Peer Review of Light-Duty Vehicle Mass-Reduction and Cost Analysis — Midsize Crossover Utility Vehicle (FEV Report)

United States
Environmental Protection
Agency

Peer Review of Light-Duty Vehicle Mass-Reduction and Cost Analysis — Midsize Crossover Utility Vehicle (FEV Report)

Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

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Peer Review of *Light-Duty Vehicle Mass-Reduction and Cost Analysis – Midsize Crossover Utility Vehicle (FEV Report)*

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Executive Summary

In December 2011, EPA contracted with SRA International (SRA) to conduct a peer review of *Light-Duty Vehicle Mass-Reduction and Cost Analysis – Midsize Crossover Utility Vehicle (FEV Report)* developed by FEV and EDAG.

The peer reviewers selected by SRA were William Joost (U.S. Department of Energy), Glenn Daehn, Kristina Kennedy, and Tony Luscher (The Ohio State University), Douglas Richman (Kaiser Aluminum), and Srdjan Simunovic (Oak Ridge National Laboratory). In addition, Srdjan Simunovic and members of the OSU team reviewed various elements of the associated modeling. EPA would like to extend its appreciation to all of the reviewers for their efforts in evaluating this report and the modeling. The reviewers brought useful and distinctive views in response to the charge questions.

The first section of this document contains the final SRA report summarizing the peer review of the *FEV Report*, including the detailed comments of each peer reviewer and a compilation of reviewer comments according to the series of specific questions set forth in the peer review charge. The SRA report also contains the peer reviewers' resumes, completed conflict of interest and bias questionnaires for each reviewer, and the peer review charge letter. The second major section contains our responses to the peer reviewers' comments. In this section, we repeat the compiled comments provided by SRA and, after each section of comments, provide our response. We have retained the organization reflected in SRA's compilation of the comments to aid the reader in moving from the SRA report to our responses.

TO: Cheryl Caffrey, U.S. Environmental Protection Agency, Office of Transportation and Air Quality (OTAQ)

FROM: Brian Menard, SRA International

DATE: June 27, 2012

SUBJECT: Peer Review of *Light-Duty Vehicle Mass-Reduction and Cost Analysis – Midsize Crossover Utility Vehicle (FEV Report))*, developed by FEV and EDAG.

1. Background

In developing programs to reduce greenhouse gas (GHG) emissions from light-duty highway vehicles, the U.S. Environmental Protection Agency's Office of Transportation and Air Quality (OTAQ) has to evaluate the safety of lightweighted automotive designs as well as the methods and costs of proposed technologies to achieve this design.

The 2012 study by FEV, *Light-Duty Vehicle Mass-Reduction and Cost Analysis – Midsize Crossover Utility Vehicle (FEV Report)* is a continuation (e.g., Phase 2 study) of the original Phase 1 Low Development study from Lotus Engineering. The report reviews the amount of mass reduction in the Low Development case ("20%") from the Lotus Engineering Phase 1 study. This is done through analysis of the assumptions for the Body-in-White (BIW), and through an up-to-date re-analysis of light weighting options for all of the other vehicle components of which the Lotus Engineering assumptions are a part. An in-depth cost evaluation of all technologies is included. The FEV Report consists of two parts: In the first part, FEV's contractor, EDAG, has designed and developed the BIW structure in CAE in order to demonstrate that it meets Federal Motor Vehicle Safety Standards (FMVSS) for Light-Duty Vehicles using LS-DYNA. The analysis includes materials, methods, and related costs to assembly and manufacturing. The second part of the report is an in-depth investigation of "other than BIW" vehicle systems based upon discussions with suppliers, Lotus Phase 1 report ideas, and FEV's experience and expertise.

This report documents the peer review of the *FEV Report*. Section 2 of this memorandum describes the process for selecting reviewers, administering the review process, and closing the peer review. Section 3 summarizes reviewer comments according to the series of specific questions set forth in matrix contained in the peer review charge. The appendices to the memorandum contain the peer reviewers' resumes, completed conflict of interest and bias questionnaires for each reviewer, and the peer review charge letter.

2. Description of Review Process

In December 2011, OTAQ contacted SRA International to facilitate the peer review of the *FEV Report*. The model and documentation were developed by FEV and EDAG.

EPA provided SRA with a short list of subject matter experts from academia and industry to serve as a "starting point" from which to assemble a list of peer reviewer candidates. SRA selected three independent (as defined in Sections 1.2.6 and 1.2.7 of EPA's *Peer Review Handbook, Third Edition)* subject matter experts to conduct the requested reviews. SRA selected subject matter experts familiar with automotive engineering and manufacturing, automotive materials, crash simulation, and cost assessment. The coverage of these subject areas is shown below in Table A.

Table A:
Peer Reviewer Experience and Expertise

Name	Affiliation	Coverage					
		Automotive materials	Bonding forming	Manufacturing assembly	Crash simulation	Cost assessment	
Douglas Richman	Kaiser Aluminum	Y	Y	Y	/	Y	
William Joost	US DOE	Y	Y	Y	/	/	
Srdjan Simunovic	Oak Ridge National Laboratory	Y	Y	/	Y	/	
Glenn Daehn et al.	The Ohio State University	Y	Y	Y	/	Y	

To ensure the independence and impartiality of the peer review, SRA was solely responsible for selecting the peer review panel. Appendix A of this report contains the resumes of the three peer reviewers. A crucial element in selecting peer reviewers was to determine whether reviewers had any actual or perceived conflicts of interest or bias that might prevent them from conducting a fair and impartial review of the *FEV Report*. SRA required each reviewer to complete and sign a conflict of interest and bias questionnaire. Appendix B of this report contains an explanation of the process and standards for judging conflict and bias along with copies of each reviewer's signed questionnaire.

SRA provided the reviewers a copy of the most recent version of the *FEV Report* as well as the peer review charge. The charge included a matrix of questions issues upon which the reviewers were asked to comment. Reviewers were also encouraged to provide additional comments, particularly in their areas of expertise and work experience. Appendix C of this report contains the memo to reviewers from SRA with the peer review charge.

A teleconference between EPA, FEV, EDAG, the reviewers, and SRA was held to allow reviewers the opportunity to raise any questions or concerns they might have about the *FEV Report* and associated modeling, and to raise any other related issues with EPA and SRA, including EPA's expectations for the reviewers' final review comments. SRA delivered the final review comments to EPA by the requested date. These reviews, contained in Appendix D of this report, included the reviewers' response to the specific charge questions and any additional comments they might have had. Individual teleconference calls were held between EPA, FEV, EDAG, and two of the reviewers, Doug Richman and Srdjan Simunovic, to elaborate on these reviewers' written comments.

3. Compilation of Review Comments

The *FEV Report* was reviewed by William Joost (U.S. Department of Energy), Glenn Daehn, Kristina Kennedy, and Tony Luscher (The Ohio State University (OSU)), Douglas Richman (Kaiser Aluminum), and

Srdjan Simunovic (Oak Ridge National Laboratory). In addition, Srdjan Simunovic and members of the OSU team reviewed various elements of the associated modeling. Appendix A contains detailed resumes for each of the reviewers. This section provides a compilation of their comments. The complete comments may be found in Appendix D.

1. **ASSUMPTIONS AND DATA SOURCES (CAE BIW and Vehicle)**	**COMMENTS**
Please comment on the validity of any data sources and assumptions embedded in the study. Such items include material choices, technology choices, vehicle design, crash validation testing, and cost assessment that could affect its findings.	**[Joost]** The material selection process used in this study suggests a good understanding of the cost and manufacturing impacts of changing between different steel, Al, Mg, and plastic/composite based materials. Generally the material selections are appropriate for the performance, manufacturing, and cost requirements of the particular systems. Identifying production examples of the materials in similar systems is very important for establishing credibility – the project team did an excellent job identifying production examples of most material replacements. There are, however, a few material selections where additional consideration may be necessary: The transmission case subsystem (pg 269) features the use of a Sr bearing Mg alloy. Recently, Sn based alloys have been produced and (I believe) used in production for similar applications. The use of Sn as an alloying ingredient accomplishes many of the same goals (improved high temp creep performance, for example) at a lower cost. It may be worth investigating these new alloys as an opportunity to reduce the cost of the lightweight transmission case subsystem. If not, the selection of a Sr alloy is reasonable. The feasibility of using hot rolled blanks in the body structure would be further emphasized by providing production examples for vehicles of >200k units per year. Similarly, the use of a 7000 series Al rear bumper is questionable – a production example for a high volume, low cost vehicle should be provided. The use of Thixomolded Mg seat components should be reconsidered. Thixomolding does have the potential to provide improved ductility compared to die casting, however the process is generally not well regarded in the automotive community due to concerns over limited supply and press tonnage limits (which limit the maximum size of the components that can be manufactured this way). If there is a production example of thixomolding for >200k unites per year in automotive, then it should be cited in the report. If there is no example then I would suggest switching to die casting (or super vacuum die casting) – the weight reduction and cost will likely be similar. It's not clear how the mass savings were achieved in the wheels and tires. The report states that a 2008 Toyota Prius wheel/tire assembly will be used in place of the stock Venza wheel – however the report also states (pg 544) that the Prius wheel will be normalized up to the 19"x7" to maintain the original styling of the Venza. The technology employed in the Prius wheel is not different from the stock Venza wheel so why should a scaled-up Prius wheel weigh less than the original Venza wheel? There are also inconsistencies in the report – table F.5-18 references eliminating the spare tire wheel while downsizing the spare tire – why would there be a tire with no wheel? Lastly, if the Prius wheel/tire is scaled up to match the stock Venza size then the spare wheel/tire must also be scaled up – it's not clear that this happened. You are taking significant credit for weight reduction in the wheels and tires (~2% of total vehicle weight) but it's not clear how this is achieved.

	Many of the parts in the frame have been changes to a GF Nylon (pg 667). This may not be unreasonable, but production examples should be provided. **[Richman]** 1) NHTSA crash test data was used for validation of collision simulation models and is an appropriate source. 2) Material property data was supplied by recognized supplier associations and are correct. 3) Cost estimates for reduced mass sheet products seem to include assumption that drive unusually high material and equipment cost. This issue leads to a technology cost effectiveness that is not representative of actual production experience for sheet products. **[OSU – Glenn Daehn]** The data and sources appear to be very good, however at the time of this review there are a few items that are unclear. First there some statements that are referenced with superscripts, however there is not a reference list that appears in the document. Second, this report does an excellent job of documenting at a high-level that the finite element analysis is carried out properly, showing agreement with masses, stiffness and crash signatures of baseline vehicles. However, it is important that all of the details be also available to the public, such as the detailed material geometry (mesh files), stress-strain flow-laws used for the materials, weld locations (more than a figure), models used for weld behavior and so on. This can be done by reference or by making the LS-DYNA models public. It is not clear at time of review how this will be done, but it would be a great service to make all this granular detail available. Similar statements can be made regarding the detail for components and materials in the costing models. **[OSU – Tony Luscher]** The data used appears to be valid and appropriate to the tasks that are completed. Vehicle data for the Toyota Venza was obtained by scanning the components and creating the CAD models. Material data was found from appropriate sources and databases. These were used to create a crash test model for the vehicle and for cost estimation. A thorough search of state-of-the-art vehicle design concepts was used as the basis of mass reduction for the various vehicle systems. **[Simunovic]** This section contains comments on validity of the data sources, material properties, and modeling approaches used in this study. The overall methodology used by the FEV is fundamentally solid and adhere to standard practices of the crashworthiness engineering [5]. However, an in-depth analysis of the model files reveals several areas that may need to be addressed to fully support the findings of the study.

	Firstly, as a matter of the established procedures for technical documentation, I suggest that the sources for the material properties should be clearly referenced; especially since the authors of the FEV study worked on similar projects for steel industry consortia [6]. Similar projects on concept vehicles [7,8] also offer guidelines on the reporting. It would also be very helpful to readers to graphically depict mechanical properties such as material stress-strain curves, failure envelopes, etc. Secondly, the technologically important issues with the high strength metallic materials, such as Advanced High Strength Steels (AHSS) [9], are their special processing requirements [10], reduction in ductility, higher possibility of fracture [11-14] (especially under high strain rates [15-17]), and joining [18-22]. Many AHSSs derive their superior mechanical properties from their tailored microstructures, which get strongly affected during welding. Active research in welding of the AHSS shows possibilities of significant reductions of the joint strengths due to the softening processes in Heat Affected Zone (HAZ). Therefore, the strength values for the welds in the current LD model (i.e. SIGY=1550 for MAT_SPOTWELD section in the input files) seems very optimistic, and may need to be reduced or elaborated upon in the report. Several versions of the reports were distributed and I may have very well missed an updated version. In case that joining discussion is indeed restricted to one page as it appears in the current FEV document, I would suggest that weld properties and constitutive models be given additional attention in the final report. Third important issue that I would suggest to be addressed is modeling of failure/fracture of the high strength materials in the LD models. Despite long research on the subject, the methods for modeling localization and failure are relatively scarce. There is still no wide consensus on how to model failure in materials. For the FEV study, special attention should be given to the joint areas (spot welds, laser welds) that can experience the degradation of properties due to the thermo-mechanical cycles that they have been exposed to. A simple way of addressing the above points would be to use failure limit strains in plasticity models that are used in the FEV models, i.e MAT_PIECEWISELINEAR_PLASTICITY. In this approach a limit strain is assigned to material, and after that limit strain is reached in a finite element, the element is gradually removed from the simulation. The values for the failure strains are dependent on mesh and element discretization, where additional simulations should be conducted to correlate energy to failure to the corresponding physical failure process zone for the given problem.

If you find issues with data sources and assumptions, please provide suggestions for available data that would improve the study.	**[Joost]** Two plastic technologies are very widely employed in this design: PolyOne and MuCell. It seems that the companies who license/manufacture these technologies were used as the primary source to determine feasibility. However they are likely to be optimistic regarding the capability of their materials. I agree that these materials are appropriate for the indicated applications, however I feel that the credibility would be improved by including other sources (OEMs, Tier 1) or more production examples for existing platforms. With such a large amount of weight reduction attributed to PolyOne and MuCell, it would be beneficial to have a very strong case for capabilities. **[OSU – Glenn Daehn]** See above. **[OSU – Tony Luscher**] None found.
ADDITIONAL COMMENTS: **[Richman]** This report is a review the 2012 FEV project to identify mass-reduction opportunities for a crossover sport utility vehicle based on the 2009 Toyota Venza. This study is a continuation of the Lotus Engineering Phase 1 Low Development (LD) study funded by the Internal Council on Sustainable Transportation (ICCT) in 2010. Goal of the FEV project is to identify practical mass reduction technologies to achieve a 20% reduction in total vehicle mass (342 Kg) at no more than 10% increase in consumer cost while meeting, or exceeding, all crashworthiness, performance and customer satisfaction attributes provided by the baseline vehicle. Body of the baseline vehicle is 31% of total vehicle mass and has a dominant influence on NVH and collision performance of the total vehicle. This project involved extensive engineering analysis of the vehicle body. BIW and closure materials and gauges were optimization to exploit the maximum mass reduction potential from advanced low mass automotive materials and advanced manufacturing processes. Mass reduction initiatives are identified for all vehicle systems including engine, transmission, interior, suspension and chassis systems. Most materials, manufacturing processes and components selected for the FEV vehicle technology package are proven, cost effective and available for use on 2017 production vehicles. Majority of mass reduction concepts utilized are consistent with recognized industry trends. Mass reduction potential attributed to individual components appear reasonable and consistent with industry experience with similar components. As an advanced design concept study this is an important and useful body of work. Results of the project provide useful insight into potential vehicle mass reduction achievable with HSS and AHSS materials. This report is a review of the methodologies employed, technologies selected and validity of findings in the FEV study. This reviewer has experience in vehicle mass reduction engineering of body, engine and suspension systems. This review focuses on those areas of the FEV project. **[OSU – Kristina Kennedy]** “Building a full vehicle model w/o the use of drawings or CAD data…” Has this method of tear-down + scanning been proven out in industry or in other projects to understand how closely this method would correlate with actual data? Is this basically “reverse engineering” and is that an acceptable method? **[OSU – Tony Luscher]** Data sources are well documented in the report and will aid if any additional investigation is needed. Several of them were checked for validity.	

[Simunovic] In this document I review the methods, data, and the FEM crash models developed in the FEV study. The models were evaluated based on the analysis of the computational simulation results and on based on the analysis of the actual model files. I want to emphasize that the scope of my review is on the computational simulations of the vehicle crashworthiness and on the modeling approaches employed by the FEV and its contractors. The primary source for my review were the FEV final draft report, the crash animations generated by the FEV, and the computer simulation output files for the NCAP and the ODB crash test configurations. Two vehicle crash models were available, the baseline and the LD model. As it will be shown in the following sections, my review was based to a large extent on the vehicle model files. Very often in the current practice, the actual model files are not sufficiently scrutinized and are evaluated only through the resulting computational simulations. In the case of large complex FEM models, such as car crash models, the model's configuration complexity and its shear size can obscure the important details of the response and camouflage the sources of errors in the model. That is particularly common when the technology envelope of the state-of-the-art is expanded, as is the case with ever-increasing sizes and complexities of the car crash models.

2. VEHICLE DESIGN METHODOLOGICAL RIGOR CAE BIW and Vehicle)	COMMENTS
Please describe the extent to which state-of-the-art design methods have been employed and the extent to which the associated analysis exhibits strong technical rigor. You are encouraged to provide comments on the information contained within the unencrypted model provided by EDAG; the technologies chosen by FEV; and the resulting final vehicle design.	**[Joost]** The report uses a (very thorough) piece-wise approach to weight reduction – each system is broken down and weight reduction opportunities for the individual components are identified. The weight-reduced components are then reassembled into the final vehicle. I believe that this provides a conservative estimate for the weight reduction potential of the Venza, where a vehicle-level redesign would provide greater weight reduction. However, I am also of the opinion that the approach used here is in line with industry practice so; while this may not yield the maximum reasonable weight reduction, it is likely to yield a value more in-line with industry-achievable weight reduction. It is particularly helpful (and credible) to see descriptions technologies that were considered, but abandoned due to performance concerns (e.g. reverting to a timing belt), manufacturing capabilities, (e.g. using a MuCell manifold), and cost (e.g. Mg oil pan). The suspension design process lacks sufficient detail to make the cost and weight estimates credible. Considerable Al is used to replace steel at a very minimal cost penalty. However, as the report indicates, detailed design and validation is necessary to confirm that these changes would be viable for the Venza. For example, changing to a hollow Al control bar is not an industry standard practice and the use of a hollow section may require significant changes to geometry in order to meet the stiffness and strength requirements. While a hollow Al control bar is feasible, I'm not confident that it can be substituted into the design so easily. A $0.40/kg-saved cost penalty for changing a significant number of components from mild steel to Al seems to be an underestimate. **[Richman]** 1) EDAG performed structural modeling. The EDAG organization is widely recognized as technically competent and highly experienced in modeling of auto body structure. Modeling approach appears technically robust and logical. 2) Body structural analysis utilized industry recognized CAE, CAD and collision modeling analysis tools and protocols. Tools used are state-of-the –art and the approach. 3) FE model was validated against physical test data for NVH and collision performance. Model correlation with physical test results is very good. No significant discrepancies or inconsistencies have been identified in the modeling results. 4) Based on these observation, the models would be considered valid and reliable for moderate A:B design comparisons that are the subject of this vehicle study.

	[OSU – Glenn Daehn] The work is well done and technically rigorous. Again, we encourage making all pertinent detail publicly available. **[OSU – Tony Luscher]** The report does an excellent job of using state-of-the-art design methods. The re-engineering process included vehicle teardown, parts scanning, and data collection of vehicle parts to build a full vehicle CAE model. This raw STL geometry was then translated into an FE meshing tool (ANSA) to create a finite element model. **[Simunovic]** The development of the LD Toyota Venza concept started with the development of the baseline FEM model of the vehicle. The FEM model was developed by a reverse engineering process of disassembly, geometry scanning, component analysis, material characterization and the incremental FEM model development. The turn-around time for this process by the FEV is quite impressive. Equally impressive are the apparent quality of the FEM mesh, the definition of joints and assembly of the overall model. The discretization of the BIW sheet materials uses proportionately sized quadrilateral shell elements, with few triangular elements. The mesh density is mostly uniform and without large variations in the FEM element sizes and the aspect ratios. The BIW model has about 6% of triangular shell elements in the sheet metal which is a very small amount given the complexities of the vehicle geometry. Figures 1-3 show the geometry and the parts variety for the baseline vehicle model. There are no apparent geometry conflicts in the model and parts are well aligned with compatible geometries and FEM meshes. This is essential for accurate modeling of currently the prevailing joining method for sheet metals, spot welding. The level of geometrical detail in the model is very high and as someone who has been involved with the vehicle crashworthiness modeling for the last twenty years, I think that the developed FEM mesh of the Venza BIW is the current state-of-the-art. Figure 4 shows some details of the BIW FEM mesh that illustrate the prevalence of the quadrilateral shell finite elements, constant aspect ratios and presence of the geometry details that are necessary for an adequate modeling of the progressive structural crush.
Please comment on the methods used to analyze the technologies and materials selected, forming techniques, bonding processes, and parts integration.	**[Joost]** The forming, joining, and integration techniques used in the report were analyzed only by referencing production examples or companies who produce similar products. Detailed design work would certainly include a more thorough analysis of the manufacturing techniques however for the scope of this report I believe that the level of analysis is appropriate. **[Richman]** 1) Body: Process used to select materials, grades and gauges for the mass optimized body sub-group is technically sound and thorough. Election of laser welding of structurally significant body panels indicates deployment of advanced manufacturing process where appropriate. 2)Non-body: Methodology used to identify, screen and select non-body mass reduction technologies is thorough,

detailed and highly effective. Munro Associates lead this segment of the project. Munro is recognized as being technically competent, highly experienced, knowledgeable and creative in benchmarking and lean engineering of automotive and non-automotive systems.

[OSU – Glenn Daehn] All is in accord with the state of the art. It is not clear how welds are represented in the FE-Model, without dissection of the LS-DYNA input stacks.

[OSU – Tony Luscher] The Toyota body repair manual was used to identify the material grades of the major parts of the body structure. These material grades were then validated by material coupon testing.

The MSC Nastran solver was used to solve for the bending and torsion stiffness of the body in white model. Good correlation was achieved between physical stiffness testing and FEA stiffness results.

[Simunovic] The development of the LD Toyota Venza concept started with the development of the baseline FEM model of the vehicle. The FEM model was developed by a reverse engineering process of disassembly, geometry scanning, component analysis, material characterization and the incremental FEM model development. The turn-around time for this process by the FEV is quite impressive. Equally impressive are the apparent quality of the FEM mesh, the definition of joints and assembly of the overall model.

The discretization of the BIW sheet materials uses proportionately sized quadrilateral shell elements, with few triangular elements. The mesh density is mostly uniform and without large variations in the FEM element sizes and the aspect ratios. The BIW model has about 6% of triangular shell elements in the sheet metal which is a very small amount given the complexities of the vehicle geometry. Figures 1-3 show the geometry and the parts variety for the baseline vehicle model.

In the following, I first give the analysis of the baseline FEM model. The baseline FEM model is very adept and can be used for illustration of some shortcomings of the LD model that I think need to be addressed. It is important to note that the LD model is much more complex due to a large number of materials and gages that resulted from the computational optimization process. This complexity and the project time constraints dramatically increase the potential for error. Unfortunately the tools for managing such complex systems are not yet mature, making the development and the evaluation of this complex vehicle model very challenging. Over the years, I have developed several simple programs that can be used to debug FEM models by directly analyzing the model files. The common approach to evaluation of large FEM models is to almost exclusively consider computational simulation results. However, these simple tools allow for evaluations of relationships within the FEM models directly from the model input files, thereby enabling debugging of the models independently from the simulations.

Review of the FEM Model for the Baseline Toyota Venza

The primary material for the BIW of the baseline vehicle, 2009 Toyota Venza, was identified in the Lotus Phase 1 Report as mild steel. Lotus Phase 1 study stated that the BIW also had about 8% of Dual Phase steel with 590 MPa designation, while everything else was commonly used mild steel sheet material. The FEV/EDAG study showed that there was more variety to the baseline design then originally anticipated. Table 1 lists the materials used in the BIW model (file Venza_biw_r006.k) that were modeled using MAT_PIECEWISE_LINEAR_PLASTICITY). Aluminum bumper was modeled using MAT_SIMPLIFIED_JOHNSON_COOK material model in LS-DYNA. The number of material models is relatively small.

Most of the CAE tools display the FEM model based on their part identification number (ID). To verify the material model assignment one must then verify material assignment for every part and then sort them accordingly. For large complex models this is a very tedious process that is very error prone. More advanced CAE tools, such as HyperMesh, have options for grouping and displaying model entities by material types and IDs. Figure 5 displays the material assignments for the baseline BIW.

The specific assignment of the materials for the BIW and the corresponding stress-strain curves are shown in the figures below. Most of the material models account for strain rate sensitivity of the material. For a given plastic strain, the yield stress is calculated by interpolating stresses between two neighboring stress strain curves based on the applied strain rate. There are established modeling recommendations for modeling strain rate sensitivity effect in crash models. The specified stress strain curves should not intersect. Extrapolated lines from their last specified linear segment should not intersect, as well. The material models should use plastic strain rate [23] instead of the total strain rate as the basis of the strain rate effect calculation. This option (VP=1) was not used in the FEV models although it is highly recommended in practice.

Figures 6-10 show the main material systems for the baseline BIW model. The material assignments correspond to the assignments in the project’s report.

The stress-strain curves for different strain rates in the above figures do not intersect. Their extrapolations however have potential for intersection at high plastic strains in Figures 7and 8. The number of the data points in Figures 9 and 10 are too large and needs to be reduced in order to avoid the interpolation errors by the simulation program. It is obvious that curves in Figures 9 and 10 were developed by analytical fits. Such approach can create undesirable artifacts such as an appearance of the yield point elongation for Dual Phase steel in Figure 10. An interpolation approach with fewer points and curves is recommended. Figure 11 illustrates the optimal piecewise linear interpolation (green curve) of the base (red) curve in Figure 10. The interpolated curve has error of 1% of the value range with respect to the actual curve and uses only 9 points.

Next, the BIW sheet material thickness distribution is shown in Figure 12. The colors indicate symmetrical distributions in

	accordance with the specified thickness distribution in the project report. In many situations, the accuracy of the crash simulation is dependent on the shell element formulation (type) used. The basic shell element formulation (reduced integration Belytschko-Tsay, LS-DYNA type 2) is computationally very efficient but has lower accuracy than more complex formulations such as the fully-integrated Bathe-Dvorkin shell element (LS-DYNA type 16). Figure 12 shows the shell element formulations in the BIW model. The current crash modeling recommendation is to use shell element type 16 when possible. The Bathe-Dvorkin shell is 3.5 times more computationally expensive than the Belytschko-Tsay shell so that in order to strike a proper balance between the accuracy and the computational speed element types can be mized in the model. This is especially true when large number of simulations is conducted, as was the case for computational optimization in the FEV study. As it can be seen in Figure 16, the baseline model employs accurate element formulation in the main structural components, while the Belytschko-Tsay formulation is employed in the remainder of the sheet metal which is an appropriate compromise for the large scale computations. Another important technical aspect of the crash simulations with the shell elements is the employed number of integration points through the thickness of the shells. The default (2 points) is insufficient for the crash analyses. Three points is also inadequate in the current simulation guidelines because it results in a very quick formation of plastic hinges in the sheet metal during crush. A minimum of 5 through-thickness integration points is currently recommended for the crash simulations. Therefore, modification of the model in this regard is suggested for the general release. Another commonly overlooked formulation aspect for the shell elements is the through thickness shear factor. Recommended value is 0.833, which was used only in bumper structures of the current model (Figure 14). Changing the factor to 0.833 is recommended. In summary, the baseline Venza FEM model is developed following most of the recommended development procedures for crash models. The modifications suggested above would meet few additional recommendations that would likely increase the robustness of the model.. The NCAP and the side MDB barrier simulation results can be compared with the actual crash tests conducted by NHTSA. The comparison of the simulation and the NCAP test shows somewhat stiffer response of the FEM model with respect to the test (Figure 1.18.18 in the last FEV report). The maximum and the average accelerations in the FEM model were accordingly higher than the test results. The baseline FEM model was deemed acceptable for the purposes of the FEV study. Another important measure of the FEM model fidelity was the crash duration time that was 20 ms shorter for the model compared to the test. This difference is noticeable because the overall crash duration of 100 milliseconds. However, for the objectives of the FEM study, the model's crash pulse was deemed acceptable, which for the described project schedule seemed quite reasonable.

Review of the Low Development Vehicle Model

The FEV engineers have used the computational optimization methods based on the response surface formulation in order to determine the distribution of material types and grades that would maximally reduce the weight of the vehicle while maintaining the performance and controlling the cost. The part distribution of the resulting optimized LD design FEM model is shown in Figure 15.

It is probably misleading to refer to the resulting FEM model as "Low Development" since it is a product of numerous computational simulations and an in-depth engineering study. The resulting inventory of the material models used in the LD FEM model is listed in Table 2. It is evident that there are numerous duplicates as well as unused materials. It would be prudent to purge the list of material models from the LD FEM model as they may lead to errors. Some of the inconsistencies that were found in the current LD FEM model may very well be a result of this model redundancy.

Two model files contain most of the material models:

- Venza_master_mat_list_r006.k
- Venza_Material_Db_Opt_dk2.k

The horizontal black line in Table 2 separates the material model specifications between the two files. These two were unchanged for the last two versions of the FEM models that were downloaded from the project download site.

Figures 16-32 below show the stress-strain curves for the materials used in the BIW of the LD FEM model.

There are obvious duplicates in the model specifications that would be prudent to eliminate and modify the model accordingly before its public release. In addition, there are some errors in the LD FEM model specifications that need to be corrected.

Correction Item 1:

Material ID 9 (Figure 30) has stress-strain curves for different strain rates different strain rate curves intersect which is not acceptable from the physical perspective.

Materials with IDs 8000006, 8000007, and 8000008 have elastic properties of lightweight materials such as Aluminum and Magnesium alloys, but they utilize yield stress functions of HSLA 350/450 steel defined in file: Venza_frt_susp_exhaust_30ms.k.

Currently, only the material 8000006 is used in the LD FEM model, although in the previous model version material ID

	8000008 was also used. **Correction Item 2:** Some material assignments in the LD FEM model are inconsistent which is probably a result of too many material models. The mapping of material IDs on the BIW FEM model reveal several unsymmetrical model assignments. The most obvious discrepancy is marked in Figure 33. Here, where one model part is modeled using the mild steel while its corresponding symmetrical counterpart is modeled using the HSLA 350/450 steel. Additional unsymmetrical material assignments are pointed with arrows in Figures 34-37. Two possible outcomes of not pairing the symmetrical components with the same material ID are illustrated in Figures 36-37. In Figure 36 the two different parts have different material assignments, which eventually refer to different material properties. In case of the marked parts in Figure 37, the material IDs are different but because of the repeated material models with different IDs, they eventually refer to the same material properties. The above inconsistencies need to be corrected before the models are released into to the open domain. **Correction Item 3:** Another area of concern is the number of through thickness integration points for the shell elements in the current LD FEM model. As it can be seen in Figure 38, almost all shell elements have just 2 integration points through the thickness. This is clearly inadequate from the accuracy standpoint and may be responsible for some of the issuable simulation results shown in the following figures. **Correction Item 4:** Figure 38 shows the thickness distribution in the LD FEM model of the BIW. In general, the thickness distribution is symmetrical with respect to the centerline of the vehicle. However, a closer inspection reveals some asymmetries in thickness assignments. The arrows in Figures 40-41 show the parts that do not have symmetrical assignment of the values with respect to the centerline of the vehicle. I have not checked the extent of the differences, but it something nonetheless that needs to be corrected.

	Concern Item 1: The following Figures 42-45 show some results that may warrant more investigation by the project engineers. Figures 42-43 show the deformation of the main front rails for the baseline vehicle during the NCAP test simulation. The overall deformation is symmetrical. In the case of the LD FEM model, as shown in Figures 44-45, the deformation is markedly different from the baseline and unsymmetrical. The cause for that may be in the unsymmetrical material assignments for the main rails that were present in the previous LD FEM model release and the simulations may have been based on that version. As I was only using the simulation files, I could not tell if that was actually the case. However, I strongly suggest following up on this point as these rails are extremely important for the crash energy management. **Concern Item 2:** One of the modeling aspects that is usually not considered in conventional mild steel vehicle designs is modeling of material fracture/failure [24]. However, in the case of the high strength materials, such as the AHSS, the material fracture is a real possibility that needs to be included in the models. One of the easiest failure models to implement is to specify equivalent strain threshold for the material failure. Once this threshold is reached during crash simulation it leads to gradual element deletion, which simulates crack formation. I would suggest consideration of such a simple model enhancement that, while not comprehensive enough for production design, is probably sufficient for the purposes of the FEV study. The strain rate sensitivity of the material models would help with the regularization of the strain localization and related numerical problems [25].
If you are aware of better methods employed and documented elsewhere to help select and analyze advanced vehicle materials and design engineering rigor for 2017-2020 vehicles, please suggest how they might be used to improve this study.	**[Joost]** This is not my area of expertise. **[OSU – Glenn Daehn]** Everything appears to be well-done and in accord with the state of the art**.** **[OSU – Tony Luscher]** None known.
ADDITIONAL COMMENTS: **[OSU – Kristina Kennedy]** FE Meshing Tool, ANSA. Did a quick Google search and did not find this product. Am familiar with ANSYS and others, but is ANSA an industry-standard tool? Just confirming the wide-use of such a tool out of curiosity. **[Richman]** The team of FEV, EDAG and Munro is an outstanding coalition of industry experts with the unique skills and expertise necessary to meet the objectives of this project.	

Mass reduction efforts were organized into two segments: body and non-body. Body mass reduction focused on selection of materials (steel, aluminum, plastics and magnesium), grades and gauges. Baseline Venza body design was not changed. Non-body mass reduction efforts examined all vehicle systems for potential cost effective mass reduction opportunities. FEV utilized technical support from two recognized, technically qualified and highly respected engineering services organizations: EDAG and Munro and Associates.

EDAG focused on body structural engineering and cost modeling. They conducted detailed reverse engineering study the baseline Venza to establish baseline vehicle mass and structural characteristics and develop CAE, FE and collision simulation models. Calibrated FE models were used to develop an optimized Venza body structure. EDAG Engineering analysis is thorough and reflects the high level of vehicle engineering expertise and know-how within the EDAG organization. Modeling and simulation technologies utilized by EDAG are state-of-the art and EDAG has recognized competencies in effectively deploying those tools.

The EDAG work presents a realistic perspective of achievable vehicle structure mass reduction using available design optimization tools, practical engineering materials and available manufacturing processes. EDAG cost modeling of the baseline and reduced mass vehicle structures.

Munro lead the process of identifying, analyzing, screening and selecting cost effective mass reduction opportunities in all vehicle systems. Munro is a highly respected engineering organization specializing in benchmarking and lean product design. Munro process for achieving product mass and cost optimization is well developed and highly effective. They utilize a creative mix of functional analysis, competitive benchmarking, cross industry comparisons, advanced materials and manufacturing process knowledge and sound engineering analysis. This segment of the study identified a significant number of practical mass reduction concepts in all 20 vehicle sub-groups. The majority of mass reduction technologies selected for the final design are in some current level of volume production and appear cost effective and realistically achievable by 2017.

FEV decomposed the total vehicle into 20 sub-systems. Each sub-system was aggressively examined to identify realistically achievable and cost effective mass reduction opportunities. Majority of mass reduction achieved (90%) is concentrated in (7) vehicle sub-systems:

	Mass Reduction
Body	68 Kg
Suspension	69
Interior	42
Brakes	41
Engine	30
Transmission	19
Frame, Mounts	17

These 7 sub-systems account for over 90% of the cost increases and decreases in this project.

This reviewer has experience in light weighting of body, suspension and engine systems. Comments in the following sections are limited to those vehicle sub-groups.

A significant number of creative and innovative mass reduction ideas were developed and selected for the remaining (17) sub-systems not discussed in this report. Many of the ideas appear to be appropriate consideration as part of a total vehicle efficiency improvement effort.

Body Optimization Overview

Body Sub-system includes: Body-in-White (BIW), Closures, Hood, Doors, Lift Gate, Fenders. This sub-system is the highest mass sub-group at 529 Kg, 31% of total vehicle mass. Body group design and material selection have a dominant influence on vehicle NVH and collision performance. For that reason, optimization of the body structure is a major focus of this project.

Body sub-system –	BIW, Closures, Bumper, Fenders
Optimization results -	71 Kg mass reduction
	$230 cost increase

FEV body mass reduction 68 Kg. (21 % of total vehicle mass reduction)

Baseline Toyota Venza body elements (BIW, closures, bumpers) are predominantly a mix of mild steel (48%) and HSS (49%) with a resulting mass of 529 Kg (31% of total Venza mass). This mix of materials represents a comprehensive use of automotive grade steels available when the Venza was originally designed.

Body related mass reductions from this baseline are indicative of improvements made possible by advances in materials technology.

Venza baseline BIW structure was used for both the Lotus “Low Development” and EDAG material optimization analysis. Both studies reduced BIW mass by similar amounts, Lotus LD: 61 Kg, EDAG: 54 Kg. Differences between Lotus and EDAG structures include: specific material grades and gauges and joining technology. Lotus LD structure used conventional resistance spot welding while the EDAG structure included continuous laser welding for structurally significant joints. BIW mass for the two structures are similar:

BIW Structure Mass	
Baseline	386 Kg
Lotus Venza LD	325 Kg (- 15.8%)
EDAG Venza	332 Kg (- 14 %)

Significant difference bending and torsional stiffness between the Lotus and EDAG structures (20%) do not appear to be fully explained by the relative difference in mass between the structures. Structural stiffness for a constant shape is dependent on material gauge and modulus and not influenced by strength properties. Auto body stiffness can be increased by improving attachment integrity. It would be helpful to understand the influence of laser seam welding on body NVH and collision performance.

Body Optimization

Body optimization was accomplished using EDAG body mass optimization process. The calibrated Venza FEA model was used. In this process alternate material type, grade and gauge were evaluated for NVH and collision performance. Baseline Venza body structure was not altered. Materials evaluated include advanced high strength steels (AHSS), aluminum, magnesium, plastics. Material gauges were selected based on component part requirements (NVH, Collision) and properties of specific materials. The body mass optimization process explored the potential of HSS, AHSS, aluminum, magnesium and plastics.

Optimized body structure content summary:

	Baseline Mass	Optimized Mass	Mass Reduction	Materials Change
BIW	386.0 Kg	324.0	51.0 Kg (13.2%)	HSS, AHSS, Gauge
Doors	95.7	95.6	0	---------
Hood	17.8	10.1	7.7 (43%)	Aluminum
Lift Gate	15.1	7.7	7.2 (48%)	Aluminum
Fenders	6.8	4.9	1.9 (28%)	Aluminum
Bumpers	7.5	7.5	0	
	528.9 Kg	457.7 Kg	71.2 Kg (13.5%)	

BIW Optimization

The EDAG optimized BIW is predominantly HSS and AHSS with appropriate gauge reductions. Baseline Venza is composed of 78% mild steel and 22% HSS. This material mix is representative of a comprehensive use of available materials at the time this Venza model was designed. The optimization process selected HSS and AHSS for over 80% of structure.

This study provides insight into practical BIW mass reductions achievable with recent and anticipated near term future advancements in automotive steels.

Using AHSS aggressively with resultant gauge reductions achieved an 13.2% reduction in BIW mass (3% reduction in total vehicle mass). This finding is consistent with similar investigations on the part of OEM organizations in North America and Europe.

Aluminum was selected for the hood, lift gate and fenders. Mass reduction achieved for those components were: Hood: 43%, Lift gate: 48% and Fenders: 28%. Selection of aluminum for these body components is consistent with OEM production experience and several independent organization studies. The magnitude of mass reduction achieved in this body group is also consistent with production experience.

Body Modeling – Comments

The following observations are submitted in the interest of completeness and do not diminish validity of findings and conclusions of the overall project.

Body Modeling – Service Loads

Vehicle models developed in this study are valid and useful for the intended scope of this project. Models addresses overall bending and torsional stiffness, free body modal frequencies, roof strength, and four crash test load cases. These are good indicators and cover many of the primary structural performance concerns.

This analysis does not address what are commonly referred to as "service loads," including jacking, twist ditch, pothole impacts, 2G bumps, towing loads, running loads, etc. Running loads are typically suspension loads for a variety of conditions to address strength, stiffness and fatigue durability of the body and suspension attachment structures and points. Without these other considerations, the optimization process could may unrealistically reduce mass in components that have little effect on overall body stiffness or strength, yet are important for durability.

Body Modeling – Deformable Barrier

Modeling of deformable barriers has historically been an issue. Source, nature or origination of the deformable barriers (moving and fixed) used in this project are not explained. In the offset deformable barrier crash test load cases, overall deformations, including barrier deformations are reported. The reporting does, however, raise a modeling concern. Barrier deformations of over 515 mm are reported for the offset tests. The IIHS deformable barrier has 540 mm thickness of deformable material. It is not expected to compress completely. Excessive barrier deformation has the potential to change the overall acceleration and deformation scenarios reported and influence the mass optimization process.

Body Modeling – Average Acceleration

Overall acceleration issues are not reported in a format normally used by collision development engineers. Charts of unfiltered acceleration pulses are shown and comparisons are made by evaluation of peak accelerations. "Average accelerations" are referred to, but in this report average is the average of left and right side peak accelerations.

