The **ACP Process™** Applied to the **FutureSteelVehicle** Project: The Future of Product Design and Development

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ABSTRACT

WorldAutoSteel launched Phase 2 of its FutureSteelVehicle programme (FSV) with the aim to help automakers optimise steel body structures for electrified vehicles. The Phase 2 objective is to develop detailed design concepts and fully optimise a radically different body structure for a compact Battery Electric Vehicle (BEV) in production in the 2015-2020 timeframe. This paper will provide an overview of the product design methodology and how it was applied to WorldAutoSteel FutureSteelVehicle (FSV) program and result in 35% BIW mass reduction and how it has continued to evolve with each application.

The Accelerated Concept to Product (ACP) Process™ was applied in this project. The ACP Process™ is a proprietary, performance-driven, holistic product design development method, which is based on design optimization. ACP incorporates the use of multiple CAE tools in a systematic process to generate the optimal design solution. The ACP Process™ is a methodology that provides solutions, which address the challenges facing the modern product development environment. It achieves this by synchronizing the individual facets of the product development process, resulting in an overall reduction in development costs and time to market. Material selection and utilization, product performance requirements and manufacturing and assembly processes are all considered as early as possible in the design cycle. The resulting design offers a robust and highly efficient solution; which when combined with the strength and design flexibility of Advanced High Strength Steel (AHSS) or other materials; facilitates significant mass reduction for the final design.

For the development of a vehicle structure, the methodology offers four key benefits, including a demonstrated capability to reduce product development costs by 40%, reduce product mass by 25% and more, improve product performance (stiffness, durability, NVH, crash/safety, durability) as well as improve fuel efficiency based on the mass reduction results.

The paper will further disclose the results of the FSV programme, detailing steel body structure concepts for the aforementioned vehicles that meet aggressive mass targets of 190 kg, while meeting 2015-2020 crash performance objectives as well as total life cycle Greenhouse Gas emissions targets. FSV's steel portfolio, including over 20 different AHSS grades representing materials expected to be commercially available in the 2015 – 2020 technology horizon, is utilised during the material selection process with the aid of full vehicle analysis to determine material grade and thickness optimisation. Achievement of such aggressive weight reduction with steel will set a new standard for vehicle design approaches for the future.

Radically different powertrains, such as the BEV and the PHEV proposed for FutureSteelVehicle, and their related systems make new demands for increasingly efficient body components to handle the new loads. This will require innovative use of AHSS grades and steel technologies to develop structures that are stronger, leaner, greener and affordable. The presentation will explain the "state of the future" design optimisation process used and feature the aggressive steel concepts for structural subsystems incorporated into the FSV structure.

INTRODUCTION

The automotive industry is facing numerous challenges today. The product design and development process includes multi-dimensional issues, which often contradict each other. A central challenge is the need for cost reduction to compete in the global market, while continuing to meet all new and existing requirements for quality and performance.

The cost reduction objective is challenged by a few factors, including aggressive fuel economy and emissions standards. Other factors include new crash safety requirements, increasing customer demands and expectations for quality and performance and the availability of new energy sources such as electric/hybrid vehicles, plug-in technologies and fuel cells.

While today's criteria for a vehicle's environmental performance stresses fuel economy and tailpipe emissions, a more comprehensive approach is required to address the vehicle's total carbon footprint. This is accomplished with a Carbon Dioxide Life Cycle Assessment (CO_2 LCA) approach that measures the carbon dioxide emissions associated with all phases of a vehicle's life.

The key benefits of ACP Process™ are shown in Figure 1.

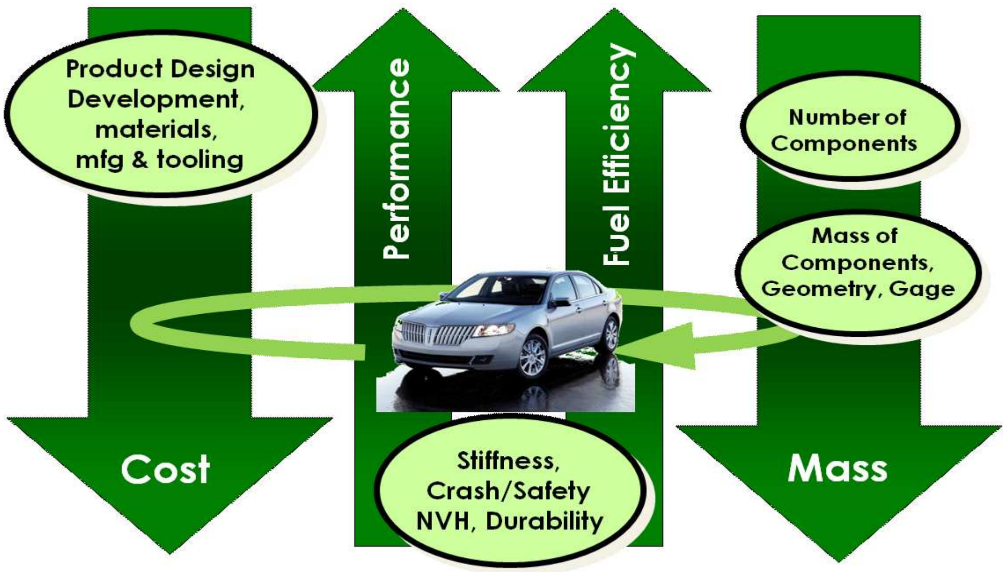


Figure 1: ACP Process™ Benefits

These requirements indicate that new approaches are necessary. Over the past 10 years, new technologies and techniques have been developed and implemented within industry research projects. The development and availability of some key enablers have also emerged, leading to a new design optimization based technique referred to as the Accelerated Concept to Product (ACP) Process. ACP views vehicle development in a completely *holistic* way. An approach such as this ultimately reduces the number of prototypes and tests, thereby reducing overall development costs.

THE ACP PROCESS™

In order to most effectively explore the design space (design volume, material and manufacturing process), while trying to reduce design cycle times, engineers are now using an automated design multidiscipline optimization-based process, called the Accelerated Concept to Product (ACP) Process. This process can help them to evaluate hundreds of design concepts, finding a set of acceptable design solutions that also contain the optimal or near-optimal design solution.

ACP is a holistic design process that investigates the entire design space available to define the most robust design solution. The tools within ACP can greatly decrease the time required to identify a set of feasible, or even near-optimal, designs prior to building and testing the first prototype. Moreover, ACP can also compensate for the limitations of human intuition and provide design engineers with the freedom and power to seek creative solutions that are not obvious to even the most experienced engineers.

