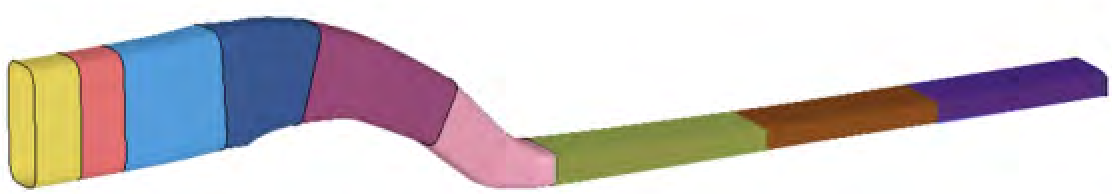


Figure 12.19: *Material & gauge parameterization*

MATERIAL	GAUGE RANGE
DP350/600	0.6 →2.3mm
DP500/800	0.6 →2.3mm
DP700/1000	0.6 →2.3mm

Table 12.3: *Material & gauge variables*

12.4.3 Problem Statement

The 3G optimization problem statement is shown in Table 12.4.

Maximize:	Mass Reduction
Subject to:	Section Force <= 35kN
By Varying:	Cross-sectional Shape (106 variables)
Material:	DP350/600, DP500/800, DP700/1000 (9 variables)
Gauge:	0.6 → 2.3 mm (9 variables)

Table 12.4: *3G Optimization problem statement*

12.5 Final Design

The final optimized design of the FSV front rail is shown in Figure 12.20. The material and corresponding gauge selections are shown in Table 12.5.

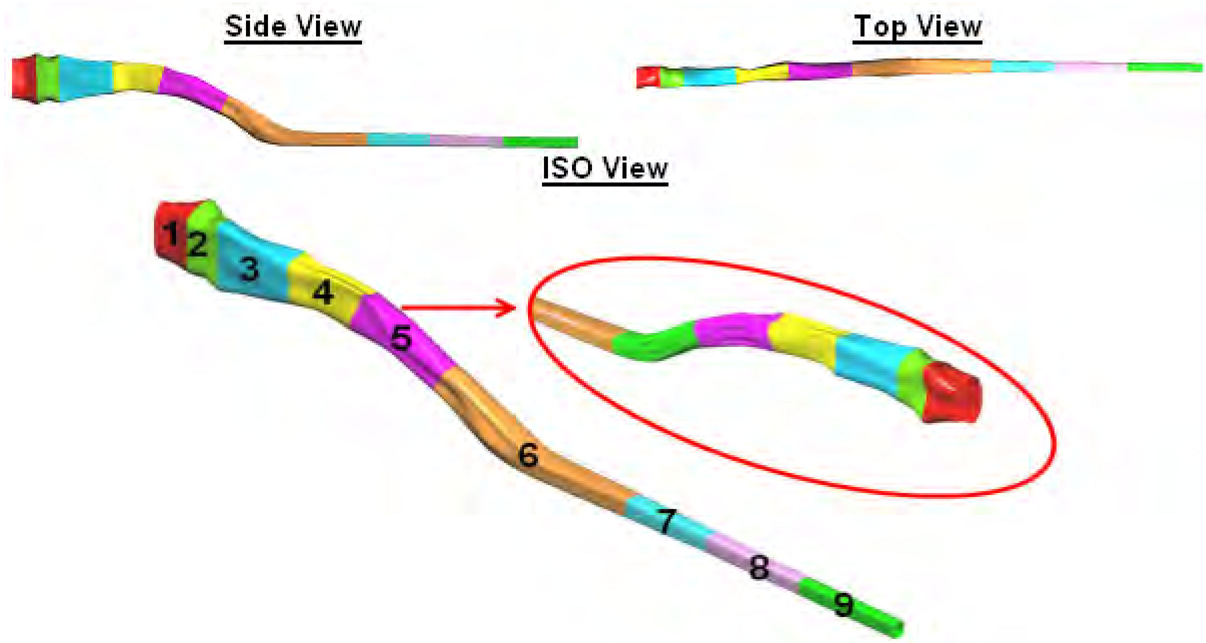


Figure 12.20: *Final design*

CROSS-SECTION	MATERIAL	GAUGE [mm]	MASS [kg]
1	DP350/600	1	0.48
2	DP500/800	1	0.46
3	DP700/1000	0.7	0.64
4	DP500/800	1.5	0.99
5	DP700/1000	2	1.58
6	DP700/1000	2.3	3.53
7	DP700/1000	1.5	0.69
8	DP700/1000	0.8	0.37
9	DP700/1000	0.6	0.26
		TOTAL	**8.98**

Table 12.5: *Final design - material & gauge selections*

The mass of the FSV optimized front rail was 8.98 kg (27% reduction in weight compared to A/SP LWFE-LWB). The comparison of the FSV optimized front rail to the A/SP LWFE-LWB is shown in Figure 12.21.

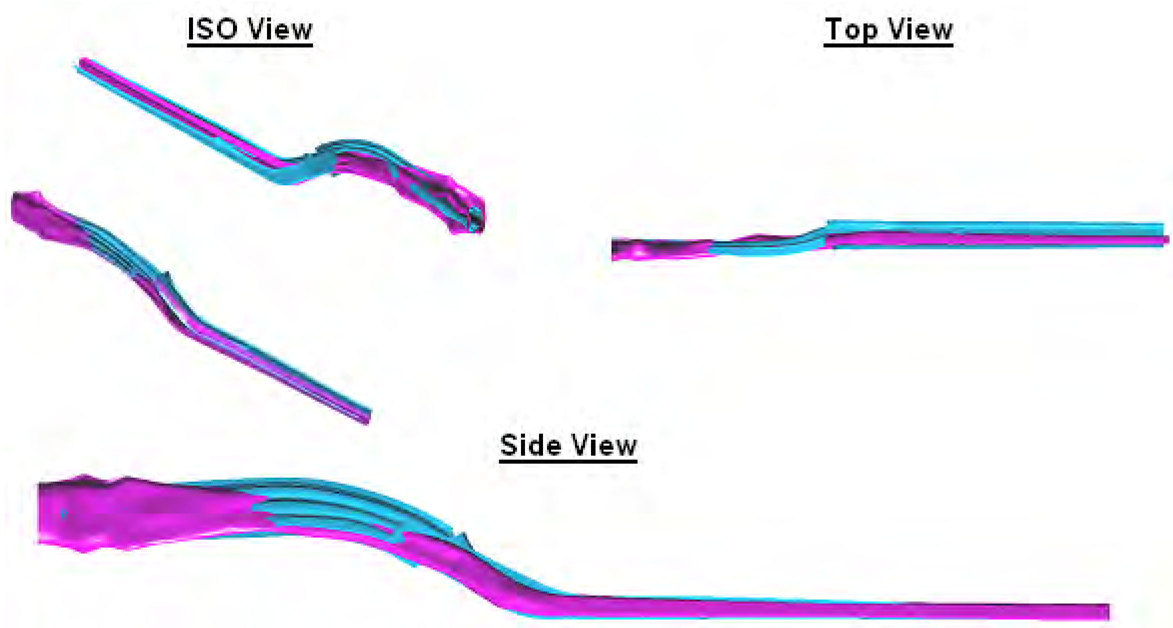


Figure 12.21: *Final design (in purple) shown in combination with original rail (in blue)*

Figure 12.22 shows the FSV optimized front rail combination of the Topology Optimization.