Average acceleration as represented by the slope of the filtered velocity/time curve is commonly used to evaluate relative collision performance of a structure. Common practice is to try to steepen the curve in the early portion of the crash sequence (up to perhaps 50 ms) and to try to flatten the curve in the later parts. The logic has to do with the motions of a restrained occupant within the structure. In addition, total velocity change, including rebound, is typically reviewed. As an example, increasing front structure strength can increase restitution and rebound, which increases the overall change in velocity, or Delta-V, and can have adverse effects on overall occupant performance. While peak accelerations are useful, unfiltered peaks can be misleading due to the noise/vibration effect, and at best represent only a partial analysis.

Body Modeling - Stiffness in Collision Simulation

In evaluating the performance of the optimized body structure, the analysts in general considered "less deformation" of the body structure to equate to "better performance." Less deformation may be an index of structural stiffness but is not necessarily an indication of better collision performance. Less deformation generally equates to higher decelerations and resulting forces on the occupant. It is likewise generally desirable to efficiently use as much of the allowable free crush space as possible, not less.

Body Modeling – Door Opening

Part of the rear impact analysis includes an analysis of rear door opening deformation and an estimate of door openability post-crash. While this is an interesting and useful analysis, it is not explained why it is done. It is not a required aspect of the regulations. Since it is in the report, a similar analysis should probably be done for the front door openings in the front crash test load cases. Most if not all manufacturers have an in-house requirement that front doors must be openable following a standard front crash test.

Non-body Design Optimization

This project included a major engineering effort to identify practical mass reduction opportunities in non-body component groups. A rigorous process was followed to identify potential mass reduction concepts. This process selected a extraordinary number of technologies that were judged to be practical, cost effective and in volume production now or will be in production by 2017. A few of the larger mass reduction ideas are discussed in the following sections.

Non-body mass reduction ideas selected for the final FEV vehicle design resulted in a 21% reduction in non-body sub-group mass reduction. A portion of the mass reduction achieved in this area was the result of vehicle mass reduction (engine, wheels, tires). The majority of non-body mass reductions are independent of other reductions in vehicle mass.

Suspension

Suspension sub-system – Wheels, Tires, Shock Absorbers,

Steering Knuckles, Control Arms, Springs, …

Optimization results - 69 Kg mass reduction

$0 cost increase

Major mass reductions in this group are:

Wheels and Tires	32.8 Kg	Resized to new weight
Shock absorber	14.1	New light weight design
Front Control Arm	1.9	Convert to Aluminum
Front and Rear Knuckle	12.6	Conversion to Cast Aluminum
Front and Rear Sta. Bar	7.0	Innovative Al tube concept

Other 0.6

Wheels

Downsizing wheels and tires (5) for the 317 Kg (18.5%) reduction in total vehicle mass is appropriate and is a normal consideration in OEM weight reduction programs. Wheel and tire combinations selected represent a 22% mass reduction from the reduction for these components. This magnitude of mass reduction is potentially achievable, but must be considered somewhat aggressive.

Knuckles

Conversion of steering knuckles to cast aluminum is a proven strategy. Estimated mass reduction by conversion to aluminum is 38% of knuckle mass. Approximately 35% of knuckles on vehicles built in North America use aluminum knuckles. Mass reduction achieved in those programs range from 35% to 45% depending on knuckle configuration. Knuckle mass reduction assessment in this study is achievable.

Control Arms

Conversion of the front control arm to forged aluminum results in a vehicle mass reduction of 2 Kg. Baseline Venza control arm design is typical of a design used widely throughout the industry. A significant proportion of these arms are produced in aluminum. Mass reduction estimates for conversion of this component is typical of the reductions seen in similar production programs.

Shock Absorber, Sway Bars

Reduced mass shock absorber/strut designs and the tubular sway bars are innovative concepts. Cost reduction of $58 is attributed to the reduced mass shock absorber concept. Production viability and cost of this ideas is not known to this reviewer.

System Cost

Total cost for mass reductions in this group is estimated to be net $0. Cost savings resulting from downsized wheels and tires ($79) and low mass shock absorbers ($58) offset cost increases for low mass arms, knuckles and stabilizer bars.

Engine

Optimization results - 30.4 Kg mass reduction

$ 43.96 cost reduction

Main sources of engine mass reduction:

Downsizing - constant performance	10.4 Kg (2.7 L to 2.4 L)
Cylinder Block – Al Mg Hybrid, liners	7.1
Valve train – Al castings, power metal	3.7
Cooling system – plastic housings	2.6

Timing Drive – Plastic covers	1.5
Other	5.1

Engine - Downsizing

Largest mass (10.4 Kg) reduction came from downsizing the engine to a smaller displacement to maintaining baseline Venza performance levels. Assessing appropriate engine weight for a downsized engine is a complex task. Changing displacement within a basic engine achieves small incremental mass reductions. A broader perspective was used in this study. Based on competitive engine technology assessments, an engine was selected representing mass optimization for the 2.4 L displacement. Mass of the new engine was adjusted based on sound engineering analysis to meet packaging and performance parameters of the baseline engine-vehicle package. This approach represents an innovative, thorough and well-engineered approach to estimating optimized engine mass reduction resting from vehicle mass reduction.

Developing a new engine involves massive investments in design, development and manufacturing. Production engines are designed for use in a broad range of vehicles and for a period of time spanning several vehicle design cycles. Manufacturers may not have the opportunity to provide a mass optimized engine for a specific vehicle.

The majority of engine mass reduction ideas selected for the FEV Venza exploit recent advances in materials and/or manufacturing technologies. Many small gains were made converting cast iron housings to cast aluminum, and cast aluminum covers and brackets to cast magnesium or plastic. Most of the engine mass reduction ideas selected have been proven in multiple high volume applications over several years. A few engine Ideas have less proven high volume field experience and were identified by FEV as “D” level selection candidates.

3. VEHICLE CRASHWORTHINESS TESTING METHODOLOGICAL RIGOR (CAE only)	COMMENTS
Please comment on the methods used to analyze the vehicle body structure's structural integrity (NVH, etc.) and safety crashworthiness.	**[Joost]** The baseline testing and comparison process (pgs. 67-128) is very thorough. The team establishes credibility in the proposed design by performing an initial baseline comparison against the production Venza – this suggests that the modeling techniques used can reasonably predict the performance of the lightweight design. It is unfortunate that the deformation mode comparisons could not be made quantitative (or semi-quantitative) somehow. Comparing how the model and test look after a crash gives an indication of deformation mode, but the comparison seems subjective. For example, image D-28 (pg 95) seems to show slightly different failure mechanisms in the CAE model versus the real test. The report notes that the bushing mountings were rigid in the model while they likely failed in the real vehicle. I would expect that these failures are designed into the vehicle to support crash energy management. The results crash pulses (pg 98) for the model and test look fairly similar, but it is unfortunate that this crash energy mechanism was not captured. The intrusion correlation for the baseline model is very good. This again adds credibility to the modeling approach used here. On page 386 the report states that the Mg CCB was not included in the crash or NVH analysis. Replacing a steel CCB with Mg is likely to have a significant impact on both crash and NVH performance. The technology is viable (and has been used on production vehicles as stated) however the crash energy management and NVH performance must be offset by adding weight elsewhere in the vehicle. The CCB plays a role in crash and a major role in NVH so I do not think that it is appropriate to suggest that the material replacement will have the reported results in this case. My suggestion is to leave the CCB as steel in the weight analysis (or go back and redo the crash and NVH modeling, which I suspect is not viable). **[Richman]** 1) LS-Dyna and MSC-Nastran are current and accepted tools for this kind of analysis. FEM analysis is part science and part art. EDAG has the experienced engineers and analysts required to generate valid simulation models and results. 2) EDAG was thorough in their analysis, load-case selections and data for evaluation 3) The handling of acceleration data from the crash test simulations is a bit unusual, and further analysis of the data is recommended.

	[OSU – Tony Luscher] Trifilar suspension apparatus was used to find the CG and moments of inertia of the engine and other major components. The dynamic FEA modal setup was run using NASTRAN. Vibration modes were analyzed by the CAE model and then compared with physical test data in order to correlate the FEA model to the physical model. Five different load case configurations with appropriate barriers were placed against the full vehicle baseline model. Models were created with high detail and fidelity. **[Simunovic]** The correlations and modifications of the baseline vehicle FEM model to the experimental results were primarily done on the measurements of vibrational and stiffness characteristics of the BIW. Once the stiffness of the BIW model was tuned to the experimental results, it was considered to be sufficiently accurate to form the foundation for the crash model. The vehicle crash FEM model was then correlated to the NCAP and MDB side impact. The correlations were primarily based on the deformation modes and the FEM model was found to be satisfactory for the purposes of the FEV study. Comparison of the deformation in the NCAP crash in Figures 46-49 shows very good correlation of the deformation modes. The deformation of the subframe shown in the Figures 48-49 also shows very high fidelity of the simulated deformation compared to the experiment. In summary, the correlation of the baseline FEM model with the NCAP test is quite satisfactory. The correlation with the side MDB test was not elaborated in the report. However, the side impact is perhaps the most important and limiting design aspect for the lightweight vehicles. The side impact is almost exclusively a structural problem that does not compound the benefits of the reduced mass, as is the case of the frontal impact. A documented correlation of the baseline FEM model with the side impact experiment will in my opinion be a very beneficial technical addition to the FEV project that would significantly support the findings of the technical feasibility of the lightweight opportunities in the existing vehicle design space.
Please describe the extent to which state-of-the-art crash simulation testing methods have been employed as well as the extent to which the associated analysis exhibits strong technical rigor.	**[Joost]** This is not my area of expertise. **[Richman]** 1) CAE modeling guidelines used appear to provide a rigorous and logical technical approach to the development of the FE and the methods of analysis. 2) Method of evaluating and comparing acceleration levels in the various crash test scenarios is a bit unusual, a more accepted method of comparing velocity/time plots and average accelerations is suggested. **[OSU – Tony Luscher]** Global vehicle deformation and vehicle crash behaviors were analyzed and compared to the deformation modes of test photographs. Fidelity was good. A few notes on these comparisons are noted on this page in the additional comments section.

	[Simunovic] The FEV Low Development vehicle study has been reviewed following the instructions by the US EPA. It has been found that the FEV study followed most of the current technical guidelines and the state-of-the-art practices for computational crash simulation and design. Several inconsistencies were found in the developed FEM models that need to be addressed and corrected before the FEM models are released for the general use.
If you have access to FMVSS crash setups to run the model under different scenarios in LS-DYNA, are you able to validate the FEV/EDAG design and results? In addition, please comment on the AVI files provided.	**[Joost]** N/A **[OSU – Tony Luscher]** This reviewer has expertise in crash simulation. However due to time constraints the model was not run under different scenarios in LS-DYNA. No AVI files were found.
If you are aware of better methods and tools employed and documented elsewhere to help validate advanced materials and design engineering rigor for 2017-2020 vehicles, please suggest how they might be used to improve the study.	**[Joost]** N/A **[Richman]** Methods and tools were appropriate. **[OSU – Tony Luscher]** None found.
ADDITIONAL COMMENTS: **[OSU – Kristina Kennedy]** "Bending and torsional stiffness values did not provide acceptable performance (when replacing with HSS)". This is an "of course" comment, right? HSS would absolutely produce worse results when replacing steel. These results were expected, correct? **[OSU – Tony Luscher]** The caption on Figures 1.8.13 to 1.8.14 state that they are at 100 ms although the previous paragraph lists them as occurring at 80 ms. The muffler deformation looks quite different in Figure 1.8.14. Figure 1.8.33 is unclear and cannot be seen.	

4. VEHICLE MANUFACTURING COST METHODOLOGICAL RIGOR (CAE BIW and Vehicle)	COMMENTS
Please comment on the methods used to analyze the mass-reduced vehicle body structure's manufacturing costs.	**[Joost]** Overall, the costing methods used in this study seem to be very thorough. The details of the approach provide considerable credibility to the cost estimates, however there will always be concerns regarding the accuracy of cost models for systems where a complete, detailed engineering design has not been established. I believe that this report does a good job of representing the cost penalties/benefits of the technologies but I would still anticipate negative response from industry. There a few examples where I believe that the cost was underestimated or where additional data could be helpful in corroborating the results: The engine cost comparison suggests that the 2.4L engine will cost less than the 2.7L engine due to reduced material content (smaller engine). The analysis goes on to say that the remaining costs (manufacturing, install, etc.) would be about the same for both engines. This seems credible, but is it possible to compare the price of both engine types as well? It may be possible to find prices for both of these engines from a Toyota dealer, and while price is certainly different than cost, it would be helpful in establishing that the cost differential estimate is reasonably accurate. Regarding the cylinder head subsystem (pg 211), the report notes that a switch from Mg to plastic for the head covers introduces engineering challenges related to the cam phaser circuitry. While the report identifies two production examples of this change, these are for high cost engines. It seems unlikely that the designs would achieve the quoted cost savings given that this has only been applied to high cost engines and there are recognized difficulties in the engineering/design. Regarding the body redesign, the estimated cost increase due to materials and manufacturing ($231.43, pg 333) for a weight savings of 67.7kg produces a weight reduction penalty of about $3.42/kg-saved which seems appropriate for the materials and assembly processes suggested in the report. I don't find the cost estimates for the seats to be credible (pg 378). If it's possible to reduce the weight of the seats (which represent a significant portion of vehicle weight) while saving significant cost, why would there be any steel seats in production? These are "bolt on" parts that are provided to the OEMs by suppliers so this would be a relatively easy change to make if the cost/weight trade-off shown in this report is true. The report should, at the very least, address why these kinds of seats are not more prevalent in current vehicles. Why is there a cost savings for the front axle hub (pg 555)? If you are proposing to scallop the hub during forging then you will still need the same amount of input material – some of it will be removed during scalloping, but you will not get a cost

savings. Also, it's not made explicitly clear that the current hub is forged. If you are proposing to move from a cast hub to a forged hub then the cost will most certainly increase. If the cost savings here is due to the estimated weight savings in the final part (i.e. pay for less material) then this indicates that the model is not correctly capturing the yield from the process.

[Richman] Body structure mass optimization was conducted by EDAG. Body structure was not altered form the baseline structure. Mass optimization process examined an appropriate range of material types, grades and gauges. Material properties used appear valid for the respective materials and grades. NVH and collision performance results appear consistent and logical with no significant dis-continuities of inconsistencies. In general the process used is excellent and the results appear realistic and valid.

Costing models were maintained by EDAG. A complete baseline vehicle cost model was developed and calibrated to the estimated cost of the current Venza. The baseline model was used to track cost changes driven by mass reduction technologies.

Cost estimates for mass reduction technologies are based on detailed analysis of the products, materials and process utilized. Estimating costs for new or emerging technologies is a challenging process. Advanced technology cost estimates are based on a combination scaling from known products if available, benchmarking from similar products, material supplier costs, analysis of advanced manufacturing cost, and expert estimates. Labor rates and manufacturing overheads are maintained at documented industry typical levels.

This cost tracking approach is fundamentally sound and valid. Cost estimates for new technologies are subject to validity of cost estimates and engineering judgments in the estimate. This project included rigorous engineering assessments of all mass reduction technology costs.

For most mass reduction technologies selected, cost estimates appear realistic and are consistent with current production costs and prior vehicle mass reduction studies. In the area of body sheet materials there appears to be some assumptions that result in estimated technology costs as much as 25% higher than volume production experience would suggest. This are is discussed in more detail in this report.

Costs attributed to optimization of the body are reported as:

	Cost	Mass Reduction $/Kg saved	
BIW	$ 110	$ 2.19	HSS, AHHS
Hood	$ 39	$ 5.08	Aluminum
Lift Gate	$ 30	$ 4.16	Aluminum
Fenders	$ 22	$10.93	Aluminum

	Total $ 210 $ 3.20 Cost increases projected for HSS and AHSS are marginally higher than have been reported in analytical studies and OEM experience in volume production. Production vehicle studies of AHSS in auto body applications have suggested cost impact of reduced body mass can offset a majority of the cost premiums associated with these materials. Cost increases projected for aluminum sheet application are significantly higher than has been seen in prior studies and in production OEM experience. The optimized body includes three aluminum components: Hood, Fenders and Lift Gate. Mass reductions attributed to these three product areas are consistent with OEM production experience. Estimated cost increases are significantly higher than have been seen in production experience. Using the hood as an example, total cost of the baseline hood is estimated to be $43 while total cost of the aluminum hood is estimated to be $93. Mass savings with the aluminum hood is 7.7 Kg resulting in a net cost per Kg mass reduction of $6.49. Production program experience with aluminum hoods typical find a cost premium below $4.50 per Kg mass reduction. Processing costs for a steel or aluminum hood should be similar. That similarity is reflected the EDAG cost model. The main cost difference between hoods is in material cost. Examining the EDAG cost model it appears aluminum sheet products were assessed a base metal cost and a grade premium. The two factors appear to be combined in the cost model results a raw material cost substantially higher than actual market price for these materials. EDAG cost models for auto body sheet materials (AHSS and aluminum) appear to be overstating raw material costs. A review of the costing models and correlation with market prices for the materials and how raw material cost for sheet products is established in the models may be appropriate. **[OSU – Tony Luscher]** Mass reduction was analyzed first on a system level and then by a component level basis. Mass reduction concepts were based upon a very comprehensive literature review of new materials and manufacturing processes and alternative designs ideas that appear in the open literature and at trade shows. An assessment of these was made in terms of technological readiness, fitness for use in mass production, risk, and cost. In addition there were consultation with industry and experts. **[Simunovic]** This is not my area of expertise.
Please describe the extent to which state-of-the-art costing methods have been employed as well as the extent to which the associated analysis exhibits strong technical rigor.	**[Joost]** This is not my area of expertise. **[Richman]** Costing models are thorough covering all elements of total production cost (material, processing, equipment, tooling, freight, packaging, …). Baseline cost model was calibrated to baseline vehicle cost projection. The basic model is complete and sound. Cost estimates for mass reduction technologies are the result of a rigorous engineering process utilizing benchmarking data, material and component costs from suppliers and detailed analysis of manufacturing costs. Sound creative engineering analysis was used to scale product cost to this specific vehicle application. Accuracy of new technology cost

	estimates is dependent on the knowledge, skill , experience and engineering judgment of the individuals making the estimates. Munro Associates conducted this segment of the project. Munro is a highly respected organization with strong qualifications in product cost analysis. It is reasonable to assume cost estimates in this study are valid estimates for the mass reduction technologies. One area of cost estimate concern is reduced mass sheet products. In this area, material and equipment costs attributed to the reduced mass technologies are significantly higher than actual production experience would support. Source of the discrepancy is not clear form the information in the project review documents. **[OSU – Tony Luscher]** The impact of costs, associated with mass reduction, was evaluated using FEV's methodology and tools as previously employed on prior powertrain analyses for EPA. Cost reduction assumptions are clearly laid out and are reasonable. The report does a good job of realizing the inherent challenges and risks in applying any new technology, let alone lightweight technology, to a vehicle platform. FEV describes the component interactions both positive and negative in its recommendations. The actual values in the EXCEL files were not checked. **[Simunovic]** This is not my area of expertise.
If you are aware of better methods and tools employed and documented elsewhere to help estimate costs for advanced vehicle materials and design for 2017-2020 vehicles, please suggest how they might be used to improve this study.	**[Joost]** This is not my area of expertise. **[Richman]** Process methodology and execution used is one of the best this reviewer has seen. **[OSU – Tony Luscher]** None found. **[Simunovic]** This is not my area of expertise.
ADDITIONAL COMMENTS: **[Joost]** The change from a cast Al engine block with cast Fe liners to a cast-over Mg/Al hybrid with PWTA coated cylinders is very interesting, but the cost penalty estimate seems low relative to what I would expect. Previous work exploring the use of Mg intensive engines (which did not include the added complexity of cast-in Al liners) suggests a cost penalty of $3.89 per pound saved (see http://www1.eere.energy.gov/vehiclesandfuels/pdfs/lm_08/3_automotive_metals-cast.pdf report B) versus this report which suggests a cost penalty of $3.51 per kilogram saved, about half as expensive. The cited study was performed on a 2.5 L engine, comparable to the Venza. The primary difference is that the Venza study includes downsizing which would save on material costs, but I'm not confident that the savings would be as substantial as indicated in this report. It seems that something has been underestimated.	

There are several examples where a cost savings has been calculated by reducing the size of a component, despite using more expensive material. For example the Front Rotor/Drum and Shield subsystem shows a savings for the caliper subsystem and a modest increase in the cost of the rotor and shield. Some of the cost savings here is due to reducing the size of the system (scaling to the 2008 Toyota Prius). However, there would still be a weight savings (albeit lower) if the conventional cast iron materials were used and downsized to the 2008 Toyota Prius – this is the likely outcome in a real automotive environment. Given the option to choose a more expensive, exotic, untested system that saves significant weight versus a conventional low cost system that saves less weight, it seems like an OEM would choose the conventional solution. In this case the suggested weight savings are technically possible but would never happen in a practical automotive environment.

[Richman] A review of cost development for reduced mass sheet product should be reviewed. Current model would lead to de-selecting some low mass sheet based solutions due to unrepresentative cost assessment.

[OSU – Kristina Kennedy] Table 1.7.1: NVH Results Summary. The "Weight Test Condition" and "Weight BIW" are ALSO outside of limits (> 5%), but not noted in results. Only those highlighted in red are noted as "failures". All failures (> 5%) should be called out specifically since that was their target.

[OSU – Tony Luscher] There are many typos and fragmented sentences in these sections. These should be corrected. Bookmark references do not all work.

5. CONCLUSION AND FINDINGS	COMMENTS
Are the study's conclusions adequately backed up by the methods and analytical rigor of the study?	**[Joost]** Yes. I identified various areas where the analysis or report could be improved, but overall the methods used here provide a credible and reasonable estimate of the potential for weight savings. Based on some of my earlier comments I would expect that actual costs to be somewhat higher than predicted in this study. Additionally, real vehicles share components across platforms so using vehicle-specific components would add additional cost. It is possible that the cost curve would cross $0/lb-saved at a lower total weight savings than suggested here. **[Richman]** Study conclusions and findings are well supported by the analytical rigor, tools used and expertise of the organizations involved. EDAG conducted a detailed reverse engineering process to define baseline Venza component mass and structural performance. The process included: vehicle teardown, identification of component mass and material composition and component scanning to create digital models of structural components. Part connections (spot weld, seam weld, laser weld), dimensions (location, weld diameter, weld length), and characteristics were documented during scanning process. Material property data was obtained by coupon testing part samples. Scan data, part weight and material information were used to create a CAE model of the vehicle structure. A finite element (FE) model was created from the CAE model using ANSA mesh software. The FE model was used to evaluate NVH characteristics (bending, torsion, modal analysis) of the structure using NASTRAN. Model results were compared and calibrated with analytical test results to establish the baseline analysis model. CAE crash performance simulations (LS-DYNA) were conducted to verify model correlation with actual vehicle crash test performance in National Highway Traffic Safety Association (NHTSA) regulatory performance testing. Model results were calibrated to actual Venza crash performance data. The correlated crash model became the baseline crash model for the remaining load cases. EDAG is widely recognized as highly competent and experienced in vehicle structural modeling, NVH and collision simulation and structural engineering. LS-Dyna, MSC/Nastran and ANSA are valid and widely-used simulation tools, commonly used and accepted within the engineering community and the industry to perform this analysis. The approach used by EDAG to develop Venza structural models is a state-of-the art methodology utilizing proven modeling tools. Structural models developed in this project were calibrated to physical test results of actual vehicle structures. Simulation results appear reasonable and logical, building confidence in the fidelity of the analysis. Models have excellent correlation to actual vehicle performance. FMVSS crash results are consistent with bending and torsional stiffness properties. There is no apparent reason to question results of this modeling and simulation effort. These models would be expected to be valid for comparison of design alternatives. These models would be expected to provide reliable assessments of NVH and collision performance of the Venza structure.

	Report conclusions with regard to NVH and collision performance do not substantially overreach the capability and results of the analysis. In some relatively minor areas, assessment to of the "optimized" structure is not fully supported by generally recognized measures of structural performance. These few relatively uncertainties do not diminish the overall conclusion that the modeling and simulation efforts are well done and the major conclusions are valid useable. **[OSU – Glenn Daehn]** At the time of review, Section G "Conclusions and Recommendations" is unavailable. We hope that in this section FEV will point out the most promising actions that auto makers may take to reduce mass while conserving cost. **[OSU – Tony Luscher]** The report's conclusions are based on sound engineering principals of good rigor.
Are the conclusions about the design, development, validation, and cost of the mass-reduced design valid?	**[Joost]** Yes. As above, there is reason to believe that the true cost will be higher than predicted here, but I think this analysis provides a useful estimate. **[Richman]** Design development and validation conclusions are well supported in this study. Cost model is valid and cost conclusions are generally realistic. There appears to be a systematic discrepancy in cost modeling of low mass sheet products. This discrepancy has a minor impact on conclusions of this study. **[OSU – Glenn Daehn]** This study is carefully crafted with excellent attention to engineering detail. It is important to note that the overall environment for vehicle design, manufacture and use is continually changing. See the "Additional Comments" section of this document for further development of the implications of this. **[OSU – Tony Luscher]** This reviewer found the overall work to be thorough and well documented. Therefore the conclusions are well supported and validated by the engineering and modeling in the report.
Are you aware of other available research that better evaluates and validates the technical potential for mass-reduced vehicles in the 2017-2020 timeframe?	**[Joost]** I have not seen a report as thorough as this. There are several examples of resources that provide useful information regarding weight reduction potential such as Cheah, L.W. Cars on a Diet: The Material and Energy Impacts of Passenger Vehicle Weight Reduction in the U.S. Joshi, A.M. Optimizing Battery Sizing and Vehicle Lightweighting for an Extended Range Electric Vehicle Lutsey, N. Review of technical literature and trends related to automobile mass-reduction technology **[Richman]** This reviewer has monitored automotive mass reduction studies in North America and Europe for several years. This study is the best evaluation of mass reduction opportunities and associated costs this reviewer has seen. **[OSU – Glenn Daehn]** There are no more comprehensive or detailed studies that we are aware of. This is an excellent compilation of ideas for practical vehicle mass reduction and fuel efficiency improvement.

	[OSU – Tony Luscher] None found.

ADDITIONAL COMMENTS:

[OSU – Glenn Daehn] The study does an excellent job within its scope. As this reviewer sees the scope, the driving question is: Can a well-engineered relatively modern vehicle (2010 Toyota Venza) have its mass reduced by 20% or more, without significant cost penalty and while maintaining crashworthiness. The answer to that question is a clear "YES". Further, this conclusion is backed with rigor and attention to detail. This is in my mind, very clear, well-done and technically rigorous.

This reviewer believes that there are a few other important questions that were not asked. These include:

1) Will the proposed changes in design pose any other important risks in manufacture or use? This can include: warranty exposure, durability, increased noise, vibration and harshness, maintenance concerns, etc., etc.

2) Will increasing regulatory constraints and/or consumer expectations require increases in vehicle mass, opposing the mass reductions provided by the improved practices outlined in this study?

Both these issues will make vehicle light weighting more difficult than this report suggests. With respect to issue 1) there are a number of materials and design substitutions that may produce concerns with durability, manufacturability and warranty claims. For example when substituting polymers for metals, there are new environmental embrittlement modes that may cause failure and warranty claims. Also, if substituting aluminum for steel, multi-material connections may cause galvanic corrosion problems. When using thinner sheets of higher strength steel, formability may be reduced and springback may be more problematic. Both these issues may preclude the use of the stronger material with a similar design and may also increase the time and cost involved with die development. Lastly there are always risks in any new design. For example, when using new brake designs, pad wear and squeal may be more pronounced. All of these issues may cause a manufacturer to avoid the new technology.

There are also local constrains on material thicknesses that are outside this review methodology. For example while a roof rail may meet crash and stiffness criteria, it may deflect excessively or permanently if a 99th percentile male pulls on it exiting a vehicle. Similarly, parking lot and hail dents may require greater thickness gauges than this study may indicate.

The problem of vehicle light-weighting and improved fuel economy is seen here through the lens as being an engineering problem to be solved. And in many ways it is. However, the forces of consumer expectations and behaviors are an essential part of the problem. As an interesting anecdote, the Model T Ford had a fuel economy of about 20 MPG, very similar to the average fuel economy of vehicles on the road today. No modern consumer would choose a Model T for many obvious reasons. Our cars have become extensions of our living rooms with many electrical motors driving windows, mirrors, seats and complex and costly HVAC and infotainment systems. All of these systems add weight, complexity and use power. Further increased complexity of engines to improve emissions and increase fuel economy has increased engine mass.

This study shows that with good engineering we can reduce vehicle mass of an existing vehicle by 20% with little to no increased cost or adverse consumer reaction. Based on our current course, it is just as likely this benefit will be taken by improved mandated safety and emission features as well as improved creature comforts.

Much can be gained through enlightened consumer behavior (assuming the average consumer wants to reduce energy use and carbon footprint). While much of this is outside the scope of this report, in particular it would be useful if the average consumer would understand the lifecycle environmental impacts of vehicle choice and of varied vehicle design, and would adopt a ‘less is more’ ethic and see their transportation systems as that, simply transportation. A more minimalist ethic that would move against increasing vehicle size and the creep of multiple motors for seats, mirrors, windows, etc., would reduce acquisition cost, maintenance cost and energy cost. This is in addition, of course, to the usual advice to reduce fuel consumption (limit trips, limit speed, tire pressure, carpooling, etc. etc.) is still valuable.

It should also be noted that there are other potentially low-cost actions that can be easily adopted to reduce greenhouse gas emissions and reduce dependence on foreign oil. One of these is widespread adoption of natural gas fuels for personal transportation. Use of Compressed Natural Gas (CNG), has lower fuel cost than gasoline, produces less pollution and greenhouse gas emission per energy used, and requires only very modest changes to conventional vehicle architecture, with no significant increases in complexity. The cost and size of a CNG tank and the development of refueling infrastructure are the main barriers to adoption of a technology that could have important and positive societal benefits.

This is an excellent and useful study. It is important however to recognize the limitations of purely engineering solutions. And even within the engineering realm, there are many reasons that the implementation of the solutions in this paper study will require much effort to become part of mainstream automobiles.

[OSU – Kristina Kennedy] With respect to measuring powertrain CG and moment of inertia, notes “oscillation as an undamped” condition. Just confirming, this means no dynamic dampers were used in the engine room modeling? Is this realistic? Acceptable practice?

6. OTHER POTENTIAL AREAS FOR COMMENT	COMMENTS
Has the study made substantial improvements over previous available works in the ability to understand the feasibility of 2017-2020 mass-reduction technology for light-duty vehicles? If so, please describe.	**[Joost]** Yes. Other studies have reviewed the mass saving potential of various technologies individually, or imagined the impact of combining many technologies. However I am not aware of a design study that takes an existing vehicle and assesses each piece with the thoroughness used here. **[Richman]** Yes. Overall objectives) of the project (20% mass reduction, less than 10% cost increase) are timely and consistent with industry interests in the short term. Retaining the OEM designed and field proven body structure eliminates uncertainty related to evaluation of novel and un-proven structures. This analysis clearly identifies body mass reduction achievable with new and near term future grades of HSS and AHSS. An exhaustive list of non-body mass reduction concepts are evaluated in this study. Some of these technologies are well known and understood in the industry, other are new, creative and innovative. Each technology is reviewed from an engineering and cost perspective and scaled to the specific application. The technology selection process was analytical, rigorous and un-biased. Majority of technologies selected are appropriate for the mass reduction and cost objectives of the project. This information provides helpful information to industry engineers considering mass reduction alternatives for other vehicle programs. **[OSU – Glenn Daehn]** Without question. The only similar study also targeted the Venza. This provides much additional analysis and many additional ideas beyond the Lotus study. **[OSU – Glenn Daehn]** The major contribution of this study was to pull together and evaluate all of the current proven concepts that are applicable to a lightweight vehicle in the 2017-2020 timeframe. It is successful in this regard.
Do the study design concepts have critical deficiencies in its applicability for 2017-2020 mass-reduction feasibility for which revisions should be made before the report is finalized? If so, please describe.	**[Joost]** No – I would not say that any deficiencies here are "critical". **[Richman]** Major findings of the project appear practical for implementation by 2017-20. Two technologies selected for inclusion in the final vehicle concept appear "speculative" for 2017-20, Co-cast magnesium/aluminum block and MMC brake rotors. Both technologies are identified as "D" level for implementation. Designing, developing and establishing production capacity for a new engine block is a time consuming and costly process. Investments would be required by OEM manufactures and casting suppliers. It is not clear the level of human resources

	and capital investment required for this technology could be justified the basis of the mass reduction potential of (7 Kg). Aluminum MMC brake rotors were selected for inclusion in the final vehicle configuration. In the judgment of this reviewer, this technology is the most speculative technology selected for the final vehicle configuration. MMC rotors have been in development for over 25 years. Development experience with these rotors has generally not been acceptable for typical customer service. The minimum mass MMC rotor design selected in this project is a radical (by automotive standards) multi piece bolted composite design with an MMC rotor disc. This design is identified as a "D" rated technology and a mass savings of 9 Kg. The aluminum MMC portion of the mas reduced rotor assembly would be regarded as "speculative" at this time. Cost models used to assess low mass sheet product may have some questionable assumptions. For this project, adjustment in the cost model is unlikely to influence he material selection process. Correction in this area would have a greater impact on technology screening and selection to achieve mass reductions above 20%. **[OSU – Glenn Daehn]** Conclusions and recommendations section is missing. This is an important opportunity to reinforce the most important actions that automakers can take. The report still lacks the ability to trace some technical details all the way back to the source. This is described previously.
Are there fundamentally different lightweight vehicle design technologies that you expect to be much more common (either in addition to or instead of) than the one Lotus has assessed for the 2017-2020 timeframe (Low Development)?	**[Joost]** Not in the 2017-2020 time frame. Switching to an advanced steel dominant body with a few instances of Mg and Al seems appropriate for the time frame. The considerable use of lightweight plastics is also in line with my expectations for available technology in this time frame. **[Richman]** No. The result of his study is a logical and cost effective advancement in the development of more efficient passenger vehicles for the 2017-20 time frame. **[OSU – Glenn Daehn]** It seems apparent that vehicles are moving more and more to multi-materials construction and as we move away from steel-based construction, joined primarily by resistance spot welds, there will be need for additional joining technologies. Laser welding is mentioned as one possible replacement for resistance spot welds, but it is expected that over time there will be much more use of structural adhesives, self piercing rivets, conformal joints and other joining strategies for the BIW.
Are there any other areas outside of the direct scope of the analysis (e.g., vehicle performance, durability, drive ability, noise, vibration, and hardness) for which the mass-reduced vehicle design is likely to exhibit any compromise	**[Joost]** All of the areas listed here are somewhat concerning, but given the switch to fairly conventional materials I believe that durability, driveability, and NVH should be not be a significant issue. Detailed analysis work in these areas would likely require some redesign which may add cost or weight, but I don't think it would be overwhelming. **[Richman]** None identified by this reviewer. **[OSU – Glenn Daehn]** Yes. There are many other details with respect to nuances of customer expectations, durability,

from the baseline vehicle?	warranty risks and manufacturability that are discussed elsewhere in this review. This does not diminish the importance of this great work. Just points out there are an enormous amount of detailed work required to build an automobile, and the job is not finished.

ADDITIONAL COMMENTS:

[OSU – Kristina Kennedy] Overall, well-written and well-done…my conclusion (which they also reached) is YES, NVH WILL SUFFER when replacing steel with HSS and will OF COURSE make the vehicle MORE STIFF.

[Simunovic] The FEV report is quite exhaustive. I would suggest that it be released in a hypertext format that can allow different navigation paths through it. Also, the dynamic Web-based technologies can be used for effective model documentation, presentation and distribution. I would also recommend that more details on the actual optimization process, including the objective function specification, and the final consolidation of the model, be added to the documentation.

4. References

FEV. *Light-Duty Vehicle Mass-Reduction and Cost Analysis – Midsize Crossover Utility Vehicle*. 2012.

Appendix A: Resumes of Peer Reviewers

William Joost

3300 East West Hwy Apt 534 william.joost@gmail.com Mobile: (202) 674-8900
Hyattsville, MD 20782

Education:

Working toward Ph.D. Materials Science and Engineering Est. May 2014
University of Maryland, College Park, MD.

M.S. Materials Science and Engineering May 2009
Arizona State University, Tempe, AZ.

B.S. Materials Engineering May 2005
Rensselaer Polytechnic Institute (RPI), Troy, NY.

Employment Experience:

General Engineer Jan. 2010-Present
U.S. Department of Energy, Washington, DC

- Serves as the Technology Area Development Manager for the Lightweight Materials portfolio in the Vehicle Technologies Program (VTP). Supports research on improving properties, manufacturability & joining, and modeling & simulation of advanced steels, aluminum alloys, and magnesium alloys for automotive applications.
- Directs a budget of ~$10M per year supporting research in structural metals for conventional and electric drive vehicles. Manages projects that involve teams from diverse disciplines including materials science, mechanical engineering, computer science, and physics. Supports interaction between participants from industry, national laboratories, and academia.
- Develops solicitation topics, coordinates proposal reviews, and manages project performance. Participates in the formulation, justification, tracking, and execution of the Lightweight Materials budget. Manages publication of Annual Report for the Lightweight Materials sub-program. Coordinates activities in metals with the Office of Advanced Manufacturing, U.S Department of Energy.
- Led the light-duty vehicles portion of the 2011 VTP Advanced Materials Workshop. Used the industry-supported results to develop new program goals, establish weight reduction targets for vehicle systems, and draft road mapping priorities.

Manufacturing Engineer/Equipment Engineering Supervisor Apr. 2008-Dec. 2009
Heraeus Materials Technology LLC, Chandler, AZ

- Managed the Equipment Engineering Team, responsible for maintaining functionality, capability, and uptime of ~180 pieces of capital equipment including high power, high vacuum, and precision machining tools.
- Created a high yielding process technique for Pt-containing alloys, saving more than $500,000 per year in refining costs
- Developed vacuum induction melting (VIM) and hot rolling processing techniques for specialty Co, Ni, and Fe based alloys and intermetallic materials
- Introduced a scrap metal recycling process for machining chips of Co and Pt based alloys, reducing scrap costs by more than $40,000 per month

Process Engineer/Manufacturing Engineering Production Supervisor Oct. 2005-Apr. 2008
Heraeus Materials Technology LLC, Chandler, AZ

- Managed a 16-person rolling team across four shifts
- Developed a stress/strain model of the hot rolling process which included equipment behavior and material characteristics
- Modeled material properties as a function of alloy and ingot dimensions to automate roll schedule creation
- Applied Design of Experiments methodology in melting and hot rolling processes to identify significant process factors and improve yields on high value sputtering targets

Research Experience:

Graduate Researcher in Ph.D. program, Materials Science and Engineering — Aug. 2010 - Present

University of Maryland, College Park, MD

- Exploring the microstructural-scale deformation behavior of Ti alloys using computational materials science techniques
- Developing finite element models (ANSYS) of Ti microstructures and determining the impact of grain interaction stresses on the deformation mechanisms during creep

Graduate Researcher in M.S. program, Materials Science and Engineering — Jan. 2007-May 2009

Arizona State University, Tempe, AZ

- Determined sputtering recipes for optimal deposition of textured Ru films in perpendicular magnetic recording media
- Characterized the effects of CoCrX alloy seed layers for Ru in perpendicular magnetic recording media by X-ray diffraction, Rutherford backscattering, atomic force microscopy, and transmission electron microscopy
- Demonstrated improved coherency at the interface of Ru films deposited on CoCrV seed layers by calculation of Ru film strain energy

Publications and Presentations

1) Joost, W., Das, A., Alford, T.L. "Effects of varying CoCrV seed layer deposition pressure on Ru crystallinity in perpendicular magnetic recording media" *Journal of Applied Physics*, **106**, 073517 (2009).

2) Joost, W. “Lightweight Materials for Vehicles: Needs, Goals, and Future Technologies.” Invited presentation at the 47th Sagamore Army Materials Research Conference on Advanced Lightweight Metals Technology, St. Michaels, MD, 06/17/2010.

3) Joost, W. “Lightweight Materials for Vehicles: Needs, Goals, and Future Technologies.” Invited keynote presentation at the 3rd Annual Advanced Lightweight Materials for Vehicles conference, Detroit, MI, 8/11/2010.

4) Joost, W. “Materials Development for Vehicle Weight Reduction and the Impacts on Energy Efficiency.” Invited keynote presentation at the Materials Science and Technology (MS&T) 2011 conference, Columbus, OH, 10/18/2011.

GLENN S. DAEHN

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The Ohio State University
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EDUCATION:

STANFORD UNIVERSITY — Palo Alto, CA
Ph.D., Materials Science & Engineering, 1988.

STANFORD UNIVERSITY — Palo Alto, CA
M.S., Materials Science & Engineering, 1985.

NORTHWESTERN UNIVERSITY — Evanston, Illinois
B.S. (departmental honors), Materials Science & Engineering, 1983.
Received Gotaas Award for outstanding undergraduate research.

EXPERIENCE:

11/87-pres — Professor (1996-pres), Assoc, Asst. OHIO STATE UNIVERSITY, Columbus, OH
Teaching and research focus on mechanical behavior and processing of structural materials. High velocity sheet metal forming and mechanical behavior of composites are focus areas.

7/04-10/07 — V. P. Technology EXCERA MATERIALS GROUP — Worthington, OH
Co-founder (1993) developer/manufacturer ceramic composites by reactive processing. Sabbatical in 04-05 academic year. OSU-based, technology now commercialized by Fireline, Inc. & Rex Materials Group.

1/97-7/97 — Visiting Scientist, ROCKWELL SCIENCE CENTER, — Thousand Oaks, CA
Sabbatical period; engaged in manufacturing and materials performance issues.

9/83-11/87 — Research Assistant, STANFORD UNIVERSITY, — Palo Alto, CA
Dissertation under Oleg D. Sherby: laminated composites of superplastic ultrahigh carbon steel and stainless steel.