KEY ENABLERS

OEM's and software companies have developed many virtual tools to reduce cost in the product design and development process. Such virtual approaches primarily use Computer Aided Engineering (CAE) methodologies, mostly based on the Finite Element Method (FEM). All these virtual tools or environments try to connect Design, CAE and Manufacturing while reducing cost. The ACP Process™ uses several software tools such as an optimization code, CAD parameterization, Modeling/morphing, FEM solvers (static and crash), pre/post processors and formability/stamping solutions.

The availability of new, fast and low-cost hardware such as the High Performance Cluster (HPC) System is another key ingredient for this type of approach to cost reduction.

Another key focus is on the availability of new and advanced manufacturing processes. It can be thought of as the road map to achieving more affordable, safer, lighter weight and environmentally friendly vehicle (Figure 2).

Additionally, new advanced materials offer solutions for cost reduction, while addressing mass reduction and the need to meet the latest fuel economy and emissions, such as CAFÉ standards. Aluminum, composite materials and even magnesium are being aggressively investigated for mass reduction with multi-material solutions, challenging the steel industry to enable additional mass reduction capability with steel for the vehicle body-in-white (BIW) and closures. This is the new direction in the automotive industry and the FutureSteelVehicle program was initiated by WorldAutoSteel to respond to this challenge.

Product development challenges of this magnitude require a new process that incorporates all of these enablers implemented at the initial stage of product design and development. Combining these key enablers with the ACP Process™ has proven that the mass can be reduced by at least 15-20%. This paper will describe the ACP Process™ and illustrate how it has been successfully applied to the product design and development of two research projects: The Future Generation Passenger Compartment (FGPC) and Future Steel Vehicle (FSV).

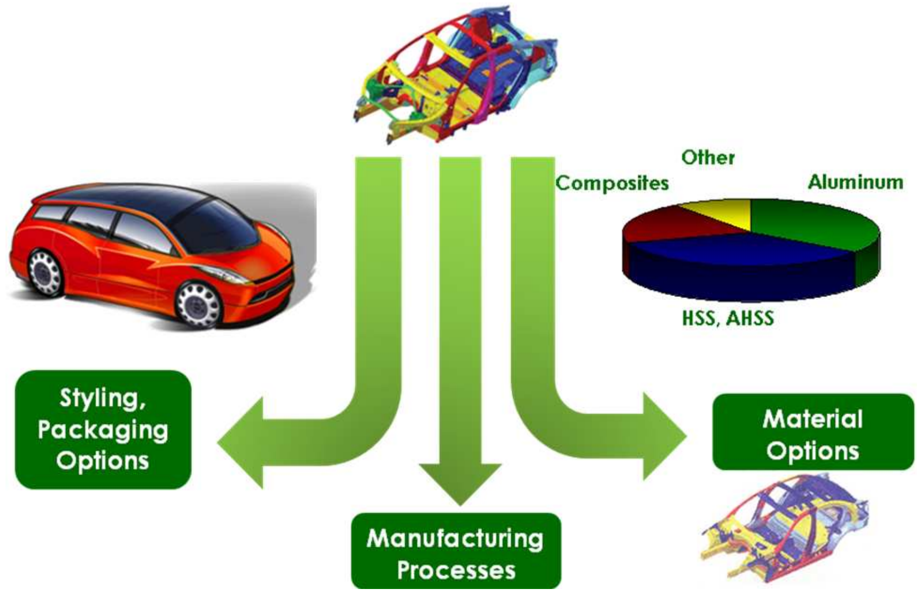


Figure 2: ACP Enablers

ACP PROCESS™ METHODOLOGY
The ACP Process™ is a holistic product development process with multi-disciplinary loading based on topology optimization and geometry, grade and gauge (3G) optimization. Using multiple CAE tools; including modeling tools, application-specific tools, solver technology and optimization solutions; CAE, design and manufacturing are all synchronized. Once an optimal concept is identified, the ACP Process™ further generates the design, analyzes it and optimizes it using loading, manufacturing, material and cost constraints. It then outputs Computer Aided Design (CAD) data of an optimized concept design, suitable for detailed design and manufacturing. Figure 3 illustrates the difference between the conventional and ACP Process™ approaches to product development.

Figure 3: Current Product Development & ACP Process™ Comparison

The process can be applied to product development in two ways:

1. Clean Sheet Product Design
First, ACP can be applied for a ***clean sheet design*** (development of a brand new product). For this type of product development, engineers start from A-class surface and occupant space. The WorldAutoSteel FSV project applied the enhanced optimization approach conducted for the pilot project to a full vehicle body structure while addressing metal forming and assembly capability. FSV addressed electrified vehicle powertrains, consider a technology horizon of 2020 and set a mass reduction target of 35 percent. This aggressive mass target will be achieved by leveraging the advanced steel grades, advanced steel manufacturing technologies and advanced design optimization using ETA's ACP Process™ steps 1-4 (Figure 4).

2. Product Design Refinement
ACP can be applied for ***existing product refinement***. In this case, engineers start with a current product design, which they intend to update, typically improving the design's performance, mass and cost reduction, while at the same time maintaining the packaging, manufacturing and styling. This is not a clean sheet design and so Step 1 is not required. Step 2 represents the modification of the current design to identify any new load paths and where appropriate refine the existing ones. However, since this is primarily a refinement of an existing design, Step 3 is not required and thus the ACP Process™ can jump directly Step 4, a detailed 2G definition of the vehicle's geometry. Step 5 is the final validation and sensitivity study of the optimized design.

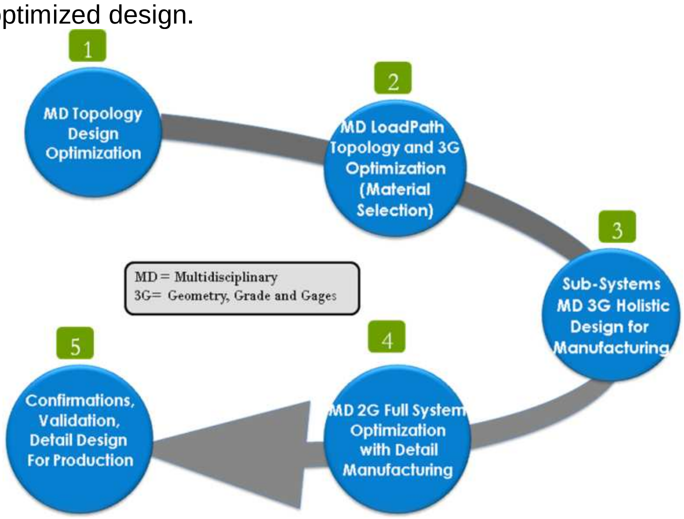


Figure 4: ACP Process™ Overview

<u>1. Multi-Disciplinary (MD) Topology Optimization for the Vehicle Skeleton</u>

The first stage of the process is to develop and define styling, occupant and packaging requirements. Remaining factors and requirements are then formed around these definitions.