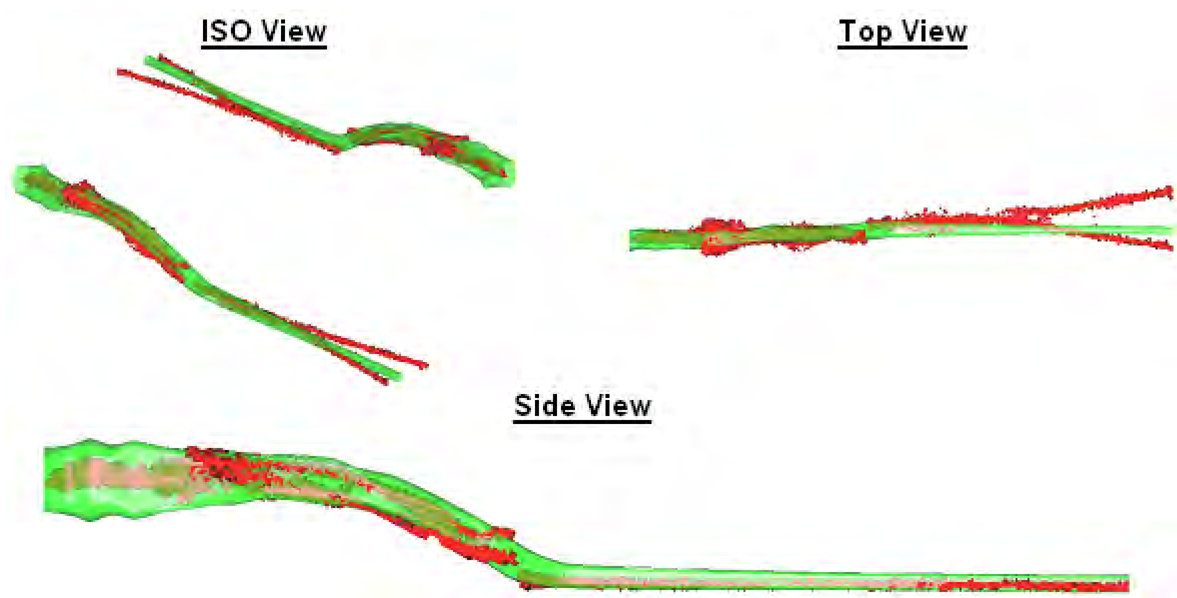


Figure 12.22: *Design (in green) shown in combination with Topology Optimization (in red)*

12.6 Final Validation

The final optimized design was validated for the test procedures: US-NCAP zero degree front crash and IIHS front crash 40% ODB. The static stiffnesses (torsion and bending) were calculated for the final optimized design, and compared to those of the baseline model.

12.6.1 US-NCAP Zero Degree Front Crash

The CAE results of the US-NCAP zero degree front crash procedure is shown in Figure 12.23.

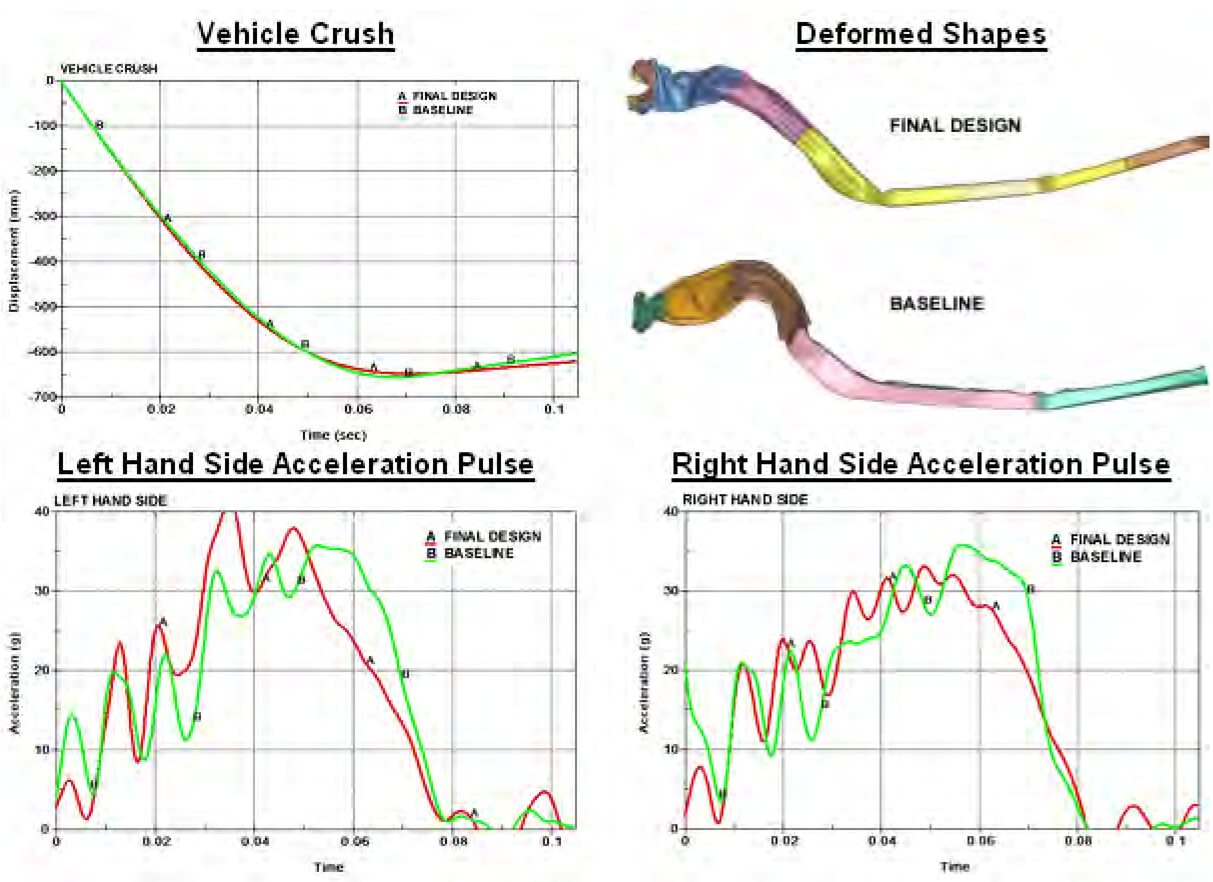


Figure 12.23: *NCAP - final design & original rail - deformed plots & Acceleration*

The donor vehicle and the final design models are shown in Figure 12.24.