SELECT PROFESSIONAL AWARDS & ACTIVITIES:

2010 – pres	Executive Director; Honda-Ohio State Partnership
2010	Named Fellow ASM International
2010 -	Member, Board of Trustees, ASM Materials Education Foundation.
2010-	Chair, International Impulse Forming Group
2009 - pres	Director, Ohio Manufacturing Institute – New organization focused on linking industry and Ohio's research assets
2009	Innovators Award of Ohio State College of Engineering
2008-	Founding Vice-Chair, International Impulse Forming Group
2007	ASM Jacquet-Lucas Award for Excellence in Metallography.

2002-3	Served on National Research Council Committee on “Use of Lightweight Materials in 21st Century Army Trucks”
1996	One of 13 invited speakers at second National Academy of Engineering Frontiers of Engineering Meeting
1995-1997	Chair, TMS Shaping and Forming Committee
1995	Named Mars G. Fontana Professor of Metallurgical Engineering.
1992	National Young Investigator of National Science Foundation.
1992	Army Research Office Young Investigator Award.
1992&’00, 04	Lumley Research Award of Ohio State University College of Engineering.
1992	Robert Lansing Hardy Gold Medal of TMS, recognizing outstanding promise in the broad field of metallurgy.
1990	ASM Marcus A. Grossmann Young Author Award, for "Deformation of Whisker-Reinforced MMC's Under Changing Temperature Conditions".

SELECTED RECENT PUBLICATIONS

“Creep Behavior and Deformation Mechanisms for Nanocluster-Strengthened Ferritic Steels”, M. C. Brandes, L. Kovarik, M. Miller, G. S. Daehn and M. J. Mills, in press: *Acta Materialia (*2011).

“Predictive Mechanism for Anisotropy Development in the Earth’s Inner Core”, D. M. Reaman, G. S. Daehn and W. R. Panero, accepted in *Earth Planetary Science Letters* (2011).

“Dislocation Mediated Time-Dependent Deformation in Crystalline Solids”, M. J. Mills and G. S. Daehn, Chapter in: *Computational Methods for Microstructure-Property Relationships*, S. Ghosh and D. M. Dimiduk, editors, Springer Science, 311-363 (2011).

“Energy Field Methods and Electromagnetic Metal Forming”, G. S. Daehn, Chapter 18 in: *Intelligent Energy Field Methods and Interdisciplinary Process Innovations,* Wenwu Zhang, Editor, CRC Press, 2011, pp. 471-504.

“Production of Low-Volume Aviation Components Using Disposable Electromagnetic Actuators” Steven Woodward, Christian Weddeling, Glenn Daehn, Verena Psyk, Bill Carson, A. Erman Tekkaya, *Journal of Materials Processing Technology*, **211**, Iss. 5, pp. 886-895, (2011).

“Electromagnetic Impulse Calibration of High Strength Sheet Metal Structures”, E. Iriondo, M. A. Gutiérrez, B. González, J. L. Alcaraz and G. S. Daehn, *Journal of Materials Processing Technology*, **211**, Iss. 5, pp. 909-915, (2011).

“Simulation and Instrumentation of Electromagnetic Compression of Steel Tubes”, A. Vivek, K-H Kim, and G. S. Daehn, *Journal of Materials Processing Technology*, **211**, Iss. 5, pp. 840-850, (2011).

Selected Patents and Applications

“Low Temperature Spot Impact Welding Driven Without Contact”, Glenn D. Daehn and John C. Lippold. US Patent 8084710, Issued December 27, 2011.

“Electromagnetic Actuator for Multiple Operations”, Glenn S. Daehn, PCT Applicaton: PCT/US08/61066, Filed 4/19/08.

“Driver Plate for Electromagnetic Forming of Sheet Metal”, John R. Bradley and Glenn S. Daehn, US Patent Application 2009/0090162, Published 4/9/09.

“Electromagnetic Metal Forming” (Uniform Pressure Actuator), G. S. Daehn, U. S. Patent, 2,069,756, Issued 7/4/06.

“Electromagetic Formation of Fuel Cell Plates” John, R. Bradley, James G. Schroth and Glenn S. Daehn, U.S. Patent 7,076.981, Issued 7/18/2006.

“High Velocity Forming of Local Features Using a Projectile”, G. S. Daehn, U. S. Patent 7,000,300, Issued 2/21/06.

“5000 series alloys with improved corrosion properties and methods for their manufacture and use”, M. C. Carroll, M. J. Mills, R. G. Buchheit, G. S. Daehn, B. Morere, P. Kobe, and H. S. Goodrich, US Patent Application 10/628579, published 5/13/04.

Courses Developed and Recently Taught:

Developed: Engineering 198a / “Engineering, Manufacturing and the Creation of Wealth”

Developed: MSE 605: Quantitative Introduction to Materials Science and Engineering
MSE 581.02: Materials Science Lab II (Junior Level)

MSE 765: Mechanical Behavior of Materials

MSE 863: Time Dependent Deformation of Solids

MSE 561 Mechanical Behavior of Materials

Kristina Kennedy

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EDUCATION

THE OHIO STATE UNIVERSITY — **Columbus, OH**
Master of Business Administration — August 2008

UNIVERSITY OF IOWA — **Iowa City, IA**
Bachelor of Science, Mechanical Engineering — December 2000

EXPERIENCE

THE OHIO STATE UNIVERSITY — Columbus, OH
Business Development Manager, Ohio Manufacturing Institute — Aug. 2010 - Present

- Coordinate collaborative R&D opportunities, including tracking possible opportunities, assembling multi-disciplinary teams, and assisting with proposal development in order to develop and improve the operation, visibility and effectiveness of OMI
- Successfully secured $100K+ seed funding and developed related procedures and documentation in order to launch Co-Located Internship Program in March 2011 to deploy OSU students to industry partners as technology transfer mechanisms within commercially-expected time-scales.
- Efficiently manage inquiries of potential customers of research and development services; develop and sustain customer satisfaction through new survey mechanism

GREIF — Delaware, OH
Regional Marketing Manager (Midwest) — Nov. 2008 – Oct. 2009

- Effectively managed cross functional engineering / marketing new product development team to ensure timely and effective roll out of earth-friendly green consumer product line.
- Key member of competitive intelligence team for green product line in charge of seeking out competitor product offerings, customer base, sales strategy and sales channels in order to gain valuable competitive knowledge, create value added reports of findings, and make sales / strategy recommendations to upper management.
- Oversaw and implemented effective go-to-market pricing strategies for all product lines based on deep analysis of current market indices, close analysis of raw material prices, and segmentation of targeted customer base.

THE OHIO STATE UNIVERSITY — Columbus, OH
Assistant Director – Outreach — Jan. 2006 – Oct. 2008

- Developed, managed and successfully executed all aspects of engineering outreach programming for the College of Engineering in order to foster educational outreach initiatives and expand the recruitment candidate pool.
- In conjunction with Math and Science Departments, developed targeted retention strategy involving special activities, student involvement workshops, and free tutoring sessions which resulted in ~15% increase in retention of undergraduate students.
- Fostered relationships with corporate sponsors and community partners in order to cultivate funding for STEM outreach and education initiatives.

HONDA RESEARCH & DEVELOPMENT — Raymond, OH
Quality Engineer III — Jan. 2001 – Jan. 2006

- Co-leader of special project team which successfully and efficiently developed and rolled out company-wide Access database making competitive information, quality information, and warranty data easily and quickly accessible to over 1100 Honda associates.
- Managed cross functional joint design and test teams in order to identify vehicle problem items and develop cost effective, timely countermeasures for implementation.

- Project Manager of special market investigation teams that saved the company over $750K in future warranty costs based on successful implementation of design changes on models including Acura TL and Honda Pilot.

LEADERSHIP

Society of Women Engineers, Central Ohio Section

- Outreach & Education Chair — Jun. 2010 – Present
- President — Jun. 2008 – Jun. 2010
- Marketing / Communications Chair — Jun. 2007 – Jun. 2008
- Member — Sept. 1996 - Present

Society of Manufacturing Engineers

- Executive Board Member — December 2011 - Present
- Member — Sept. 2010 – Present

Women in Engineering Advocacy Network (WEPAN)

- Communications Committee Co-Chair — Jun. 2007 – Jun. 2008
- Distinguished Service Award (Communications Committee) — Jun. 2008

Engineering Education Insights Magazine

- Featured Monthly Columnist — Aug. 2007 – Jun. 2008

Toastmasters, Honda R&D Section

- Vice President — Jan. 2005 – Dec. 2005

DOUGLAS A. RICHMAN

1660 Lochridge
Bloomfield Hills, Michigan 48302

Business: 248.352.4630 X 220
E-mail: doug.richman@ep.kaiseral.com

KAISER ALUMINUM FABRICATED PRODUCTS, LLC **2002 - PRESENT**

VP - Engineering and Technology

Lead engineering group providing engineering support to customers and Kaiser plants serving technically demanding automotive and industrial markets. Assist customer engineering organizations with product design guidance, metallurgical engineering and design for manufacturing. Support customer design and development of innovative aluminum products to satisfy new end product requirements. Advanced process strategic planning supporting future product requirements.

Aluminum Association

Kaiser technical representative to the Aluminum Association and ASTM.

Aluminum Association – Member - Aluminum Transportation Group (ATG)
Board of Directors – ATG
Chairman – Technology Work Group (ATG)
Member – Product Standards and Data Committee
Steering Committee – Sustainability Work Group

BOSAL INTERNATIONAL, Ann Arbor, Michigan **1999-01**

President North American Operations

P & L responsibility Bosal North America: 5 plants and Tech Center. Automotive exhaust system manufacturing and sales in the US, Canada and Mexico. North American sales of $100+MM
Member, Board of Directors - Bosal International

KAISER ALUMINUM CORPORATION

VP & General Manager Kaiser Automotive Castings and Kaiser K-Fab Operations **1996-99**

P & L responsibility for Kaiser Foundry $18MM and K-Fab, extrusion fabrication $8MM businesses.

ALCAN ALUMINUM CORPORATION1988-96

VP - Alcan Automotive Castings / General Manager Altek **1993-96**

Business development and P&L responsibility for Altek, a 50/50 Joint Venture between Alcan and Teksid (Fiat),sales $30MM. International commercialization of cast aluminum automotive control arms.

General Manager – Automotive Castings Division- North America **1992-93**

P & L responsibility, foundry producing automotive cylinder heads and intake manifolds. Expanded product focus to automotive control arms using innovative casting process technology.

Director - Engineering and Automotive Business Development **1988-91**

Responsible for automotive market strategic planning and led product and process engineering support group. Business grew from start-up to over $100 MM in four years.

GENERAL MOTORS CORPORATION, Warren, MI **1969-88**

Manager Engine Development Chevrolet-Pontiac-Cadillac Group
Manager Chevrolet L-4 and V-6 Advanced Design
Senior Development Engineer – V-8 Engine Control Systems
Development Engineer – V-8 Truck Engine Control Systems
Passenger Fleet Planner – Chevrolet Fuel Economy Planning

System Design Engineer – GM Transportation Systems
Product Assurance Analyst – Engineering Staff
Manager – Chevrolet Military Vehicle Proving Ground Operations

PROFESSIONAL AFFILIATIONS:

MBA - University of Detroit – Finance and Operations Research
BSME - General Motors Institute

Registered Professional Engineer, Michigan

Society of Automotive Engineers
Co-Director – Light Materials Section

American Extruders Council

Aluminum Association
Aluminum Transportation Group (ATG) – Member (since 1990)
Member of the Executive Committee
Chairman – Technology Work Group
Aluminum Products and Standards Group – Member (since 1998)
Sustainability Work Group – Member (since 2009)

Advanced studies / Certifications
Ohio State Univ. (Fisher College) – Certified Lean Manager
MIT – Lean Manufacturing / Value Stream Management
Plante & Moran - Executive Leadership Forum
Goldradt Institute - Theory of Constraints Leader Certification
TMB - Kaizen Implementation

Srdjan Simunovic

Computational Engineering and Energy Sciences Group	865-771-9919
Computer Science and Mathematics Division	865-241-0381(fax)
Oak Ridge National Laboratory	simunovics@ornl.gov

Department of Civil and Environmental Engineering
University of Tennessee Knoxville

***Education*:**

University of Split, Croatia	Civil Engineering	B.S.	1988
Carnegie Mellon University, USA	Civil Engineering	M.S.	1991
Carnegie Mellon University, USA	Civil Engineering	Ph.D.	1993

***Professional Expertise*:**

My research expertise includes computational modeling of materials and structures, modeling of impact and armor materials, strain rate sensitivity of materials, high velocity loading tests, polymer composite materials manufacturing and crashworthiness, physics of fracture, and effect of size on material properties. Current projects involve development of the next generation multi-physics code for simulation of nuclear fuel and nuclear reactor thermomechanics problems, impact simulation of lightweight materials for transportation, and material design optimization for impact performance.

***Professional Experience*:**

2009 – Present	**Joint Faculty Appointment**, University of Tennessee and ORNL.
2004 – Present	**Distinguished Research Staff**, Computational Materials Science and Computational Engineering and Energy Sciences Group, ORNL.
1999 – 2003	**Group Leader**, Computational Materials Science Group, ORNL.
1998 – 2003	**Senior Research Staff**, Computational Materials Science Group, ORNL.
1994 – 1998	**Research Staff**, Computational Materials Science Group,ORNL.
1993 – 1994	**Postdoctoral Researcher**, Modeling and Simulation Group, ORNL.
1990 – 1993	**Graduate Researcher**, Department of Civil Engineering, Carnegie Mellon University, Pittsburgh, PA
1988 – 1990	**Junior Lecturer**, Civil Engineering Department, University of Split, Croatia

***Recent Journal Publications (2006+)*:**

1. Piro, M. H. A., Besmann, , T. M., Simunovic, S., Lewis, B. J., Thompson, W. T., Numerical verification of equilibrium thermodynamic computations in nuclear fuel performance codes Journal of Nuclear Materials, 414 (2011) pp. 399-407.
2. Wang, Y. L., Xu, H. B., Erdman, D. L.,Starbuck, M. J., Simunovic, S., Characterization of High-Strain Rate Mechanical Behavior of AZ31 Magnesium Alloy Using 3D Digital Image Correlation, Advanced Engineering Materials, 13 (2011) pp. 943-948.
3. Barai, P., Nukala, P. K. V. V., Sampath, R., and Simunovic, S., Scaling of surface roughness in perfectly plastic disordered media. *Physical Review E.* **82** (2010) 056116.
4. Mishra, S.K., Deymier, P.A., Muralidharan, K., Frantziskonis, G., Pannala, S. and Simunovic, S.

Modeling the coupling of reaction kinetics and hydrodynamics in a collapsing cavity. Ultrasonics Sonochemistry, 2010, 17(1), 258-265.

5. Nukala, P. K. V. V., Barai, P., Zapperi, S., Alava, M. J. and Simunovic, S., Fracture roughness in three-dimensional beam lattice systems. *Physical Review E.* **82** (2010) 026103.
6. Frantziskonis, G., Muralidharan, K., Deymier, P., Simunovic, S., Nukala, P. and Pannala, S. Time-parallel multiscale/multiphysics framework. Journal of Computational Physics, 2009, 228(21), 8085-8092.
7. Nukala, P. K. V. V., Zapperi, S., Alava, M. J. and Simunovic, S., Crack roughness in the two-dimensional random threshold beam model. *Physical Review E.* **78** (2008) 046105.
8. Nukala, P. K. V. V., Zapperi, S., Alava, M. J. and Simunovic, S., Anomalous roughness of fracture surfaces in 2D fuse models. *International Journal of Fracture.* **154** (2008) pp. 119 – 130.
9. Mishra, S.K., Muralidharan, K., Deymier, P.A., Frantziskonis, G., Pannala, S. and Simunovic, S. Wavelet-Based Spatial Scaling of Coupled Reaction-Diffusion Fields. International Journal for Multiscale Computational Engineering, 2008, 6(4), 281-297.
10. Mishra, S.K., Muralidharan, K., Pannala, S., Simunovic, S., Daw, C.S., Nukala, P., Fox, R., Deymier, P.A. and Frantziskonis, G.N. Spatiotemporal compound wavelet matrix framework for multiscale/multiphysics reactor simulation: Case study of a heterogeneous reaction/diffusion system. International Journal of Chemical Reactor Engineering, 2008, 6.
11. Muralidharan, K., Mishra, S.K., Frantziskonis, G., Deymier, P.A., Nukala, P., Simunovic, S. and Pannala, S. Dynamic compound wavelet matrix method for multiphysics and multiscale problems. Physical Review E, 2008, 77(2).

Synergistic Activities:

- US DOT FHWA sponsored projects: Development of Heavy Vehicle Models for Roadside Barriers
    - Finite Element Models for Semitrailer Trucks
        - http://thyme.ornl.gov/FHWA/TractorTrailer
    - Single-Unit Truck Heavy Vehicle Finite Element Model
        - http://thyme.ornl.gov/FHWA/F800WebPage
- US DOT NHTSA sponsored project:
    - Parametric Finite Element Model of Sport Utility Vehicle
        - http://thyme.ornl.gov/newexplorer
- US DOE Office of Energy Efficiency and Renewable Energy sponsored projects on lightweight materials technologies:
    - High Strain Rate Characterization of Magnesium Alloys
        - http://thyme.ornl.gov/Mg_new
    - Dynamic Characterization and Modeling of Advanced High Strength Steel
        - http://thyme.ornl.gov/ASP_Main
    - Development of material models for composite materials, fracture, and high strain rate deformation
        - http://thyme.ornl.gov/composites
    - Crashworthiness of Aluminum Intensive Vehicles

        - http://thyme.ornl.gov/audi
    - Steel Processing Properties and their Effect on Impact Deformation of Lightweight Structures
        - http://thyme.ornl.gov/aisi
- US DOE Office of Nuclear Energy:
    - Development of new multi-physics nuclear fuel simulation code AMP

Appendix B: Conflict of Interest Statements

Conflict of Interest and Bias for Peer Review

Background

Identification and management of potential conflict of interest (COI) and bias issues are vital to the successes and credibility of any peer review consisting of external experts. The questionnaire that follows is consistent with EPA guidance concerning peer reviews.[1]

Definitions

Experts in a particular field will, in many cases, have existing opinions concerning the subject of the peer review. These opinions may be considered bias, but are not necessarily conflicts of interest.

Bias: For a peer review, means a predisposition towards the subject matter to be discussed that could influence the candidate's viewpoint.

Examples of bias would be situations in which a candidate:

1. Has previously expressed a position on the subject(s) under consideration by the panel; or

2. Is affiliated with an industry, governmental, public interest, or other group which has expressed a position concerning the subject(s) under consideration by the panel.

Conflict of Interest: For a peer review, as defined by the National Academy of Sciences,[2] includes any of the following:

1. Affiliation with an organization with financial ties directly related to the outcome;

2. Direct personal/financial investments in the sponsoring organization or related to the subject; or

3. Direct involvement in the documents submitted to the peer review panel... that could impair the individual's objectivity or create an unfair competitive advantage for the individual or organization.

---

[1] U.S. EPA (2009). Science Policy Council Peer Review Handbook. OMB (2004). Final Information Quality Bulletin for Peer Review.

[2] NAS (2003). "Policy and Procedures on Committee Composition and Balance and Conflict or Interest for Committees Used in the Development of Reports" (www.nationalacademies.org/coi).

Policy and Process

- Candidates with COI, as defined above, will not be eligible for membership on those panels where their conflicts apply.

- In general, candidates with bias, as defined above, on a particular issue will be eligible for all panel memberships; however, extreme biases, such as those likely to impair a candidate's ability to contribute to meaningful scientific discourse, will disqualify a candidate.

- Ideally, the composition of each panel will reflect a range of bias for a particular subject, striving for balance.

- Candidates who meet scientific qualifications and other eligibility criteria will be asked to provide written disclosure through a confidential questionnaire of all potential COI and bias issues during the candidate identification and selection process.

- Candidates should be prepared, as necessary, to discuss potential COI and bias issues.

- All bias issues related to selected panelists will be disclosed in writing in the final peer review record.

Conflict of Interest and Bias Questionnaire

Lotus Mass-Reduction Report (Lotus 2) Peer Review

Instructions to Candidate Reviewers

1. Please check YES/NO/DON'T KNOW in response to each question.

2. If your answer is YES or DON'T KNOW, please provide a brief explanation of the circumstances.

3. Please make a reasonable effort to answer accurately each question. For example, to the extent a question applies to individuals (or entities) other than you (e.g., spouse, dependents, or their employers), you should make a reasonable inquiry, such as emailing the questions to such individuals/entities in an effort to obtain information necessary to accurately answer the questions.

Questions

1. Are you (or your spouse/partner or dependents) or your current employer, an author, contributor, or an earlier reviewer of the document(s) being reviewed by this panel?

   YES___ NO_X_ DON'T KNOW___

2. Do you (or you spouse/partner or dependents) or your current employer have current plans to conduct or seek work related to the subject of this peer review following the completion of this peer review panel?

   YES_X_ NO___ DON'T KNOW___

   I manage lightweight materials funding for the U.S. Department of Energy's Vehicle Technologies Program so I am currently supporting work in the area of vehicle weight reduction and I anticipate continued support for work in this area. I do not actually participate in any research or development in this area, though the Department of Energy does.

3. Do you (or your spouse/partner or dependents) or your current employer have any known financial stake in the outcome of the review *(e.g.,* investment interest in a business related to the subject of peer review)?

   YES___ NO_X_ DON'T KNOW___

4. Have you (or your spouse/partner or dependents) or your current employer commented, reviewed, testified, published, made public statements, or taken positions regarding the subject of this peer review?

YES_X_   NO___   DON'T KNOW___

As a DOE employee I often give technical talks and seminars where I discuss the importance of weight reduction for transportation energy reduction. I also frequently discuss the materials engineering details of vehicle weight reduction and express my opinions on the technical challenges and appropriate research targets.

5. Do you hold personal values or beliefs that would preclude you from conducting an objective, scientific evaluation of the subject of the review?

   YES___   NO_X_   DON'T KNOW___

6. Do you know of any reason that you might be unable to provide impartial advice or comments on the subject review of the panel?

   YES___   NO_X_   DON'T KNOW___

7. Are you aware of any other factors that may create potential conflict of interest or bias issues for you as a member of the panel?

   YES___   NO_X_   DON'T KNOW___

Acknowledgment

I declare that the disclosed information is true and accurate to the best of my knowledge, and that no real, potential, or apparent conflict of interest or bias is known to me except as disclosed. I further declare that I have made reasonable effort and inquiry to obtain the information needed to answer the questions truthfully, and accurately. I agree to inform SRA promptly of any change in circumstances that would require me to revise the answers that I have provided.

William Joost
Name

Signature   03/01/2012
             Date

Conflict of Interest and Bias Questionnaire

Lotus Mass-Reduction Report (Lotus 2) Peer Review

Instructions to Candidate Reviewers

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2. If your answer is YES or DON'T KNOW, please provide a brief explanation of the circumstances.

3. Please make a reasonable effort to answer accurately each question. For example, to the extent a question applies to individuals (or entities) other than you (e.g., spouse, dependents, or their employers), you should make a reasonable inquiry, such as emailing the questions to such individuals/entities in an effort to obtain information necessary to accurately answer the questions.

Questions

1. Are you (or your spouse/partner or dependents) or your current employer, an author, contributor, or an earlier reviewer of the document(s) being reviewed by this panel?

   YES___ NO_X_ DON'T KNOW___

2. Do you (or you spouse/partner or dependents) or your current employer have current plans to conduct or seek work related to the subject of this peer review following the completion of this peer review panel?

   YES_X_ NO___ DON'T KNOW___

   OSU has plans to do research on lightweight multi-material structures for automotive applications.

3. Do you (or your spouse/partner or dependents) or your current employer have any known financial stake in the outcome of the review *(e.g.,* investment interest in a business related to the subject of peer review)?

   YES___ NO_X_ DON'T KNOW___

4. Have you (or your spouse/partner or dependents) or your current employer commented, reviewed, testified, published, made public statements, or taken positions regarding the subject of this peer review?

   YES___ NO_X_ DON'T KNOW___

5. Do you hold personal values or beliefs that would preclude you from conducting an objective, scientific evaluation of the subject of the review?

   YES___ NO_X_ DON'T KNOW___

6. Do you know of any reason that you might be unable to provide impartial advice or comments on the subject review of the panel?

   YES___ NO_X_ DON'T KNOW___

7. Are you aware of any other factors that may create potential conflict of interest or bias issues for you as a member of the panel?

   YES___ NO_X_ DON'T KNOW___

Acknowledgment

I declare that the disclosed information is true and accurate to the best of my knowledge, and that no real, potential, or apparent conflict of interest or bias is known to me except as disclosed. I further declare that I have made reasonable effort and inquiry to obtain the information needed to answer the questions truthfully, and accurately. I agree to inform SRA promptly of any change in circumstances that would require me to revise the answers that I have provided.

Glenn Daehn______________
Name

________________________ 2-1-12__________
Signature Date

Conflict of Interest and Bias Questionnaire

Lotus Mass-Reduction Report (Lotus 2) Peer Review

Instructions to Candidate Reviewers

1. Please check YES/NO/DON'T KNOW in response to each question.

2. If your answer is YES or DON'T KNOW, please provide a brief explanation of the circumstances.

3. Please make a reasonable effort to answer accurately each question. For example, to the extent a question applies to individuals (or entities) other than you (e.g., spouse, dependents, or their employers), you should make a reasonable inquiry, such as emailing the questions to such individuals/entities in an effort to obtain information necessary to accurately answer the questions.

Questions

1. Are you (or your spouse/partner or dependents) or your current employer, an author, contributor, or an earlier reviewer of the document(s) being reviewed by this panel?

   YES___ NO_X_ DON'T KNOW__

2. Do you (or you spouse/partner or dependents) or your current employer have current plans to conduct or seek work related to the subject of this peer review following the completion of this peer review panel?

   YES_X__ NO___ DON'T KNOW___

   The Ohio State University has plans to focus research efforts on lightweight structures for automotive applications.

3. Do you (or your spouse/partner or dependents) or your current employer have any known financial stake in the outcome of the review *(e.g.,* investment interest in a business related to the subject of peer review)?

   YES___ NO_X_ DON'T KNOW___

4. Have you (or your spouse/partner or dependents) or your current employer commented, reviewed, testified, published, made public statements, or taken positions regarding the subject of this peer review?

   YES___ NO_X_ DON'T KNOW___

5. Do you hold personal values or beliefs that would preclude you from conducting an objective, scientific evaluation of the subject of the review?

   YES___ NO_X_ DON'T KNOW___

6. Do you know of any reason that you might be unable to provide impartial advice or comments on the subject review of the panel?

   YES___ NO_X_ DON'T KNOW___

7. Are you aware of any other factors that may create potential conflict of interest or bias issues for you as a member of the panel?

   YES___ NO_X_ DON'T KNOW___

Acknowledgment

I declare that the disclosed information is true and accurate to the best of my knowledge, and that no real, potential, or apparent conflict of interest or bias is known to me except as disclosed. I further declare that I have made reasonable effort and inquiry to obtain the information needed to answer the questions truthfully, and accurately. I agree to inform SRA promptly of any change in circumstances that would require me to revise the answers that I have provided.

Kristina Kennedy___________
Name

Kristina Kennedy
Signature

1-25-12________
Date

Conflict of Interest and Bias Questionnaire

Lotus Mass-Reduction Report (Lotus 2) Peer Review

Instructions to Candidate Reviewers

1. Please check YES/NO/DON'T KNOW in response to each question.

2. If your answer is YES or DON'T KNOW, please provide a brief explanation of the circumstances.

3. Please make a reasonable effort to answer accurately each question. For example, to the extent a question applies to individuals (or entities) other than you (e.g., spouse, dependents, or their employers), you should make a reasonable inquiry, such as emailing the questions to such individuals/entities in an effort to obtain information necessary to accurately answer the questions.

Questions

1. Are you (or your spouse/partner or dependents) or your current employer, an author, contributor, or an earlier reviewer of the document(s) being reviewed by this panel?

   YES___ NO_X_ DON'T KNOW___

2. Do you (or you spouse/partner or dependents) or your current employer have current plans to conduct or seek work related to the subject of this peer review following the completion of this peer review panel?

   YES_X__ NO___ DON'T KNOW___

   The Ohio State University has plans to be involved in lightweight structures research.

3. Do you (or your spouse/partner or dependents) or your current employer have any known financial stake in the outcome of the review *(e.g.,* investment interest in a business related to the subject of peer review)?

   YES___ NO_X_ DON'T KNOW___

4. Have you (or your spouse/partner or dependents) or your current employer commented, reviewed, testified, published, made public statements, or taken positions regarding the subject of this peer review?

   YES___ NO_X_ DON'T KNOW___

5. Do you hold personal values or beliefs that would preclude you from conducting an objective, scientific evaluation of the subject of the review?

   YES___ NO_X_ DON'T KNOW___

6. Do you know of any reason that you might be unable to provide impartial advice or comments on the subject review of the panel?

   YES___ NO_X_ DON'T KNOW___

7. Are you aware of any other factors that may create potential conflict of interest or bias issues for you as a member of the panel?

   YES___ NO_X_ DON'T KNOW___

Acknowledgment

I declare that the disclosed information is true and accurate to the best of my knowledge, and that no real, potential, or apparent conflict of interest or bias is known to me except as disclosed. I further declare that I have made reasonable effort and inquiry to obtain the information needed to answer the questions truthfully, and accurately. I agree to inform SRA promptly of any change in circumstances that would require me to revise the answers that I have provided.

Anthony Luscher___________
Name

Anthony Luscher 1/27/2012_____
Signature Date

Conflict of Interest and Bias Questionnaire

Lotus Mass-Reduction Report (Lotus 2) Peer Review

Instructions to Candidate Reviewers

1. Please check YES/NO/DON'T KNOW in response to each question.

2. If your answer is YES or DON'T KNOW, please provide a brief explanation of the circumstances.

3. Please make a reasonable effort to answer accurately each question. For example, to the extent a question applies to individuals (or entities) other than you (e.g., spouse, dependents, or their employers), you should make a reasonable inquiry, such as emailing the questions to such individuals/entities in an effort to obtain information necessary to accurately answer the questions.

Questions

1. Are you (or your spouse/partner or dependents) or your current employer, an author, contributor, or an earlier reviewer of the document(s) being reviewed by this panel?

   YES___ NO_X_ DON'T KNOW___

2. Do you (or you spouse/partner or dependents) or your current employer have current plans to conduct or seek work related to the subject of this peer review following the completion of this peer review panel?

   YES_X_ NO___ DON'T KNOW___

3. Do you (or your spouse/partner or dependents) or your current employer have any known financial stake in the outcome of the review *(e.g.,* investment interest in a business related to the subject of peer review)?

   YES_X_ NO___ DON'T KNOW___

4. Have you (or your spouse/partner or dependents) or your current employer commented, reviewed, testified, published, made public statements, or taken positions regarding the subject of this peer review?

   YES_X_ NO___ DON'T KNOW___

5. Do you hold personal values or beliefs that would preclude you from conducting an objective, scientific evaluation of the subject of the review?

   YES___ NO_X_ DON'T KNOW___

6. Do you know of any reason that you might be unable to provide impartial advice or comments on the subject review of the panel?

   YES___ NO_X_ DON'T KNOW___

7. Are you aware of any other factors that may create potential conflict of interest or bias issues for you as a member of the panel?

   YES___ NO_X_ DON'T KNOW___

Acknowledgment

I declare that the disclosed information is true and accurate to the best of my knowledge, and that no real, potential, or apparent conflict of interest or bias is known to me except as disclosed. I further declare that I have made reasonable effort and inquiry to obtain the information needed to answer the questions truthfully, and accurately. I agree to inform SRA promptly of any change in circumstances that would require me to revise the answers that I have provided.

D. A. Richman________
Name

DA Richman
____
Signature

Feb. 14, 2012______
Date

*** Submitted with attachment explaining “Yes” responses to questions 2, 3 and 4.

To: Brian P. Menard
SRA International, Inc.

Date: Feb. 14, 2012

From: Douglas A. Richman
Kaiser Aluminum Fabricated Products, LLC

Subject: <u>Peer Review - Peer Review FEV Light Duty Vehicle Report</u>

Brian,

This note is written to clarify "yes" responses on questions 2, 3 and 4 of the Conflict of Interest survey.

My current position is Vice President of Engineering and Technology for Kaiser Aluminum Fabricated Products, LLC. A portion of Kaiser business (<10%) is involved in the development of lightweight materials and semi-finished mill products for use in motor vehicles. My role at Kaiser Aluminum involves me in this work. It is the intention of Kaiser and myself, as employee, to continue active involvement in supplying highly engineered aluminum products to automotive industry customers. This may include commenting, reviewing, testifying, publishing, making public statements, or taking positions on the subject matter of this review. Both Kaiser Aluminum and I have a financial stake in the outcome of the review.

My responsibilities in Kaiser include representing Kaiser on the Aluminum Association – Aluminum Transportation Group (ATG) where I am a member of the ATG Executive Committee. The ATG actively develops and promotes aluminum weight reduction technologies in a number of transportation sectors including automotive. ATG efforts include funding third party weight reduction technology development and reporting resultant advancements to customer groups, government entities and trade media. As an ATG representative I am regularly involved in commenting, reviewing, publishing, making public statements, and taking positions on the subject matter of this review. The Aluminum Association and I have a financial stake in the outcome of the review.

From our discussion, understand that it is often the case in peer reviews that reviewers have a range of conflicts and biases, and that it is critical that these conflicts and biases be disclosed. I also understand that an independent, impartial, and expert panel should and will reflect the range of conflicts and biases. I agree to review the materials provided me in the most impartial, objective, and scientific manner possible.

Regards,

D. A. Richman

Conflict of Interest and Bias Questionnaire

Lotus Mass-Reduction Report (Lotus 2) Peer Review

Instructions to Candidate Reviewers

1. Please check YES/NO/DON'T KNOW in response to each question.

2. If your answer is YES or DON'T KNOW, please provide a brief explanation of the circumstances.

3. Please make a reasonable effort to answer accurately each question. For example, to the extent a question applies to individuals (or entities) other than you (e.g., spouse, dependents, or their employers), you should make a reasonable inquiry, such as emailing the questions to such individuals/entities in an effort to obtain information necessary to accurately answer the questions.

Questions

1. Are you (or your spouse/partner or dependents) or your current employer, an author, contributor, or an earlier reviewer of the document(s) being reviewed by this panel?

   YES___ NO_X_ DON'T KNOW___

2. Do you (or you spouse/partner or dependents) or your current employer have current plans to conduct or seek work related to the subject of this peer review following the completion of this peer review panel?

   YES___ NO_X_ DON'T KNOW___

3. Do you (or your spouse/partner or dependents) or your current employer have any known financial stake in the outcome of the review *(e.g.,* investment interest in a business related to the subject of peer review)?

   YES___ NO_X_ DON'T KNOW___

4. Have you (or your spouse/partner or dependents) or your current employer commented, reviewed, testified, published, made public statements, or taken positions regarding the subject of this peer review?

   YES___ NO_X_ DON'T KNOW___

5. Do you hold personal values or beliefs that would preclude you from conducting an objective, scientific evaluation of the subject of the review?

   YES___ NO_X_ DON'T KNOW___

6. Do you know of any reason that you might be unable to provide impartial advice or comments on the subject review of the panel?

   YES___ NO_X_ DON'T KNOW___

7. Are you aware of any other factors that may create potential conflict of interest or bias issues for you as a member of the panel?

   YES___ NO_X_ DON'T KNOW___

Acknowledgment

I declare that the disclosed information is true and accurate to the best of my knowledge, and that no real, potential, or apparent conflict of interest or bias is known to me except as disclosed. I further declare that I have made reasonable effort and inquiry to obtain the information needed to answer the questions truthfully, and accurately. I agree to inform SRA promptly of any change in circumstances that would require me to revise the answers that I have provided.

Srdjan Simunovic___
Name

____
Signature

2/28/2012_______
Date

Honesty and Service®

Appendix C: Peer Review Charge

Charge to Peer Reviewers of
Light-Duty Vehicle Mass-Reduction and Cost Analysis – Midsize Crossover Utility Vehicle

In developing programs to reduce greenhouse gas (GHG) emissions from light-duty highway vehicles, the U.S. Environmental Protection Agency's Office of Transportation and Air Quality (OTAQ) has to evaluate the safety of lightweighted automotive designs as well as the methods and costs of proposed technologies to achieve this design.

The 2012 study by FEV, *Light-Duty Vehicle Mass-Reduction and Cost Analysis – Midsize Crossover Utility Vehicle (FEV Report)* is a continuation (e.g., Phase 2 study) of the original Phase 1 Low Development study from Lotus Engineering. The report reviews the amount of mass reduction in the Low Development case ("20%") from the Lotus Engineering Phase 1 study. This is done through analysis of the assumptions for the Body-in-White (BIW), and through an up-to-date re-analysis of light weighting options for all of the other vehicle components of which the Lotus Engineering assumptions are a part. An in-depth cost evaluation of all technologies is included. The FEV Report consists of two parts: In the first part, FEV's contractor, EDAG, has designed and developed the BIW structure in CAE in order to demonstrate that it meets Federal Motor Vehicle Safety Standards (FMVSS) for Light-Duty Vehicles using LS-DYNA. The analysis includes materials, methods, and related costs to assembly and manufacturing. The second part of the report is an in-depth investigation of "other than BIW" vehicle systems based upon discussions with suppliers, Lotus Phase 1 report ideas, and FEV's experience and expertise.

You are being asked to review and provide expert comments on both parts of the FEV report, which you will be able to access via FEV's FTP site. This site will also provide you access to the CAE model, which you will review to ensure that the CAE code represents the information presented in the report, and related AVI files to allow you to review the modeling results. The written report supplies charts and figures of the results. If you have the FMVSS crash setups, then you may choose to run the unencrypted model in those scenarios; however, you are not required to do so. *Please Note: NHTSA staff has offered to assist you by providing FEA results or a configured input deck to relieve you from having to run the model. Should you choose to do this, SRA and EPA will coordinate between you and NHTSA.* You will also review the design and cost portions of the model. The cost part of the project is a bottom-up approach based on the specific vehicle systems including BIW, brakes, suspension, closures, and engine, and accounting for details of every cost factor.

EPA is seeking your expert opinion on the technologies utilized, methodologies employed, and validity of findings regarding the FEV report. The CAE modeling portion of the FEV report, written by EDAG, begins by comparing the baseline Toyota Venza model crash results with the actual Venza FMVSS crash results, and also compares the bending and torsional stiffness values. The report next presents the results of the CAE model when Lotus Engineering Phase 1 Low Development ideas are implemented, along with the corresponding NVH results. EDAG then takes on a new design for the BIW, utilizing its optimization program for components development given loads and other parameters, and presents NVH data and full vehicle crash simulation as well as manufacturing cost estimation. EDAG has not included material properties, forming techniques, or bonding techniques as the changes to the BIW outside of the steel family are minor.

EPA is also seeking your expert opinion on the technologies utilized, methodologies employed and validity of findings in areas "other than the BIW" for this mass reduced design. FEV has analyzed the Toyota Venza in a number of systems, sub systems, and sub sub-systems and has chosen a number of areas for mass reduction. Some of the ideas are taken directly from the Lotus Engineering Phase 1 report, and some are new. FEV presents a breakout of the mass within each system, the ideas considered and the ideas chosen in the system, use of the technologies in industry today, and their cost impact on vehicle production. FEV has approximately 4,000 cost spreadsheets containing details of the costing process. Although the report includes only a summary of these spreadsheets within an appendix, the spreadsheets themselves are available for review should you choose to do so. In addition to performing detailed cost breakout, FEV has also contacted suppliers to verify some of the cost estimates.

In your review of the report, EPA asks that you orient your comments, to the extent of your expertise and experience, toward the following five areas: (1) assumptions and data sources, (2) vehicle design methodological rigor; (3) vehicle crashworthiness testing methodological rigor (CAE only); (4) vehicle manufacturing cost methodological rigor; and (5) conclusion and findings. You should provide your responses in the table that is attached to this peer review charge, adding comments, as necessary, at the end of each section of the table.

This broad span of technical areas suggests that reviewers may well have much deeper technical expertise and experience in some areas and a working knowledge in others. As a result, the level of detailed technical review to be given by each reviewer might vary significantly across the general category areas. Although EPA is requesting response to the areas specified above as well as to general issues set out in section 6 of the table, you are strongly encouraged to identify additional topics or depart from these examples as necessary to best apply your particular area(s) of expertise in review of the overall study.

Comments should be sufficiently clear and detailed to allow readers to thoroughly understand their relevance to the FEV report. **All materials provided to you as well as your review comments should be treated as confidential, and should neither be released nor discussed with others outside of the review panel. Once EPA, FEV, and EDAG have made their reports public, EPA will notify you that you may release or discuss the peer review materials and your review comments with others.**

Please deliver your final written comments to SRA International no later than Wednesday, March 29.

Should you have questions about what is required in order to complete this review or need additional background material, please contact Brian Menard at SRA (Brian_Menard@sra.com) or (434-817-4133). If you have any questions about the EPA peer review process itself, please contact Ms. Ruth Schenk in EPA's Quality Office, National Vehicle and Fuel Emissions Laboratory (schenk.ruth@epa.gov) or (734-214-4017).