During topology optimization, the goal is to define the BIW of the vehicle. The BIW structure is formed based on where material is required in the design to withstand the major vehicle loads, such as body stiffness and crash loads.

The ACP Process™ uses topology software and performs multidisciplinary load representations for all major loads that define vehicle architectures (crash and static):

1. Front NCAP
2. Front 40% Offset Deformable Barrier (ODB)
3. Side Impact (IIHS, FMVSS 214)
4. FMVSS NPRM 214 - Pole Impact
5. FMVSS 301 (Flat barrier, ODB)
6. Torsion & Bending Stiffness

These load cases generate the skeleton of the vehicle. The initial material concentration throughout the vehicle design can identify where potential load paths could exist and is evaluated under multiple loading conditions [16]. Figure 5 shows a summary of the eight loadcases applied and in the frame the final optimized structure for a 30% mass fraction. The percentage mass fraction is defined before the optimization is started and in this case represents the structure remaining after 70% of the original design volume had been removed. Typically, the topology optimization is run for a variety of decreasingly smaller mass fractions so that the relative importance of the emerging load paths can be ranked against each other.

The load paths that are found in the vehicle material are then converted into structures. The size and location of the sections around the material is then defined. Next, the structures are developed using the required Geometry, Grade and Gauge (3G) [4,10].

Figure 5: ACP Process™ MD Topology Optimization for the Vehicle Skeleton (FSV)

2. MD Load path Optimization and 3G Design Optimization

The goal of the ACP Process™ is to identify the optimal design solution within the available design space. At the heart of this process is 3G optimization method [1].

The process determines the optimal design solution while under multi-disciplinary loading conditions. In parallel, load paths, Geometry, Grade and Gauge (3G) are defined based on all of the possible material available. The extent of the design space is defined by three criteria, whose relationship is illustrated in Figure 6[5].

- **Design Variables -** The combinations of design variables that the ACP Process™ can evaluate
  a. **Loadpath -** The position of any given structural member
  b. **Geometry -** The cross-sectional shape of that structure member
  c. **Grade -** The choice of material that the structural member is made of
  d. **Gauge -** The thickness of material that the structural member is made of

It is imperative to use engineering expertise in order to define the design variables and their corresponding space. One needs to completely understand the effects of applied loads in the system and think of possible solutions. The ACP Process™ does not invent rather is consider solutions within the defined design space, therefore it is strictly dependent on the input that the product design development team provides (design space and design variables). A Feasible Design is one which meets the required performance of the Design Constraints. It is from these feasible designs that the optimal, that is the one that best meets the Design Objective, will emerge.

- **Design Constraints**

Design constraints define the required performance that the design must meet. For example, under multidisciplinary loading, a design might be required to simultaneously meet a maximum acceleration pulse for the NCAP Front Impact loading, while maintaining a maximum passenger compartment intrusion under IIHS Front Impact loading. This is a design requirement that places the design responses in direct conflict with each other. This fact illustrates one of ACP's key strengths which is the ability of the process to provide a truly *balanced*, or optimal, design solution.

- **Design Objective**

The design objective is the overall goal of the optimization. For example, for the BIW of a vehicle the design objective may be the greatest possible structural efficiency, or lightest design solution.

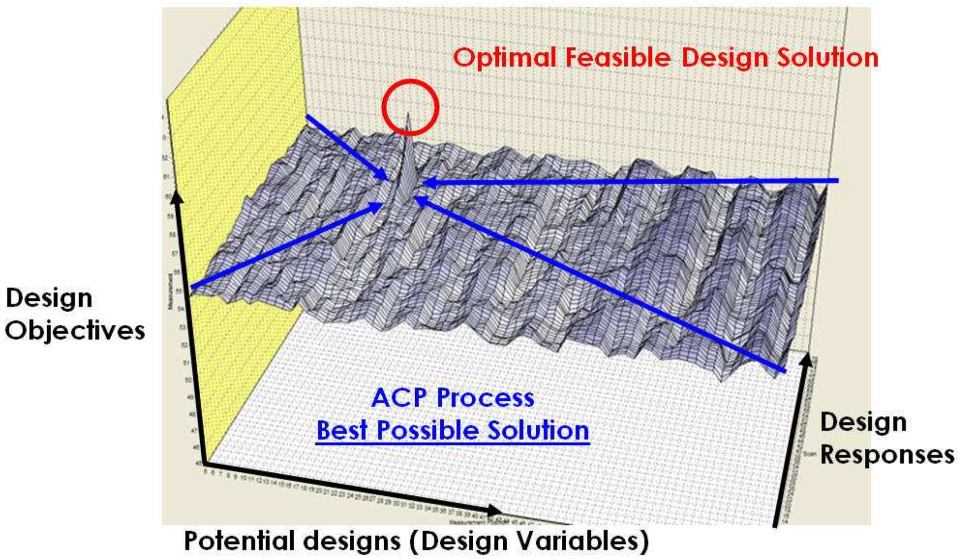


Figure 6: The ACP Design Environment

Figure 6 is a representation of the design environment that the ACP Process™ is working within. The first axis defines all possible combinations of the design variables as individual designs. Depending on the total design variable count this could result in an enormous number of unique designs. The second axis represents the response of each design to the load cases under consideration. Note that from all possible responses there is a subset of feasible designs that meet the required design constraints. This is the control group of the ACP Process™, for it is only the feasible designs that are of interest. The third axis represents how well each design meets the design objective.

When considering the designs generated by the ACP Process™ it is important to consider the following.

- **The ACP Process™ is essentially a *Search Engine***

In itself the ACP Process™ is unable to "invent", rather it searches the predefined available design space for the best possible solution which meets all of the design constraints

➢ **Optimization Enablers**

As noted previously, the ACP Process™ does not “invent”, rather it “balances.” Therefore, when reviewing the specific design variable selections for a given design it is inappropriate to consider them in isolation. For example, the choice of a particular material grade should not be considered without first understanding the choice of cross-sectional shape and gauge of that component and its relationship to all other components within the structure excited by the same loading condition.