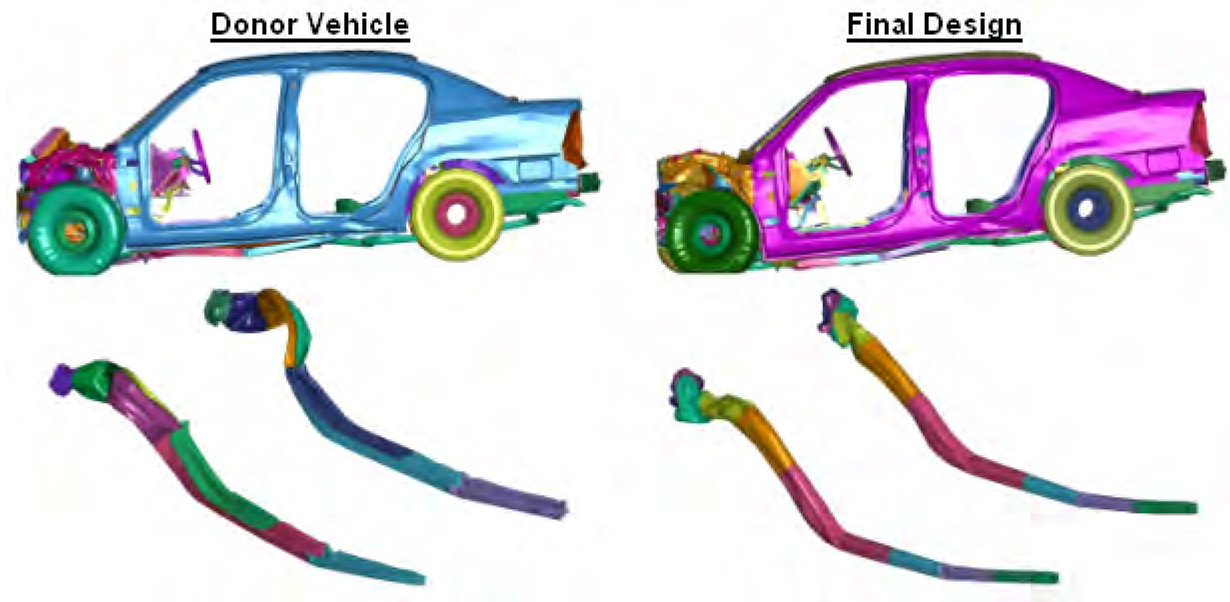


Figure 12.24: *NCAP - donor vehicle & final design*

12.6.2 IIHS Front Crash 40% ODB

The IIHS front 40% offset crash was analysed on the final design as shown in Figure 12.25. The corresponding results of the CAE analysis is shown compared to the baseline design in Figure 12.26.

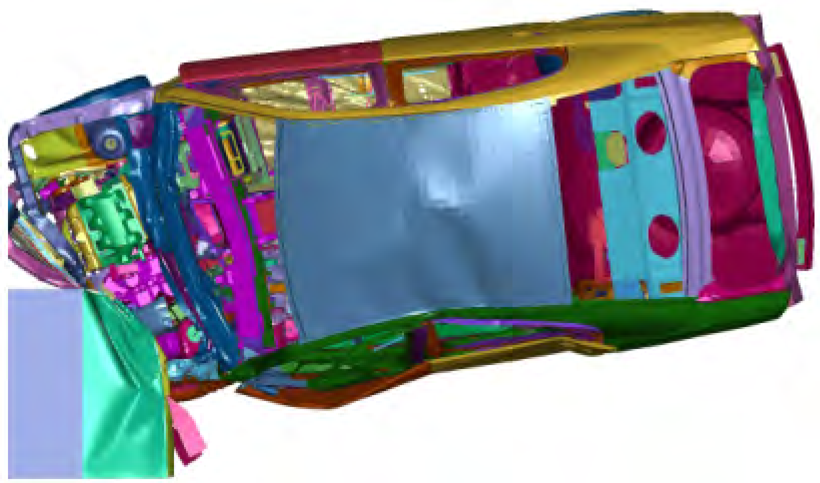


Figure 12.25: *IIHS front 40% offset crash procedure*

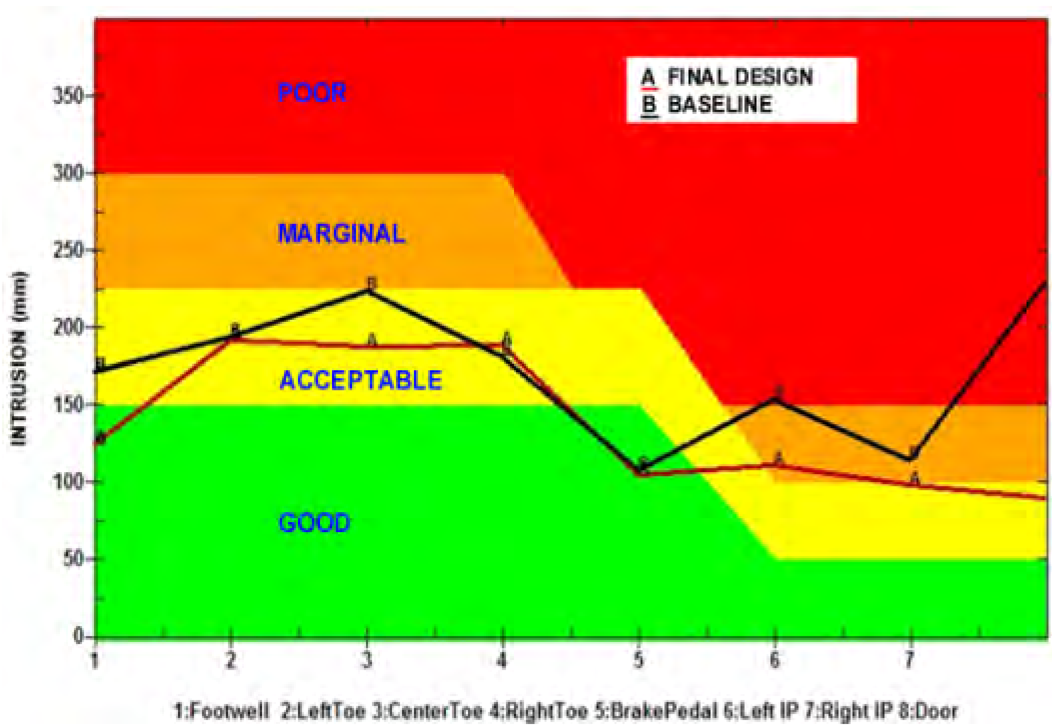


Figure 12.26: *IIHS front impact 40% offset crash results- donor vehicle & final design*

12.6.3 Static Stiffness

Following were values attained from CAE analysis results (shown in Figure 12.27).