Appendix D: Reviews

Review of Light-Duty Vehicle Mass-Reduction and Cost Analysis – Midsize Crossover Utility Vehicle (FEV Report)

William Joost
U.S. Department of Energy

1. ASSUMPTIONS AND DATA SOURCES (CAE BIW and Vehicle)	COMMENTS
Please comment on the validity of any data sources and assumptions embedded in the study. Such items include material choices, technology choices, vehicle design, crash validation testing, and cost assessment that could affect its findings.	The material selection process used in this study suggests a good understanding of the cost and manufacturing impacts of changing between different steel, Al, Mg, and plastic/composite based materials. Generally the material selections are appropriate for the performance, manufacturing, and cost requirements of the particular systems. Identifying production examples of the materials in similar systems is very important for establishing credibility – the project team did an excellent job identifying production examples of most material replacements. There are, however, a few material selections where additional consideration may be necessary: The transmission case subsystem (pg 269) features the use of a Sr bearing Mg alloy. Recently, Sn based alloys have been produced and (I believe) used in production for similar applications. The use of Sn as an alloying ingredient accomplishes many of the same goals (improved high temp creep performance, for example) at a lower cost. It may be worth investigating these new alloys as an opportunity to reduce the cost of the lightweight transmission case subsystem. If not, the selection of a Sr alloy is reasonable. The feasibility of using hot rolled blanks in the body structure would be further emphasized by providing production examples for vehicles of >200k units per year. Similarly, the use of a 7000 series Al rear bumper is questionable – a

	production example for a high volume, low cost vehicle should be provided. The use of Thixomolded Mg seat components should be reconsidered. Thixomolding does have the potential to provide improved ductility compared to die casting, however the process is generally not well regarded in the automotive community due to concerns over limited supply and press tonnage limits (which limit the maximum size of the components that can be manufactured this way). If there is a production example of thixomolding for >200k unites per year in automotive, then it should be cited in the report. If there is no example then I would suggest switching to die casting (or super vacuum die casting) – the weight reduction and cost will likely be similar. It's not clear how the mass savings were achieved in the wheels and tires. The report states that a 2008 Toyota Prius wheel/tire assembly will be used in place of the stock Venza wheel – however the report also states (pg 544) that the Prius wheel will be normalized up to the 19"x7" to maintain the original styling of the Venza. The technology employed in the Prius wheel is not different from the stock Venza wheel so why should a scaled-up Prius wheel weigh less than the original Venza wheel? There are also inconsistencies in the report – table F.5-18 references eliminating the spare tire wheel while downsizing the spare tire – why would there be a tire with no wheel? Lastly, if the Prius wheel/tire is scaled up to match the stock Venza size then the spare wheel/tire must also be scaled up – it's not clear that this happened. You are taking significant credit for weight reduction in the wheels and tires (~2% of total vehicle weight) but it's not clear how this is achieved. Many of the parts in the frame have been changes to a GF Nylon (pg 667). This may not be unreasonable, but production examples should be provided.
If you find issues with data sources and assumptions, please provide suggestions for available data that would improve the study.	Two plastic technologies are very widely employed in this design: PolyOne and MuCell. It seems that the companies who license/manufacture these technologies were used as the primary source to determine feasibility. However they are likely to be optimistic regarding the capability of their materials. <u>I agree that these materials are appropriate for the indicated applications</u>, however I feel that the credibility would be improved by including

	other sources (OEMs, Tier 1) or more production examples for existing platforms. With such a large amount of weight reduction attributed to PolyOne and MuCell, it would be beneficial to have a very strong case for capabilities.
ADDITIONAL COMMENTS:	

2. VEHICLE DESIGN METHODOLOGICAL RIGOR (CAE BIW and Vehicle)	COMMENTS
Please describe the extent to which state-of-the-art design methods have been employed and the extent to which the associated analysis exhibits strong technical rigor. You are encouraged to provide comments on the information contained within the unencrypted model provided by EDAG; the technologies chosen by FEV; and the resulting final vehicle design.	The report uses a (very thorough) piece-wise approach to weight reduction – each system is broken down and weight reduction opportunities for the individual components are identified. The weight-reduced components are then reassembled into the final vehicle. I believe that this provides a conservative estimate for the weight reduction potential of the Venza, where a vehicle-level redesign would provide greater weight reduction. However, I am also of the opinion that the approach used here is in line with industry practice so; while this may not yield the maximum reasonable weight reduction, it is likely to yield a value more in-line with industry-achievable weight reduction. It is particularly helpful (and credible) to see descriptions technologies that were considered, but abandoned due to performance concerns (e.g. reverting to a timing belt), manufacturing capabilities, (e.g. using a MuCell manifold), and cost (e.g. Mg oil pan). The suspension design process lacks sufficient detail to make the cost and weight estimates credible. Considerable Al is used to replace steel at a very minimal cost penalty. However, as the report indicates, detailed design and validation is necessary to confirm that these changes would be viable for the Venza. For example, changing to a hollow Al control bar is not an industry standard practice and the use of a hollow section may require significant changes to geometry in order to meet the stiffness and strength requirements. While a hollow Al control bar is feasible, I’m not confident that it can be substituted into the design so easily. A $0.40/kg-saved cost penalty for changing a significant number of components from mild steel to Al seems to be an underestimate.

Please comment on the methods used to analyze the technologies and materials selected, forming techniques, bonding processes, and parts integration.	The forming, joining, and integration techniques used in the report were analyzed only by referencing production examples or companies who produce similar products. Detailed design work would certainly include a more thorough analysis of the manufacturing techniques however for the scope of this report I believe that the level of analysis is appropriate.
If you are aware of better methods employed and documented elsewhere to help select and analyze advanced vehicle materials and design engineering rigor for 2017-2020 vehicles, please suggest how they might be used to improve this study.	This is not my area of expertise
ADDITIONAL COMMENTS:	

3. **VEHICLE CRASHWORTHINESS TESTING METHODOLOGICAL RIGOR. (CAE only)**	**COMMENTS**
Please comment on the methods used to analyze the vehicle body structure's structural integrity (NVH, etc.) and safety crashworthiness.	The baseline testing and comparison process (pgs. 67-128) is very thorough. The team establishes credibility in the proposed design by performing an initial baseline comparison against the production Venza – this suggests that the modeling techniques used can reasonably predict the performance of the lightweight design. It is unfortunate that the deformation mode comparisons could not be made quantitative (or semi-quantitative) somehow. Comparing how the model and test look after a crash gives an indication of deformation mode, but the comparison seems subjective. For example, image D-28 (pg 95) seems to show slightly different failure mechanisms in the CAE model versus the real test. The report notes that the bushing mountings were rigid in the model while they likely failed in the real vehicle. I would expect that these failures are designed into the vehicle to support crash energy management. The results crash pulses (pg 98) for the model and test look fairly similar, but it is unfortunate that this crash energy mechanism was not captured. The intrusion correlation for the baseline model is very good. This again adds credibility to the modeling approach used here. On page 386 the report states that the Mg CCB was not included in the crash or NVH analysis. Replacing a steel CCB with Mg is likely to have a significant impact on both crash and NVH performance. The technology is viable (and has been used on production vehicles as stated) however the crash energy management and NVH performance must be offset by adding weight elsewhere in the vehicle. The CCB plays a role in crash and a major role in NVH so I do not think that it is appropriate to suggest that the material replacement will have the reported results in this case. My suggestion is to leave the CCB as steel in the weight analysis (or go back and redo the crash and NVH modeling, which I suspect is not viable).

Please describe the extent to which state-of-the-art crash simulation testing methods have been employed as well as the extent to which the associated analysis exhibits strong technical rigor.	This is not my area of expertise
If you have access to FMVSS crash setups to run the model under different scenarios in LS-DYNA, are you able to validate the FEV/EDAG design and results? In addition, please comment on the AVI files provided.	N/A
If you are aware of better methods and tools employed and documented elsewhere to help validate advanced materials and design engineering rigor for 2017-2020 vehicles, please suggest how they might be used to improve the study.	
ADDITIONAL COMMENTS:	

4. VEHICLE MANUFACTURING COST METHODOLOGICAL RIGOR (CAE BIW and Vehicle)	COMMENTS
Please comment on the methods used to analyze the mass-reduced vehicle body structure's manufacturing costs.	Overall, the costing methods used in this study seem to be very thorough. The details of the approach provide considerable credibility to the cost estimates, however there will always be concerns regarding the accuracy of cost models for systems where a complete, detailed engineering design has not been established. I believe that this report does a good job of representing the cost penalties/benefits of the technologies but I would still anticipate negative response from industry. There a few examples where I believe that the cost was underestimated or where additional data could be helpful in corroborating the results: The engine cost comparison suggests that the 2.4L engine will cost less than the 2.7L engine due to reduced material content (smaller engine). The analysis goes on to say that the remaining costs (manufacturing, install, etc.) would be about the same for both engines. This seems credible, but is it possible to compare the price of both engine types as well? It may be possible to find prices for both of these engines from a Toyota dealer, and while price is certainly different than cost, it would be helpful in establishing that the cost differential estimate is reasonably accurate. Regarding the cylinder head subsystem (pg 211), the report notes that a switch from Mg to plastic for the head covers introduces engineering challenges related to the cam phaser circuitry. While the report identifies two production examples of this change, these are for high cost engines. It seems unlikely that the designs would achieve the quoted cost savings given that this has only been applied to high cost engines and there are recognized difficulties in the engineering/design. Regarding the body redesign, the estimated cost increase due to materials and manufacturing ($231.43, pg 333) for a weight savings of 67.7kg produces a weight reduction penalty of about $3.42/kg-saved which seems appropriate for

	the materials and assembly processes suggested in the report. I don't find the cost estimates for the seats to be credible (pg 378). If it's possible to reduce the weight of the seats (which represent a significant portion of vehicle weight) while saving significant cost, why would there be any steel seats in production? These are "bolt on" parts that are provided to the OEMs by suppliers so this would be a relatively easy change to make if the cost/weight trade-off shown in this report is true. The report should, at the very least, address why these kinds of seats are not more prevalent in current vehicles. Why is there a cost savings for the front axle hub (pg 555)? If you are proposing to scallop the hub during forging then you will still need the same amount of input material – some of it will be removed during scalloping, but you will not get a cost savings. Also, it's not made explicitly clear that the current hub is forged. If you are proposing to move from a cast hub to a forged hub then the cost will most certainly increase. If the cost savings here is due to the estimated weight savings in the final part (i.e. pay for less material) then this indicates that the model is not correctly capturing the yield from the process.
Please describe the extent to which state-of-the-art costing methods have been employed as well as the extent to which the associated analysis exhibits strong technical rigor.	This is not my area of expertise
If you are aware of better methods and tools employed and documented elsewhere to help estimate costs for advanced vehicle materials and design for 2017-2020 vehicles, please suggest how they might be used to improve this study.	This is not my area of expertise

ADDITIONAL COMMENTS
The change from a cast Al engine block with cast Fe liners to a cast-over Mg/Al hybrid with PWTA coated cylinders is very interesting, but the cost penalty estimate seems low relative to what I would expect. Previous work exploring the use of Mg intensive engines (which did not include the added complexity of cast-in Al liners) suggests a cost penalty of $3.89 per pound saved (see http://www1.eere.energy.gov/vehiclesandfuels/pdfs/lm_08/3_automotive_metals-cast.pdf report B) versus this report which suggests a cost penalty of $3.51 per kilogram saved, about half as expensive. The cited study was performed on a 2.5 L engine, comparable to the Venza. The primary difference is that the Venza study includes downsizing which would save on material costs, but I'm not

confident that the savings would be as substantial as indicated in this report. It seems that something has been underestimated.

There are several examples where a cost savings has been calculated by reducing the size of a component, despite using more expensive material. For example the Front Rotor/Drum and Shield subsystem shows a savings for the caliper subsystem and a modest increase in the cost of the rotor and shield. Some of the cost savings here is due to reducing the size of the system (scaling to the 2008 Toyota Prius). However, there would still be a weight savings (albeit lower) if the conventional cast iron materials were used and downsized to the 2008 Toyota Prius – this is the likely outcome in a real automotive environment. Given the option to choose a more expensive, exotic, untested system that saves significant weight versus a conventional low cost system that saves less weight, it seems like an OEM would choose the conventional solution. In this case the suggested weight savings are technically possible but would never happen in a practical automotive environment.

5. **CONCLUSION AND FINDINGS**	**COMMENTS**
Are the study's conclusions adequately backed up by the methods and analytical rigor of the study?	Yes. I identified various areas where the analysis or report could be improved, but overall the methods used here provide a credible and reasonable estimate of the potential for weight savings. Based on some of my earlier comments I would expect that actual costs to be somewhat higher than predicted in this study. Additionally, real vehicles share components across platforms so using vehicle-specific components would add additional cost. It is possible that the cost curve would cross $0/lb-saved at a lower total weight savings than suggested here.
Are the conclusions about the design, development, validation, and cost of the mass-reduced design valid?	Yes. As above, there is reason to believe that the true cost will be higher than predicted here, but I think this analysis provides a useful estimate.
Are you aware of other available research that better evaluates and validates the technical potential for mass-reduced vehicles in the 2017-2020 timeframe?	I have not seen a report as thorough as this. There are several examples of resources that provide useful information regarding weight reduction potential such as Cheah, L.W. Cars on a Diet: The Material and Energy Impacts of Passenger Vehicle Weight Reduction in the U.S. Joshi, A.M. Optimizing Battery Sizing and Vehicle Lightweighting for an Extended Range Electric Vehicle Lutsey, N. Review of technical literature and trends related to automobile mass-reduction technology
ADDITIONAL COMMENTS	

6. OTHER POTENTIAL AREAS FOR COMMENT	COMMENTS
Has the study made substantial improvements over previous available works in the ability to understand the feasibility of 2017-2020 mass-reduction technology for light-duty vehicles? If so, please describe.	Yes. Other studies have reviewed the mass saving potential of various technologies individually, or imagined the impact of combining many technologies. However I am not aware of a design study that takes an existing vehicle and assesses each piece with the thoroughness used here.
Do the study design concepts have critical deficiencies in its applicability for 2017-2020 mass-reduction feasibility for which revisions should be made before the report is finalized? If so, please describe.	No – I would not say that any deficiencies here are "critical"
Are there fundamentally different lightweight vehicle design technologies that you expect to be much more common (either in addition to or instead of) than the one Lotus has assessed for the 2017-2020 timeframe (Low Development)?	Not in the 2017-2020 time frame. Switching to an advanced steel dominant body with a few instances of Mg and Al seems appropriate for the time frame. The considerable use of lightweight plastics is also in line with my expectations for available technology in this time frame.
Are there any other areas outside of the direct scope of the analysis (e.g., vehicle performance, durability, drive ability, noise, vibration, and hardness) for which the mass-reduced vehicle design is likely to exhibit any compromise from the baseline vehicle?	All of the areas listed here are somewhat concerning, but given the switch to fairly conventional materials I believe that durability, driveability, and NVH should be not be a significant issue. Detailed analysis work in these areas would likely require some redesign which may add cost or weight, but I don't think it would be overwhelming.
ADDITIONAL COMMENTS	

The Ohio State University

Kristina Kennedy's General Comments –

(1) "Building a full vehicle model w/o the use of drawings or CAD data…" → Has this method of tear-down + scanning been proven out in industry or in other projects to understand how closely this method would correlate with actual data? Is this basically "reverse engineering" and is that an acceptable method?
(2) FE Meshing Tool, ANSA → Did a quick Google search and did not find this product. Am familiar with ANSYS and others, but is ANSA an industry-standard tool? Just confirming the wide-use of such a tool out of curiosity.
(3) "Bending and torsional stiffness values did not provide acceptable performance (when replacing with HSS)" → This is an "of course" comment, right? HSS would absolutely produce worse results when replacing steel. These results were expected, correct?
(4) Table 1.7.1: NVH Results Summary → The "Weight Test Condition" and "Weight BIW" are ALSO outside of limits (> 5%), but not noted in results. Only those highlighted in red are noted as "failures". All failures (> 5%) should be called out specifically since that was their target.
(5) With respect to measuring powertrain CG and moment of inertia, notes "oscillation as an undamped" condition → Just confirming, this means no dynamic dampers were used in the engine room modeling? Is this realistic? Acceptable practice?
(6) Overall, well-written and well-done…my conclusion (which they also reached) is YES, NVH WILL SUFFER when replacing steel with HSS and will OF COURSE make the vehicle MORE STIFF.

1. ASSUMPTIONS AND DATA SOURCES (CAE BIW and Vehicle)	COMMENTS
Please comment on the validity of any data sources and assumptions embedded in the study. Such items include material choices, technology choices, vehicle design, crash validation testing, and cost assessment that could affect its findings.	**Glenn Daehn's comments** The data and sources appear to be very good, however at the time of this review there are a few items that are unclear. First there some statements that are referenced with superscripts, however there is not a reference list that appears in the document. Second, this report does an excellent job of documenting at a high-level that the finite element analysis is carried out properly, showing agreement with masses, stiffness and crash signatures of baseline vehicles. However, it is important that all of the details be also available to the public, such as the detailed material geometry (mesh files), stress-strain flow-laws used for the materials, weld locations (more than a figure), models used for weld behavior and so on. This can be done by reference or by making the LS-DYNA models public. It is not clear at time of review how this will be done, but it would be a great service to make all this granular detail available. Similar statements can be made regarding the detail for components and materials in the costing models. **Tony Luscher's comments** The data used appears to be valid and appropriate to the tasks that are completed. Vehicle data for the Toyota Venza was obtained by scanning the components and creating the CAD models. Material data was found from appropriate sources and databases. These were used to create a crash test model for the vehicle and for cost estimation. A thorough search of state-of-the-art vehicle design concepts was used as the basis of mass reduction for the various vehicle systems.

If you find issues with data sources and assumptions, please provide suggestions for available data that would improve the study.	**<u>Glenn Daehn's comments</u>** See above. **<u>Tony Luscher's comments</u>** None found.
ADDITIONAL COMMENTS: **<u>Tony Luscher's comments</u>** Data sources are well documented in the report and will aid if any additional investigation is needed. Several of them were checked for validity.	

2. VEHICLE DESIGN METHODOLOGICAL RIGOR (CAE BIW and Vehicle)	COMMENTS
Please describe the extent to which state-of-the-art design methods have been employed and the extent to which the associated analysis exhibits strong technical rigor. You are encouraged to provide comments on the information contained within the unencrypted model provided by EDAG; the technologies chosen by FEV; and the resulting final vehicle design.	**Glenn Daehn's comments** The work is well done and technically rigorous. Again, we encourage making all pertinent detail publicly available. **Tony Luscher's comments** The report does an excellent job of using state-of-the-art design methods. The re-engineering process included vehicle teardown, parts scanning, and data collection of vehicle parts to build a full vehicle CAE model. This raw STL geometry was then translated into an FE meshing tool (ANSA) to create a finite element model.
Please comment on the methods used to analyze the technologies and materials selected, forming techniques, bonding processes, and parts integration.	**Glenn Daehn's comments** All is in accord with the state of the art. It is not clear how welds are represented in the FE-Model, without dissection of the LS-DYNA input stacks. **Tony Luscher's comments** The Toyota body repair manual was used to identify the material grades of the major parts of the body structure. These material grades were then validated by material coupon testing. The MSC Nastran solver was used to solve for the bending and torsion stiffness of the body in white model. Good correlation was achieved between physical stiffness testing and FEA stiffness results.
If you are aware of better methods employed and documented elsewhere to help select and analyze advanced vehicle materials and design engineering rigor for 2017-2020 vehicles, please suggest how they might be used to improve this study.	**Glenn Daehn's comments** Everything appears to be well-done and in accord with the state of the art. **Tony Luscher's comments** None known.
ADDITIONAL COMMENTS:	

3. VEHICLE CRASHWORTHINESS TESTING METHODOLOGICAL RIGOR. (CAE only)	COMMENTS
Please comment on the methods used to analyze the vehicle body structure's structural integrity (NVH, etc.) and safety crashworthiness.	**Tony Luscher's comments** Trifilar suspension apparatus was used to find the CG and moments of inertia of the engine and other major components. The dynamic FEA modal setup was run using NASTRAN. Vibration modes were analyzed by the CAE model and then compared with physical test data in order to correlate the FEA model to the physical model. Five different load case configurations with appropriate barriers were placed against the full vehicle baseline model. Models were created with high detail and fidelity
Please describe the extent to which state-of-the-art crash simulation testing methods have been employed as well as the extent to which the associated analysis exhibits strong technical rigor.	**Tony Luscher's comments** Global vehicle deformation and vehicle crash behaviors were analyzed and compared to the deformation modes of test photographs. Fidelity was good. A few notes on these comparisons are noted on this page in the additional comments section.
If you have access to FMVSS crash setups to run the model under different scenarios in LS-DYNA, are you able to validate the FEV/EDAG design and results? In addition, please comment on the AVI files provided.	**Tony Luscher's comments** This reviewer has expertise in crash simulation. However due to time constraints the model was not run under different scenarios in LS-DYNA. No AVI files were found.
If you are aware of better methods and tools employed and documented elsewhere to help validate advanced materials and design engineering rigor for 2017-2020 vehicles, please suggest how they might be used to improve the study.	**Tony Luscher's comments** None found.
ADDITIONAL COMMENTS:	**Tony Luscher's comments** The caption on Figures 1.8.13 to 1.8.14 state that they are at 100 ms although the previous paragraph lists them as occurring at 80 ms. The muffler deformation looks quite different in Figure 1.8.14. Figure 1.8.33 is unclear and cannot be seen.

4. VEHICLE MANUFACTURING COST METHODOLOGICAL RIGOR (CAE BIW and Vehicle)	COMMENTS
Please comment on the methods used to analyze the mass-reduced vehicle body structure's manufacturing costs.	**<u>Tony Luscher's comments</u>** Mass reduction was analyzed first on a system level and then by a component level basis. Mass reduction concepts were based upon a very comprehensive literature review of new materials and manufacturing processes and alternative designs ideas that appear in the open literature and at trade shows. An assessment of these was made in terms of technological readiness, fitness for use in mass production, risk, and cost. In addition there were consultation with industry and experts. These were found to be very thorough.
Please describe the extent to which state-of-the-art costing methods have been employed as well as the extent to which the associated analysis exhibits strong technical rigor.	**<u>Tony Luscher's comments</u>** The impact of costs, associated with mass reduction, was evaluated using FEV's methodology and tools as previously employed on prior powertrain analyses for EPA. Cost reduction assumptions are clearly laid out and are reasonable. The report does a good job of realizing the inherent challenges and risks in applying any new technology, let alone lightweight technology, to a vehicle platform. FEV describes the component interactions both positive and negative in its recommendations. The actual values in the EXCEL files were not checked.
If you are aware of better methods and tools employed and documented elsewhere to help estimate costs for advanced vehicle materials and design for 2017-2020 vehicles, please suggest how they might be used to improve this study.	**<u>Tony Luscher's comments</u>** None found.
ADDITIONAL COMMENTS **<u>Tony Luscher's comments</u>** There are many typos and fragmented sentences in these sections. These should be corrected. Bookmark references do not all work.	

5. **CONCLUSION AND FINDINGS**	**COMMENTS**
Are the study's conclusions adequately backed up by the methods and analytical rigor of the study?	**<u>Glenn Daehn's comments</u>** At the time of review, Section G "Conclusions and Recommendations" is unavailable. We hope that in this section FEV will point out the most promising actions that auto makers may take to reduce mass while conserving cost. **<u>Tony Luscher's comments</u>** The report's conclusions are based on sound engineering principals of good rigor.
Are the conclusions about the design, development, validation, and cost of the mass-reduced design valid?	**<u>Glenn Daehn's comments</u>** This study is carefully crafted with excellent attention to engineering detail. It is important to note that the overall environment for vehicle design, manufacture and use is continually changing. See the "Additional Comments" section of this document for further development of the implications of this. **<u>Tony Luscher's comments</u>** This reviewer found the overall work to be thorough and well documented. Therefore the conclusions are well supported and validated by the engineering and modeling in the report.
Are you aware of other available research that better evaluates and validates the technical potential for mass-reduced vehicles in the 2017-2020 timeframe?	**<u>Glenn Daehn's comments</u>** There are no more comprehensive or detailed studies that we are aware of. This is an excellent compilation of ideas for practical vehicle mass reduction and fuel efficiency improvement. **<u>Tony Luscher's comments</u>** None found.
ADDITIONAL COMMENTS	**<u>Glenn Daehn's comments</u>** The study does an excellent job within its scope. As this reviewer sees the scope, the driving question is: Can a well-engineered relatively modern vehicle (2010 Toyota Venza) have its mass reduced by 20% or more, without significant cost penalty and while maintaining

	crashworthiness. The answer to that question is a clear "YES". Further, this conclusion is backed with rigor and attention to detail. This is in my mind, very clear, well-done and technically rigorous. This reviewer believes that there are a few other important questions that were not asked. These include: 1) Will the proposed changes in design pose any other important risks in manufacture or use? This can include: warranty exposure, durability, increased noise, vibration and harshness, maintenance concerns, etc., etc. 2) Will increasing regulatory constraints and/or consumer expectations require increases in vehicle mass, opposing the mass reductions provided by the improved practices outlined in this study? Both these issues will make vehicle light weighting more difficult than this report suggests. With respect to issue 1) there are a number of materials and design substitutions that may produce concerns with durability, manufacturability and warranty claims. For example when substituting polymers for metals, there are new environmental embrittlement modes that may cause failure and warranty claims. Also, if substituting aluminum for steel, multi-material connections may cause galvanic corrosion problems. When using thinner sheets of higher strength steel, formability may be reduced and springback may be more problematic. Both these issues may preclude the use of the stronger material with a similar design and may also increase the time and cost involved with die development. Lastly there are always risks in any new design. For example, when using new brake designs, pad wear and squeal may be more pronounced. All of these issues may cause a manufacturer to avoid the new technology. There are also local constrains on material thicknesses that are outside this review methodology. For example while a roof rail may meet crash

	and stiffness criteria, it may deflect excessively or permanently if a 99th percentile male pulls on it exiting a vehicle. Similarly, parking lot and hail dents may require greater thickness gauges than this study may indicate. The problem of vehicle light-weighting and improved fuel economy is seen here through the lens as being an engineering problem to be solved. And in many ways it is. However, the forces of consumer expectations and behaviors are an essential part of the problem. As an interesting anecdote, the Model T Ford had a fuel economy of about 20 MPG, very similar to the average fuel economy of vehicles on the road today. No modern consumer would choose a Model T for many obvious reasons. Our cars have become extensions of our living rooms with many electrical motors driving windows, mirrors, seats and complex and costly HVAC and infotainment systems. All of these systems add weight, complexity and use power. Further increased complexity of engines to improve emissions and increase fuel economy has increased engine mass. This study shows that with good engineering we can reduce vehicle mass of an existing vehicle by 20% with little to no increased cost or adverse consumer reaction. Based on our current course, it is just as likely this benefit will be taken by improved mandated safety and emission features as well as improved creature comforts. Much can be gained through enlightened consumer behavior (assuming the average consumer wants to reduce energy use and carbon footprint). While much of this is outside the scope of this report, in particular it would be useful if the average consumer would understand the lifecycle environmental impacts of vehicle choice and of varied vehicle design, and would adopt a 'less is more' ethic and see their transportation systems as that, simply transportation. A more minimalist ethic that would move against increasing vehicle size and the creep of multiple motors for seats, mirrors, windows, etc., would reduce acquisition cost, maintenance cost and energy cost. This is in addition, of course, to the usual advice to reduce fuel consumption (limit trips, limit speed, tire pressure,

	carpooling, etc. etc.) is still valuable. It should also be noted that there are other potentially low-cost actions that can be easily adopted to reduce greenhouse gas emissions and reduce dependence on foreign oil. One of these is widespread adoption of natural gas fuels for personal transportation. Use of Compressed Natural Gas (CNG), has lower fuel cost than gasoline, produces less pollution and greenhouse gas emission per energy used, and requires only very modest changes to conventional vehicle architecture, with no significant increases in complexity. The cost and size of a CNG tank and the development of refueling infrastructure are the main barriers to adoption of a technology that could have important and positive societal benefits. This is an excellent and useful study. It is important however to recognize the limitations of purely engineering solutions. And even within the engineering realm, there are many reasons that the implementation of the solutions in this paper study will require much effort to become part of mainstream automobiles.

6. OTHER POTENTIAL AREAS FOR COMMENT	COMMENTS
Has the study made substantial improvements over previous available works in the ability to understand the feasibility of 2017-2020 mass-reduction technology for light-duty vehicles? If so, please describe.	**<u>Glenn Daehn's comments</u>** Without question. The only similar study also targeted the Venza. This provides much additional analysis and many additional ideas beyond the Lotus study. **<u>Tony Luscher's comments</u>** The major contribution of this study was to pull together and evaluate all of the current proven concepts that are applicable to a lightweight vehicle in the 2017-2020 timeframe. It is successful in this regard.
Do the study design concepts have critical deficiencies in its applicability for 2017-2020 mass-reduction feasibility for which revisions should be made before the report is finalized? If so, please describe.	**<u>Glenn Daehn's comments</u>** Conclusions and recommendations section is missing. This is an important opportunity to reinforce the most important actions that automakers can take. The report still lacks the ability to trace some technical details all the way back to the source. This is described previously.
Are there fundamentally different lightweight vehicle design technologies that you expect to be much more common (either in addition to or instead of) than the one Lotus has assessed for the 2017-2020 timeframe (Low Development)?	**<u>Glenn Daehn's comments</u>** It seems apparent that vehicles are moving more and more to multi-materials construction and as we move away from steel-based construction, joined primarily by resistance spot welds, there will be need for additional joining technologies. Laser welding is mentioned as one possible replacement for resistance spot welds, but it is expected that over time there will be much more use of structural adhesives, self piercing rivets, conformal joints and other joining strategies for the BIW.
Are there any other areas outside of the direct scope of the analysis (e.g., vehicle performance, durability, drive ability, noise, vibration, and hardness) for which the mass-reduced vehicle design is likely to exhibit any compromise from the baseline vehicle?	**<u>Glenn Daehn's comments</u>** Yes. There are many other details with respect to nuances of customer expectations, durability, warranty risks and manufacturability that are discussed elsewhere in this review. This does not diminish the importance of this great work. Just points out there are an enormous amount of detailed work required to build an automobile, and the job is

	not finished.
ADDITIONAL COMMENTS	

Review of FEV Engineering Study:

"Light-Duty Vehicle Mass Reduction and Cost Analysis – Midsize Crossover Utility Vehicle "

By: Douglas Richman (Kaiser Aluminum and the Aluminum Association)

1.0 Introduction

This report is a review the 2012 FEV project to identify mass-reduction opportunities for a crossover sport utility vehicle based on the 2009 Toyota Venza. This study is a continuation of the Lotus Engineering Phase 1 Low Development (LD) study funded by the Internal Council on Sustainable Transportation (ICCT) in 2010. Goal of the FEV project is to identify practical mass reduction technologies to achieve a 20% reduction in total vehicle mass (342 Kg) at no more than 10% increase in consumer cost while meeting, or exceeding, all crashworthiness, performance and customer satisfaction attributes provided by the baseline vehicle.

Body of the baseline vehicle is 31% of total vehicle mass and has a dominant influence on NVH and collision performance of the total vehicle. This project involved extensive engineering analysis of the vehicle body. BIW and closure materials and gauges were optimization to exploit the maximum mass reduction potential from advanced low mass automotive materials and advanced manufacturing processes. Mass reduction initiatives are identified for all vehicle systems including engine, transmission, interior, suspension and chassis systems. Most materials, manufacturing processes and components selected for the FEV vehicle technology package are proven, cost effective and available for use on 2017 production vehicles.

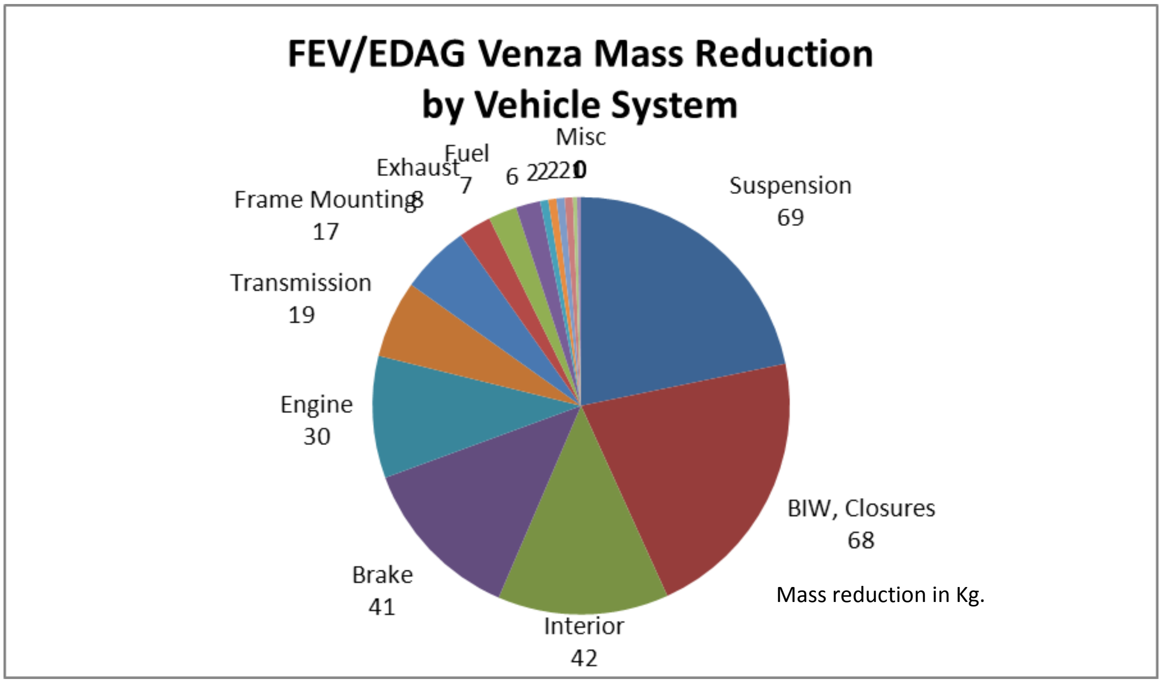
Majority of mass reduction concepts utilized are consistent with recognized industry trends. Mass reduction potential attributed to individual components appear reasonable and consistent with industry experience with similar components. As an advanced design concept study this is an important and useful body of work. Results of the project provide useful insight into potential vehicle mass reduction achievable with HSS and AHSS materials.

This report is a review of the methodologies employed, technologies selected and validity of findings in the FEV study. This reviewer has experience in vehicle mass reduction engineering of body, engine and suspension systems. This review focuses on those areas of the FEV project.

2.0 FEV Project Summary

Mass reduction technologies selected in this project achieve:

Mass reduction	317 Kg (18.5%)
Cost impact	$92 (reduction)



FEV/EDAG Venza
Mass Reduction by Vehicle System

Vehicle content is decomposed into 20 vehicle sub-groups. Mass reduction opportunities are identified in all 20 sub-groups. Over 90% of the mass reduction achieved is concentrated in 7 vehicle systems. Within each of these sub-systems a relatively short list of mass reduction technologies generated the majority of mass reductions achieved. Over 95% of all cost variances (increases and decreases) result from the technology changes in the same 7 vehicle sub-groups. Key sub-groups are:

Body
Suspension
Interior
Brakes
Engine
Transmission
Frame / Mounting

1.1 Mass Reduction Methodology

Mass reduction efforts were organized into two segments: body and non-body. Body mass reduction focused on selection of materials (steel, aluminum, plastics and magnesium), grades and gauges. Baseline Venza body design was not changed. Non-body mass reduction efforts examined all vehicle systems for potential cost effective mass reduction opportunities. FEV utilized technical support from two recognized, technically qualified and highly respected engineering services organizations: EDAG and Munro and Associates.

EDAG focused on body structural engineering and cost modeling. They conducted detailed reverse engineering study the baseline Venza to establish baseline vehicle mass and structural characteristics and develop CAE, FE and collision simulation models. Calibrated FE models were used to develop an optimized Venza body structure. EDAG Engineering analysis is thorough and reflects the high level of vehicle engineering expertise and know-how within the EDAG organization. Modeling and simulation technologies utilized by EDAG are state-of-the art and EDAG has recognized competencies in effectively deploying those tools.

The EDAG work presents a realistic perspective of achievable vehicle structure mass reduction using available design optimization tools, practical engineering materials and available manufacturing processes. EDAG cost modeling of the baseline and reduced mass vehicle structures.

Munro lead the process of identifying, analyzing, screening and selecting cost effective mass reduction opportunities in all vehicle systems. Munro is a highly respected engineering organization specializing in benchmarking and lean product design. Munro process for achieving product mass and cost optimization is well developed and highly effective. They utilize a creative mix of functional analysis, competitive benchmarking, cross industry comparisons, advanced materials and manufacturing process knowledge and sound engineering analysis. This segment of the study identified a significant number of practical mass reduction concepts in all 20 vehicle sub-groups. The majority of mass reduction technologies selected for the final design are in some current level of volume production and appear cost effective and realistically achievable by 2017.

1.2 Cost Analysis Methodology

Costing models were maintained by EDAG. A complete baseline vehicle cost model was developed and calibrated to the estimated cost of the current Venza. The baseline model was used to track cost changes driven by mass reduction technologies.

Cost estimates for mass reduction technologies are based on detailed analysis of the products, materials and process utilized. Estimating costs for new or emerging technologies is a challenging process. Advanced technology cost estimates are based on a combination scaling from known products if available, benchmarking from similar products, material supplier costs, analysis of advanced manufacturing cost, and expert estimates. Labor rates and manufacturing overheads are maintained at documented industry typical levels.

This cost tracking approach is fundamentally sound and valid. Cost estimates for new technologies are subject to validity of cost estimates and engineering judgments in the estimate. This project included rigorous engineering assessments of all mass reduction technology costs.

For most mass reduction technologies selected, cost estimates appear realistic and are consistent with current production costs and prior vehicle mass reduction studies. In the area of body sheet materials there appears to be some assumptions that result in estimated technology costs as much as 25% higher than volume production experience would suggest. This are is discussed in more detail in this report.

2.0 Baseline Vehicle Model - Body

EDAG conducted a detailed reverse engineering process to define baseline Venza component mass and structural performance. The process included: vehicle teardown, identification of component mass and material composition and component scanning to create digital models of structural components. Part connections (spot weld, seam weld, laser weld), dimensions (location, weld diameter, weld length), and characteristics were documented during scanning process. Material property data was obtained by coupon testing part samples.

Scan data, part weight and material information were used to create a CAE model of the vehicle structure. A finite element (FE) model was created from the CAE model using ANSA mesh software. The FE model was used to evaluate NVH characteristics (bending, torsion, modal analysis) of the structure using NASTRAN. Model results were compared and calibrated with analytical test results to establish the baseline analysis model. CAE crash performance simulations (LS-DYNA) were conducted to verify model correlation with actual vehicle crash test performance in National Highway Traffic Safety Association (NHTSA) regulatory performance testing. Model results were calibrated to actual Venza crash performance data. The correlated crash model became the baseline crash model for the remaining load cases.

EDAG is widely recognized as highly competent and experienced in vehicle structural modeling, NVH and collision simulation and structural engineering. LS-Dyna, MSC/Nastran and ANSA are valid and widely-used simulation tools, commonly used and accepted within the engineering community and the industry to perform this analysis. The approach used by EDAG to develop Venza structural models is a state-of-the art methodology utilizing proven modeling tools.

Structural models developed in this project were calibrated to physical test results of actual vehicle structures. Simulation results appear reasonable and logical, building confidence in the fidelity of the analysis. Models have excellent correlation to actual vehicle performance. FMVSS crash results are consistent with bending and torsional stiffness properties. There is no apparent reason to question results of this modeling and simulation effort. These models would be expected to be valid for comparison of design alternatives. These models would be expected to provide reliable assessments of NVH and collision performance of the Venza structure.

Report conclusions with regard to NVH and collision performance do not substantially overreach the capability and results of the analysis. In some relatively minor areas, assessment to of the “optimized” structure is not fully supported by generally recognized measures of structural performance. These few relatively uncertainties do not diminish the overall conclusion that the modeling and simulation efforts are well done and the major conclusions are valid useable.

2.1 Lotus “Low Development” Structure

This project included evaluation of the Lotus Engineering “Low Development” Toyota Venza reduced weight structure. Lotus low-development design used the baseline Venza structure with “optimized” deployment of advanced high strength steels. Lotus optimization process selected AHSS grades and gauges based on a load path analysis derived from a Lotus developed FEA model of the Venza structure.

EDAG baseline modal analysis model was used to evaluate Lotus selected material grades and gauges. Modal analysis results and corresponding weight reduction were comparable, but the bending and torsional stiffness values did not provide acceptable performance. Torsional stiffness is 20.4% less, and bending stiffness is 20.0% less than the 5% target performance established by EDAG. Further crash validations of Lotus Engineering’s study were not conducted, since it did not meet the NVH targeted performance.

3.0 Mass Reduction

FEV decomposed the total vehicle into 20 sub-systems. Each sub-system was aggressively examined to identify realistically achievable and cost effective mass reduction opportunities. Majority of mass reduction achieved (90%) is concentrated in (7) vehicle sub-systems:

	Mass Reduction
Body	68 Kg
Suspension	69
Interior	42
Brakes	41
Engine	30
Transmission	19
Frame, Mounts	17

These 7 sub-systems account for over 90% of the cost increases and decreases in this project.

This reviewer has experience in light weighting of body, suspension and engine systems. Comments in the following sections are limited to those vehicle sub-groups.

A significant number of creative and innovative mass reduction ideas were developed and selected for the remaining (17) sub-systems not discussed in this report. Many of the ideas appear to be appropriate consideration as part of a total vehicle efficiency improvement effort.

3.1 Body Optimization Overview

Body Sub-system includes: Body-in-White (BIW), Closures, Hood, Doors, Lift Gate, Fenders. This sub-system is the highest mass sub-group at 529 Kg, 31% of total vehicle mass. Body group design and material selection have a dominant influence on vehicle NVH and collision performance. For that reason, optimization of the body structure is a major focus of this project.

Body sub-system –	BIW, Closures, Bumper, Fenders
Optimization results -	71 Kg mass reduction $230 cost increase

FEV body mass reduction 68 Kg. (21 % of total vehicle mass reduction)

Baseline Toyota Venza body elements (BIW, closures, bumpers) are predominantly a mix of mild steel (48%) and HSS (49%) with a resulting mass of 529 Kg (31% of total Venza mass). This mix of materials represents a comprehensive use of automotive grade steels available when the Venza was originally designed.