➢ **Targets**

The design constraints define the required performance. The ACP Process™ seeks to find the best possible solution with respect to the design objective where it meets the performance goal.

➢ **Performance**

Depending on the freedom that the ACP Process™ is given, the resulting design solutions can be very unconventional. Notably, each design’s performance has been measured against the design constraints and so each can confidently be considered a valid design.

Figure 7 shows ACP’s automated process. The system evaluates hundreds of design solutions automatically. The process starts with an approximated vehicle FE model, of which geometry is parameterized. This initial geometry begins the process and is evaluated, then new design solutions are generated using changes in geometry, grade and gauge (3G optimization). The design team monitors the design changes when these new solutions are found. The process continues until the objectives are met (meeting minimum mass and performance targets). Several design solutions can be found and after further study the best design concept is selected [8,9,10].

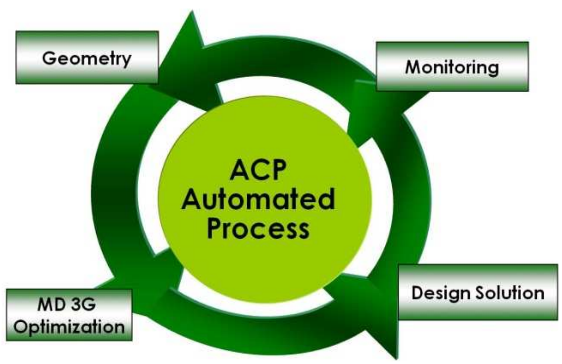


Figure 7: ACP Process™ – A Fully Automated Process

3. Sub-System Multi-Disciplinary (MD) 3G Holistic Optimization and Selection of Major Member Manufacturing Process

After the full-vehicle system load path and general section geometry, grade and gauge is determined by the ACP Process™, manual design modification for high level manufacturability is performed. The full system is ready for detailed design for a selection of manufacturability processes, materials and gauges.

To achieve this, the full-system would be decoupled into major load carrying sub-systems which they define the characteristics of the vehicle such as front rail and rear longitudinal, shotgun, rocker, B-pillar and side roof rail [1]. The ACP Process™ identifies the optimal design solution within the available design space and details design variables based on high fidelity 3G optimization for each of sub-systems [2]. The material of each subsystem with its manufacturing process will be the output for the next step of the ACP Process™ [9,10].

4. Full Vehicle System MD 2G Optimization with Detailed Manufacturing

After the major sub-systems are designed by ACP Process™, the components are modified by manual design manipulation based on selected manufacturing processes. The new vehicle architecture is then integrated into the full-vehicle system based on the ACP selections of materials and manufacturing processes. A full vehicle BIW and closures structure will be designed in detail (joining, interactions, sub-assemblies) using design specifications and manufacturing evaluations to meet vehicle performance targets[3].

This resulting design represents the most robust load path, geometry, gauge and grade of the materials on the vehicle.

Since this model can contain inefficiencies due to modifications based on new material choices and manufacturing processes, multi-disciplinary 2G optimization is performed in this phase. This is done to make sure that the new design (based on sub-systems) still meets all vehicle performance targets in terms of crash, stiffness and low frequency NVH while considering the manufacturing process.

Manufacturability using one step and incremental formability for all the components will be done. Design changes to remove any manufacturing issues (strain, wrinkling, cracking and thinning).

At this stage in the ACP Process™, the expectation is that the designed vehicle system meets all vehicle performance and a 25 - 30% mass reduction, based on vehicle class and mass targets [8].

5. Confirmations, Validation and Detailed Design for Production

During this stage, the engineering team gets confirmation of total design solution, incorporating all load cases of BIW and closures for durability, crash/safety, NVH and ride and handling. A sensitivity study is done and minor design modifications are made. The vehicle model is validated virtually and is prepared for prototyping and testing [8].

ACP PROCESS™ FULL VEHICLE PROGRAM IMPLEMENTATION

ACP has been successfully applied to two major full vehicle steel research programs. The first important segment of the research was regarding vehicle mass reduction. This project was conducted by the Auto/Steel Partnership (A/SP), as part of the Future Generation Passenger Compartment (FGPC) project. The project demonstrated the feasibility of the approach and it effectiveness at achieving significant mass reduction. Also, it demonstrated that this methodology was no longer a "pie-in-the-sky" proposal--it was truly something that automobile manufacturers could employ immediately.

FGPC PROGRAM

In Future Generation Passenger Compartment **(FGPC)** Phase 1, completed in 2007 and funded by A/SP members and the U.S. Department of Energy, the goal was to develop a lightweight passenger compartment using AHSS. The team developed a conceptual optimization methodology, which realized a mass reduction of 30 percent when compared with a typical passenger compartment of the same vehicle class.

The FGPC Phase 1 donor vehicle was the UltraLight Steel Auto Body - Advanced Vehicle Concepts (ULSAB-AVC). The vehicle packaging was adapted for both a conventional diesel and hydrogen fuel cell powertrains. The 30 percent reduction was achieved while maintaining compliance with current and future (2015) crash/safety performance, stiffness and durability regulations. A series of sensitivity studies proved the robustness of the design through its ability to accommodate variations in the vehicle's curb weight and side impact barrier height [4].

In addition to exceeding the original goal by five percent while maintaining the structural parameters for stiffness and durability, the optimized design actually improved the vehicle's crashworthiness.

FGPC-Validation, the second phase of the program, began in 2007 as the research group sought to prove how conceptual ideas developed in Phase 1 could be applied to a production vehicle. Using a 2008 OEM donor production luxury vehicle as the baseline product, the group set out to develop a concept design with the goal of reducing the passenger compartment's structural mass by 20 percent.

The results showed that the mass of the passenger compartment structure could be reduced between 15 and 20 percent with minimal increased costs. This provides a cost effective solution relative to the non-steel material solutions, which would have significantly increased the costs to achieve this type of mass reduction.

The program also proved that advanced joining technology (laser-welding or adhesive bonding) could increase the overall mass reduction to 20 percent. Sensitivity studies established the viability of the load paths and robustness of the optimized design.

Figures 8 and 9 show the results of the FGPC-Validation study. Figure 8 illustrates the baseline vehicle's material content compared to that of the mass optimized concept solution. Using a preponderance of dual phase, martensitic and boron steels rather than the conventional steel used in the baseline donor model is one key factor in the mass reduction.