- Torsion: 17,094 $\frac{\text{Nm}}{\text{deg}}$ (Baseline: 17,788 $\frac{\text{Nm}}{\text{deg}}$)
- Bending: 11,870 $\frac{\text{N}}{\text{mm}}$ (Baseline: 12,122 $\frac{\text{N}}{\text{mm}}$)

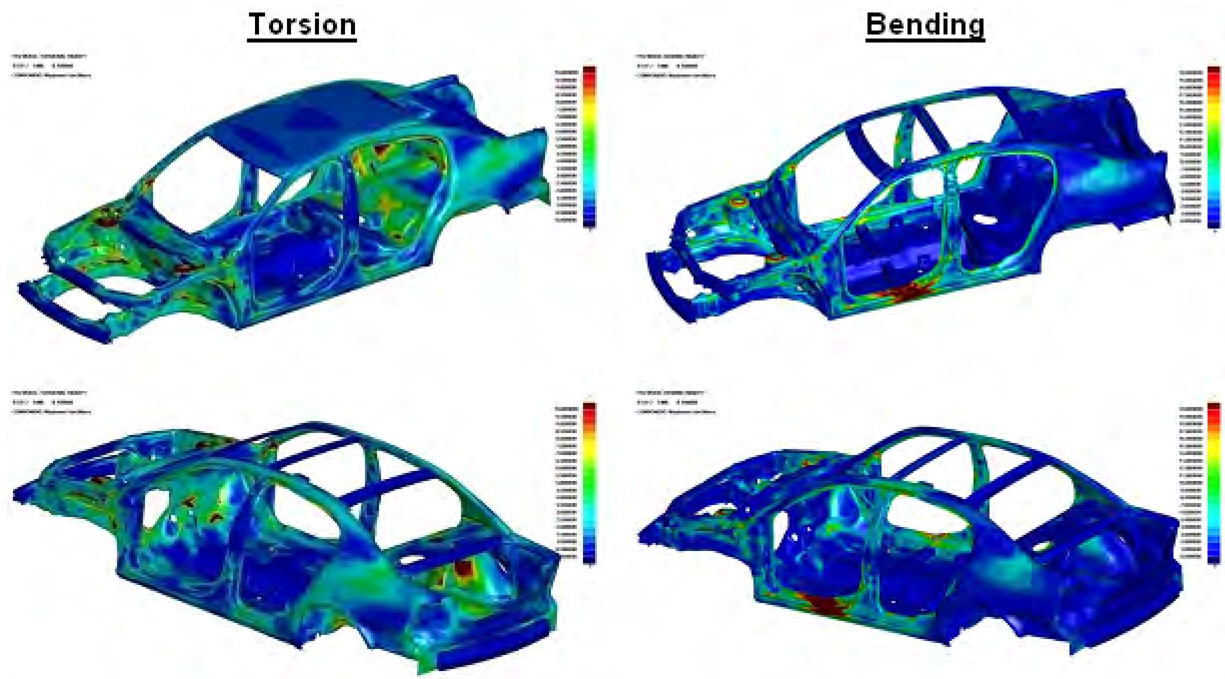


Figure 12.27: *Static stiffness*

12.7 Conclusion

The proposed design optimization method (Topology and 3G) proved to be effective for the FSV pilot project. The final FSV optimized front rail design realized a mass savings of 27% and 45%, as compared to the LWFE-LWB (A/SP optimized design) and the donor vehicle front rail, respectively (as shown in Figure 12.28).

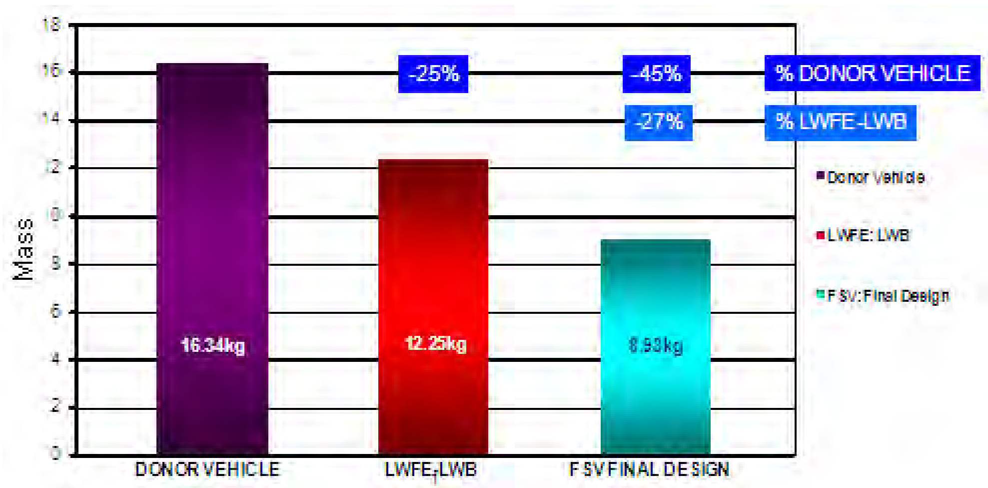


Figure 12.28: *Front rail: donor vehicle, LWFE & LSV pilot project comparison*

12.8 Manufacturability

The optimization did not consider any manufacturability constraints. The only objective of the optimization was to identify what the structure sought, free from any additional considerations.

The circumferential variation along the length of the rail is shown in Figure 12.29 and the corresponding dimensions are listed in Table 12.6.