Body related mass reductions from this baseline are indicative of improvements made possible by advances in materials technology.

Venza baseline BIW structure was used for both the Lotus “Low Development” and EDAG material optimization analysis. Both studies reduced BIW mass by similar amounts, Lotus LD: 61 Kg, EDAG: 54 Kg. Differences between Lotus and EDAG structures include: specific material grades and gauges and joining technology. Lotus LD structure used conventional resistance spot welding while the EDAG structure included continuous laser welding for structurally significant joints. BIW mass for the two structures are similar:

BIW Structure Mass	
Baseline	386 Kg
Lotus Venza LD	325 Kg (- 15.8%)
EDAG Venza	332 Kg (- 14 %)

Significant difference bending and torsional stiffness between the Lotus and EDAG structures (20%) do not appear to be fully explained by the relative difference in mass between the structures. Structural stiffness for a constant shape is dependent on material gauge and modulus and not influenced by strength properties. Auto body stiffness can be increased by improving attachment integrity. It would be helpful to understand the influence of laser seam welding on body NVH and collision performance.

3.1 Body Optimization

Body optimization was accomplished using EDAG body mass optimization process. The calibrated Venza FEA model was used. In this process alternate material type, grade and gauge were evaluated for NVH and collision performance. Baseline Venza body structure was not altered. Materials evaluated include advanced high strength steels (AHSS), aluminum, magnesium, plastics. Material gauges were selected based on component part requirements (NVH, Collision) and properties of specific materials. The body mass optimization process explored the potential of HSS, AHSS, aluminum, magnesium and plastics.

Optimized body structure content summary:

	Baseline Mass	Optimized Mass	Mass Reduction	Materials Change
BIW	386.0 Kg	324.0	51.0 Kg (13.2%)	HSS, AHSS, Gauge
Doors	95.7	95.6	0	---------
Hood	17.8	10.1	7.7 (43%)	Aluminum
Lift Gate	15.1	7.7	7.2 (48%)	Aluminum
Fenders	6.8	4.9	1.9 (28%)	Aluminum
Bumpers	7.5	7.5	0	
	528.9 Kg	457.7 Kg	71.2 Kg (13.5%)	

3.1.1 BIW Optimization

The EDAG optimized BIW is predominantly HSS and AHSS with appropriate gauge reductions. Baseline Venza is composed of 78% mild steel and 22% HSS. This material mix is representative of a comprehensive use of available materials at the time this Venza model was designed. The optimization process selected HSS and AHSS for over 80% of structure.

This study provides insight into practical BIW mass reductions achievable with recent and anticipated near term future advancements in automotive steels. Using AHSS aggressively with resultant gauge reductions achieved an 13.2% reduction in BIW mass (3% reduction in total vehicle mass). This finding is consistent with similar investigations on the part of OEM organizations in North America and Europe.

Aluminum was selected for the hood, lift gate and fenders. Mass reduction achieved for those components were: Hood: 43%, Lift gate: 48% and Fenders: 28%. Selection of aluminum for these body components is consistent with OEM production experience and several independent organization studies. The magnitude of mass reduction achieved in this body group is also consistent with production experience.

3.1.2 Body Optimization - Costs

Costs attributed to optimization of the body are reported as:

	Cost	Mass Reduction $/Kg saved	
BIW	$ 110	$ 2.19	HSS, AHHS
Hood	$ 39	$ 5.08	Aluminum
Lift Gate	$ 30	$ 4.16	Aluminum
Fenders	$ 22	$10.93	Aluminum
Total	$ 210	$ 3.20	

Cost increases projected for HSS and AHSS are marginally higher than have been reported in analytical studies and OEM experience in volume production. Production vehicle studies of AHSS in auto body applications have suggested cost impact of reduced body mass can offset a majority of the cost premiums associated with these materials.

Cost increases projected for aluminum sheet application are significantly higher than has been seen in prior studies and in production OEM experience. The optimized body includes three aluminum components: Hood, Fenders and Lift Gate. Mass reductions attributed to these three product areas are consistent with OEM production experience. Estimated cost increases are significantly higher than have been seen in production experience.

Using the hood as an example, total cost of the baseline hood is estimated to be $43 while total cost of the aluminum hood is estimated to be $93. Mass savings with the aluminum hood is 7.7 Kg resulting in a net cost per Kg mass reduction of $6.49. Production program experience with aluminum hoods typical find a cost premium below $4.50 per Kg mass reduction. Processing costs for a steel or aluminum hood should be similar. That similarity is reflected the EDAG cost model. The main cost difference between hoods is in material cost. Examining the EDAG cost model it appears aluminum sheet products were assessed a base metal cost and a grade premium. The two factors appear to be combined in the cost model results a raw material cost substantially higher than actual market price for these materials.

EDAG cost models for auto body sheet materials (AHSS and aluminum) appear to be overstating raw material costs. A review of the costing models and correlation with market prices for the materials and how raw material cost for sheet products is established in the models may be appropriate.

3.1.3 Body Modeling – Comments

The following observations are submitted in the interest of completeness and do not diminish validity of findings and conclusions of the overall project.

Body Modeling – Service Loads

Vehicle models developed in this study are valid and useful for the intended scope of this project. Models addresses overall bending and torsional stiffness, free body modal frequencies, roof strength, and four crash test load cases. These are good indicators and cover many of the primary structural performance concerns.

This analysis does not address what are commonly referred to as “service loads,” including jacking, twist ditch, pothole impacts, 2G bumps, towing loads, running loads, etc. Running loads are typically suspension loads for a variety of conditions to address strength, stiffness and fatigue durability of the body and suspension attachment structures and points. Without these other considerations, the optimization process could may unrealistically reduce mass in components that have little effect on overall body stiffness or strength, yet are important for durability.

Body Modeling – Deformable Barrier

Modeling of deformable barriers has historically been an issue. Source, nature or origination of the deformable barriers (moving and fixed) used in this project are not explained. In the offset deformable barrier crash test load cases, overall deformations, including barrier deformations are reported. The reporting does, however, raise a modeling concern. Barrier deformations of over 515 mm are reported for the offset tests. The IIHS deformable barrier has 540 mm thickness of deformable material. It is not expected to compress completely. Excessive barrier deformation has the potential to change the overall acceleration and deformation scenarios reported and influence the mass optimization process.

Body Modeling – Average Acceleration

Overall acceleration issues are not reported in a format normally used by collision development engineers. Charts of unfiltered acceleration pulses are shown and comparisons are made by evaluation of peak accelerations. “Average accelerations” are referred to, but in this report average is the average of left and right side peak accelerations.

Average acceleration as represented by the slope of the filtered velocity/time curve is commonly used to evaluate relative collision performance of a structure. Common practice is to try to steepen the curve in the early portion of the crash sequence (up to perhaps 50 ms) and to try to flatten the curve in the later parts. The logic has to do with the motions of a restrained occupant within the structure. In addition, total velocity change, including rebound, is typically reviewed. As an example, increasing front structure strength can increase restitution and rebound, which increases the overall change in velocity, or Delta-V, and can have adverse effects on overall occupant performance. While peak accelerations are useful, unfiltered peaks can be misleading due to the noise/vibration effect, and at best represent only a partial analysis.

Body Modeling - Stiffness in Collision Simulation

In evaluating the performance of the optimized body structure, the analysts in general considered "less deformation" of the body structure to equate to "better performance." Less deformation may be an index of structural stiffness but is not necessarily an indication of better collision performance. Less deformation generally equates to higher decelerations and resulting forces on the occupant. It is likewise generally desirable to efficiently use as much of the allowable free crush space as possible, not less.

Body Modeling – Door Opening

Part of the rear impact analysis includes an analysis of rear door opening deformation and an estimate of door openability post-crash. While this is an interesting and useful analysis, it is not explained why it is done. It is not a required aspect of the regulations. Since it is in the report, a similar analysis should probably be done for the front door openings in the front crash test load cases. Most if not all manufacturers have an in-house requirement that front doors must be openable following a standard front crash test.

3.2 Non-body Design Optimization

This project included a major engineering effort to identify practical mass reduction opportunities in non-body component groups. A rigorous process was followed to identify potential mass reduction concepts. This process selected a extraordinary number of technologies that were judged to be practical, cost effective and in volume production now or will be in production by 2017. A few of the larger mass reduction ideas are discussed in the following sections.

Non-body mass reduction ideas selected for the final FEV vehicle design resulted in a 21% reduction in non-body sub-group mass reduction. A portion of the mass reduction achieved in this area was the result of vehicle mass reduction (engine, wheels, tires). The majority of non-body mass reductions are independent of other reductions in vehicle mass.

3.2.1 Suspension

Suspension sub-system – Wheels, Tires, Shock Absorbers,
Steering Knuckles, Control Arms, Springs, …

Optimization results - 69 Kg mass reduction
$0 cost increase

Major mass reductions in this group are:

Wheels and Tires	32.8 Kg	Resized to new weight
Shock absorber	14.1	New light weight design
Front Control Arm	1.9	Convert to Aluminum

Front and Rear Knuckle	12.6	Conversion to Cast Aluminum
Front and Rear Sta. Bar	7.0	Innovative Al tube concept
Other	0.6	

Wheels

Downsizing wheels and tires (5) for the 317 Kg (18.5%) reduction in total vehicle mass is appropriate and is a normal consideration in OEM weight reduction programs. Wheel and tire combinations selected represent a 22% mass reduction from the reduction for these components. This magnitude of mass reduction is potentially achievable, but must be considered somewhat aggressive.

Knuckles

Conversion of steering knuckles to cast aluminum is a proven strategy. Estimated mass reduction by conversion to aluminum is 38% of knuckle mass. Approximately 35% of knuckles on vehicles built in North America use aluminum knuckles. Mass reduction achieved in those programs range from 35% to 45% depending on knuckle configuration. Knuckle mass reduction assessment in this study is achievable.

Control Arms

Conversion of the front control arm to forged aluminum results in a vehicle mass reduction of 2 Kg. Baseline Venza control arm design is typical of a design used widely throughout the industry. A significant proportion of these arms are produced in aluminum. Mass reduction estimates for conversion of this component is typical of the reductions seen in similar production programs.

Shock Absorber, Sway Bars

Reduced mass shock absorber/strut designs and the tubular sway bars are innovative concepts. Cost reduction of $58 is attributed to the reduced mass shock absorber concept. Production viability and cost of this ideas is not known to this reviewer.

System Cost

Total cost for mass reductions in this group is estimated to be net $0. Cost savings resulting from downsized wheels and tires ($79) and low mass shock absorbers ($58) offset cost increases for low mass arms, knuckles and stabilizer bars.

3.2.2 Engine

Optimization results - 30.4 Kg mass reduction
$ 43.96 cost reduction

Main sources of engine mass reduction:

Downsizing - constant performance	10.4 Kg	(2.7 L to 2.4 L)
Cylinder Block – Al Mg Hybrid, liners	7.1	
Valve train – Al castings, power metal	3.7	
Cooling system – plastic housings	2.6	
Timing Drive – Plastic covers	1.5	
Other	5.1	

Engine - Downsizing

Largest mass (10.4 Kg) reduction came from downsizing the engine to a smaller displacement to maintaining baseline Venza performance levels. Assessing appropriate engine weight for a downsized engine is a complex task. Changing displacement within a basic engine achieves small incremental mass reductions. A broader perspective was used in this study. Based on competitive engine technology assessments, an engine was selected representing mass optimization for the 2.4 L displacement. Mass of the new engine was adjusted based on sound engineering analysis to meet packaging and performance parameters of the baseline engine-vehicle package. This approach represents an innovative, thorough and well-engineered approach to estimating optimized engine mass reduction resting from vehicle mass reduction.

Developing a new engine involves massive investments in design, development and manufacturing. Production engines are designed for use in a broad range of vehicles and for a period of time spanning several vehicle design cycles. Manufacturers may not have the opportunity to provide a mass optimized engine for a specific vehicle.

The majority of engine mass reduction ideas selected for the FEV Venza exploit recent advances in materials and/or manufacturing technologies. Many small gains were made converting cast iron housings to cast aluminum, and cast aluminum covers and brackets to cast magnesium or plastic. Most of the engine mass reduction ideas selected have been proven in multiple high volume applications over several years. A few engine Ideas have less proven high volume field experience and were identified by FEV as “D” level selection candidates.

Cylinder Block

Cylinder block mass reductions were achieved by utilizing a hybrid design with magnesium outer jacket die cast over an aluminum core structure. This process is in limited production in Europe. Considering engineering, manufacturing and investment issues associated with this technology, FEV identifies this as “D” (difficult) technology for 2017 availability.

Cylinder Liners

Parent metal (aluminum) cylinder liners were selected for mass reduction. FEV selected a steel plasma coating process to achieve required bore wear characteristics.

While this process has been used in low volume applications for over 10 years it has not been demonstrated high volume production levels. FEV identifies this as a “D” technology for 2017 production.

1. ASSUMPTIONS AND DATA SOURCES (CAE BIW and Vehicle)	COMMENTS
Please comment on the validity of any data sources and assumptions embedded in the study. Such items include material choices, technology choices, vehicle design, crash validation testing, and cost assessment that could affect its findings.	1) NHTSA crash test data was used for validation of collision simulation models and is an appropriate source. 2) Material property data was supplied by recognized supplier associations and are correct. 3) Cost estimates for reduced mass sheet products seem to include assumption that drive unusually high material and equipment cost. This issue leads to a technology cost effectiveness that is not representative of actual production experience for sheet products.
If you find issues with data sources and assumptions, please provide suggestions for available data that would improve the study.	
ADDITIONAL COMMENTS:	

2. VEHICLE DESIGN METHODOLOGICAL RIGOR (CAE BIW and Vehicle)	COMMENTS
Please describe the extent to which state-of-the-art design methods have been employed and the extent to which the associated analysis exhibits strong technical rigor. You are encouraged to provide comments on the information contained within the unencrypted model provided by EDAG; the technologies chosen by FEV; and the resulting final vehicle design.	1) EDAG performed structural modeling. The EDAG organization is widely recognized as technically competent and highly experienced in modeling of auto body structure. Modeling approach appears technically robust and logical. 2) Body structural analysis utilized industry recognized CAE, CAD and collision modeling analysis tools and protocols. Tools used are state-of-the –art and the approach. 3) FE model was validated against physical test data for NVH and collision performance. Model correlation with physical test results is very good. No significant discrepancies or inconsistencies have been identified in the modeling results. 4) Based on these observation, the models would be considered valid and reliable for moderate A:B design comparisons that are the subject of this vehicle study.
Please comment on the methods used to analyze the technologies and materials selected, forming techniques, bonding processes, and parts integration.	1) Body: Process used to select materials, grades and gauges for the mass optimized body sub-group is technically sound and thorough. Election of laser welding of structurally significant body panels indicates deployment of advanced manufacturing process where appropriate. 2) Non-body: Methodology used to identify, screen and select non-body mass reduction technologies is thorough, detailed and highly effective. Munro Associates lead this segment of the project. Munro is recognized as being technically competent, highly experienced, knowledgeable and creative in benchmarking and lean engineering of automotive and non-automotive systems.
If you are aware of better methods employed and documented elsewhere to help select and analyze advanced vehicle materials and design engineering rigor for 2017-2020 vehicles, please suggest how they might be used to improve this study.	

ADDITIONAL COMMENTS:

The team of FEV, EDAG and Munro is an outstanding coalition of industry experts with the unique skills and expertise necessary to meet the objectives of this project.

3. **VEHICLE CRASHWORTHINESS TESTING METHODOLOGICAL RIGOR. (CAE only)**	**COMMENTS**
Please comment on the methods used to analyze the vehicle body structure's structural integrity (NVH, etc.) and safety crashworthiness.	1) LS-Dyna and MSC-Nastran are current and accepted tools for this kind of analysis. FEM analysis is part science and part art. EDAG has the experienced engineers and analysts required to generate valid simulation models and results. 2) EDAG was thorough in their analysis, load-case selections and data for evaluation 3) The handling of acceleration data from the crash test simulations is a bit unusual, and further analysis of the data is recommended.
Please describe the extent to which state-of-the-art crash simulation testing methods have been employed as well as the extent to which the associated analysis exhibits strong technical rigor.	1) CAE modeling guidelines used appear to provide a rigorous and logical technical approach to the development of the FE and the methods of analysis. 2) Method of evaluating and comparing acceleration levels in the various crash test scenarios is a bit unusual, a more accepted method of comparing velocity/time plots and average accelerations is suggested.
If you have access to FMVSS crash setups to run the model under different scenarios in LS-DYNA, are you able to validate the FEV/EDAG design and results? In addition, please comment on the AVI files provided.	
If you are aware of better methods and tools employed and documented elsewhere to help validate advanced materials and design engineering rigor for 2017-2020 vehicles, please suggest how they might be used to improve the study.	Methods and tools were appropriate.
ADDITIONAL COMMENTS:	

4. VEHICLE MANUFACTURING COST METHODOLOGICAL RIGOR (CAE BIW and Vehicle)	COMMENTS
Please comment on the methods used to analyze the mass-reduced vehicle body structure's manufacturing costs.	Body structure mass optimization was conducted by EDAG. Body structure was not altered form the baseline structure. Mass optimization process examined an appropriate range of material types, grades and gauges. Material properties used appear valid for the respective materials and grades. NVH and collision performance results appear consistent and logical with no significant dis-continuities of inconsistencies. In general the process used is excellent and the results appear realistic and valid.
Please describe the extent to which state-of-the-art costing methods have been employed as well as the extent to which the associated analysis exhibits strong technical rigor.	Costing models are thorough covering all elements of total production cost (material, processing, equipment, tooling, freight, packaging, …). Baseline cost model was calibrated to baseline vehicle cost projection. The basic model is complete and sound. Cost estimates for mass reduction technologies are the result of a rigorous engineering process utilizing benchmarking data, material and component costs from suppliers and detailed analysis of manufacturing costs. Sound creative engineering analysis was used to scale product cost to this specific vehicle application. Accuracy of new technology cost estimates is dependent on the knowledge, skill , experience and engineering judgment of the individuals making the estimates. Munro Associates conducted this segment of the project. Munro is a highly respected organization with strong qualifications in product cost analysis. It is reasonable to assume cost estimates in this study are valid estimates for the mass reduction technologies. One area of cost estimate concern is reduced mass sheet products. In this area, material and equipment costs attributed to the reduced mass technologies are significantly higher than actual production experience would support. Source of the discrepancy is not clear form the

	information in the project review documents.
If you are aware of better methods and tools employed and documented elsewhere to help estimate costs for advanced vehicle materials and design for 2017-2020 vehicles, please suggest how they might be used to improve this study.	Process methodology and execution used is one of the best this reviewer has seen.
ADDITIONAL COMMENTS A review of cost development for reduced mass sheet product should be reviewed. Current model would lead to de-selecting some low mass sheet based solutions due to unrepresentative cost assessment.	

5. CONCLUSION AND FINDINGS	COMMENTS
Are the study's conclusions adequately backed up by the methods and analytical rigor of the study?	Study conclusions and findings are well supported by the analytical rigor, tools used and expertise of the organizations involved.
Are the conclusions about the design, development, validation, and cost of the mass-reduced design valid?	Design development and validation conclusions are well supported in this study. Cost model is valid and cost conclusions are generally realistic. There appears to be a systematic discrepancy in cost modeling of low mass sheet products. This discrepancy has a minor impact on conclusions of this study.
Are you aware of other available research that better evaluates and validates the technical potential for mass-reduced vehicles in the 2017-2020 timeframe?	This reviewer has monitored automotive mass reduction studies in North America and Europe for several years. This study is the best evaluation of mass reduction opportunities and associated costs this reviewer has seen.
ADDITIONAL COMMENTS	

6. OTHER POTENTIAL AREAS FOR COMMENT	COMMENTS
Has the study made substantial improvements over previous available works in the ability to understand the feasibility of 2017-2020 mass-reduction technology for light-duty vehicles? If so, please describe.	Yes. Overall objectives) of the project (20% mass reduction, less than 10% cost increase) are timely and consistent with industry interests in the short term. Retaining the OEM designed and field proven body structure eliminates uncertainty related to evaluation of novel and un-proven structures. This analysis clearly identifies body mass reduction achievable with new and near term future grades of HSS and AHSS. An exhaustive list of non-body mass reduction concepts are evaluated in this study. Some of these technologies are well known and understood in the industry, other are new, creative and innovative. Each technology is reviewed from an engineering and cost perspective and scaled to the specific application. The technology selection process was analytical, rigorous and un-biased. Majority of technologies selected are appropriate for the mass reduction and cost objectives of the project. This information provides helpful information to industry engineers considering mass reduction alternatives for other vehicle programs.
Do the study design concepts have critical deficiencies in its applicability for 2017-2020 mass-reduction feasibility for which revisions should be made before the report is finalized? If so, please describe.	Major findings of the project appear practical for implementation by 2017-20. Two technologies selected for inclusion in the final vehicle concept appear "speculative" for 2017-20, Co-cast magnesium/aluminum block and MMC brake rotors. Both technologies are identified as "D" level for implementation. Designing, developing and establishing production capacity for a new engine block is a time consuming and costly process. Investments would be required by OEM manufactures and casting suppliers. It is not clear the level of human resources and capital investment required for this

	technology could be justified the basis of the mass reduction potential of (7 Kg). Aluminum MMC brake rotors were selected for inclusion in the final vehicle configuration. In the judgment of this reviewer, this technology is the most speculative technology selected for the final vehicle configuration. MMC rotors have been in development for over 25 years. Development experience with these rotors has generally not been acceptable for typical customer service. The minimum mass MMC rotor design selected in this project is a radical (by automotive standards) multi piece bolted composite design with an MMC rotor disc. This design is identified as a "D" rated technology and a mass savings of 9 Kg. The aluminum MMC portion of the mas reduced rotor assembly would be regarded as "speculative" at this time. Cost models used to assess low mass sheet product may have some questionable assumptions. For this project, adjustment in the cost model is unlikely to influence he material selection process. Correction in this area would have a greater impact on technology screening and selection to achieve mass reductions above 20%.
Are there fundamentally different lightweight vehicle design technologies that you expect to be much more common (either in addition to or instead of) than the one Lotus has assessed for the 2017-2020 timeframe (Low Development)?	No. The result of his study is a logical and cost effective advancement in the development of more efficient passenger vehicles for the 2017-20 time frame.
Are there any other areas outside of the direct scope of the analysis (e.g., vehicle performance, durability, drive ability, noise, vibration, and hardness) for which the mass-reduced vehicle design is likely to exhibit any compromise from the baseline vehicle?	None identified by this reviewer.
ADDITIONAL COMMENTS	

Review of Light-Duty Vehicle Mass-Reduction and Cost Analysis – Midsize Crossover Utility Vehicle (FEV Report)

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Summary

This document is a review of the reports, computational models and simulations by the FEV and its contractors on the design of a lightweight midsize crossover utility vehicle. The FEV study is an extension of the previous study titled "An Assessment of Mass Reduction Opportunities for a 2017 – 2020 Model Year Vehicle Program" (Lotus Phase 1 Study). Starting from the research findings and the vehicle used in that study, FEV engineers have developed a lightweight vehicle concept that utilizes designs, materials and manufacturing processes that are regarded to be technologically and commercially feasible for the 2017-2020 car model year. This design is termed as the "Low Development" concept as it assumes that the technologies needed for this design are sufficiently mature and that they not encompass any unresolved fundamental technology barriers. Overall, the main developments and general findings of the FEV study are sound when viewed from the perspective of crashworthiness modeling and the underlying formulations and practices employed. However, I have identified several issues with the developed models that in my opinion have to be addressed before the final conclusions and the models are released into the open domain. Given the scrutiny that the study and the vehicle models are expected to undergo after they are released to the general public, it is important that these issues are resolved as much as possible so that they do not distract from otherwise sound technical results.

1. Introduction

This document provides expert review of the 2012 study by FEV, Light-Duty Vehicle Mass-Reduction and Cost Analysis – Midsize Crossover Utility Vehicle (FEV Report). The FEV Study study builds on the previous 2010 Lotus project [1] that developed two lightweight conceptual designs of the existing vehicle, 2009 Toyota Venza. The first design, referred to as the "Low Development" vehicle, was based on the materials and technologies that were deemed feasible for 2017 production. Its estimated reduction in mass compared to the baseline production vehicle was 21%.

The FEV study under review documents the design process with a goal of 20% mass reduction corresponding to the Low Development (LD) case ("20%") as specified in the Lotus Engineering Phase 1 study. The weight reduction is pursued through analysis of the Body-in-White (BIW), and through an up-to-date re-analysis of light weighting options for all of the other vehicle components. The FEV study includes an in-depth cost assessment of all the light weighting technologies. However, this subject matter is not in my core expertise area, so that I have not attempted a comprehensive review, except for few general opinions that were a result of engineering intuition.

The FEV study consists of two parts: In the first part, FEV's contractor, design and engineering company EDAG, has designed and developed a reduced-weight BIW structure using computer Aided Engineering (CAE). The objective was to demonstrate that a lightweight design modification of an existing vehicle has a strong potential to meet the Federal Motor Vehicle Safety Standards (FMVSS) for Light-Duty Vehicles. The study was conducted in the virtual domain, using the Finite Element Method (FEM) [2,3] computational tools. The BIW models were developed using the state-of-the-art measurement and CAE tools. The simulations were conducted using computer codes MSC NASTRAN and LS-DYNA [4]. The research and development investigated application of new high-strength materials, new manufacturing and assembly methods for the BIW as it provides most potential for vehicle weight reduction. The second part of the report is an in-depth investigation and design of lightweight "other than BIW" vehicle systems. The resulting design is based upon discussions with suppliers, Lotus Phase 1 report ideas, and FEV's experience and expertise in the subject matter.

In this document I review the methods, data, and the FEM crash models developed in the FEV study. The models were evaluated based on the analysis of the computational simulation results and on based on the analysis of the actual model files. I want to emphasize that the scope of my review is on the computational simulations of the vehicle crashworthiness and on the modeling approaches employed by the FEV and its contractors. The primary source for my review were the FEV final draft report, the crash animations generated by the FEV, and the computer simulation output files for the NCAP and the ODB crash test configurations. Two vehicle crash models were available, the baseline and the LD model. As it will be shown in the following sections, my review was based to a large extent on the vehicle model files. Very often in the current practice, the actual model files are not sufficiently scrutinized and are evaluated only through the resulting computational simulations. In the case of large complex FEM models, such as car crash models, the model's configuration complexity and its shear size can obscure the important details of the response and camouflage the sources of errors in the model. That is particularly common when the technology envelope of the state-of-the-art is expanded, as is the case with ever-increasing sizes and complexities of the car crash models.

2. Methodology of the Review

The review of the 2012 study by FEV, Light-Duty Vehicle Mass-Reduction and Cost Analysis – Midsize Crossover Utility Vehicle was conducted in order to provide specific opinions on the following aspects of the study as charged by the EPA: (1) assumptions and data sources; (2) vehicle design methodological rigor; (3) vehicle crashworthiness testing methodological rigor-CAE only; (4) vehicle manufacturing cost methodological rigor; (5) conclusion and findings; and (6) other comments. Each of the subjects is further split into sub-topics as needed. As noted above, I do not extensively comment on item (4) as it is not in my field of expertise. The following sections follow the outline of the EPA charge questions.

3. Assumptions and Data Sources

This section contains comments on validity of the data sources, material properties, and modeling approaches used in this study. The overall methodology used by the FEV is fundamentally solid and adhere to standard practices of the crashworthiness engineering [5]. However, an in-depth analysis of the model files reveals several areas that may need to be addressed to fully support the findings of the study.

Firstly, as a matter of the established procedures for technical documentation, I suggest that the sources for the material properties should be clearly referenced; especially since the authors of the FEV study worked on similar projects for steel industry consortia [6]. Similar projects on concept vehicles [7,8] also offer guidelines on the reporting. It would also be very helpful to readers to graphically depict mechanical properties such as material stress-strain curves, failure envelopes, etc.

Secondly, the technologically important issues with the high strength metallic materials, such as Advanced High Strength Steels (AHSS) [9], are their special processing requirements [10], reduction in ductility, higher possibility of fracture [11-14] (especially under high strain rates [15-17]), and joining [18-22]. Many AHSSs derive their superior mechanical properties from their tailored microstructures, which get strongly affected during welding. Active research in welding of the AHSS shows possibilities of significant reductions of the joint strengths due to the softening processes in Heat Affected Zone (HAZ). Therefore, the strength values for the welds in the current LD model (i.e. SIGY=1550 for MAT_SPOTWELD section in the input files) seems very optimistic, and may need to be reduced or elaborated upon in the report. Several versions of the reports were distributed and I may have very well missed an updated version. In case that joining discussion is indeed restricted to one page as it appears in the current FEV document, I would suggest that weld properties and constitutive models be given additional attention in the final report.

Third important issue that I would suggest to be addressed is modeling of failure/fracture of the high strength materials in the LD models. Despite long research on the subject, the methods for modeling localization and failure are relatively scarce. There is still no wide consensus on how to model failure in materials. For the FEV study, special attention should be given to the joint areas (spot welds, laser welds) that can experience the degradation of properties due to the thermo-mechanical cycles that they have been exposed to. A simple way of addressing the above points would be to use failure limit strains in plasticity models that are used in the FEV models, i.e MAT_PIECEWISELINEAR_PLASTICITY. In this approach a limit strain is assigned to material, and after that limit strain is reached in a finite element, the element is gradually removed from the simulation. The values for the failure strains are dependent on mesh and element discretization, where additional simulations should be conducted to correlate energy to failure to the corresponding physical failure process zone for the given problem.

4. Vehicle Design Methodological Rigor

The development of the LD Toyota Venza concept started with the development of the baseline FEM model of the vehicle. The FEM model was developed by a reverse engineering process of disassembly, geometry scanning, component analysis, material characterization and the incremental FEM model development. The turn-around time for this process by the FEV is quite impressive. Equally impressive are the apparent quality of the FEM mesh, the definition of joints and assembly of the overall model.

The discretization of the BIW sheet materials uses proportionately sized quadrilateral shell elements, with few triangular elements. The mesh density is mostly uniform and without large variations in the FEM element sizes and the aspect ratios. The BIW model has about 6% of triangular shell elements in the sheet metal which is a very small amount given the complexities of the vehicle geometry. Figures 1-3 show the geometry and the parts variety for the baseline vehicle model.

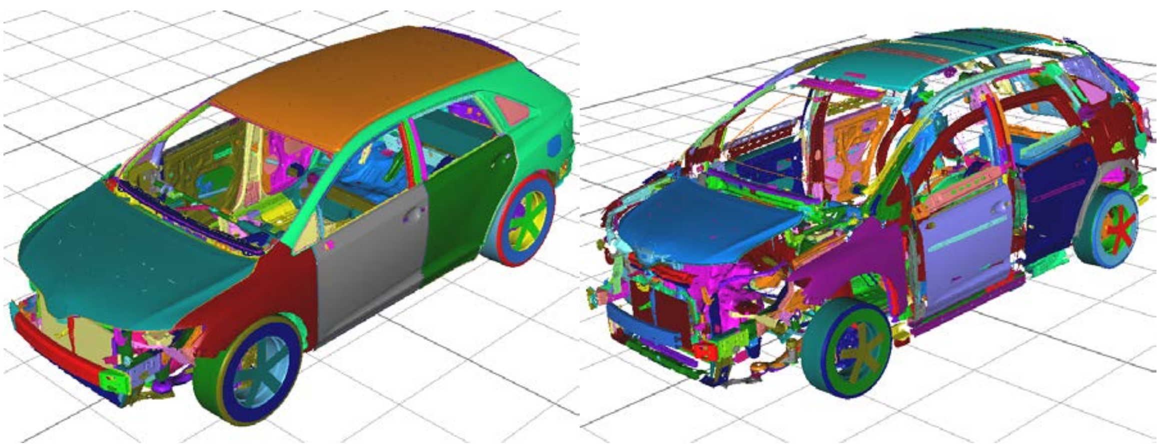


Figure 1. Baseline Vehicle Model and Expanded Parts. Colors denote different parts.

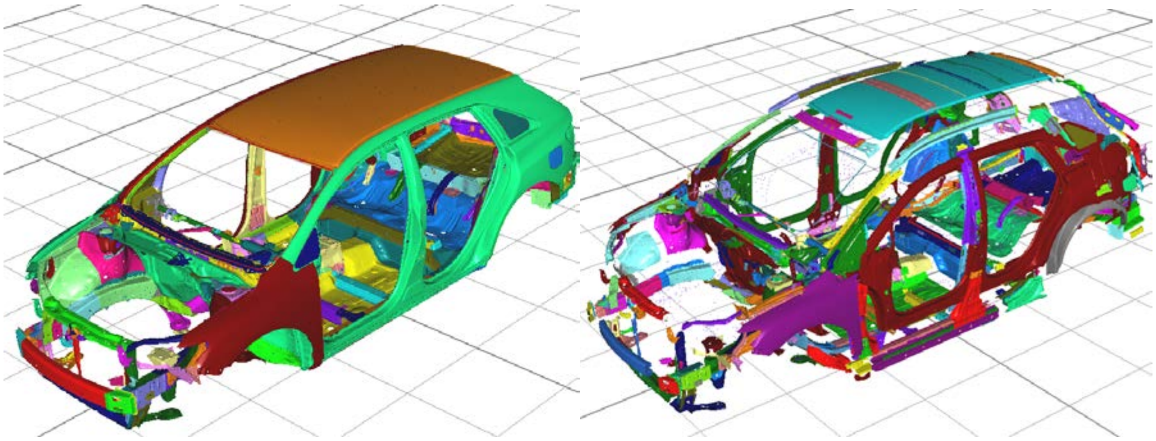


Figure 2. Baseline Body in White Model. Colors denote different parts.

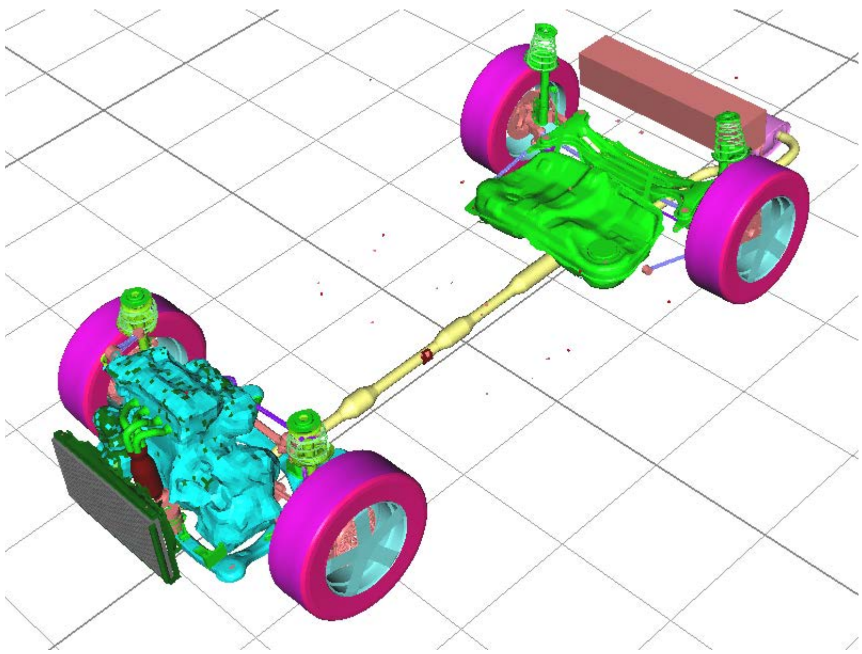


Figure 3. Baseline Vehicle, Unsprung Components. Colors denote different parts.

There are no apparent geometry conflicts in the model and parts are well aligned with compatible geometries and FEM meshes. This is essential for accurate modeling of currently the prevailing joining method for sheet metals, spot welding. The level of geometrical detail in the model is very high and as someone who has been involved with the vehicle crashworthiness modeling for the last twenty years, I think that the developed FEM mesh of the Venza BIW is the current state-of-the-art. Figure 4 shows some details of the BIW FEM mesh that illustrate the prevalence of the quadrilateral shell finite elements, constant aspect ratios and presence of the geometry details that are necessary for an adequate modeling of the progressive structural crush.

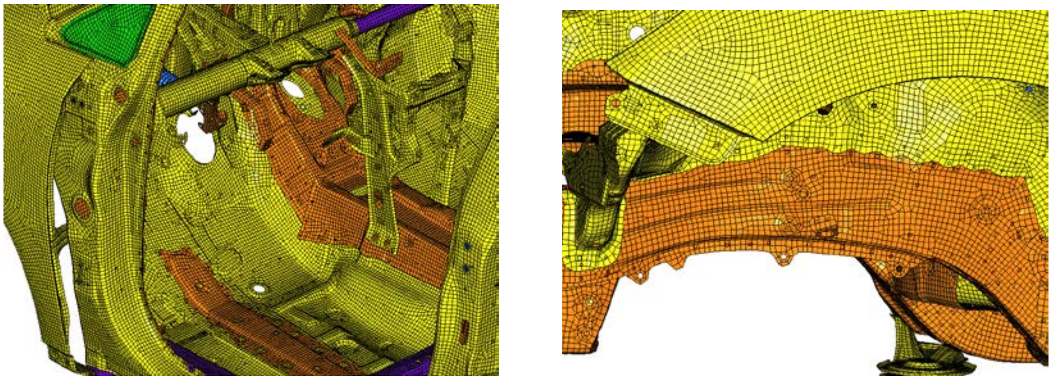


Figure 4. Mesh Detail and Quality.

In the following, I first give the analysis of the baseline FEM model. The baseline FEM model is very adept and can be used for illustration of some shortcomings of the LD model that I think need to be addressed. It is important to note that the LD model is much more complex due to a large number of materials and gages that resulted from the computational optimization process. This complexity and the project time constraints dramatically increase the potential for error. Unfortunately the tools for managing such complex systems are not yet mature, making the development and the evaluation of this complex vehicle model very challenging. Over the years, I have developed several simple programs that can be used to debug FEM models by directly analyzing the model files. The common approach to evaluation of large FEM models is to almost exclusively consider computational simulation results. However, these simple tools allow for evaluations of relationships within the FEM models directly from the model input files, thereby enabling debugging of the models independently from the simulations.

Review of the FEM Model for the Baseline Toyota Venza

The primary material for the BIW of the baseline vehicle, 2009 Toyota Venza, was identified in the Lotus Phase 1 Report as mild steel. Lotus Phase 1 study stated that the BIW also had about 8% of Dual Phase steel with 590 MPa designation, while everything else was commonly used mild steel sheet material. The FEV/EDAG study showed that there was more variety to the baseline design then originally anticipated. Table 1 lists the materials used in the BIW model (file Venza_biw_r006.k) that were modeled using MAT_PIECEWISE_LINEAR_PLASTICITY). Aluminum bumper was modeled using MAT_SIMPLIFIED_JOHNSON_COOK material model in LS-DYNA. The number of material models is relatively small.

Table 1. Baseline Model, Piecewise Linear Plasticity Material Models.

Material ID	Load Curve ID	Material Title in Model

10001	100017	MILD 140-270
10002	100034	DP 350-600
10003	100167	BH 210-340
10004	280090	BH 260-370
10005	280090	BH 280-400
10006	100143	HSLA 350-450
10007	100200	HSLA 490-600
10008	100101	HF 1050-1500
10010	100500	Q&T 5160 523MPA
10011	100300	SF 570/640
10012	1000700	DP 700-1000
10013	100600	MS 1250-1500
10019	0	Fuel tank strap
10022	0	Radiator fan module
10023	31	Exhaust
10024	108	Exhaust pipe Steel-25KSI
10025	109	Exhaust muffler STEEL 120KSI
10027	100233	DP 500-800
10028	55028	MS 950-1200
10029	55000	HF 1300
25203	1012	Al_alloy_wheel
27001	27001	Windshield_Backlite_Glass
4100001	0	Steel-coil spring
4100002	0	Steel_suspension-hight strength
4100004	0	steel-lingage 273 Mpa

Most of the CAE tools display the FEM model based on their part identification number (ID). To verify the material model assignment one must then verify material assignment for every part and then sort them accordingly. For large complex models this is a very tedious process that is very error prone. More advanced CAE tools, such as HyperMesh, have options for grouping and displaying model entities by material types and IDs. Figure 5 displays the material assignments for the baseline BIW.

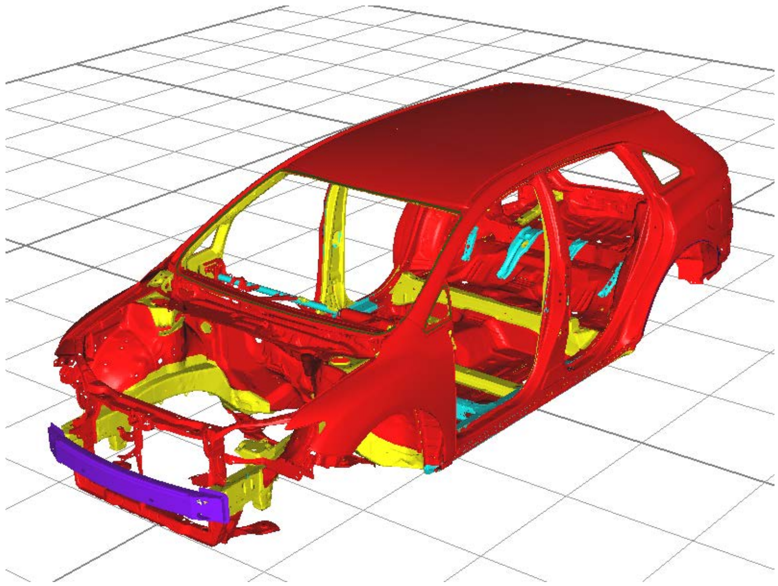
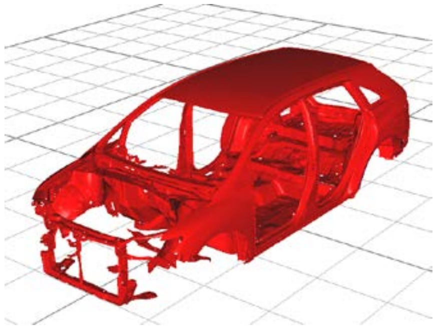


Figure 5. BIW Baseline Model. Colors denote different sheet materials.