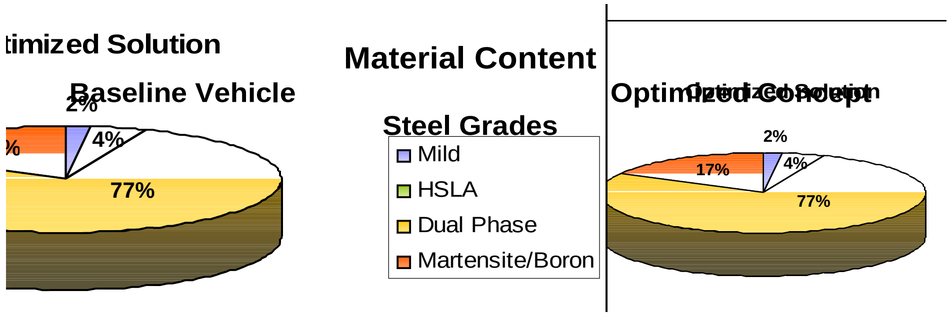


Figure 8: FGPC Material Content

Figure 9 shows the passenger compartment's weight for the baseline model and the two alternative FGPC solutions. The solution that used advanced joining technology (laser-weld or adhesive bonding) was 20 percent lighter than the baseline.

Cost information shown on Figure 9 demonstrates that material costs are lower for the FGPC solution, but forming costs are substantially higher. Total manufacturing costs for the lowest weight solution are predicted to be 5 percent higher than the baseline.

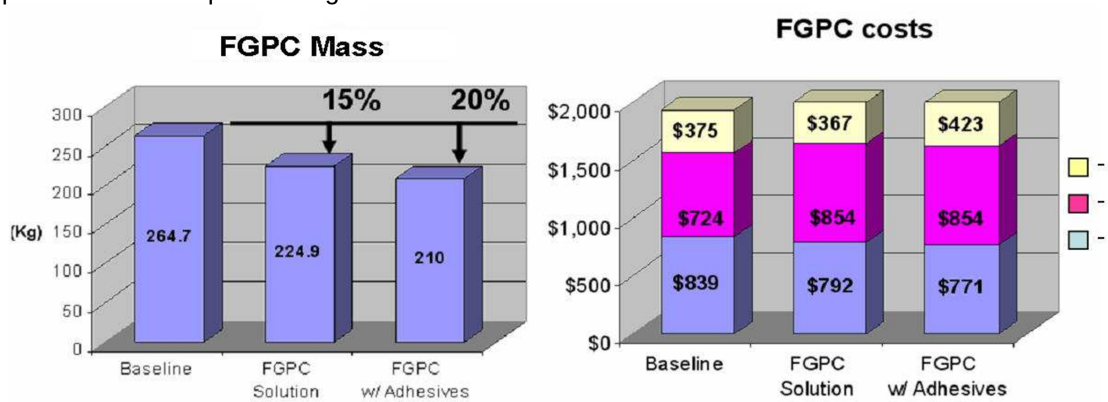


Figure 9: FGPC Mass and Cost Reduction

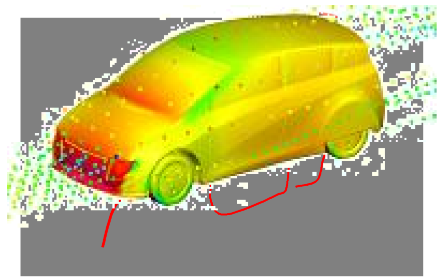
FGPC Validation Phase achieved 15 to 20 percent mass reduction, but could not reach the desired 30 percent level while adhering to the manufacturing, packaging and architectural constraints adopted by the project [5,8].

FSV PROGRAM

The FutureSteelVehicle (FSV) program consists of three phases [16]:

- Phase 1: Engineering Study (2008 - 2009)
- Phase 2: Concept Designs (2009 - 2010)

- Phase 3: Demonstration and Implementation (Beyond 2011)



A. Component & Passenger Packaging Study
C. Styling Study
B. Aerodynamic Study

Figure 10: FSV Packaging and Styling

The content of Phase 1 was a comprehensive assessment and identification of advanced powertrains and future automotive technology applicable to high-volume vehicle production in the 2015-2020 time frame [11]. The FSV program is currently at the end of Phase 2, designing optimized AHSS / UHSS body structures for four vehicles: Battery electric (BEV) and plug-in hybrid electric (PHEV-20) for A/B Class vehicles; and Plug-in hybrid electric (PHEV-40) and fuel cell (FCEV) for C/D class vehicles. This includes the optimization of multiple solutions for seven different sub-systems: the rocker, B-pillar, roof, rear and front rails, front upper load path and battery tunnel load path members. The FSV engineering team recommended the BEV with a range of 250 km as the focus of the Phase 2 detailed design, as this powertrain was considered a more challenging design for steel since it is the heaviest powertrain option (Figure 10).

FSV's Expanded Steel Portfolio

Mild 140/270	DP 350/600	TRIP 600/980
BH 210/340	TRIP 350/600	TWIP 500/980
BH 260/370	SF 570/640	DP 700/1000
BH 280/400	HSLA 550/650	CP 800/1000
IF 260/410	TRIP 400/700	MS 950/1200
IF 300/420	SF 600/780	CP 1000/1200
DP300/500	CP 500/800	DP 1150/1270
FB 330/450	DP 500/800	MS 1150/1400
HSLA 350/450	TRIP 450/800	CP 1050/1470
HSLA 420/500	CP 600/900	HF 1050/1500
FB 450/600	CP 750/900	MS 1250/1500

Denotes grades used for ULSAB-AVC
Denotes steel added in FSV

Figure 11: FSV's Expanded Steel Portfolio

1. Body Structure Mass Targets

The mass target for the proposed A/B Class BEV body structure was 190 kg, which represents a 35% reduction over a baseline vehicle, setting a new goal for vehicle light weighting beyond the ULSAB-AVC program's 25% achievement [12]. To meet the aggressive mass target, the body structure design methodology combines an advanced steel materials portfolio (Figure 11), advanced steel manufacturing technologies and the above described ACP Process™ and is applied to a clean sheet design targeted at the BEV powertrain. The SAE Vehicle Innovation Award-winning design optimization process used to develop structures for FSV has the same energy and resource efficiency objective that mirrors what happens in nature, creating radically different, non-intuitive architectures optimized for the structure's function within the total system [13]. In addition to traditional technology solution selection criteria that consider mass and cost, the FSV program also considers technologies that reduce the total carbon footprint of the vehicle by applying a life cycle assessment (LCA) approach [14].