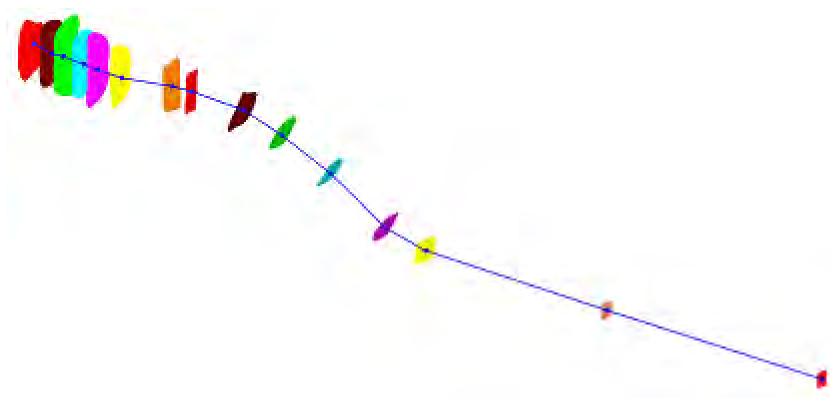


Figure 12.29: *Final design - cross-sectional variation along rail*

CROSS-SECTION	PERIMETER [mm]	PERIMETER [% Change]	SECTION-DISTANCE [mm]
1	483.5	-	
2	522.5	8%	61
3	612.3	17%	58
4	514.7	-16%	60
5	550.8	7%	47
6	471.2	-14%	76
7	429.2	-9%	165
8	347.1	-19%	65
9	382.4	10%	159
10	325.4	-15%	138
11	290.4	-11%	172
12	304.5	5%	212
13	269.1	-12%	134
14	173.6	-35%	603
15	158	-9%	720

* % change in perimeter from previous cross-section

* * Distance between section centroids

Table 12.6: *Final design - cross-sectional variation along rail*

Based upon the analysis shown in Table 12.6 a hydro-formed tube was considered as a potentially viable concept.

Figure 12.30 shows the equivalent tube diameters corresponding to the cross-sectional changes along the length of the final design. Using these equivalent diameters, the circumferential strain was calculated along the length of the hydro-formed tube as shown in Figure 12.31.

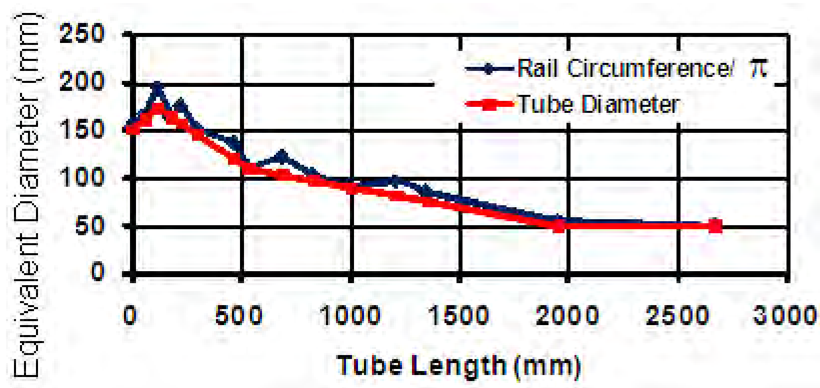


Figure 12.30: *Final design hydroformed tube concept - equivalent diameters*

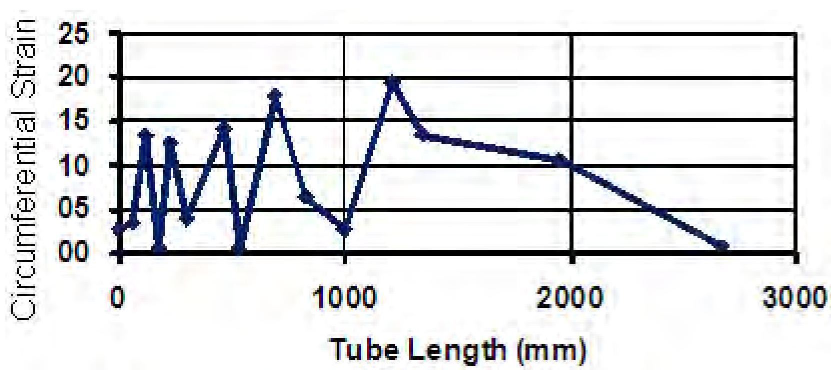


Figure 12.31: *Final design hydroformed tube concept - circumferential strain*

Substituting TRIP450/780 for DP500/800 and TRIP650/980 for DP700/1000, Figure 12.32 shows a potential hydro-formed tube concept based on the results of this optimization. This is only a potential concept and it is recognized that there could be design modifications necessary based on manufacturing feasibility and costs.

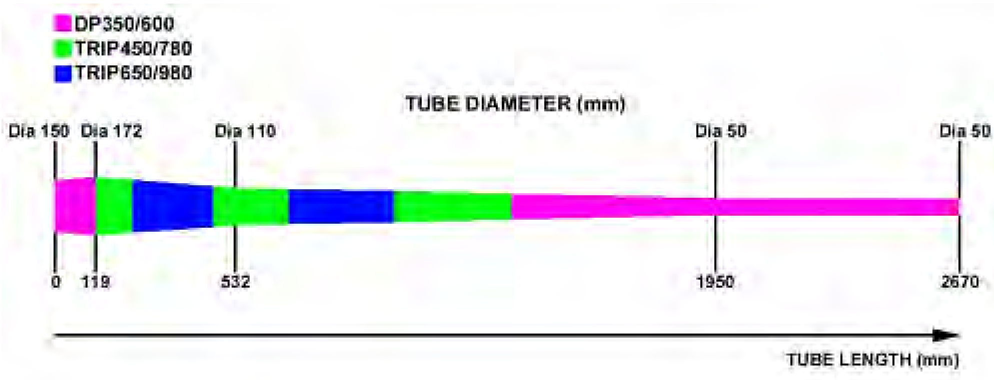


Figure 12.32: *Final design hydroformed tube concept - geometry & material*

The approach for the FSV program will be similar to that of the FSV front rail. However, appropriate manufacturing constraints will be applied to the optimization process accordingly.

12.9 3G Optimization Process

The 3G optimization used the HEEDS search algorithm to conduct an efficient search for optimized designs, in a fraction of the time it would take to perform a few manual design iterations.

12.9.1 HEEDS Search Algorithm

The key characteristics of the HEEDS search algorithm are the following:

- Hybrid
  - Blend of 'methods' used simultaneously, not sequentially
  - Multiple optimization methodologies used; evolutionary methods, simulated annealing, response surface methods, gradient methods & more
  - Takes advantage of best attributes of each approach
  - Global & local search performed together
- Adaptive
  - Each 'method' adapts itself to the design space
  - Master controller determines the contribution of each 'method' to the search process
  - Efficiently learns about design space & effectively searches even very complicated spaces
- Both single and multi-objective capabilities

12.9.2 How HEEDS Works

The basic steps of the HEEDS algorithm are shown in Figure 12.33. At the beginning of an optimization study, HEEDS creates an initial set of randomly generated designs. HEEDS evaluate the performances of the designs, either sequentially or in parallel. As the assessments are completed, HEEDS post-processes each design's performance to determine its constraint and objective function values. Aimed with the results of each design's performance and its search history to date, HEEDS uses an adaptive strategy that combines aspects of multiple search techniques to create a new set of designs for evaluation.

Figure 12.34 shows the Hybrid Adaptive Search strategy used by HEEDS. This intelligent search process is then repeated over a number of cycles while searching for the optimal design. The number of designs required to find the optimal depends on the total number of design variables considered and on the nature of the response, whether it is smooth, noisy, multi-modal, discontinuous, etc.