The specific assignment of the materials for the BIW and the corresponding stress-strain curves are shown in the figures below. Most of the material models account for strain rate sensitivity of the material. For a given plastic strain, the yield stress is calculated by interpolating stresses between two neighboring stress strain curves based on the applied strain rate. There are established modeling recommendations for modeling strain rate sensitivity effect in crash models. The specified stress strain curves should not intersect. Extrapolated lines from their last specified linear segment should not intersect, as well. The material models should use plastic strain rate [23] instead of the total strain rate as the basis of the strain rate effect calculation. This option (VP=1) was not used in the FEV models although it is highly recommended in practice.

Figures 6-10 show the main material systems for the baseline BIW model. The material assignments correspond to the assignments in the project's report.



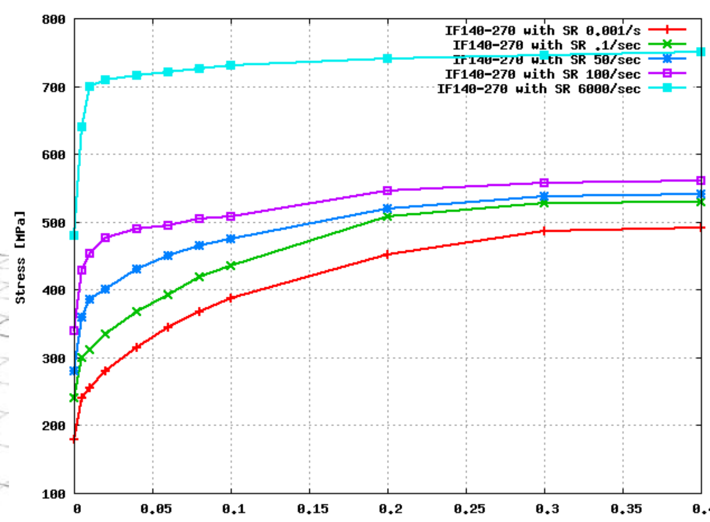


Figure 6. Material ID 10001, Table ID 100017.

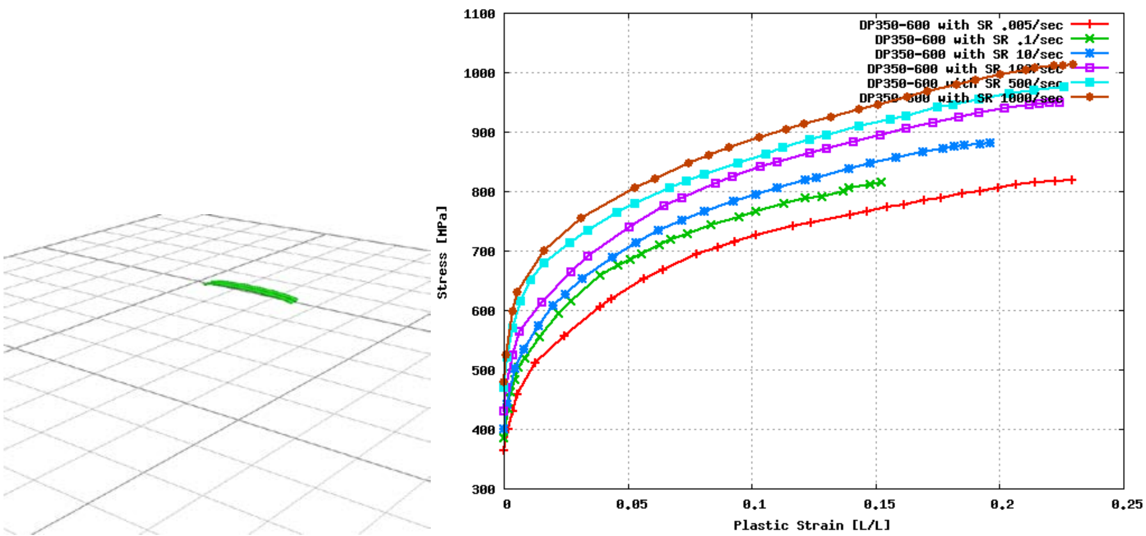


Figure 7. Material ID 10002, Table ID 100034.

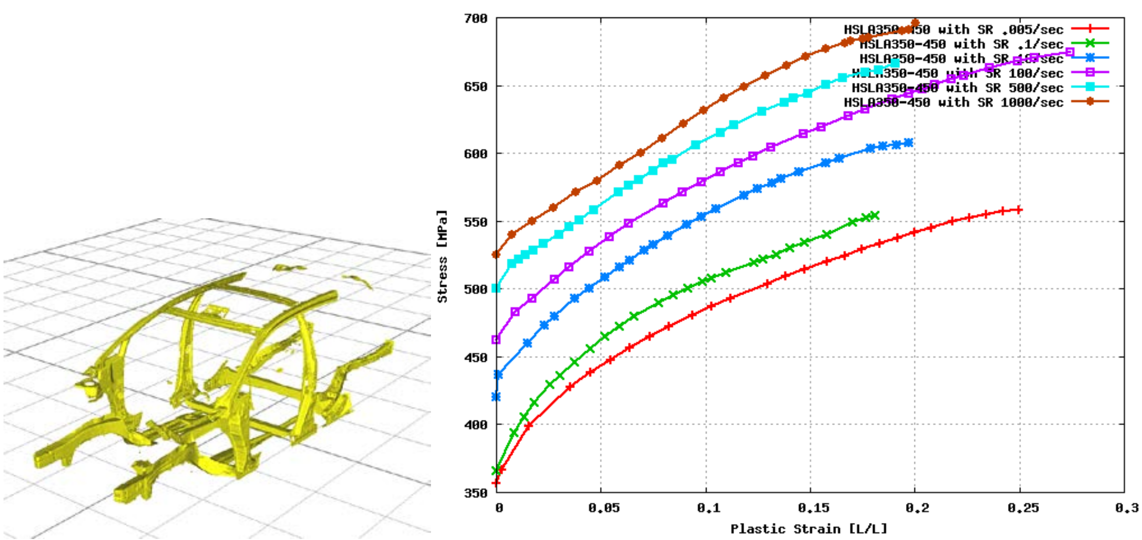


Figure 8. Material ID 10006, Table ID 100143.

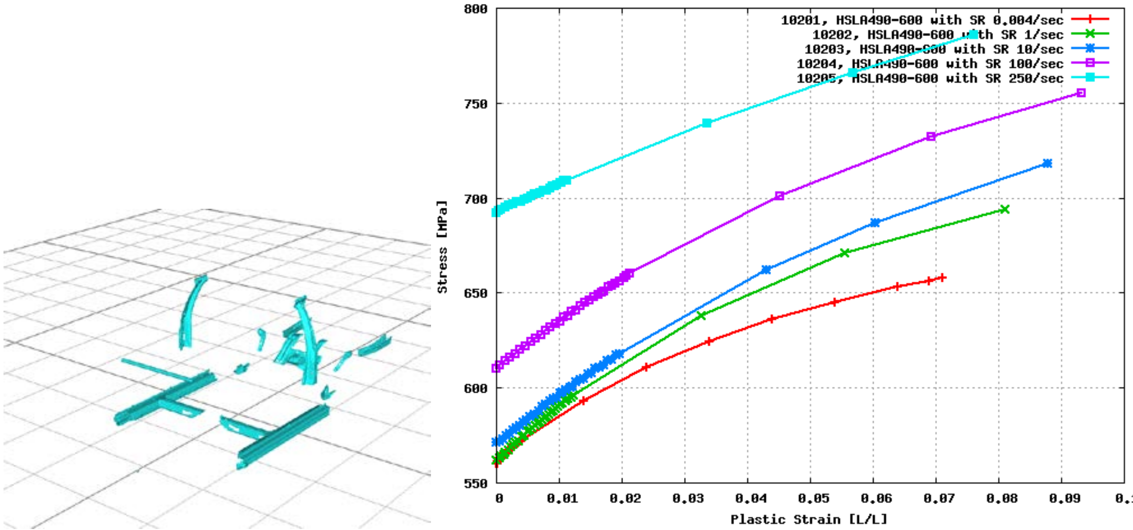


Figure 9. Material ID 10007, Table ID 100200.

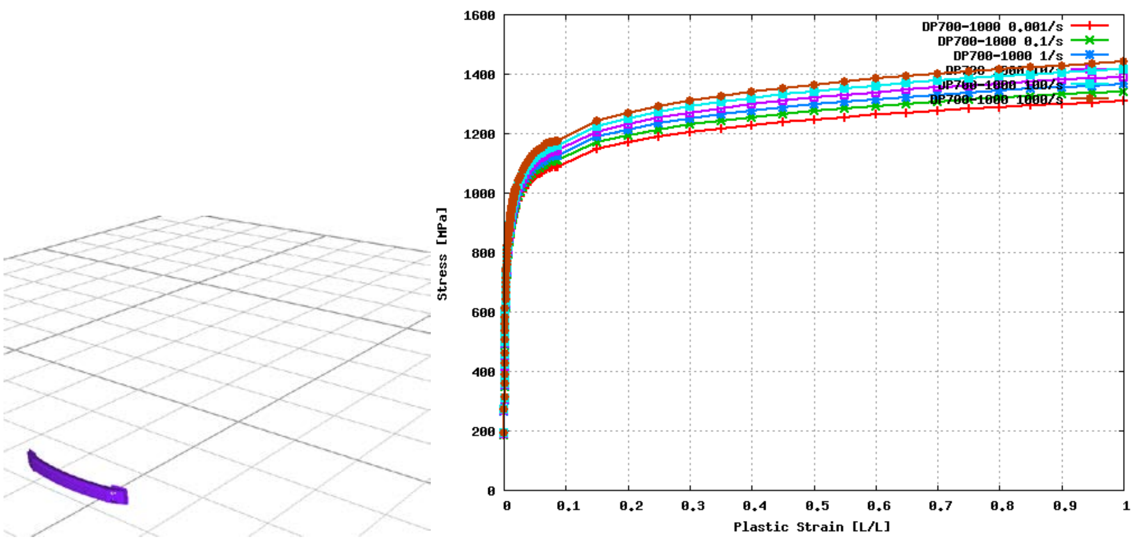


Figure 10. Material ID 10012, Table ID 1000700.

The stress-strain curves for different strain rates in the above figures do not intersect. Their extrapolations however have potential for intersection at high plastic strains in Figures 7and 8. The number of the data points in Figures 9 and 10 are too large and needs to be reduced in order to avoid the interpolation errors by the simulation program. It is obvious that curves in Figures 9 and 10 were developed by analytical fits. Such approach can create undesirable artifacts such as an appearance of the yield point elongation for Dual Phase steel in Figure 10. An interpolation approach with fewer points and curves is recommended. Figure 11 illustrates the optimal piecewise linear interpolation (green curve) of the base (red) curve in Figure 10. The interpolated curve has error of 1% of the value range with respect to the actual curve and uses only 9 points.

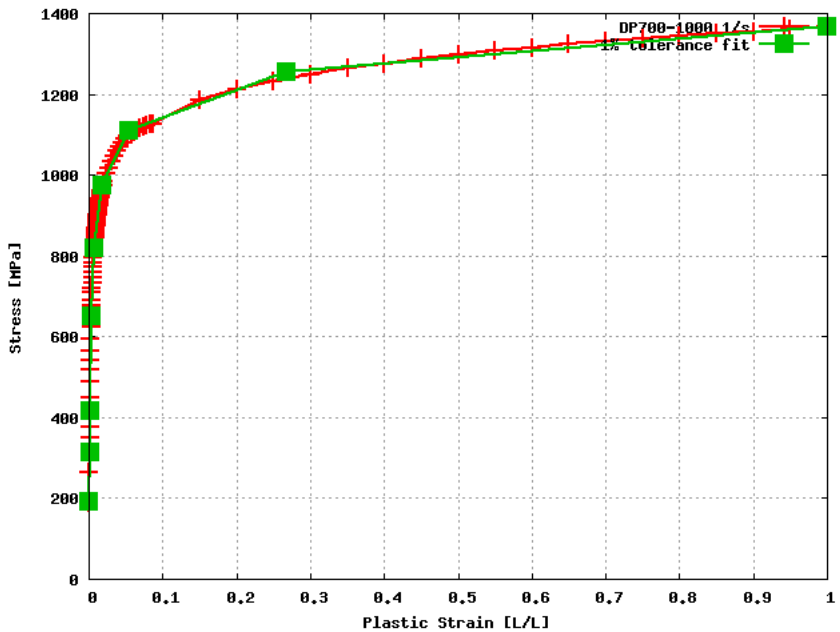


Figure 11. Optimal Linear Piecewise Approximation (tolerance is 1% value range) of the Lowest Curve in Figure 10..

Next, the BIW sheet material thickness distribution is shown in Figure 12. The colors indicate symmetrical distributions in accordance with the specified thickness distribution in the project report.

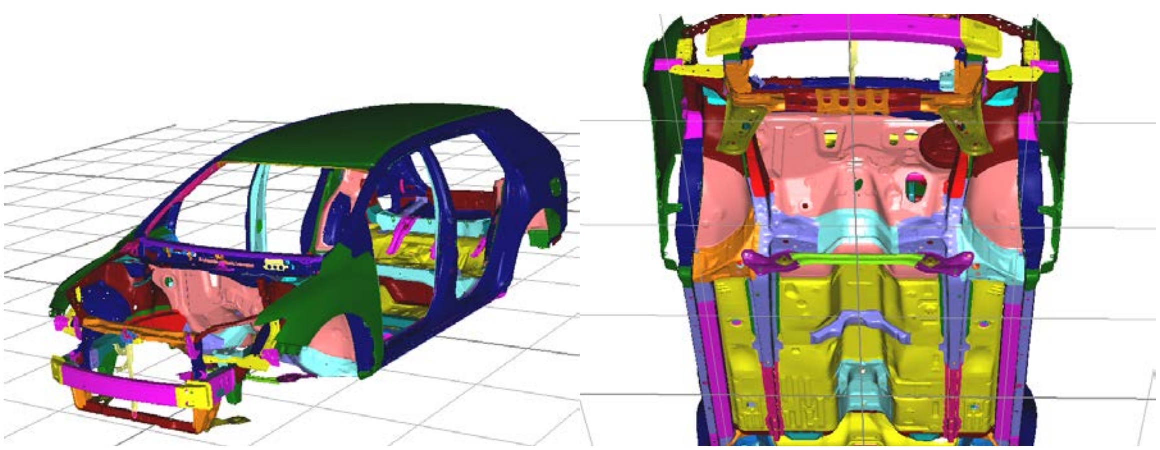


Figure 12. Baseline Model. Colors denote material thickness.

In many situations, the accuracy of the crash simulation is dependent on the shell element formulation (type) used. The basic shell element formulation (reduced integration Belytschko-Tsay, LS-DYNA type 2) is computationally very efficient but has lower accuracy than more complex formulations such as the fully-integrated Bathe-Dvorkin shell element

(LS-DYNA type 16). Figure 12 shows the shell element formulations in the BIW model. The current crash modeling recommendation is to use shell element type 16 when possible. The Bathe-Dvorkin shell is 3.5 times more computationally expensive than the Belytschko-Tsay shell so that in order to strike a proper balance between the accuracy and the computational speed element types can be mized in the model. This is especially true when large number of simulations is conducted, as was the case for computational optimization in the FEV study. As it can be seen in Figure 16, the baseline model employs accurate element formulation in the main structural components, while the Belytschko-Tsay formulation is employed in the remainder of the sheet metal which is an appropriate compromise for the large scale computations.

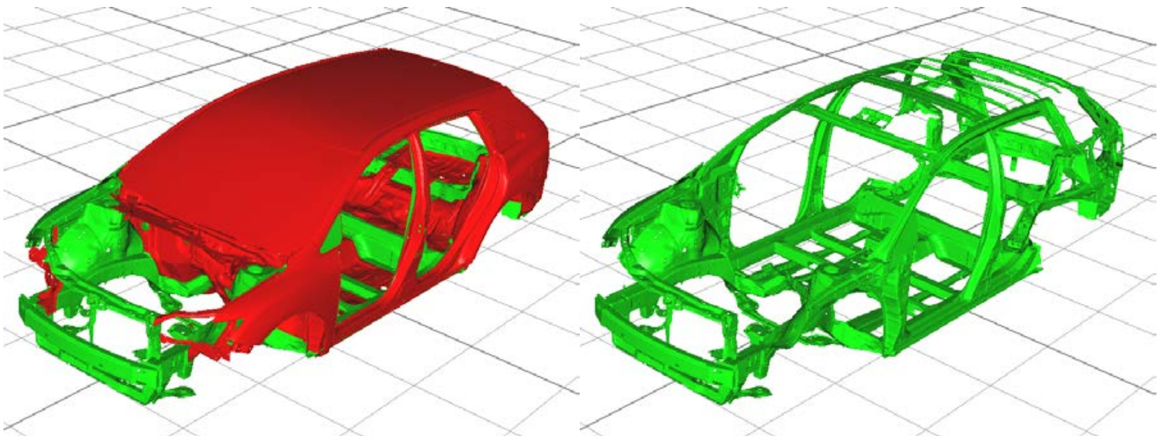


Figure 12. Baseline Model. Shell Element Formulation, Belytshcko-Tsay (red, ELFORM=2) and Bathe-Dvorkin (green, ELFORM=16) .

Another important technical aspect of the crash simulations with the shell elements is the employed number of integration points through the thickness of the shells. The default (2 points) is insufficient for the crash analyses. Three points is also inadequate in the current simulation guidelines because it results in a very quick formation of plastic hinges in the sheet metal during crush. A minimum of 5 through-thickness integration points is currently recommended for the crash simulations. Therefore, modification of the model in this regard is suggested for the general release.

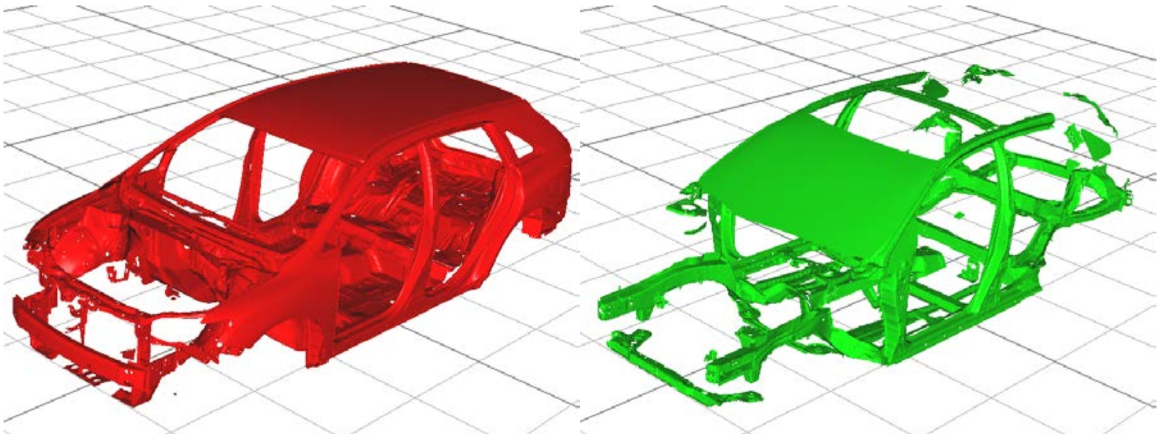


Figure 13. Baseline Model. Shell element through thickness integration points, 3 (red) and 5 (green).

Another commonly overlooked formulation aspect for the shell elements is the through thickness shear factor. Recommended value is 0.833, which was used only in bumper structures of the current model (Figure 14). Changing the factor to 0.833 is recommended.

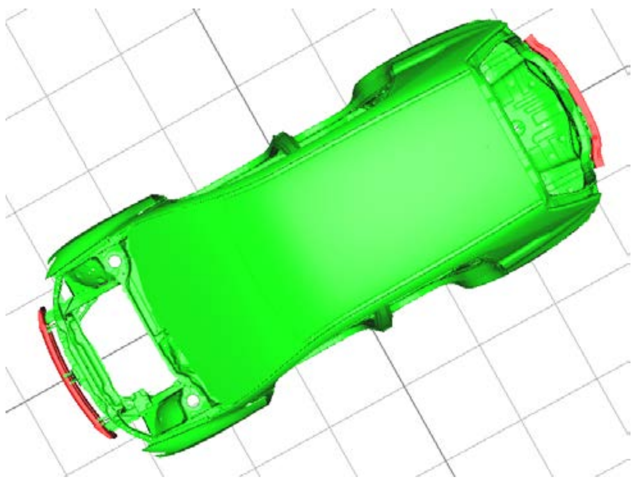


Figure 14. Baseline Model. Shear Factor, 1 (green), 0.833 (red).

In summary, the baseline Venza FEM model is developed following most of the recommended development procedures for crash models. The modifications suggested above would meet few additional recommendations that would likely increase the robustness of the model.. The NCAP and the side MDB barrier simulation results can be compared with the actual crash tests conducted by NHTSA. The comparison of the simulation and the NCAP test shows somewhat stiffer response of the FEM model with respect to the test (Figure 1.18.18 in the last FEV report). The maximum and the average accelerations in the FEM model were accordingly higher than the test results. The baseline FEM model was deemed acceptable for the purposes of the FEV study. Another important measure of the FEM model fidelity was the crash duration time that was 20 ms shorter for the model compared to the test. This difference is noticeable because the overall crash duration of 100 milliseconds. However, for the objectives of the FEM study, the model's crash pulse was deemed acceptable, which for the described project schedule seemed quite reasonable.

Review of the Low Development Vehicle Model

The FEV engineers have used the computational optimization methods based on the response surface formulation in order to determine the distribution of material types and grades that would maximally reduce the weight of the vehicle while maintaining the performance and controlling the cost. The part distribution of the resulting optimized LD design FEM model is shown in Figure 15.

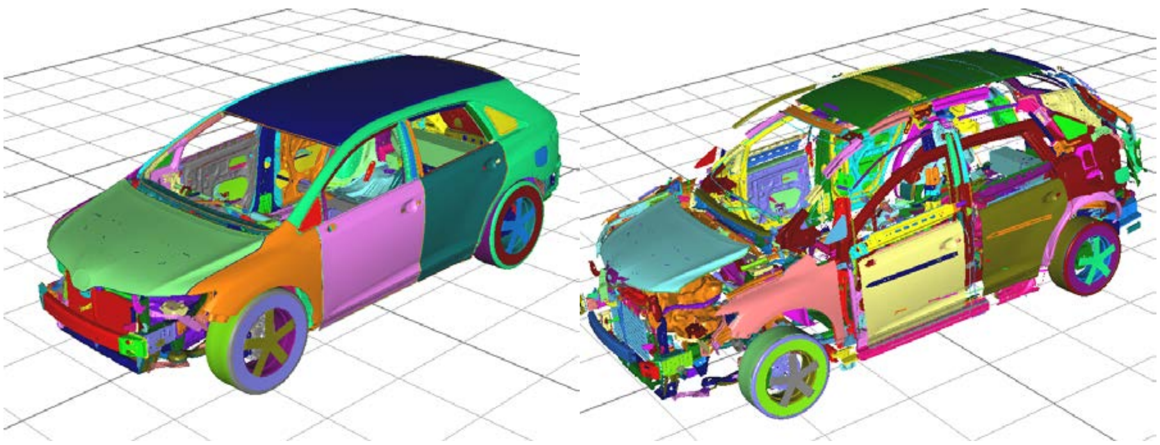


Figure 15. Low Development Design Model. Colors denote different parts.

It is probably misleading to refer to the resulting FEM model as "Low Development" since it is a product of numerous computational simulations and an in-depth engineering study. The resulting inventory of the material models used in the LD FEM model is listed in Table 2. It is evident that there are numerous duplicates as well as unused materials. It would be prudent to purge the list of material models from the LD FEM model as they may lead to errors. Some of the inconsistencies that were found in the current LD FEM model may very well be a result of this model redundancy.

Two model files contain most of the material models:

- Venza_master_mat_list_r006.k
- Venza_Material_Db_Opt_dk2.k

The horizontal black line in Table 2 separates the material model specifications between the two files. These two were unchanged for the last two versions of the FEM models that were downloaded from the project download site.

Table 2. Low Development Model, Piecewise Linear Plasticity Material Models.

Material ID	Load Curve ID	Material Name
10001	100017	MILD 140-270
10002	100034	DP 350-600
10003	100167	BH 210-340
10004	280090	BH 260-370
10005	280090	BH 280-400
10006	100143	HSLA 350-450
10007	100200	HSLA 490-600
10008	100101	HF 1050-1500
10010	100500	Q&T 5160 523MPA
10011	100300	SF 570/640
10012	1000700	DP 700-1000
10013	100600	MS 1250-1500
10019	0	Fuel tank strap
10022	0	Radiator fan module
10024	108	Exhaust pipe Steel-25KSI
10025	109	Exhaust muffler STEEL 120KSI
10027	100233	DP 500-800
10028	55028	MS 950-1200
10029	55000	HF 1300
15203	1012	Al_alloy_wheel
25203	1012	Al_alloy_wheel
27001	27001	Windshield_Backlite_Glass
110001	100017	MILD 140-270 : ORIGINAL DENSITY
110002	100034	DP 350-600
110003	100167	BH 210-340 : ORIGINAL DENSITY
110004	280090	BH 260-370
110005	280090	BH 280-400
110007	100200	HSLA 490-600 : ORIGINAL DENSITY
110008	100101	HF 1050-1500
110010	100500	Q&T 5160 523MPA
110011	100300	SF 570/640
110012	1000700	DP 700-1000
110027	100233	DP 500-800
110028	55028	MS 950-1200
110029	55000	HF 1300
127001	27001	Windshield_Backlite_Glass
210001	100017	MILD 140-270 : 20%down
210004	280090	BH 260-370
210006	100143	HSLA 350-450 : 20%down
210007	100200	HSLA 490-600 : 20%down
210010	100500	Q&T 5160 523MPA : 20%down

Material ID	Load Curve ID	Material Name
210011	100300	SF 570/640 : 20%down
210023	31	Exhaust
210024	108	Exhaust pipe Steel-25KSI
210025	109	Exhaust muffler STEEL 120KSI
310001	100017	MILD 140-270 : ORIGINAL DENSITY
310003	100167	BH 210-340 : ORIGINAL DENSITY
310004	280090	BH 260-370 : ORIGINAL DENSITY
310005	280090	BH 280-400 : ORIGINAL DENSITY
310006	100143	HSLA 350-450 : ORIGINAL DENSITY
310007	100200	HSLA 490-600 : ORIGINAL DENSITY
310010	100500	Q&T 5160 523MPA : ORIGINAL DENSITY
310011	100300	SF 570/640 : ORIGINAL DENSITY
310013	100600	MS 1250-1500 : ORIGINAL DENSITY
310022	0	Radiator fan module
325203	1012	Al_alloy_wheel
410001	100017	MILD 140-270 : FOR_ITER_201_03
410003	100167	BH 210-340 : FOR_ITER_201_03
410005	280090	BH 280-400 : FOR_ITER_201_03
510001	100017	MILD 140-270 : FOR_ITER_201_03
610001	100017	MILD 140-270 : FOR_ITER_201_03
710001	100017	MILD 140-270 : FOR_ITER_201_03
710002	100034	DP 350-600 : FOR_ITER_201_03
810001	100017	MILD 140-270 : FOR_ITER_201_03
810002	100034	DP 350-600 : FOR_ITER_201_03
810006	100143	HSLA 350-450 : FOR_ITER_201_03
810007	100200	HSLA 490-600 : FOR_ITER_201_03
810012	1000700	DP 700-1000 : FOR_ITER_201_03
910012	1000700	DP 700-1000 : FOR_ITER_201_03
4100001	0	Steel-coil spring
4100002	0	Steel_suspension-high strength
4100004	0	steel-lingage 273 Mpa
14100001	0	Steel-coil spring
14100002	0	Steel_suspension-high strength
14100004	0	steel-lingage 273 Mpa
1	10000101	MILD 140/270
2	10000228	IF140/270
3	10000139	BH 210/340
4	10000177	BH 260/370
5	10000177	BH 280/400
6	10000049	DP300/500

Material ID	Load Curve ID	Material Name
7	10000132	HSLA 350/450
8	10000107	DP 350/600
9	10000183	HSLA 420/500
10	10000036	FB 450/600
11	10000144	HSLA 490/600
12	10000084	TWIP 500/980
13	10000150	DP 500/800
14	0	HSLA 550/650
15	10000156	SF 570/640
16	10000114	TRIP 600/980
17	10000200	DP 700/1000
18	10000207	CP 800/1000
19	10000077	MS 950/1200
20	10000187	CP 1000/1200
21	10000208	CP 1050/1470
22	10000126	HF 1050-1500
23	10000078	MS 1150-1400
24	10000164	MS 1250-1500
25	10000163	Q&T 5160 523MPA
26	10000076	HF 1300
700010	10000036	FB 450/600 : FOR_ITER_201_03
8000006	29	AL_aa5182_novelis
8000007	28	AL_AA6451_Novelis
8000008	29	Magnesium_MG60

Figures 16-32 below show the stress-strain curves for the materials used in the BIW of the LD FEM model.

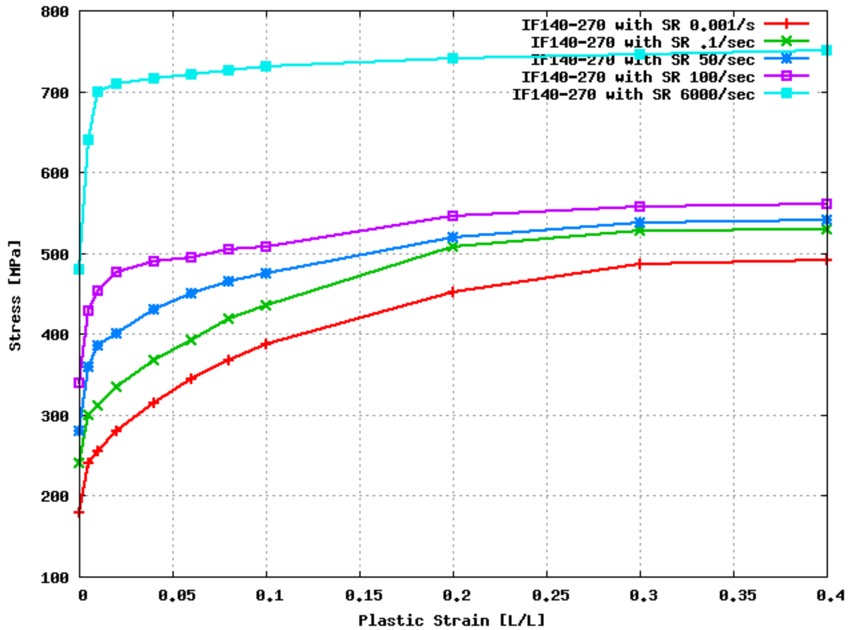


Figure 16. Material ID 10001, Table ID 100017.

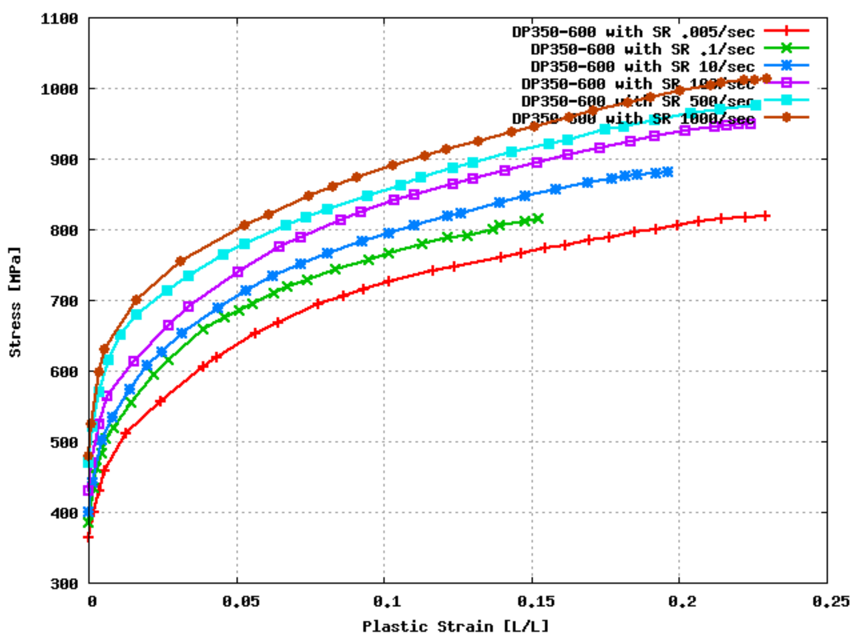


Figure 17. Material ID 10002, Table ID 100034.

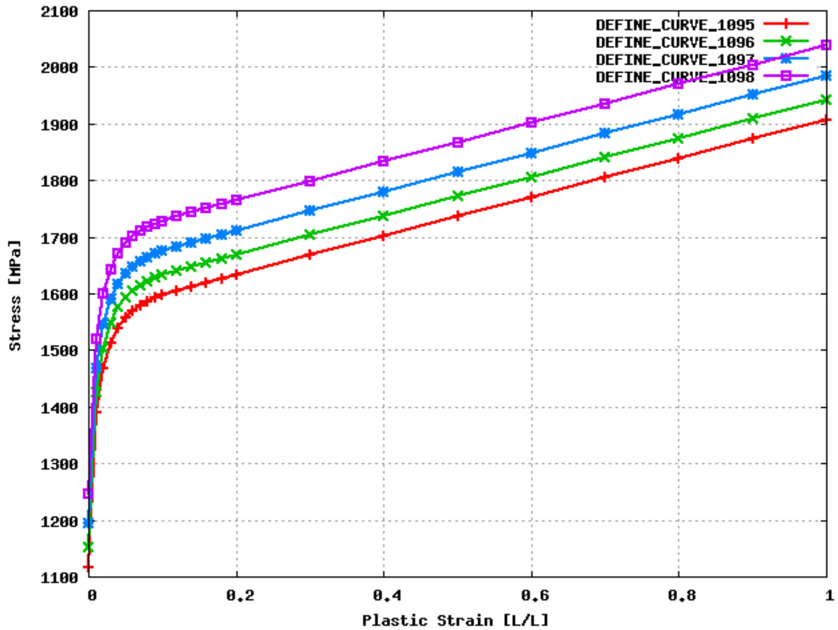


Figure 18. Material ID 10008, Table ID 100101.

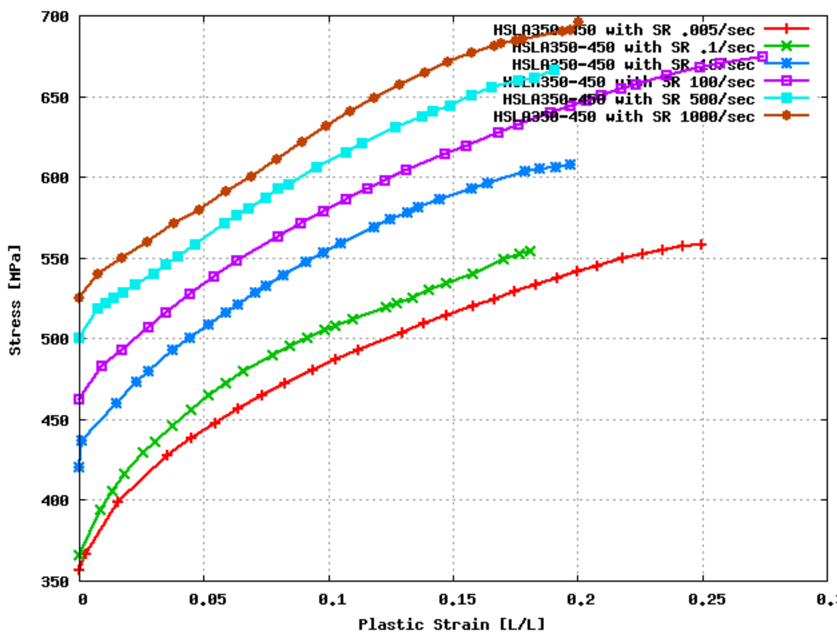


Figure 19. Material 10006, Table ID 100143.

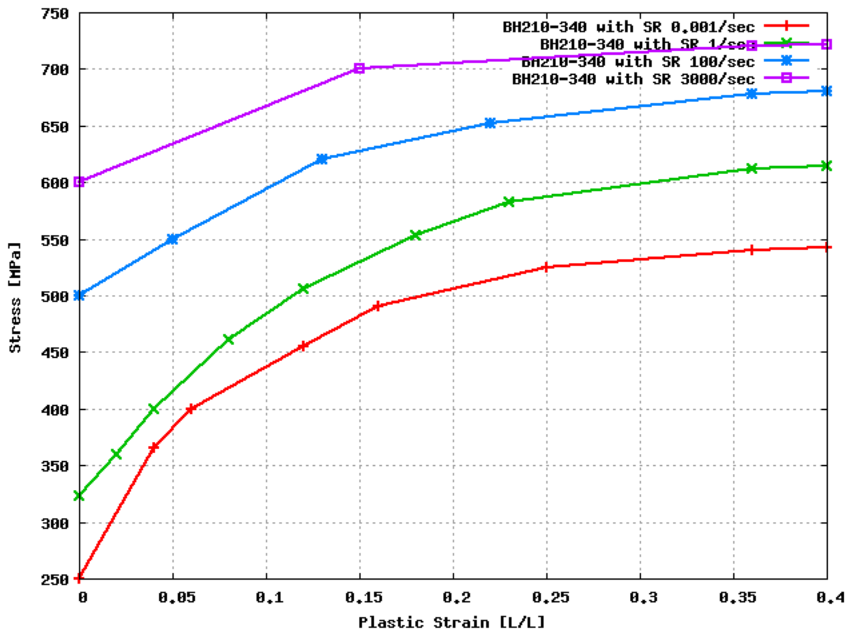


Figure 20. Material 10003, Table ID 100167.

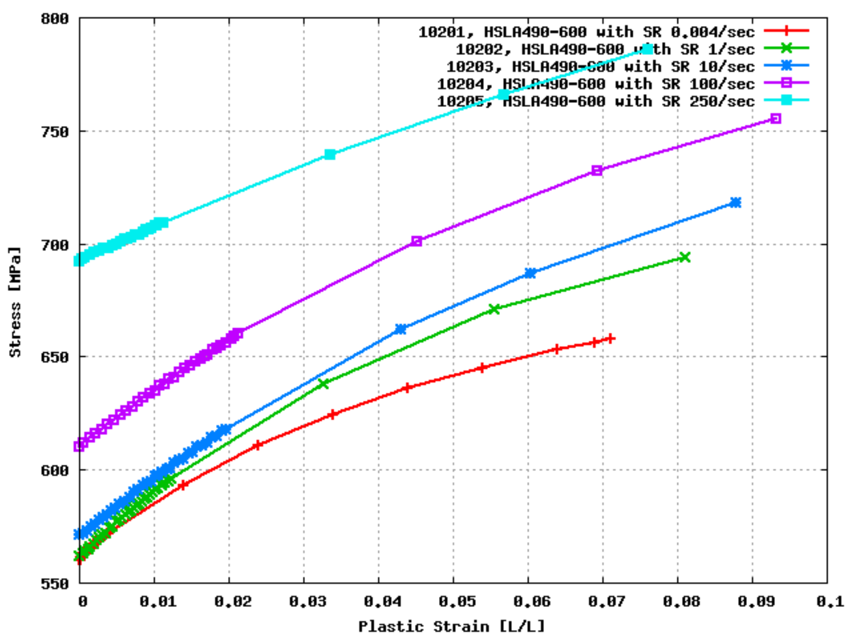


Figure 21. Material ID 10007, Table ID 100200.

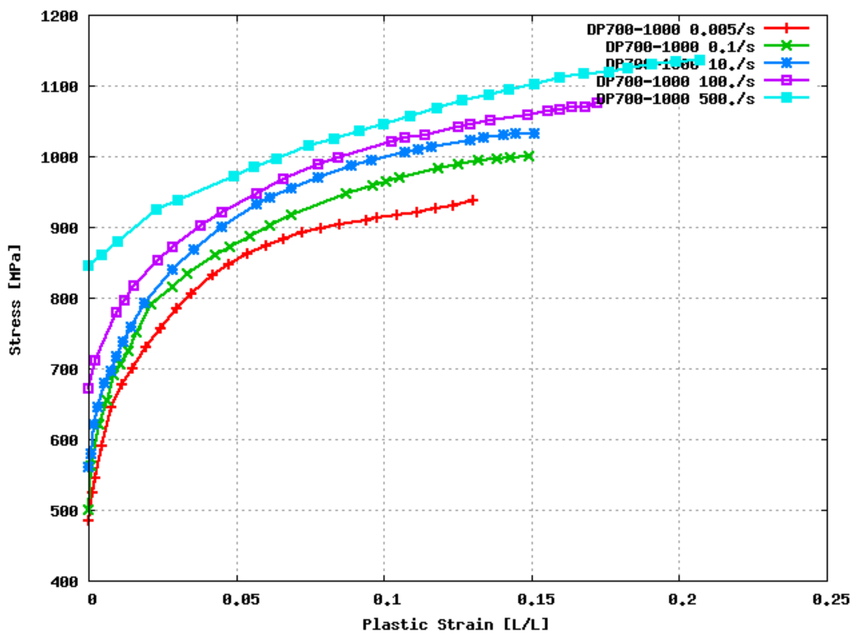


Figure 22. Material ID 10027, Table ID 100233.