2. Phase 2 Design Methodology

2.1. Packaging and Computational Fluid Dynamic Simulation

After the Phase 1 technology assessment, studies of powertrain packaging, interior occupant space, ingress/egress requirements, vision/obscuration, luggage volume requirements, and ergonomic and reach studies of interior components established the component and passenger package space requirements. An exterior styling was applied to the packaging, followed by several computational fluid dynamic simulations, resulting in a drag coefficient of C_d = 0.25 (Figure 12).

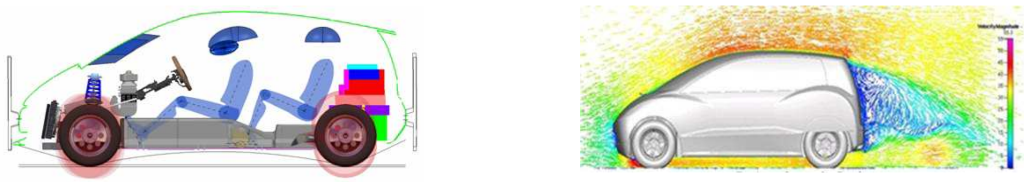


Figure 12: BEV packaging theme and aerodynamic study

2.2. Topology Optimization

As a first step in the ACP Process™, the objective of the topology optimization is to provide an initial structure based on the available structure package space as shown in Figure 13. The FSV program developed this structure by considering three longitudinal load cases, two lateral load cases, one vertical load case, bending and torsional static stiffnesses. The topology optimization eliminates elements from a finite element mesh that represents the available structural design space, i.e. the volume within which structure can exist (Figure 13). The elimination of elements is based on strain energy, thereby revealing the optimal load paths.

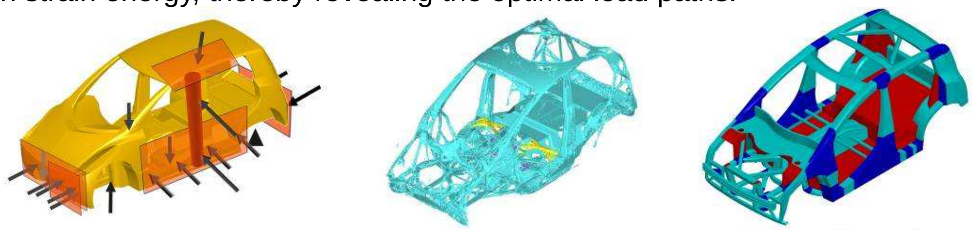


Figure 13: BEV structural design space, topology optimization results and interpreted CAD model

A target reduction or mass fraction is defined as a goal for the optimization. For this analysis, the topology optimization goals were 30%, 20% and 10% mass fractions (Figure 13). With the results obtained from the topology optimization, the geometry is interpreted into a CAD model (Figure 13) using engineering judgment. This model represents the initial skeleton geometry of the FSV and forms the basis of the next step in the optimization process.

2.3. Low Fidelity 3G (Geometry, Grade and Gauge) and Sub-System Optimization

Though the topology optimization was able to provide an initial starting point for the FSV's geometry, it is limited by its static approximation of dynamic crash loads and does not consider grade variations of the sheet metal within the structure. Therefore, the load path optimization is moved to the dynamic design domain (using LS-DYNA® Finite Element Analysis Software) combined with a multi-discipline optimization program (HEEDS® Multidisciplinary Design Optimization Program), which also addresses a low fidelity optimization of the major load path cross-sections, grades and gauges of the body structure. The output is designated the Low Fidelity Geometry, Grade and Gauge (LF3G) optimization.

Figure 14: LF3G optimization, reference body structure and structural sub-systems

The final FSV body structure attained from the LF3G optimization is shown in Figure 14, which does not represent section shapes that can necessarily be manufactured and assembled nor are they structurally efficient from a topography perspective. To create the required reference body structure, the LF3G body structure was combined with engineering judgement of current benchmarked designs (Figure 14). This reference assumes typical manufacturable sections and joint designs combined with extensive use of AHSS achieving a calculated mass for the sheet steel baseline (Figure 14) of 218 kg. Based on load path mapping, seven structural sub-systems (Figure 14) were selected for further optimization using a broad bandwidth of manufacturing technologies.

2.4. 3G Optimization of Sub-Systems

The optimization objective was to minimize the mass of each sub-system and simultaneously maintain the deformation energy in the sub-systems as that in the full LF3G model for each respective load case. The solutions obtained from the structural sub-system multi-discipline 3G optimization runs had appropriate material strengths and gauges, optimized to give a low mass solution, that met the structural performance targets. These solutions were assessed considering the general manufacturing technology guidelines to ensure manufacturability of the sub-system. For example, the rocker sub-system model was optimized with AHSS / UHSS steel technologies for four different manufacturing methods (Figure 15). Each of the 12 manufacturing interpretations for the rocker structure have equivalent in-vehicle performance. The manufacturing interpretations of each of the sub-systems formed the basis for determining the blank size, blank mass, part mass and the other related manufacturing parameters.

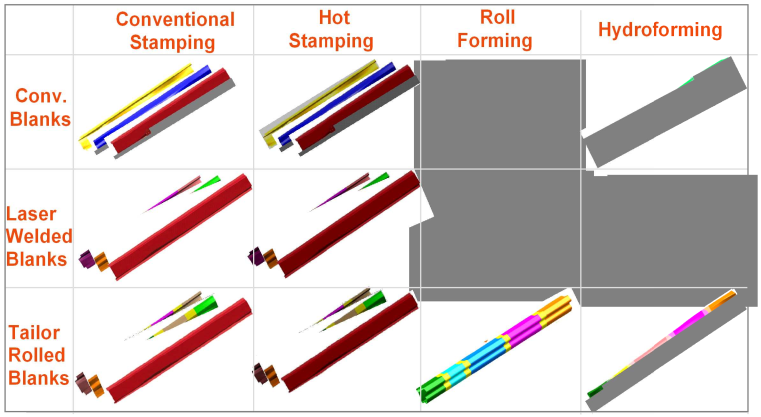


Figure 15: Rocker Solution Alternative Manufacturing Scenarios

2.5 BEV Sub-Systems Selection

Steel's flexibility enabled the achievement of a variety of solutions for the selected sub-systems. Within this portfolio of solutions are applications that all vehicle manufacturers and segments will find relevant. These solutions demonstrate dramatically reduced mass and GHG emissions in seven optimised sub-system structures, at lower or comparable costs to conventional solutions.