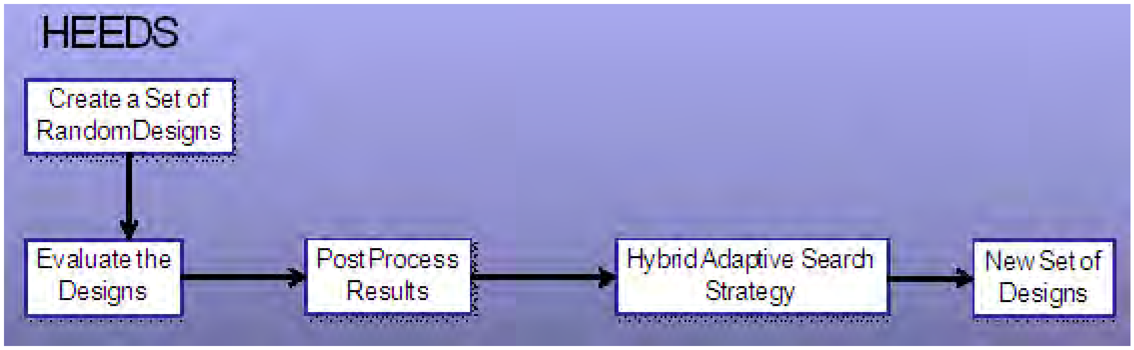


Figure 12.33: *HEEDS Algorithm - basic loop*

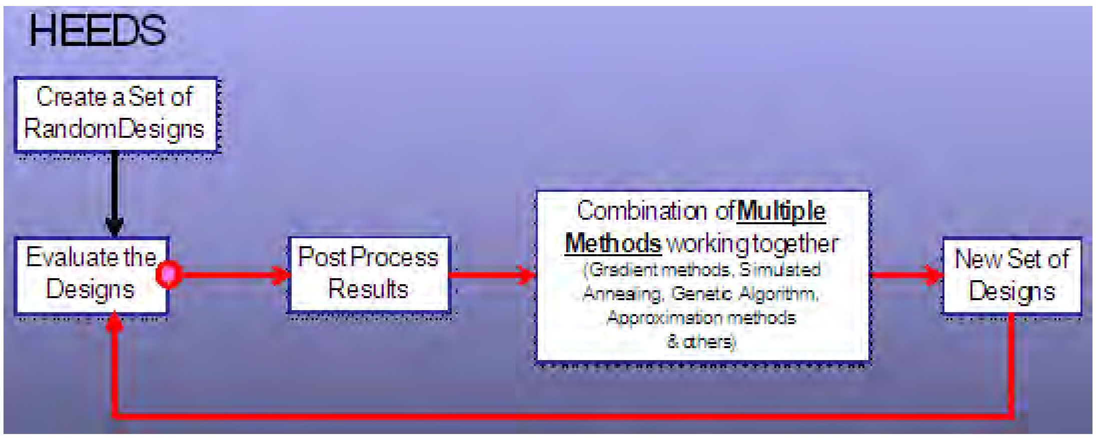


Figure 12.34: *Hybrid Adaptive Search Strategy*

As a general rule of thumb, previous experience can be used to identify the approximate minimum number of design evaluations required. Such an approximation is shown in Figure 12.35.

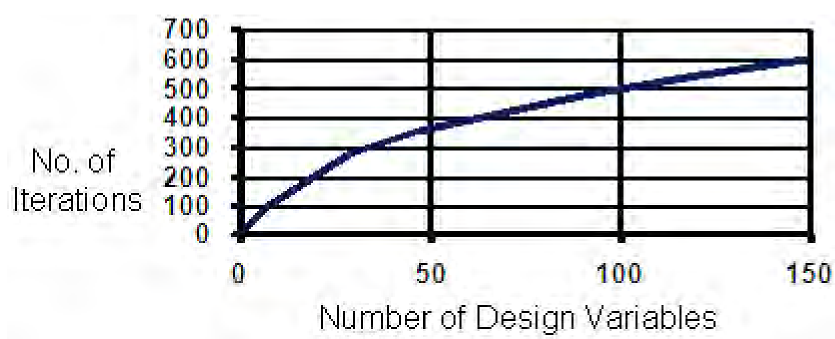


Figure 12.35: *Estimate for recommended number of design iterations*

The minimum number of design evaluations is also dependent on the amount of time available for the optimization. HEEDS will tune its search in order to find the best design within the number of evaluations allowed. However, if the number of iterations considered is much smaller than the recommended minimum, it could result in a sub-optimal solution.

Once the number of design evaluations has been estimated, the likely amount of time required for the optimization can be predicted, as shown in Table 12.7. This will depend upon the time required to perform each evaluation, which itself will depend on the number of load cases considered and runtime for each evaluation. If there are five load cases to be considered, this may require five individual analysis to be performed for each evaluation.

$$\text{Total Time} = \frac{\text{(No of Evaluations) x (Time for each Evaluation)}}{\text{(No of Evaluations run in Parallel)}}$$

Example:						
One Design Iteration Time	=	2 Days	Total Number of Iterations	=	200	
In Series			In Parallel (10 Machines)			
Total Time	=	400 Days	Total Time	=	40	Days

Table 12.7: *Time calculation*

There are three ways that the optimization runtime can be reduced. The first is to reduce the number of design evaluations required. This will depend on the efficiency of the search methodology. In multiple benchmark studies, HEEDS has been shown to be one of the most efficient search methods available over a broad class of optimization problems. The second is to execute multiple design evaluations simultaneously, in parallel. The third way is to reduce the runtime of each individual analysis. This can be achieved by simplifying the model, running the analysis in parallel on multiple CPUs and by running the analysis for the shortest possible duration, for example to peak displacement at 100 ms rather than final spring back at 300 ms.

Once started, when is it appropriate to stop the optimization? Obviously, the theoretical goal would be to find the global optimal solution. However, without prior knowledge this is impossible. The practice goal is thus the best possible solution, which may be the global best, within the available time. There are numerous convergence criteria available to detect optimization stagnation within HEEDS but probably the best method is interrogation of the optimization results by the user themselves.

As an example of HEEDS search efficiency consider the following example;

- 50 design variables
- Each variable has 10 possible choices (a relatively small number)
- Total number of possible designs = 1050
- Odds of finding the optimal solution by luck: 1 in 1050
- Odds of winning the Mega Millions Lottery: 1 in 1.758
- HEEDS can usually find an optimal or near optimal solution within 100–500 iterations, depending on the problem

12.9.3 3G Optimization Applied to FSV Pilot Project

12.9.3.1 Optimization Response

Figure 12.36 shows the mass response during the optimization. Each individual evaluation is shown as a blue point. The current best design is shown in the red "staircase" line. Blue points below this line are not feasible designs. Note, this may also be true for some of the blue points above this line too. As the number of evaluations increase, the bandwidth of the mass variation decreases, approaching a practical optimal design at about 700 designs.