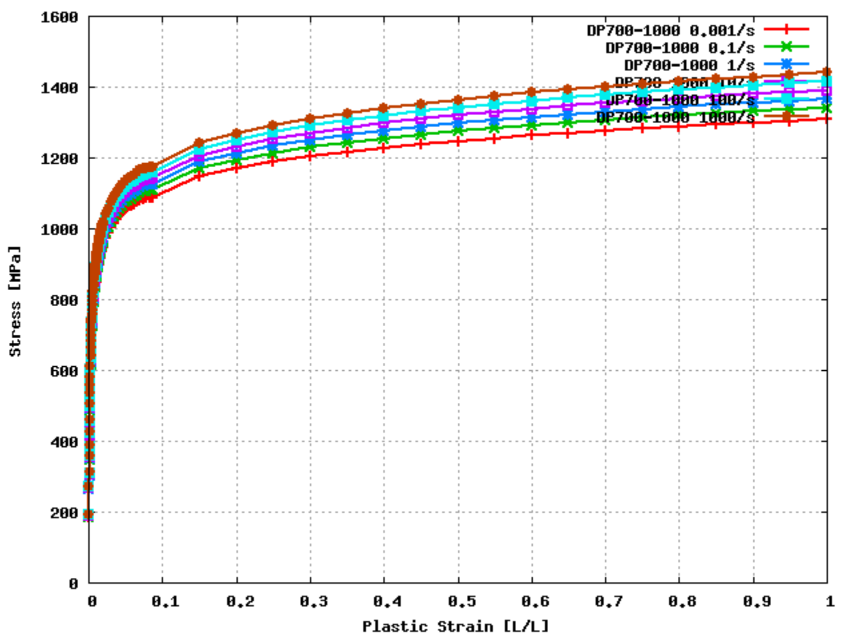


Figure 23. Material ID 10012, Table ID 1000700.

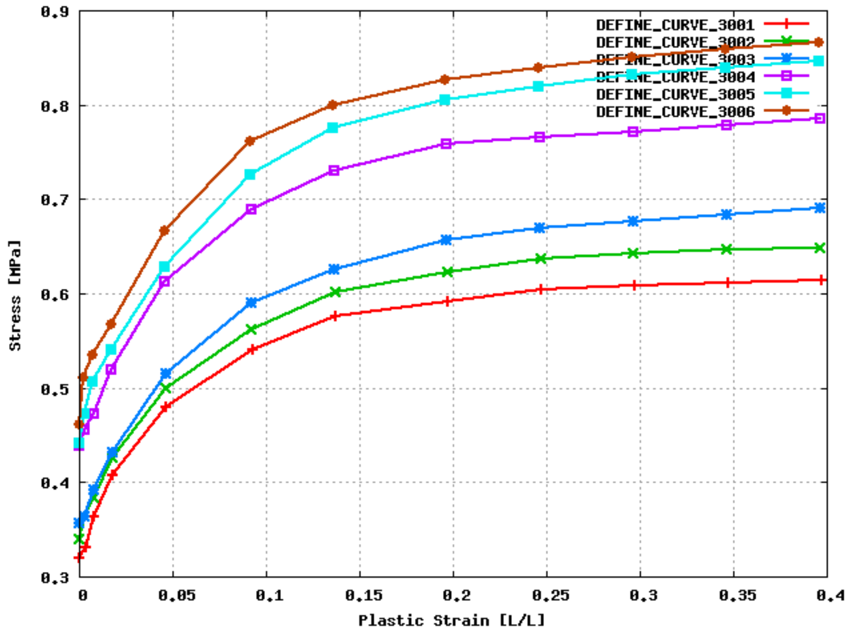


Figure 24. Material ID 6, Table ID 10000049.

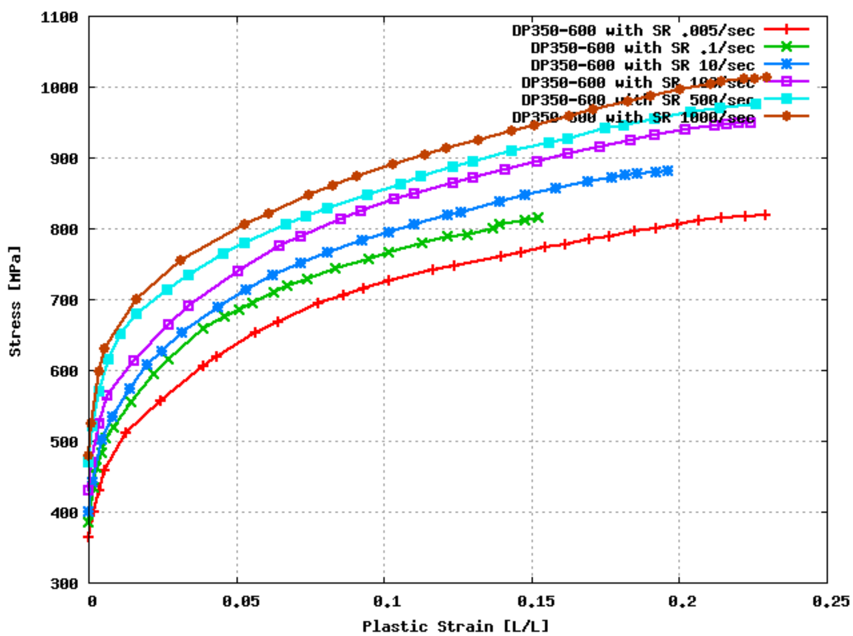


Figure 25. Material ID 8, Table ID 10000107.

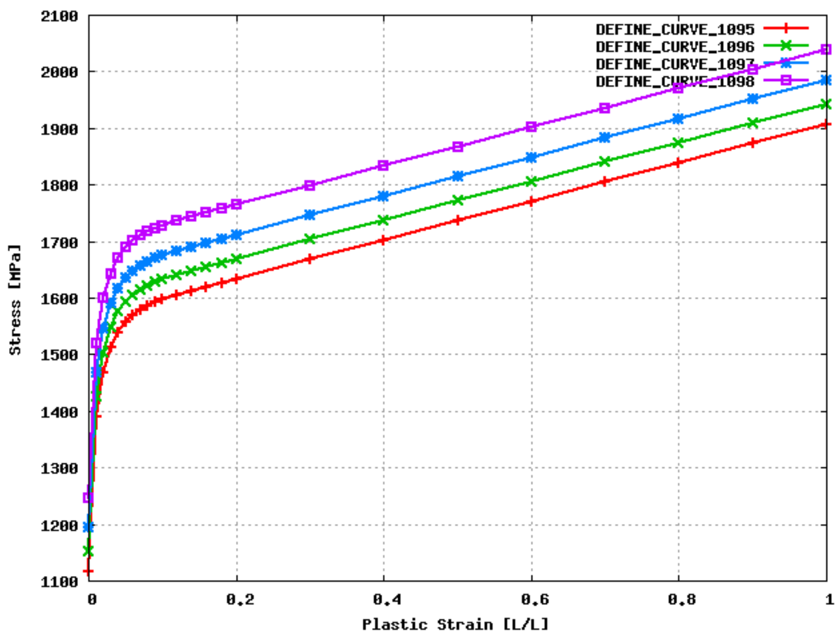


Figure 26. Material 22, Table ID 10000126.

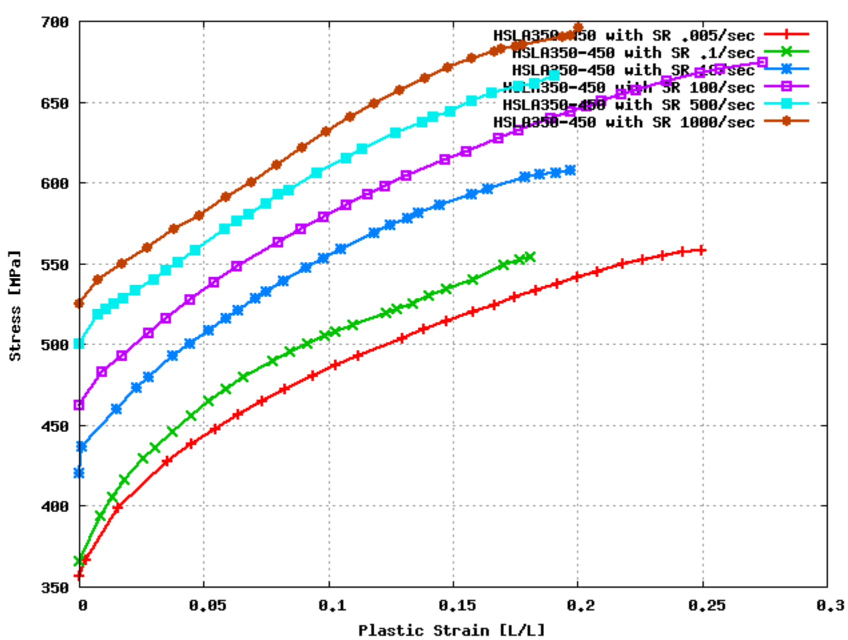


Figure 27. Material ID 7, Table ID 10000132

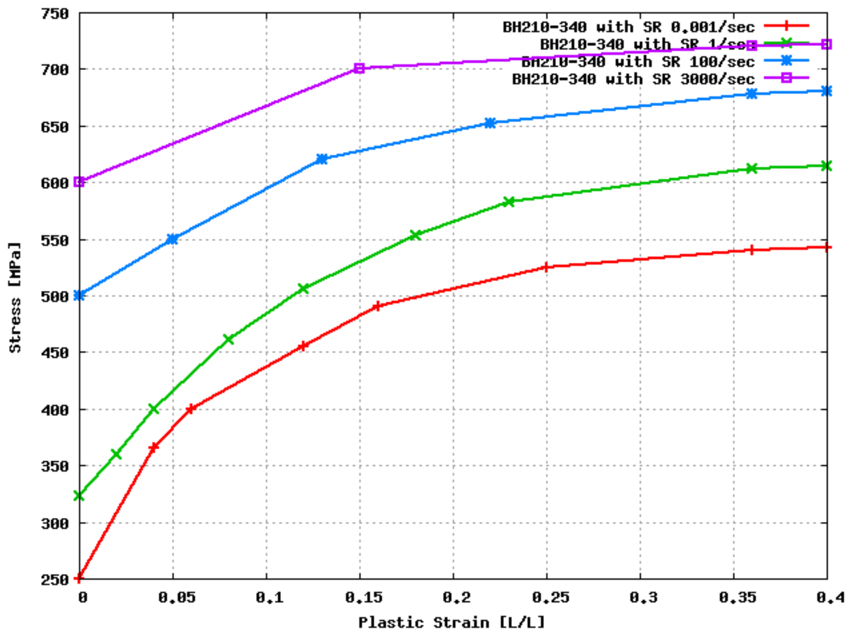


Figure 28. Material ID 3, Table ID 10000139.

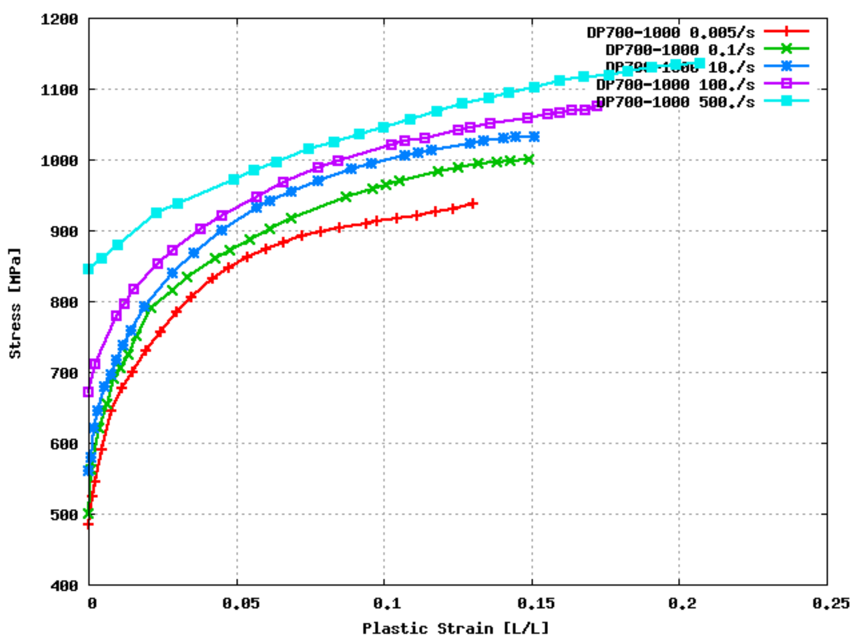


Figure 29. Material ID 13, 10000150.

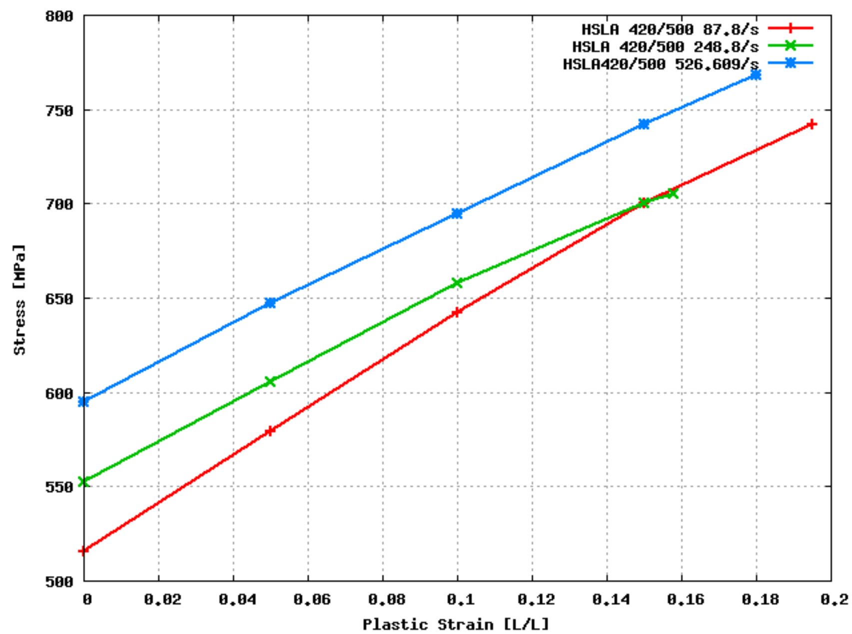


Figure 30. Material ID 9, 10000183.

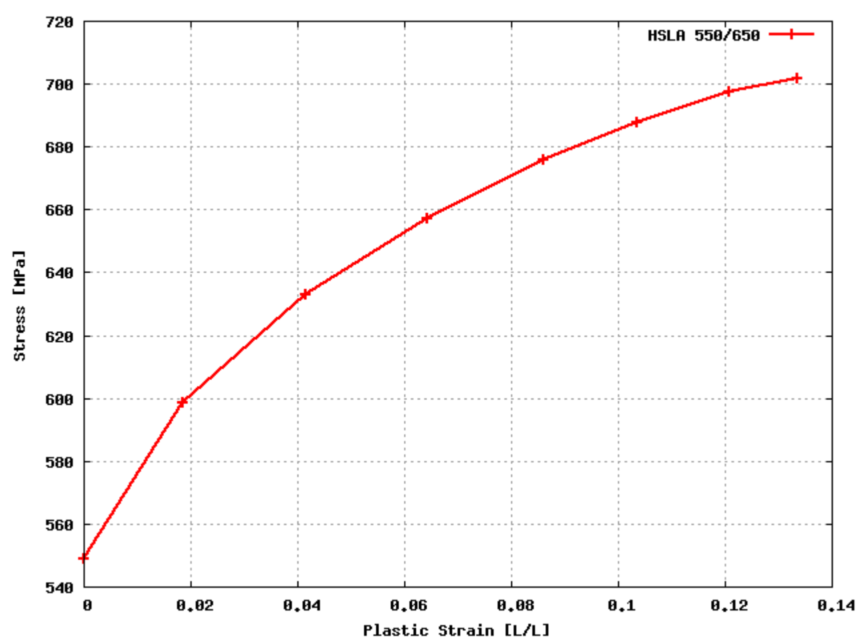


Figure 31. Material ID 14.

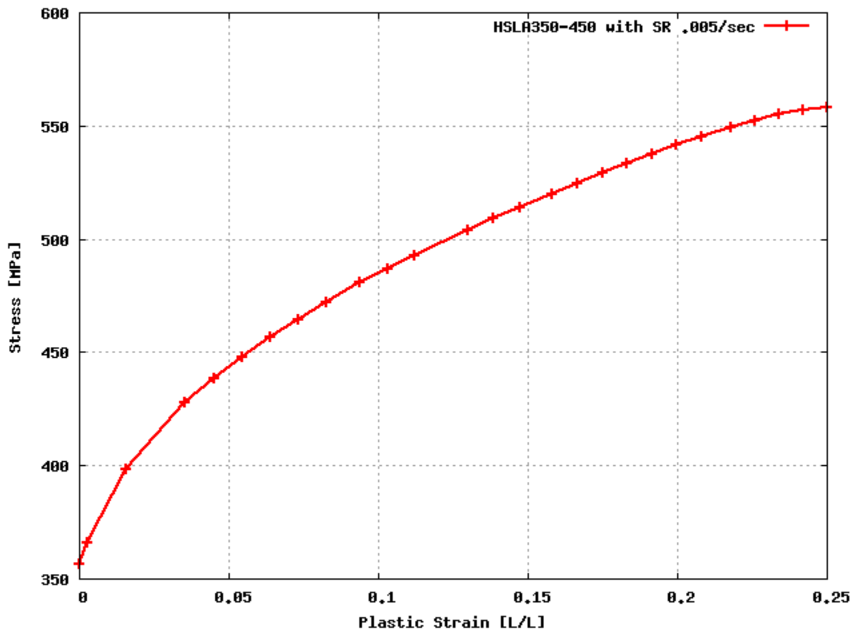


Figure 32. Material ID 8000006, Curve ID 29.

There are obvious duplicates in the model specifications that would be prudent to eliminate and modify the model accordingly before its public release. In addition, there are some errors in the LD FEM model specifications that need to be corrected.

Correction Item 1:

Material ID 9 (Figure 30) has stress-strain curves for different strain rates different strain rate curves intersect which is not acceptable from the physical perspective.

Materials with IDs 8000006, 8000007, and 8000008 have elastic properties of lightweight materials such as Aluminum and Magnesium alloys, but they utilize yield stress functions of HSLA 350/450 steel defined in file: Venza_frt_susp_exhaust_30ms.k.
Currently, only the material 8000006 is used in the LD FEM model, although in the previous model version material ID 8000008 was also used.

Correction Item 2:

Some material assignments in the LD FEM model are inconsistent which is probably a result of too many material models. The mapping of material IDs on the BIW FEM model reveal several unsymmetrical model assignments. The most obvious discrepancy is marked in Figure 33. Here, where one model part is modeled using the mild steel while its corresponding symmetrical counterpart is modeled using the HSLA 350/450 steel.

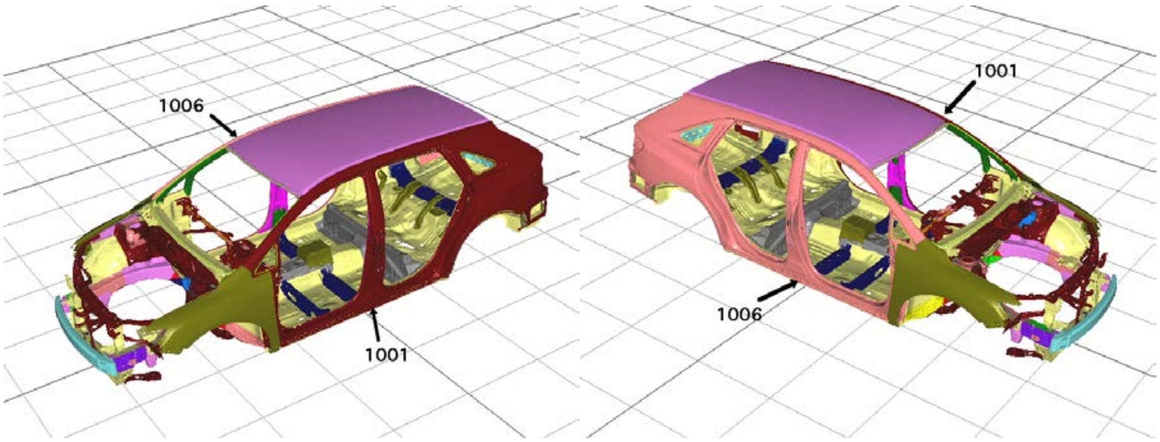


Figure 33. Low Development Model. Colors denote different material models. Arrows point to part 12151 (material ID 1006 – HSLA 350/450) and part 12101 (material ID 1001 – Mild Steel).

Additional unsymmetrical material assignments are pointed with arrows in Figures 34-37.

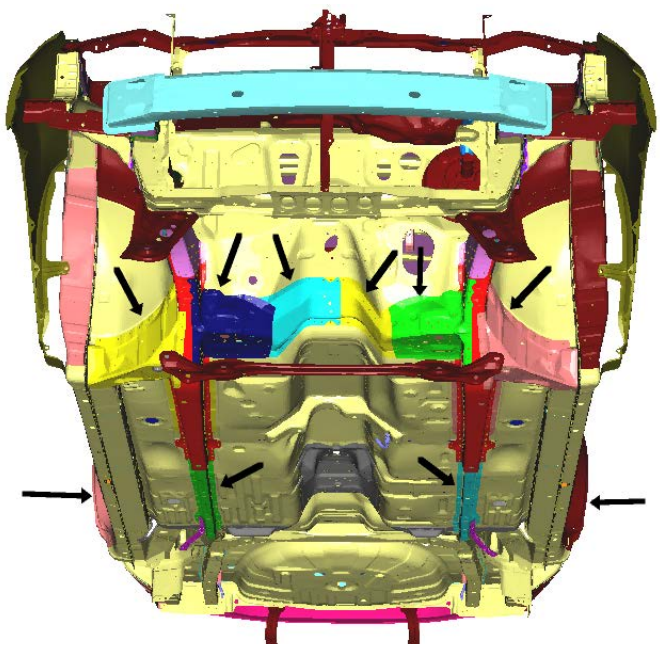


Figure 34. Low Development Model. Colors denote different material models. Arrows point to parts with unsymmetrical material ID assignments.

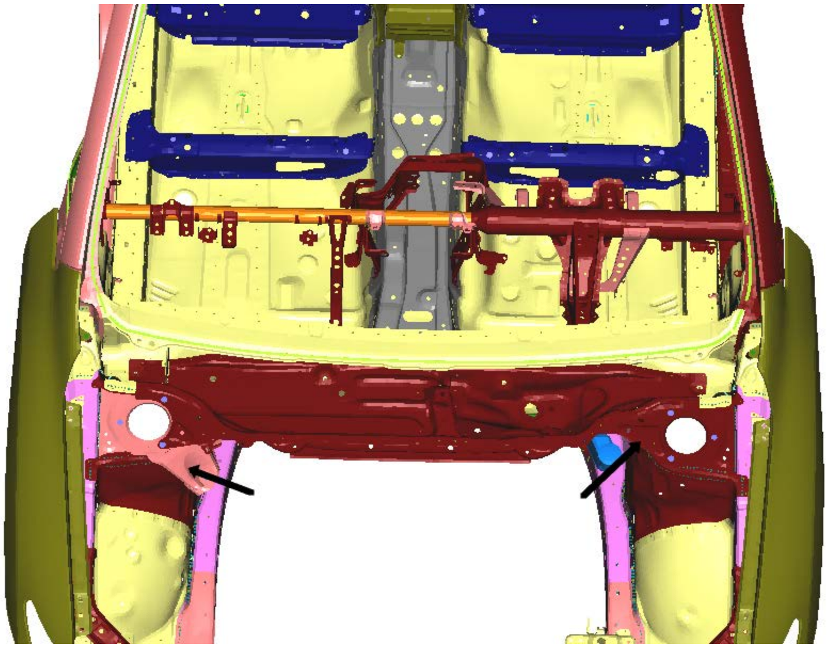


Figure 35. Low Development Model. Colors denote different material models. Arrows point to parts with unsymmetrical material ID assignments..

Two possible outcomes of not pairing the symmetrical components with the same material ID are illustrated in Figures 36-37. In Figure 36 the two different parts have different material assignments, which eventually refer to different material properties. In case of the marked parts in Figure 37, the material IDs are different but because of the repeated material models with different IDs, they eventually refer to the same material properties.

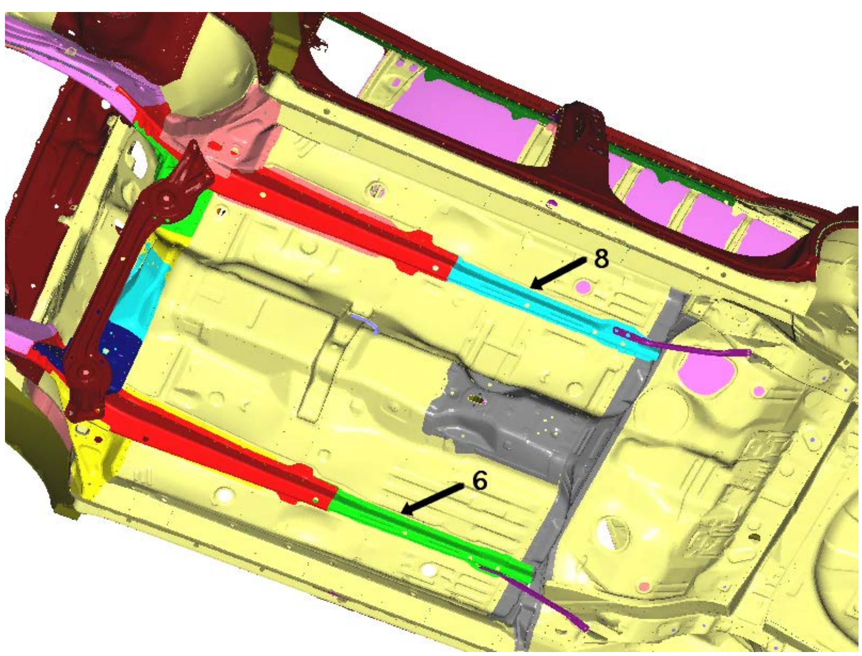


Figure 36. Low Development Model. Colors denote different material models. Arrows point to part 17313 (material ID 8 – DP 350/600) and part 17363 (material ID 6 – DP 300/500).

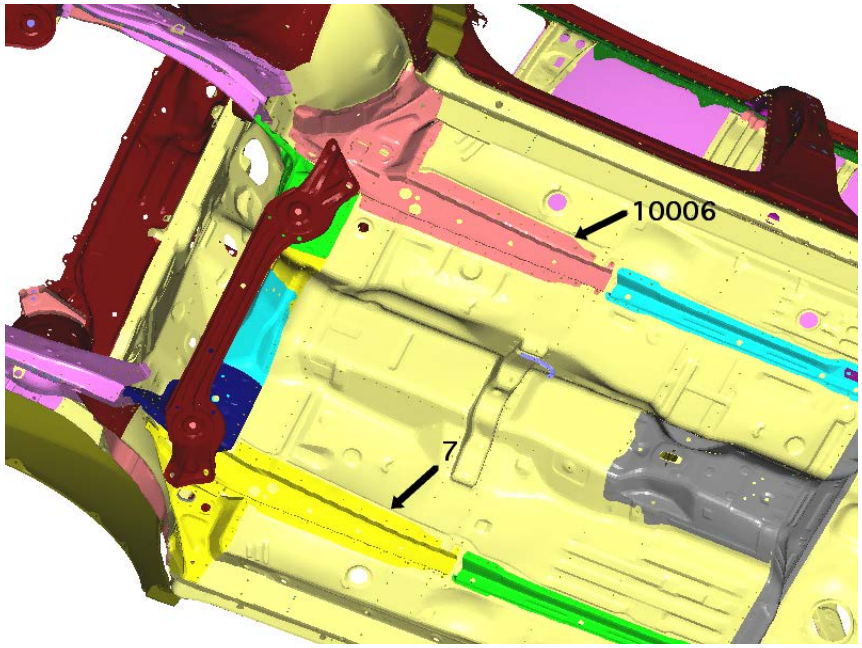


Figure 37. Low Development Model. Colors denote different material models. Arrows point to part 11710 (material ID 10006 – HSLA 350-450) and part 11760 (material ID 7 – HSLA 350/450).

The above inconsistencies need to be corrected before the models are released into to the open domain.

Correction Item 3:

Another area of concern is the number of through thickness integration points for the shell elements in the current LD FEM model. As it can be seen in Figure 38, almost all shell elements have just 2 integration points through the thickness. This is clearly inadequate from the accuracy standpoint and may be responsible for some of the issuable simulation results shown in the following figures.

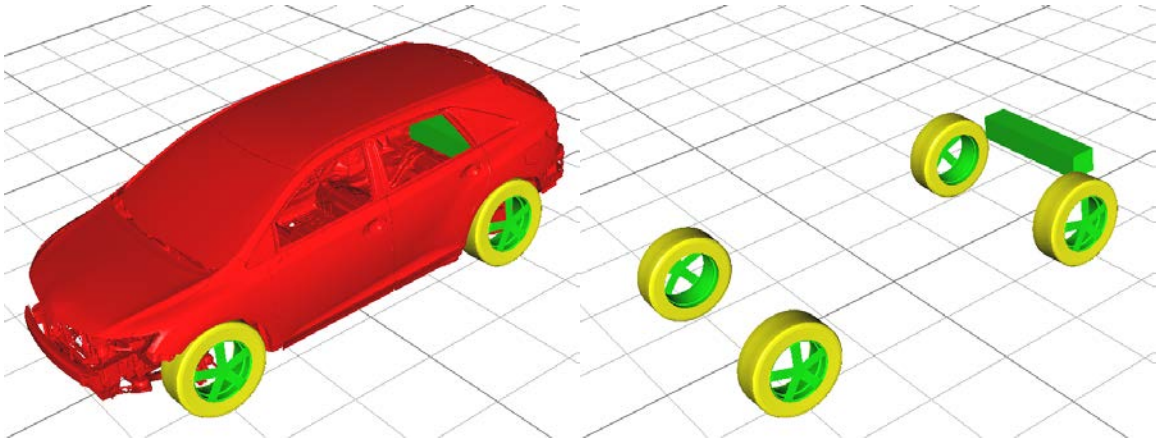


Figure 38. Low Development Model. Colors denote number of through thickness integration points in shells, 2 (red), 3 (green) and 5 (yellow).

Correction Item 4:

Figure 38 shows the thickness distribution in the LD FEM model of the BIW. In general, the thickness distribution is symmetrical with respect to the centerline of the vehicle. However, a closer inspection reveals some asymmetries in thickness assignments.

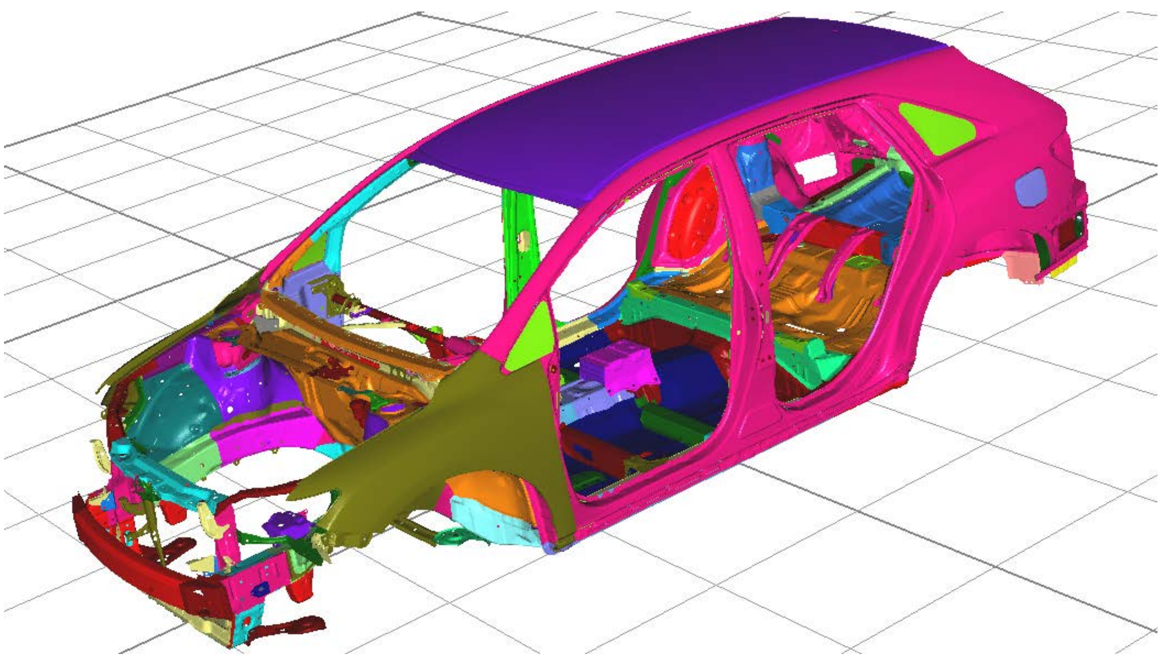


Figure 39. Low Development Model. Colors denote thickness of the sheet materials.

The arrows in Figures 40-41 show the parts that do not have symmetrical assignment of the values with respect to the centerline of the vehicle. I have not checked the extent of the differences, but it something nonetheless that needs to be corrected.

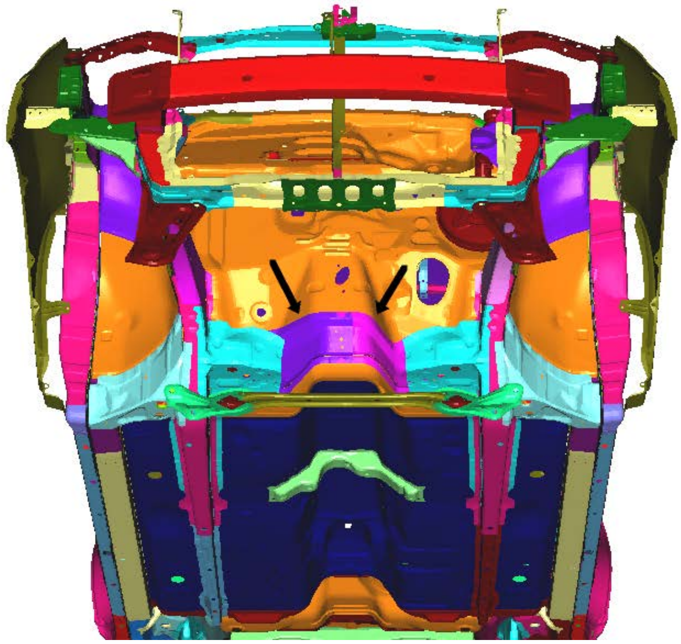


Figure 40. Low Development Model. Colors denote thickness of the sheet materials. Arrows point to unsymmetrical thickness assignments.

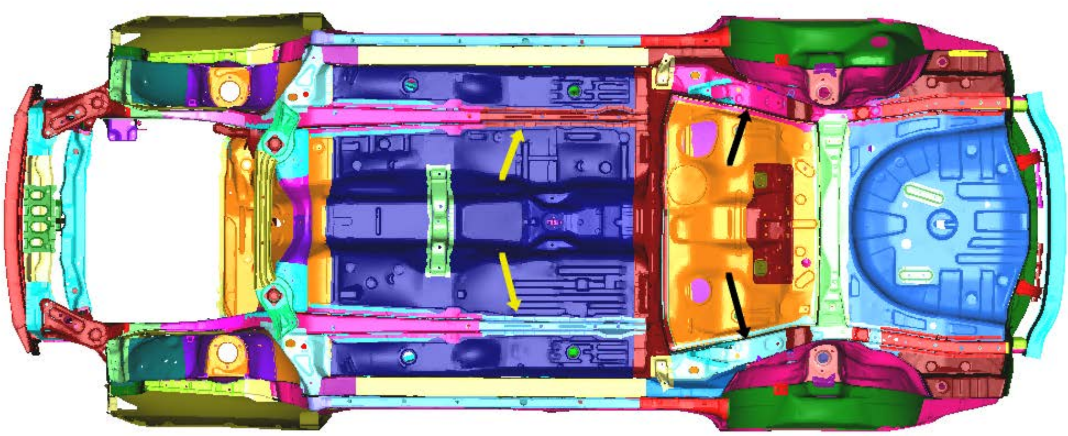


Figure 41. Low Development Model. Colors denote thickness of the sheet materials. Arrows point to unsymmetrical thickness assignments.

Concern Item 1:

The following Figures 42-45 show some results that may warrant more investigation by the project engineers. Figures 42-43 show the deformation of the main front rails for the baseline vehicle during the NCAP test simulation. The overall deformation is symmetrical. In the case of the LD FEM model, as shown in Figures 44-45, the deformation is markedly different from the baseline and unsymmetrical. The cause for that may be in the unsymmetrical material assignments for the main rails that were present in the previous LD FEM model release and the simulations may have been based on that version. As I was only using the simulation files, I could not tell if that was actually the case. However, I strongly suggest following up on this point as these rails are extremely important for the crash energy management.

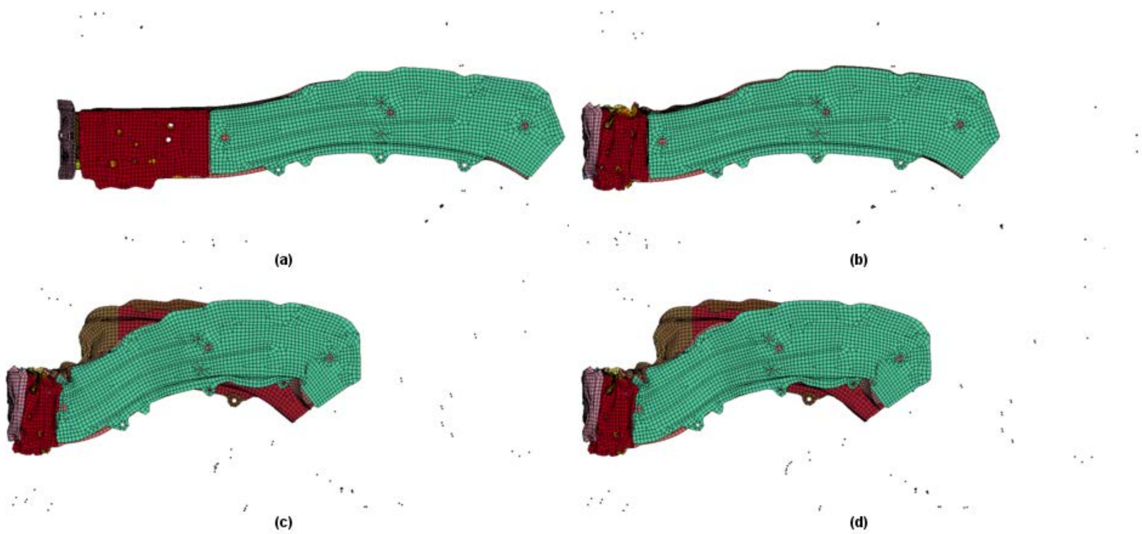


Figure 42. Baseline Model. Side view of the deformation sequence of the main rails for the NCAP test simulation.

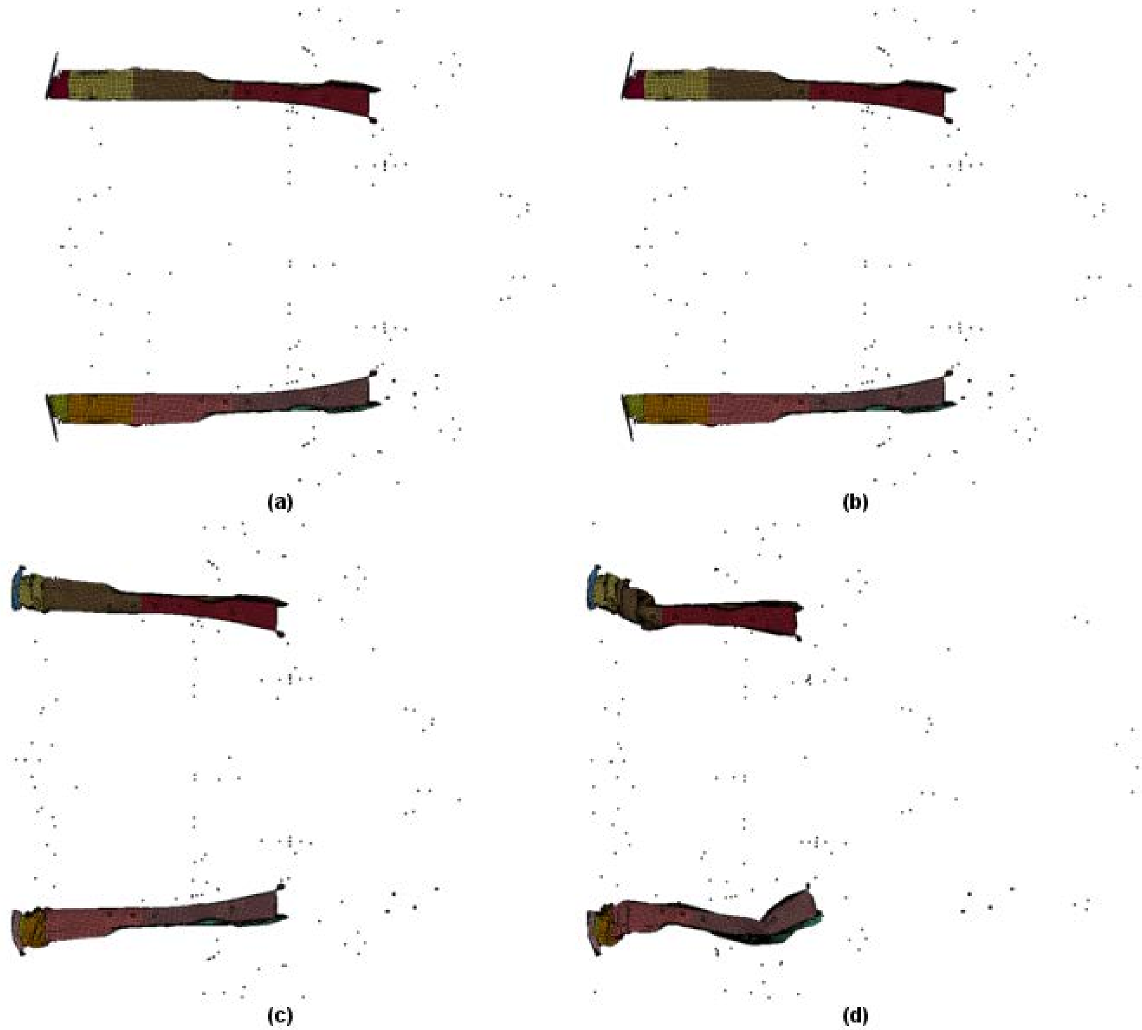


Figure 43. Baseline Model. Top view of the deformation sequence of the main rails for the NCAP test simulation.