The next step in the FSV design process is to select the most appropriate sub-system options from those developed through the design methodology. The programme engineering team made these decisions based on the following factors:

- **Mass**
- **Cost -** A "technical cost modeling" approach was applied to all parts to estimate the subsystem manufacturing costs
- **Life Cycle Assessment (LCA) for GHG** - An analysis of each sub-system's impact on the total LCA of the vehicle conducted with the UCSB GHG Comparison Model.

Beyond these criteria the selection process considered the technology time horizon to be within the 2015-2020 timeframe. It also considered the joining compatibility between the technologies. Hence, the FSV sub-systems recommendations were divided into three categories, based on the level of difficulty of the manufacturing technology, and the time period during which these technologies would be feasible for high-volume production.

3. Body-in-White Design, Assembly & Performance of FSV BEV

Body-in-white	FSV BEV
Benchmark Mass (kg)	290
Target Mass (kg)	190
Achieved Mass (kg)	187.7

Table 1: FSV program achievement

3.1 FSV Battery Electric Vehicle final light-weight body-in-white structure

The Battery Electric Vehicle body-in-white (BIW) structure achieved mass savings of 101 kg (-35%) compared to the baseline body structure mass as shown in Table 1. The mass reduction has been realized through the use of advanced and ultra high-strength steel grades combined with steel technologies such as roll forming and multi-thickness blanks. Even though there is a cost premium associated with the use of higher grade steels, the consequently achieved weight savings balances the overall costs of manufacturing and assembly. The BEV body-in-white structure, the different grades of steel and the steel grade distribution are shown in Figure 16.

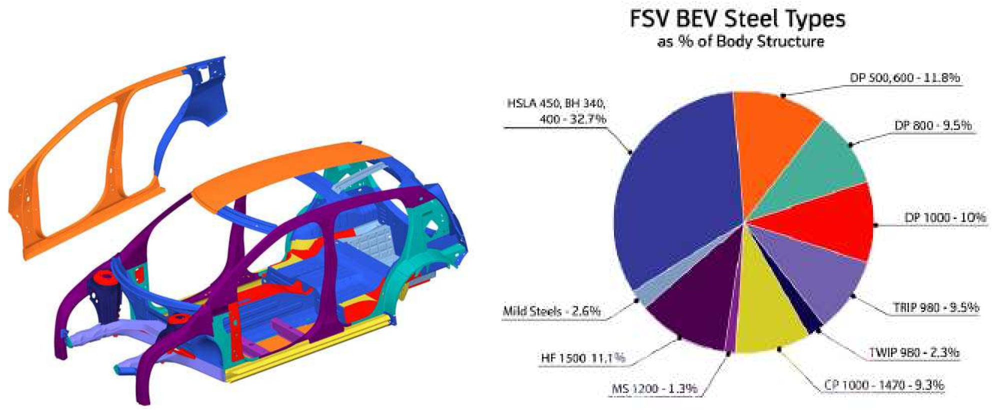


Figure 16: FSV BEV body-in-white steel grades used and distribution

4.2 Forming simulation & joining issues

Figure 17 illustrates the different manufacturing technologies implemented for the FSV body-in-white structure. The main technologies include cold stamping of monolithic and laser welded blanks, hot stamping and roll forming.

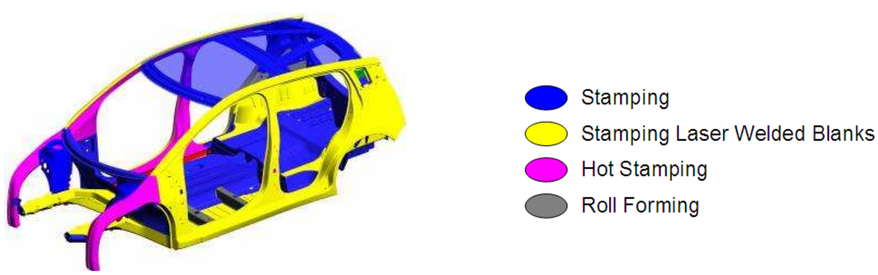


Figure 17: FSV body-in-white manufacturing processes

Single step simulation was done on all the parts of the BIW. Parts that play an important role in crashworthiness like B-pillars, shotguns and roof rails were made through a hot forming process. In that case, a single step simulation with IF260/410 material parameters was used. Some parts, which have complicated shapes like front rails, body side outer and rear rails require the incremental analysis method for predicting the manufacturing results more accurately. In Figure 18, the results of the incremental analysis of the body side outer made with DP600 0.8 mm and BH220 0.6 mm for the rear parts are shown. Although some minor changes are needed, it proves that the stamped component design is safe.

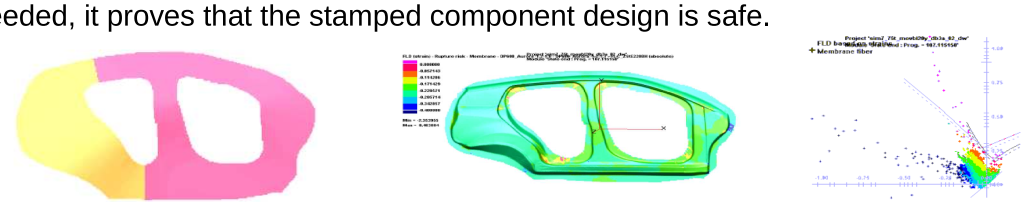


Figure 18: FSV body side outer incremental analysis results

Some of the most common assembly joining techniques were considered. The joining processes selected for the FSV body-in-white assembly were resistance spot welding, laser welding, laser brazing, roller hemming and adhesive bonding. Figure 19 and Table 2 below detail the quantity for each joining technique used:

Spot Welds
Laser Welds
Adhesive

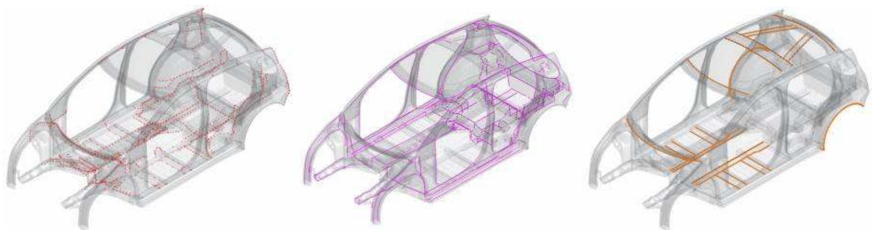


Figure 19: Joining techniques used for FSV BIW assembly

Joining Techniques	Total
Total number of Spot Welds	1001
Total Length of Laser Welds	87.26 m
Total Length of Adhesive	19.11 m

Note:
- Laser Welds includes: Laser Welding (Remote), Laser Brazing
- Adhesive includes: Structural adhesive (1-Part Epoxy), Anti-flutter, Hem adhesive

Table 2: Joining techniques details used for FSV BIW assembly

Specific attention has been paid to the design in order to avoid impossible welding stack-ups such as mild steel 0.6 mm - mild steel 0.6 mm - PHS 2.0 mm.