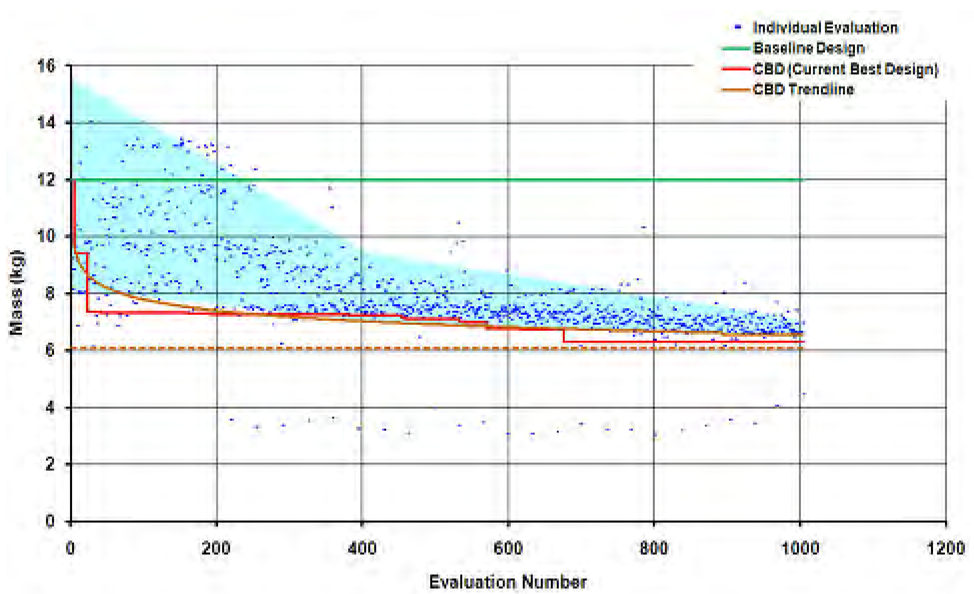


Figure 12.36: *Mass during optimization*

Figure 12.37 and Figure 12.38 show the variation in material and gauge choice for the current best design during the optimization. In most cases the optimization has identified the best material and gauge choice for each section early in the process.

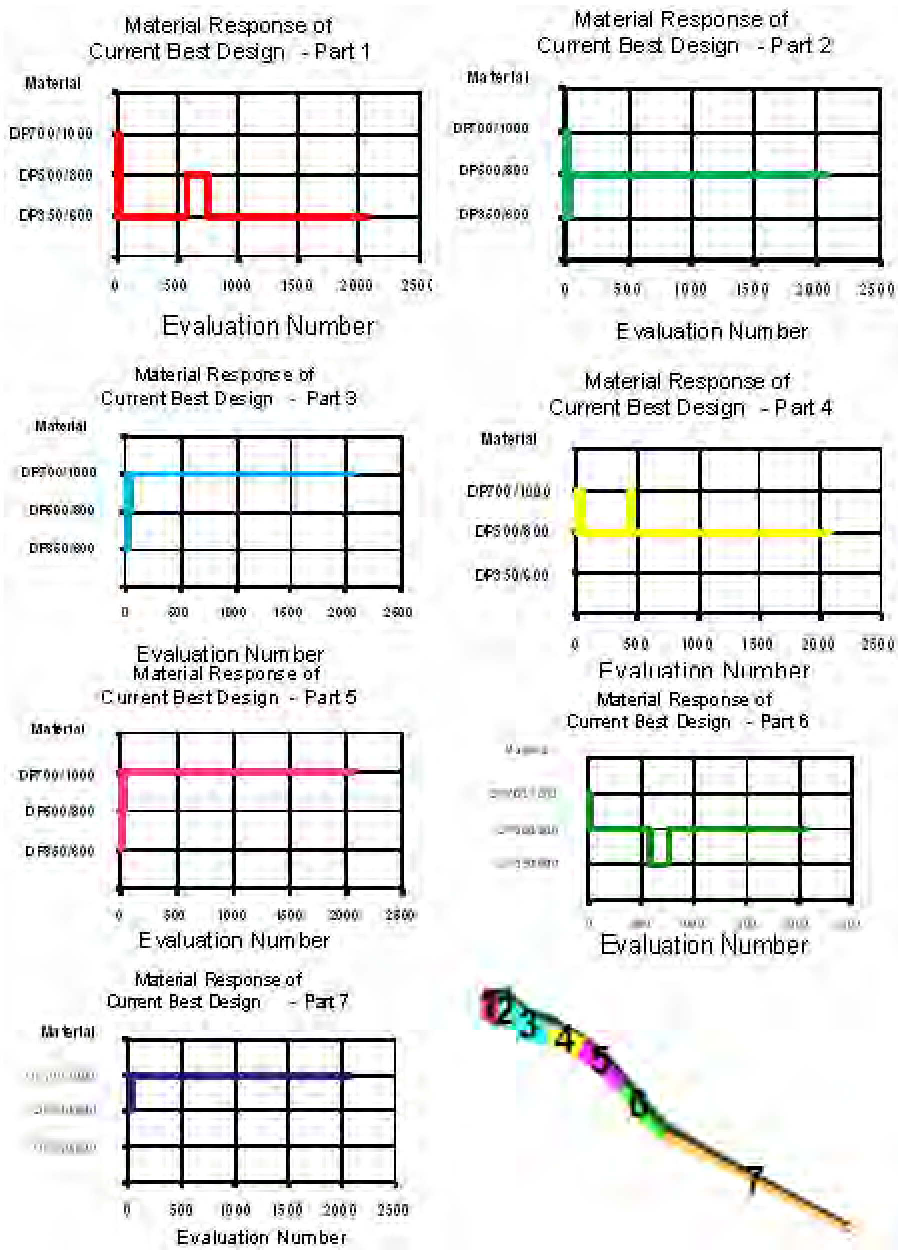


Figure 12.37: *Plot of performance - 143 feasible designs within 10% mass of optimal, material choices*