4.3 Crash worthiness, stiffness and NVH

The detailed design of the FSV body structure was supported by computer aided engineering (CAE) analysis, to verify the structural performance. The CAE analysis results were compared to the FSV targets to quantify the performance of the FSV body structure in terms of static stiffness, crashworthiness and durability. As illustrated in Tables 3 and 4, it can be seen that the FSV body structure meets or surpasses the performance targets.

Analysis Type	Target	FSV Model Results
US NCAP	Peak pulse < 35 g, footwell intrusion < 100 mm	Peak pulse 36.6 g, footwell intrusion 32.3 mm
Euro NCAP	Peak pulse (driver side) <35 g, footwell intrusion < 100 mm	Peak pulse 32.2 g, footwell intrusion 90 mm
FMVSS 301R	Battery should remain protected and should not contact other parts after the crash	Battery is protected and there is no contact with other parts after crash
ECE R32	Battery should remain protected and should not contact other parts after the crash	Battery is protected and there is no contact with other parts after crash
IIHS Side Impact	B-Pillar intrusion with respect to driver seat centerline ≥ 125 mm	136 mm
US SINCAP Side Impact	B-Pillar intrusion with respect to driver seat centerline ≥ 125 mm	215 mm
FMVSS 214 Pole Impact	Door inner intrusion with respect to driver seat centerline ≥ 125 mm	173 mm
Euro NCAP Pole Impact	Door inner intrusion with respect to driver seat centerline ≥ 125 mm	169 mm
FMVSS 216a and IIHS Roof	Driver and passenger side roof structure should sustain load > 28.2 kN within the plate movement of 127 mm (FMVSS 216a), > 37.5 kN (IIHS)	Sustains load = 45 kN for driver side, = 43 kN for passenger side
RCAR/IIHS Low Speed	Damage is limited to the bumper and	There is no damage in components other

Impact	crash box	than the bumper and crashbox

Table 3: FSV CAE analysis results – Crashworthiness

Analysis Type	Target	FSV Model Results
Torsion stiffness (kN-m/deg)	≈ 20.0	19.972
Global Modes	**Target**	**Frequency**
Torsion	>40 Hz (both modes), separated by 3 Hz	54.8
Vertical bending		60.6

Table 4: FSV CAE analysis results - Stiffness

As an example, see Figure 20 for the Insurance Institute for Highway Safety (IIHS) side impact crash test setup and results.

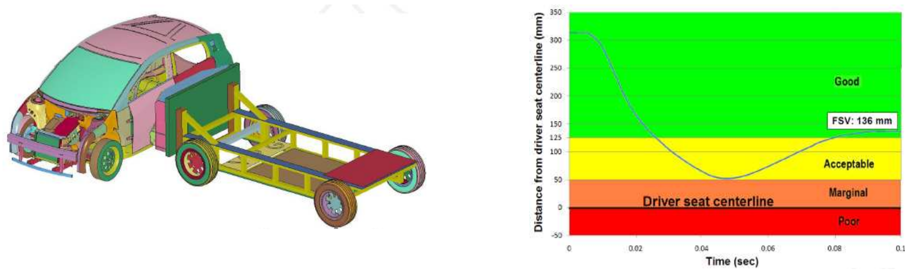


Figure 20: IIHS side impact crash test and B-pillar intrusion

A complete noise and vibration analysis has been performed by LMS for FSV at the concept stage. Measurements were conducted on two small Mitsubishi vehicles that both share the same body, yet one is equipped with an internal combustion engine and the other with an electric motor. The outcome was used as a starting point to identify assets and pitfalls of electric motor noise and draw a set of NVH targets for FSV. Compared to a combustion engine, the electric motor shows significantly lower sound pressure levels, except for an isolated high frequency peak heard at high speeds (3500 Hz when the vehicle drives at top speed) which is lowered by increased use of acoustic absorbent materials in the motor compartment. For low and mid frequencies, moderate electric motor forces imply less stringent noise and vibration design constraints and a possibility to reduce the body mass. Finite element simulations at low and mid frequencies lead to reshaping the suspension mounts, the rear roof, the front header and the cowl top connection area, each change driving large reductions of noise levels while adding little to no mass. Damping sheets prove unnecessary. Lighter damping solutions such as vibration damping steels were examined and proved to be successful in the mid frequency range. Overall, the change from combustion engine to electric motor is compatible with mass reductions and similar or better noise and vibration performances.

CONCLUSION

In conclusion, by applying the ACP Process™ and incorporating the use of unique optimization tools, advanced materials and advanced manufacturing technology, manufacturers can addresses many of the current product development challenges which face the automotive industry today.

- Reduce cost of product design development by 40% in concept and development phase (referenced to the programs ETA has completed for its clients).
- The process has proven to reduce mass by 20% beyond the mass reduction that has previously been achieved with AHSS – at little or no additional cost.
- The ACP Process™ can be used for any product such as vehicle components (closures, chassis/suspensions, interiors and seat).
- Though the ACP Process™ has been applied to mass reduction studies, it can be equally applied to any other design objective the Product Development Team requires such as cost reduction, reduced carbon footprint etc.

- The ACP Process™ is indifferent to material type.

The FutureSteelVehicle project used the ACP Process™ combined with an expanded portfolio of steels and manufacturing technologies that foretell the future of steel grades readily available in the 2015 to 2020 time frame. The state-of-the-future design methodology used to develop the FSV body structure is at the leading edge of computer-aided optimisation techniques and helped the program to achieve an optimal mass efficient design. Key achievements are:

- Employs state-of-the-future design innovations that exploit steel's versatility and strength
- Achieves 35% BEV body structure mass savings compared to benchmark ICE vehicle
- Uses 97% High-Strength (HSS) and Advanced High-Strength Steel (AHSS), of which nearly 50% is over the 1000 [MPa] strength steels
- Enables 5-star safety ratings
- Reduces total Lifetime Emissions by nearly 70% compared to ICEg
- Reduces mass and emissions at no cost penalty

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