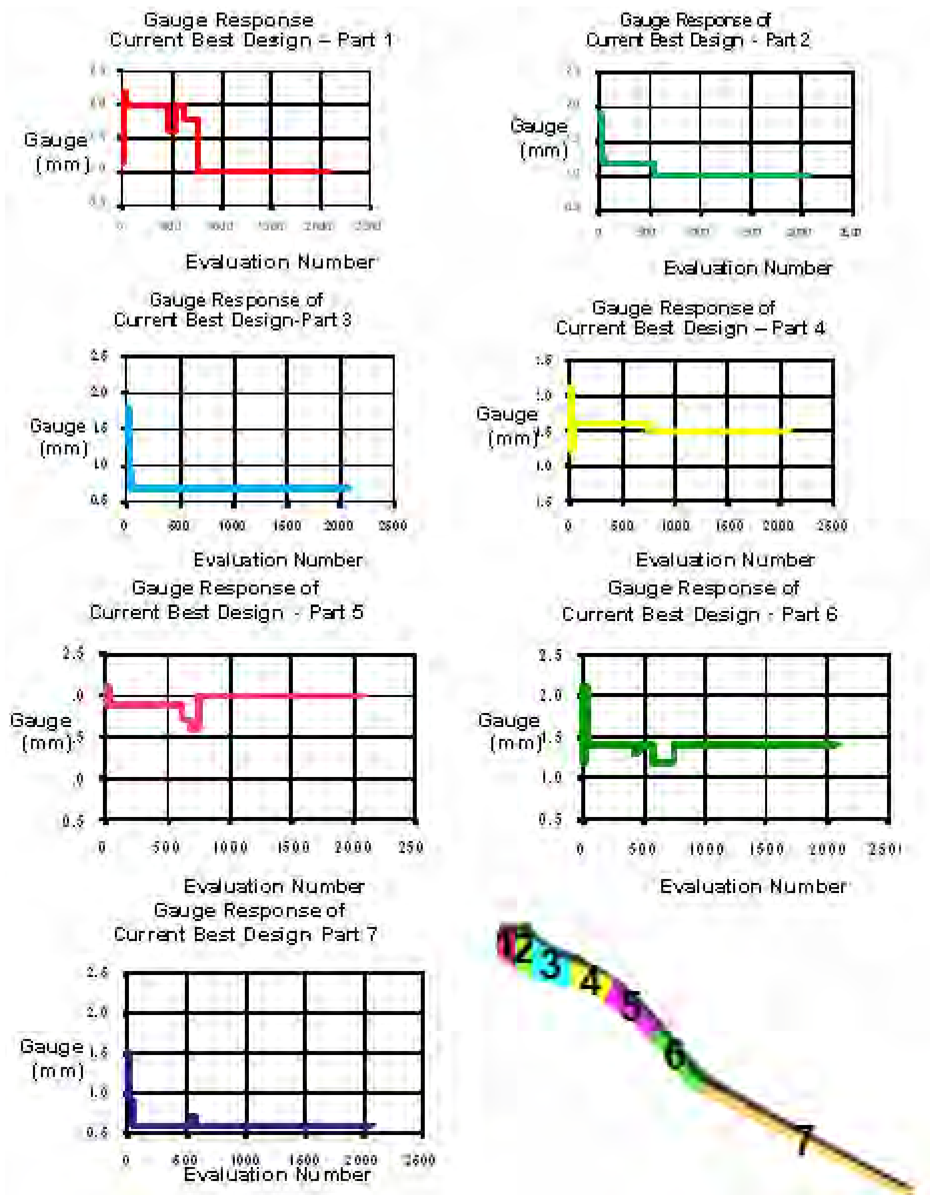


Figure 12.38: *Plot of performance - 143 feasible designs within 10% mass of optimal, gauge choices*

12.9.3.2 Feasible Designs

In total 2079 individual designs were evaluated, of which 968 were considered feasible. A feasible design is one that achieved section forces of less than 35 kN. Figure 12.39 illustrates the range of performance and material and gauge choices for all feasible designs (Note the variation in mass for these designs).

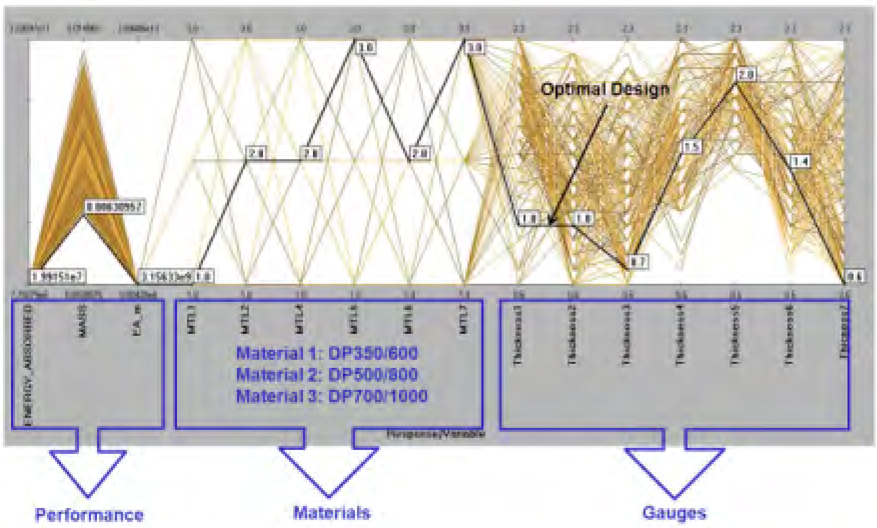


Figure 12.39: *Performance, material & gauge choice for all 968 feasible designs*

Figure 12.40 shows the same data but for the 143 feasible designs within 10% mass of the optimal. Note the significantly smaller range of choices.

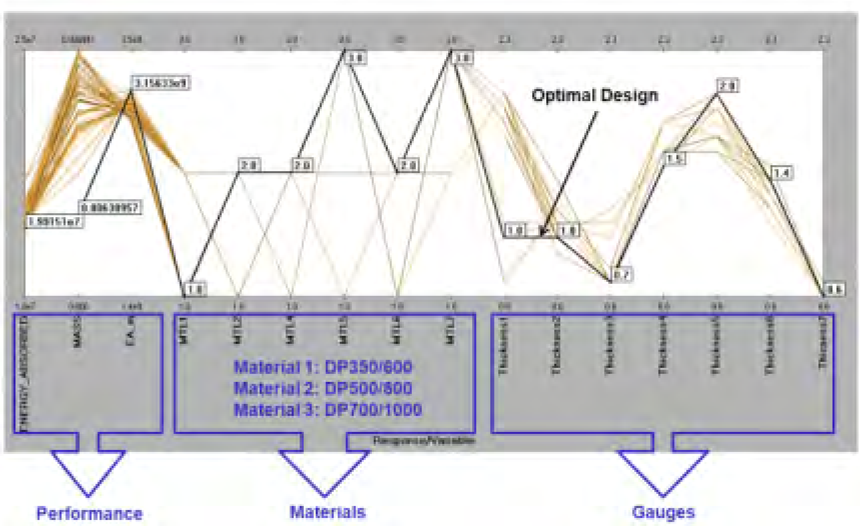


Figure 12.40: *Performance, material & gauge choice for 143 feasible designs within 10% mass of optimal*

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