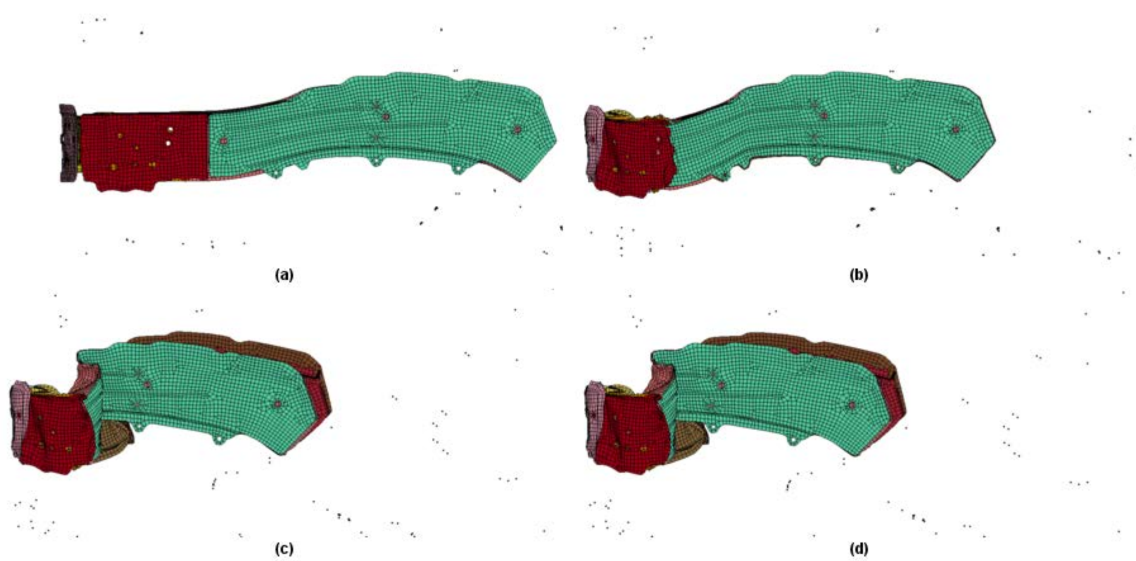


Figure 44. Low Development Model. Side view of the deformation sequence of the main rails for the NCAP test simulation.

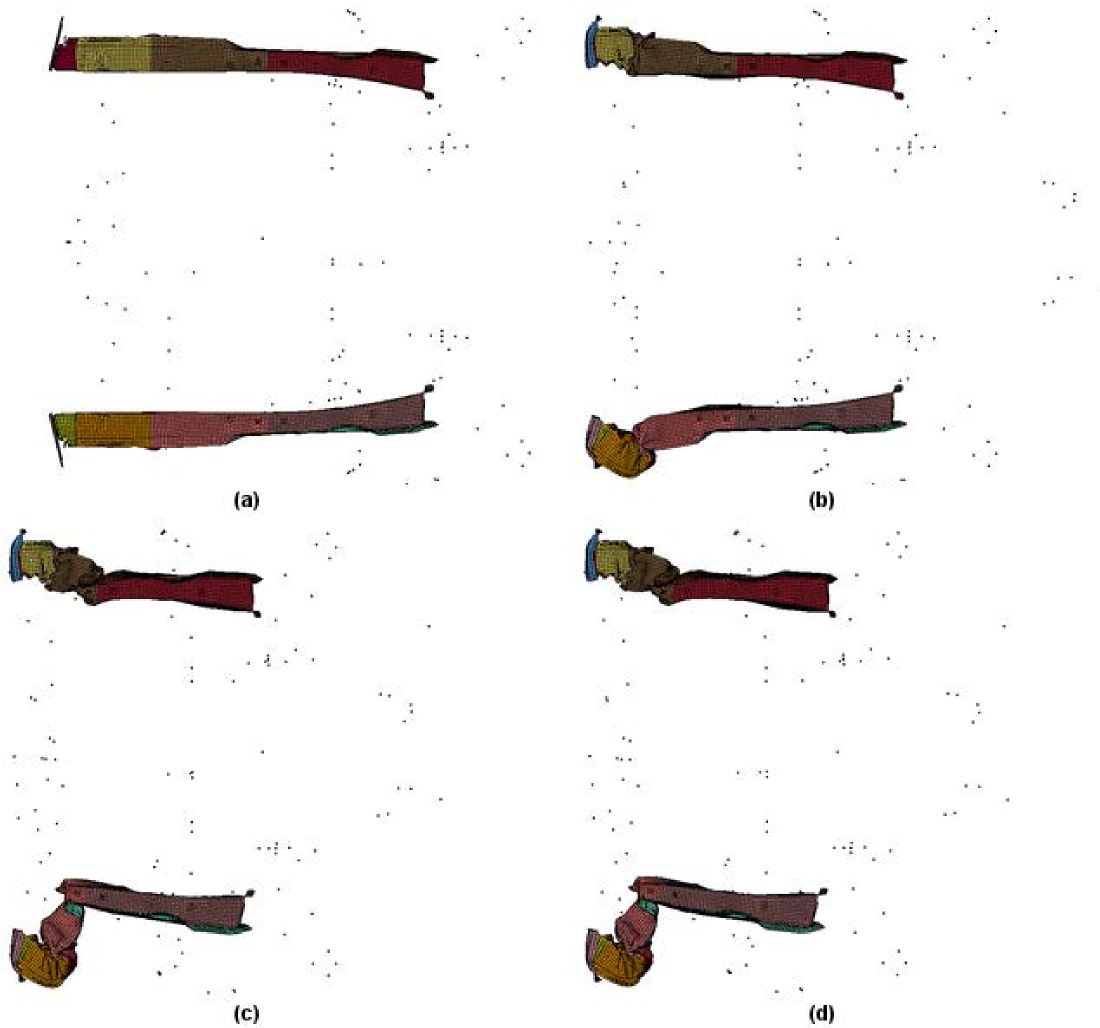


Figure 45. Low Development Model. Top view of the deformation sequence of the main rails for the NCAP test simulation.

Concern Item 2:

One of the modeling aspects that is usually not considered in conventional mild steel vehicle designs is modeling of material fracture/failure [24]. However, in the case of the high strength materials, such as the AHSS, the material fracture is a real possibility that needs to be included in the models. One of the easiest failure models to implement is to specify equivalent strain threshold for the material failure. Once this threshold is reached during crash simulation it leads to gradual element deletion, which simulates crack formation. I would suggest consideration of such a simple model enhancement that, while not comprehensive enough for production design, is probably sufficient for the purposes of the FEV study. The strain rate sensitivity of the material models would help with the regularization of the strain localization and related numerical problems [25].

5. Vehicle Crashworthiness Testing Methodological Rigor

The correlations and modifications of the baseline vehicle FEM model to the experimental results were primarily done on the measurements of vibrational and stiffness characteristics of the BIW. Once the stiffness of the BIW model was tuned to the experimental results, it was considered to be sufficiently accurate to form the foundation for the crash model. The vehicle crash FEM model was then correlated to the NCAP and MDB side impact. The correlations were primarily based on the deformation modes and the FEM model was found to be satisfactory for the purposes of the FEV study.

Comparison of the deformation in the NCAP crash in Figures 46-49 shows very good correlation of the deformation modes. The deformation of the subframe shown in the Figures 48-49 also shows very high fidelity of the simulated deformation compared to the experiment.

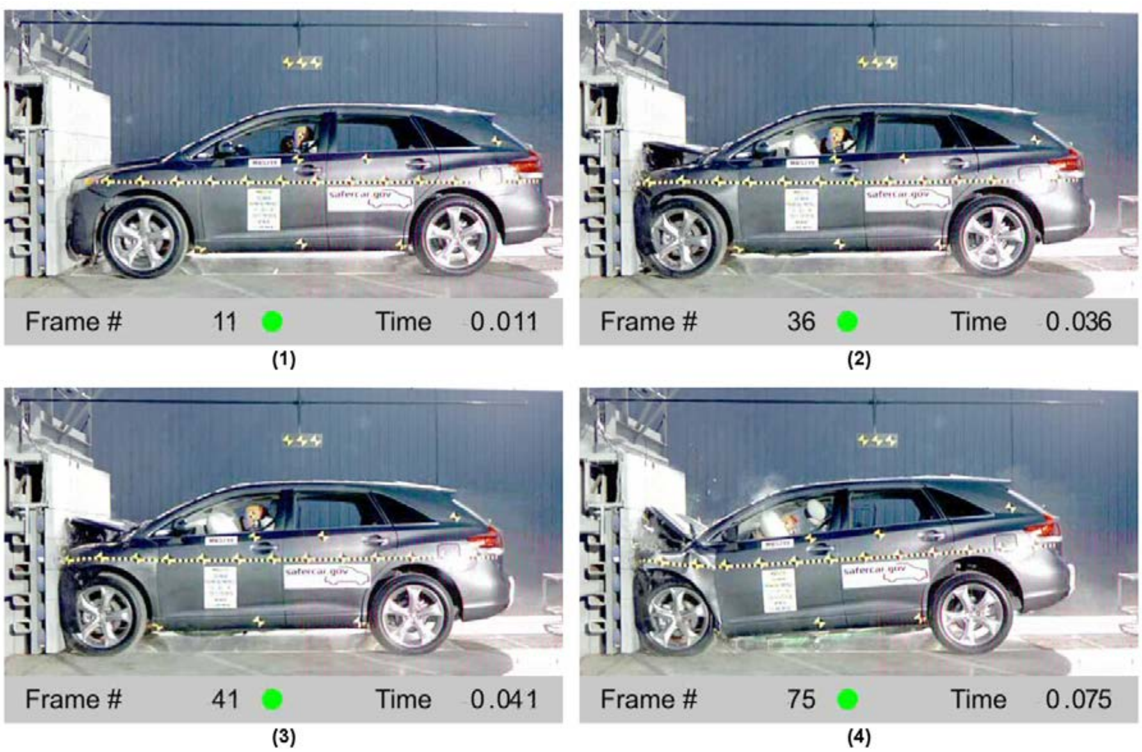


Figure 46. Vehicle side kinematics during NCAP test

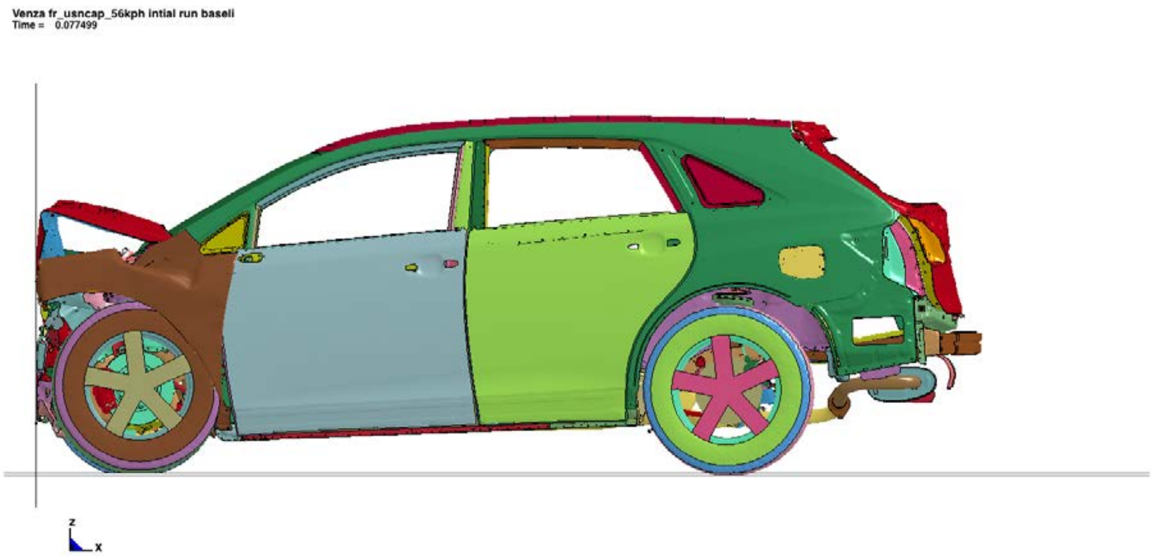


Figure 47. Baseline Model. Vehicle side kinematics during NCAP test

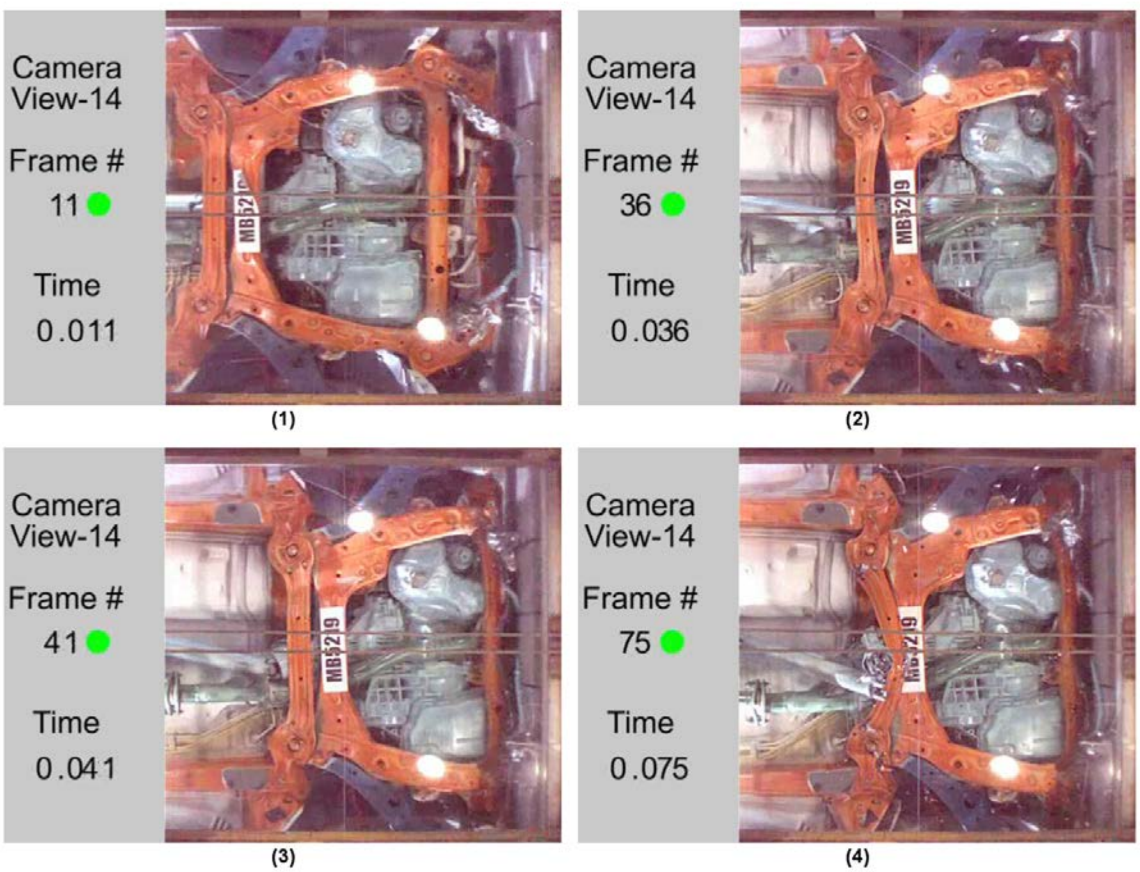


Figure 48. Vehicle subframe deformation for NCAP test

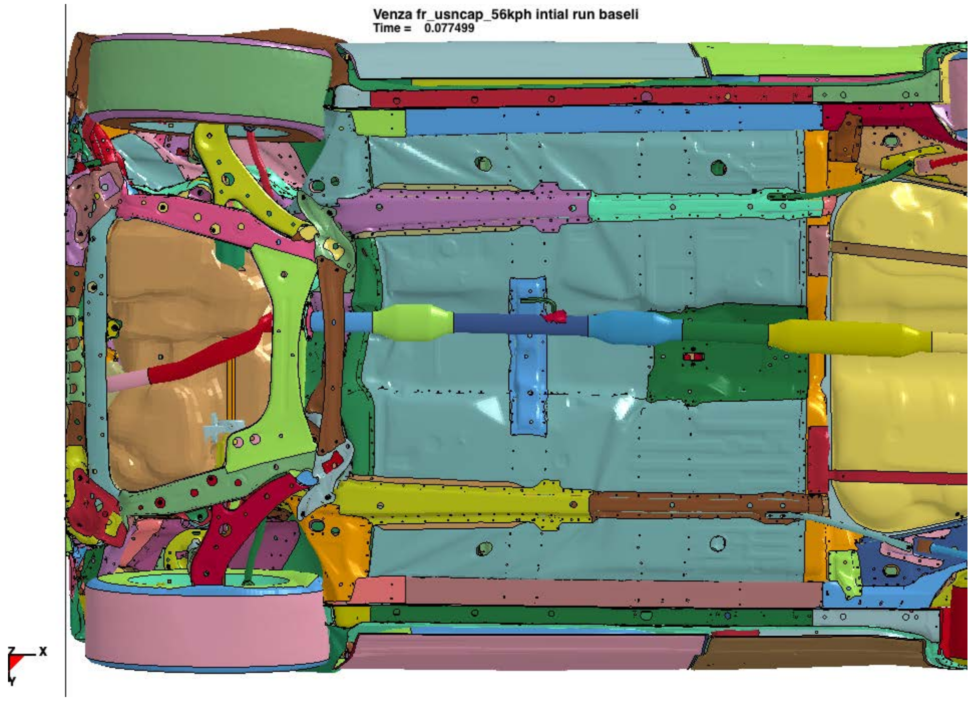


Figure 49. Baseline Model. Vehicle subframe deformation for NCAP test

In summary, the correlation of the baseline FEM model with the NCAP test is quite satisfactory. The correlation with the side MDB test was not elaborated in the report. However, the side impact is perhaps the most important and limiting design aspect for the lightweight vehicles. The side impact is almost exclusively a structural problem that does not compound the benefits of the reduced mass, as is the case of the frontal impact. A documented correlation of the baseline FEM model with the side impact experiment will in my opinion be a very beneficial technical addition to the FEV project that would significantly support the findings of the technical feasibility of the lightweight opportunities in the existing vehicle design space.

6. Other Comments

The FEV report is quite exhaustive. I would suggest that it be released in a hypertext format that can allow different navigation paths through it. Also, the dynamic Web-based technologies can be used for effective model documentation, presentation and distribution. I would also recommend that more details on the actual optimization process, including the objective function specification, and the final consolidation of the model, be added to the documentation.

7. Conclusions

The FEV Low Development vehicle study has been reviewed following the instructions by the US EPA. It has been found that the FEV study followed most of the current technical guidelines and the state-of-the-art practices for computational crash simulation and design. Several inconsistencies were found in the developed FEM models that need to be addressed and corrected before the FEM models are released for the general use.

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[insert date]

MEMORANDUM

SUBJECT: EPA Response to Comments on the peer review of *Light-Duty Vehicle Mass-Reduction and Cost Analysis – Midsize Crossover Utility Vehicle (FEV Report)*

FROM: Cheryl Caffrey, Assessment and Standards Division
Office of Transportation and Air Quality, U.S. Environmental Protection Agency

The *FEV Report* was reviewed by William Joost (U.S. Department of Energy), Glenn Daehn, Kristina Kennedy, and Tony Luscher (The Ohio State University (OSU)), Douglas Richman (Kaiser Aluminum), and Srdjan Simunovic (Oak Ridge National Laboratory). In addition, Srdjan Simunovic and members of the OSU Team reviewed various elements of the associated modeling.

This memo includes a compilation of comments prepared by SRA International and responses and actions in response to those comments from EPA.

1. ASSUMPTIONS AND DATA SOURCES (CAE BIW and Vehicle)	COMMENTS
Please comment on the validity of any data sources and assumptions embedded in the study. Such items include material choices, technology choices, vehicle design, crash validation testing, and cost assessment that could affect its findings.	**[Joost]** The material selection process used in this study suggests a good understanding of the cost and manufacturing impacts of changing between different steel, Al, Mg, and plastic/composite based materials. Generally the material selections are appropriate for the performance, manufacturing, and cost requirements of the particular systems. Identifying production examples of the materials in similar systems is very important for establishing credibility – the project team did an excellent job identifying production examples of most material replacements. There are, however, a few material selections where additional consideration may be necessary: The transmission case subsystem (pg 269) features the use of a Sr bearing Mg alloy. Recently, Sn based alloys have been produced and (I believe) used in production for similar applications. The use of Sn as an alloying ingredient accomplishes many of the same goals (improved high temp creep performance, for example) at a lower cost. It may be worth investigating these new alloys as an opportunity to reduce the cost of the lightweight transmission case subsystem. If not, the selection of a Sr alloy is reasonable. The feasibility of using hot rolled blanks in the body structure would be further emphasized by providing production examples for vehicles of >200k units per year. Similarly, the use of a 7000 series Al rear bumper is questionable – a production example for a high volume, low cost vehicle should be provided. The use of Thixomolded Mg seat components should be reconsidered. Thixomolding does have the potential to provide improved ductility compared to die casting, however the process is generally not well regarded in the automotive community due to concerns over limited supply and press tonnage limits (which limit the maximum size of the components that can be manufactured this way). If there is a production example of thixomolding for >200k unites per year in automotive, then it should be cited in the report. If there is no example then I would suggest switching to die casting (or super vacuum die casting) – the weight reduction and cost will likely be similar. It's not clear how the mass savings were achieved in the wheels and tires. The report states that a 2008 Toyota Prius wheel/tire assembly will be used in place of the stock Venza wheel – however the report also states (pg 544) that the Prius wheel will be normalized up to the 19"x7" to maintain the original styling of the Venza. The technology employed in the Prius wheel is not different from the stock Venza wheel so why should a scaled-up Prius wheel weigh less than the original Venza wheel? There are also inconsistencies in the report – table F.5-18 references eliminating the spare tire wheel while downsizing the spare tire – why would there be a tire with no wheel? Lastly, if the Prius wheel/tire is scaled up to match

	the stock Venza size then the spare wheel/tire must also be scaled up – it's not clear that this happened. You are taking significant credit for weight reduction in the wheels and tires (~2% of total vehicle weight) but it's not clear how this is achieved. Many of the parts in the frame have been changes to a GF Nylon (pg 667). This may not be unreasonable, but production examples should be provided. **[Richman]** 1) NHTSA crash test data was used for validation of collision simulation models and is an appropriate source. 2) Material property data was supplied by recognized supplier associations and are correct. 3) Cost estimates for reduced mass sheet products seem to include assumption that drive unusually high material and equipment cost. This issue leads to a technology cost effectiveness that is not representative of actual production experience for sheet products. **[OSU – Glenn Daehn]** The data and sources appear to be very good, however at the time of this review there are a few items that are unclear. First there some statements that are referenced with superscripts, however there is not a reference list that appears in the document. Second, this report does an excellent job of documenting at a high-level that the finite element analysis is carried out properly, showing agreement with masses, stiffness and crash signatures of baseline vehicles. However, it is important that all of the details be also available to the public, such as the detailed material geometry (mesh files), stress-strain flow-laws used for the materials, weld locations (more than a figure), models used for weld behavior and so on. This can be done by reference or by making the LS-DYNA models public. It is not clear at time of review how this will be done, but it would be a great service to make all this granular detail available. Similar statements can be made regarding the detail for components and materials in the costing models. **[OSU – Tony Luscher]** The data used appears to be valid and appropriate to the tasks that are completed. Vehicle data for the Toyota Venza was obtained by scanning the components and creating the CAD models. Material data was found from appropriate sources and databases. These were used to create a crash test model for the vehicle and for cost estimation. A thorough search of state-of-the-art vehicle design concepts was used as the basis of mass reduction for the various vehicle systems.

	[Simunovic] This section contains comments on validity of the data sources, material properties, and modeling approaches used in this study. The overall methodology used by the FEV is fundamentally solid and adhere to standard practices of the crashworthiness engineering [5]. However, an in-depth analysis of the model files reveals several areas that may need to be addressed to fully support the findings of the study. Firstly, as a matter of the established procedures for technical documentation, I suggest that the sources for the material properties should be clearly referenced; especially since the authors of the FEV study worked on similar projects for steel industry consortia [6]. Similar projects on concept vehicles [7,8] also offer guidelines on the reporting. It would also be very helpful to readers to graphically depict mechanical properties such as material stress-strain curves, failure envelopes, etc. Secondly, the technologically important issues with the high strength metallic materials, such as Advanced High Strength Steels (AHSS) [9], are their special processing requirements [10], reduction in ductility, higher possibility of fracture [11-14] (especially under high strain rates [15-17]), and joining [18-22]. Many AHSSs derive their superior mechanical properties from their tailored microstructures, which get strongly affected during welding. Active research in welding of the AHSS shows possibilities of significant reductions of the joint strengths due to the softening processes in Heat Affected Zone (HAZ). Therefore, the strength values for the welds in the current LD model (i.e. SIGY=1550 for MAT_SPOTWELD section in the input files) seems very optimistic, and may need to be reduced or elaborated upon in the report. Several versions of the reports were distributed and I may have very well missed an updated version. In case that joining discussion is indeed restricted to one page as it appears in the current FEV document, I would suggest that weld properties and constitutive models be given additional attention in the final report. Third important issue that I would suggest to be addressed is modeling of failure/fracture of the high strength materials in the LD models. Despite long research on the subject, the methods for modeling localization and failure are relatively scarce. There is still no wide consensus on how to model failure in materials. For the FEV study, special attention should be given to the joint areas (spot welds, laser welds) that can experience the degradation of properties due to the thermo-mechanical cycles that they have been exposed to. A simple way of addressing the above points would be to use failure limit strains in plasticity models that are used in the FEV models, i.e MAT_PIECEWISELINEAR_PLASTICITY. In this approach a limit strain is assigned to material, and after that limit strain is reached in a finite element, the element is gradually removed from the simulation. The values for the failure strains are dependent on mesh and element discretization, where additional simulations should be conducted to correlate energy to failure to the corresponding physical failure process zone for the given problem.

If you find issues with data sources and assumptions, please provide suggestions for available data that would improve the study.	**[Joost]** Two plastic technologies are very widely employed in this design: PolyOne and MuCell. It seems that the companies who license/manufacture these technologies were used as the primary source to determine feasibility. However they are likely to be optimistic regarding the capability of their materials. I agree that these materials are appropriate for the indicated applications, however I feel that the credibility would be improved by including other sources (OEMs, Tier 1) or more production examples for existing platforms. With such a large amount of weight reduction attributed to PolyOne and MuCell, it would be beneficial to have a very strong case for capabilities. **[OSU – Glenn Daehn]** See above. **[OSU – Tony Luscher**] None found.

ADDITIONAL COMMENTS:

[Richman] This report is a review the 2012 FEV project to identify mass-reduction opportunities for a crossover sport utility vehicle based on the 2009 Toyota Venza. This study is a continuation of the Lotus Engineering Phase 1 Low Development (LD) study funded by the Internal Council on Sustainable Transportation (ICCT) in 2010. Goal of the FEV project is to identify practical mass reduction technologies to achieve a 20% reduction in total vehicle mass (342 Kg) at no more than 10% increase in consumer cost while meeting, or exceeding, all crashworthiness, performance and customer satisfaction attributes provided by the baseline vehicle.

Body of the baseline vehicle is 31% of total vehicle mass and has a dominant influence on NVH and collision performance of the total vehicle. This project involved extensive engineering analysis of the vehicle body. BIW and closure materials and gauges were optimization to exploit the maximum mass reduction potential from advanced low mass automotive materials and advanced manufacturing processes. Mass reduction initiatives are identified for all vehicle systems including engine, transmission, interior, suspension and chassis systems. Most materials, manufacturing processes and components selected for the FEV vehicle technology package are proven, cost effective and available for use on 2017 production vehicles.

Majority of mass reduction concepts utilized are consistent with recognized industry trends. Mass reduction potential attributed to individual components appear reasonable and consistent with industry experience with similar components. As an advanced design concept study this is an important and useful body of work. Results of the project provide useful insight into potential vehicle mass reduction achievable with HSS and AHSS materials.

This report is a review of the methodologies employed, technologies selected and validity of findings in the FEV study. This reviewer has experience in vehicle mass reduction engineering of body, engine and suspension systems. This review focuses on those areas of the FEV project.

[OSU – Kristina Kennedy] "Building a full vehicle model w/o the use of drawings or CAD data…" Has this method of tear-down + scanning been proven out in industry or in other projects to understand how closely this method would correlate with actual data? Is this basically "reverse engineering" and is that an acceptable method?

[OSU – Tony Luscher] Data sources are well documented in the report and will aid if any additional investigation is needed. Several of them were checked for validity.

[Simunovic] In this document I review the methods, data, and the FEM crash models developed in the FEV study. The models were evaluated based on the analysis of the computational simulation results and on based on the analysis of the actual model files. I want to emphasize that the scope of my review is on the computational simulations of the vehicle crashworthiness and on the modeling approaches employed by the FEV and its contractors. The primary source for my review were the FEV final draft report, the crash animations generated by the FEV, and the computer simulation output files for the NCAP and the ODB crash test configurations. Two vehicle crash models were available, the baseline and the LD model. As it will be shown in the following sections, my review was based to a large extent on the vehicle model files. Very often in the current practice, the actual model files are not sufficiently scrutinized and are evaluated only through the resulting computational simulations. In the case of large complex FEM models, such as car crash models, the model's configuration complexity and its shear size can obscure the important details of the response and camouflage the sources of errors in the model. That is particularly common when the technology envelope of the state-of-the-art is expanded, as is the case with ever-increasing sizes and complexities of the car crash models.

2. VEHICLE DESIGN METHODOLOGICAL RIGOR CAE BIW and Vehicle)	COMMENTS
Please describe the extent to which state-of-the-art design methods have been employed and the extent to which the associated analysis exhibits strong technical rigor. You are encouraged to provide comments on the information contained within the unencrypted model provided by EDAG; the technologies chosen by FEV; and the resulting final vehicle design.	**[Joost]** The report uses a (very thorough) piece-wise approach to weight reduction – each system is broken down and weight reduction opportunities for the individual components are identified. The weight-reduced components are then reassembled into the final vehicle. I believe that this provides a conservative estimate for the weight reduction potential of the Venza, where a vehicle-level redesign would provide greater weight reduction. However, I am also of the opinion that the approach used here is in line with industry practice so; while this may not yield the maximum reasonable weight reduction, it is likely to yield a value more in-line with industry-achievable weight reduction. It is particularly helpful (and credible) to see descriptions technologies that were considered, but abandoned due to performance concerns (e.g. reverting to a timing belt), manufacturing capabilities, (e.g. using a MuCell manifold), and cost (e.g. Mg oil pan). The suspension design process lacks sufficient detail to make the cost and weight estimates credible. Considerable Al is used to replace steel at a very minimal cost penalty. However, as the report indicates, detailed design and validation is necessary to confirm that these changes would be viable for the Venza. For example, changing to a hollow Al control bar is not an industry standard practice and the use of a hollow section may require significant changes to geometry in order to meet the stiffness and strength requirements. While a hollow Al control bar is feasible, I'm not confident that it can be substituted into the design so easily. A $0.40/kg-saved cost penalty for changing a significant number of components from mild steel to Al seems to be an underestimate. **[Richman]** 1) EDAG performed structural modeling. The EDAG organization is widely recognized as technically competent and highly experienced in modeling of auto body structure. Modeling approach appears technically robust and logical. 2) Body structural analysis utilized industry recognized CAE, CAD and collision modeling analysis tools and protocols. Tools used are state-of-the –art and the approach. 3) FE model was validated against physical test data for NVH and collision performance. Model correlation with physical test results is very good. No significant discrepancies or inconsistencies have been identified in the modeling results. 4) Based on these observation, the models would be considered valid and reliable for moderate A:B design

	comparisons that are the subject of this vehicle study. **[OSU – Glenn Daehn]** The work is well done and technically rigorous. Again, we encourage making all pertinent detail publicly available. **[OSU – Tony Luscher]** The report does an excellent job of using state-of-the-art design methods. The re-engineering process included vehicle teardown, parts scanning, and data collection of vehicle parts to build a full vehicle CAE model. This raw STL geometry was then translated into an FE meshing tool (ANSA) to create a finite element model. **[Simunovic]** The development of the LD Toyota Venza concept started with the development of the baseline FEM model of the vehicle. The FEM model was developed by a reverse engineering process of disassembly, geometry scanning, component analysis, material characterization and the incremental FEM model development. The turn-around time for this process by the FEV is quite impressive. Equally impressive are the apparent quality of the FEM mesh, the definition of joints and assembly of the overall model. The discretization of the BIW sheet materials uses proportionately sized quadrilateral shell elements, with few triangular elements. The mesh density is mostly uniform and without large variations in the FEM element sizes and the aspect ratios. The BIW model has about 6% of triangular shell elements in the sheet metal which is a very small amount given the complexities of the vehicle geometry. Figures 1-3 show the geometry and the parts variety for the baseline vehicle model. There are no apparent geometry conflicts in the model and parts are well aligned with compatible geometries and FEM meshes. This is essential for accurate modeling of currently the prevailing joining method for sheet metals, spot welding. The level of geometrical detail in the model is very high and as someone who has been involved with the vehicle crashworthiness modeling for the last twenty years, I think that the developed FEM mesh of the Venza BIW is the current state-of-the-art. Figure 4 shows some details of the BIW FEM mesh that illustrate the prevalence of the quadrilateral shell finite elements, constant aspect ratios and presence of the geometry details that are necessary for an adequate modeling of the progressive structural crush.
Please comment on the methods used to analyze the technologies and materials selected, forming techniques, bonding processes, and parts integration.	**[Joost]** The forming, joining, and integration techniques used in the report were analyzed only by referencing production examples or companies who produce similar products. Detailed design work would certainly include a more thorough analysis of the manufacturing techniques however for the scope of this report I believe that the level of analysis is appropriate.

	[Richman] 1) Body: Process used to select materials, grades and gauges for the mass optimized body sub-group is technically sound and thorough. Election of laser welding of structurally significant body panels indicates deployment of advanced manufacturing process where appropriate. 2) Non-body: Methodology used to identify, screen and select non-body mass reduction technologies is thorough, detailed and highly effective. Munro Associates lead this segment of the project. Munro is recognized as being technically competent, highly experienced, knowledgeable and creative in benchmarking and lean engineering of automotive and non-automotive systems. **[OSU – Glenn Daehn]** All is in accord with the state of the art. It is not clear how welds are represented in the FE-Model, without dissection of the LS-DYNA input stacks. **[OSU – Tony Luscher]** The Toyota body repair manual was used to identify the material grades of the major parts of the body structure. These material grades were then validated by material coupon testing. The MSC Nastran solver was used to solve for the bending and torsion stiffness of the body in white model. Good correlation was achieved between physical stiffness testing and FEA stiffness results. **[Simunovic]** The development of the LD Toyota Venza concept started with the development of the baseline FEM model of the vehicle. The FEM model was developed by a reverse engineering process of disassembly, geometry scanning, component analysis, material characterization and the incremental FEM model development. The turn-around time for this process by the FEV is quite impressive. Equally impressive are the apparent quality of the FEM mesh, the definition of joints and assembly of the overall model. The discretization of the BIW sheet materials uses proportionately sized quadrilateral shell elements, with few triangular elements. The mesh density is mostly uniform and without large variations in the FEM element sizes and the aspect ratios. The BIW model has about 6% of triangular shell elements in the sheet metal which is a very small amount given the complexities of the vehicle geometry. Figures 1-3 show the geometry and the parts variety for the baseline vehicle model. In the following, I first give the analysis of the baseline FEM model. The baseline FEM model is very adept and can be used for illustration of some shortcomings of the LD model that I think need to be addressed. It is important to note that the LD model is much more complex due to a large number of materials and gages that resulted from the computational optimization process. This complexity and the project time constraints dramatically increase the potential for error. Unfortunately the tools for managing such complex systems are not yet mature, making the development and the

evaluation of this complex vehicle model very challenging. Over the years, I have developed several simple programs that can be used to debug FEM models by directly analyzing the model files. The common approach to evaluation of large FEM models is to almost exclusively consider computational simulation results. However, these simple tools allow for evaluations of relationships within the FEM models directly from the model input files, thereby enabling debugging of the models independently from the simulations.

Review of the FEM Model for the Baseline Toyota Venza

The primary material for the BIW of the baseline vehicle, 2009 Toyota Venza, was identified in the Lotus Phase 1 Report as mild steel. Lotus Phase 1 study stated that the BIW also had about 8% of Dual Phase steel with 590 MPa designation, while everything else was commonly used mild steel sheet material. The FEV/EDAG study showed that there was more variety to the baseline design then originally anticipated. Table 1 lists the materials used in the BIW model (file Venza_biw_r006.k) that were modeled using MAT_PIECEWISE_LINEAR_PLASTICITY). Aluminum bumper was modeled using MAT_SIMPLIFIED_JOHNSON_COOK material model in LS-DYNA. The number of material models is relatively small.

Most of the CAE tools display the FEM model based on their part identification number (ID). To verify the material model assignment one must then verify material assignment for every part and then sort them accordingly. For large complex models this is a very tedious process that is very error prone. More advanced CAE tools, such as HyperMesh, have options for grouping and displaying model entities by material types and IDs. Figure 5 displays the material assignments for the baseline BIW.

The specific assignment of the materials for the BIW and the corresponding stress-strain curves are shown in the figures below. Most of the material models account for strain rate sensitivity of the material. For a given plastic strain, the yield stress is calculated by interpolating stresses between two neighboring stress strain curves based on the applied strain rate. There are established modeling recommendations for modeling strain rate sensitivity effect in crash models. The specified stress strain curves should not intersect. Extrapolated lines from their last specified linear segment should not intersect, as well. The material models should use plastic strain rate [23] instead of the total strain rate as the basis of the strain rate effect calculation. This option (VP=1) was not used in the FEV models although it is highly recommended in practice.

Figures 6-10 show the main material systems for the baseline BIW model. The material assignments correspond to the assignments in the project’s report.

The stress-strain curves for different strain rates in the above figures do not intersect. Their extrapolations however have potential for intersection at high plastic strains in Figures 7and 8. The number of the data points in Figures 9 and 10 are too large and needs to be reduced in order to avoid the interpolation errors by the simulation program. It is obvious that curves in Figures 9 and 10 were developed by analytical fits. Such approach can create undesirable artifacts such as an appearance of the yield point elongation for Dual Phase steel in Figure 10. An interpolation approach with fewer points and curves is recommended. Figure 11 illustrates the optimal piecewise linear interpolation (green curve) of the base (red) curve in Figure 10. The interpolated curve has error of 1% of the value range with respect to the actual curve and uses only 9 points.

Next, the BIW sheet material thickness distribution is shown in Figure 12. The colors indicate symmetrical distributions in accordance with the specified thickness distribution in the project report.

In many situations, the accuracy of the crash simulation is dependent on the shell element formulation (type) used. The basic shell element formulation (reduced integration Belytschko-Tsay, LS-DYNA type 2) is computationally very efficient but has lower accuracy than more complex formulations such as the fully-integrated Bathe-Dvorkin shell element (LS-DYNA type 16). Figure 12 shows the shell element formulations in the BIW model. The current crash modeling recommendation is to use shell element type 16 when possible. The Bathe-Dvorkin shell is 3.5 times more computationally expensive than the Belytschko-Tsay shell so that in order to strike a proper balance between the accuracy and the computational speed element types can be mized in the model. This is especially true when large number of simulations is conducted, as was the case for computational optimization in the FEV study. As it can be seen in Figure 16, the baseline model employs accurate element formulation in the main structural components, while the Belytschko-Tsay formulation is employed in the remainder of the sheet metal which is an appropriate compromise for the large scale computations.

Another important technical aspect of the crash simulations with the shell elements is the employed number of integration points through the thickness of the shells. The default (2 points) is insufficient for the crash analyses. Three points is also inadequate in the current simulation guidelines because it results in a very quick formation of plastic hinges in the sheet metal during crush. A minimum of 5 through-thickness integration points is currently recommended for the crash simulations. Therefore, modification of the model in this regard is suggested for the general release.

Another commonly overlooked formulation aspect for the shell elements is the through thickness shear factor. Recommended value is 0.833, which was used only in bumper structures of the current model (Figure 14). Changing the factor to 0.833 is recommended.

In summary, the baseline Venza FEM model is developed following most of the recommended development procedures for crash models. The modifications suggested above would meet few additional recommendations that would likely

	increase the robustness of the model.. The NCAP and the side MDB barrier simulation results can be compared with the actual crash tests conducted by NHTSA. The comparison of the simulation and the NCAP test shows somewhat stiffer response of the FEM model with respect to the test (Figure 1.18.18 in the last FEV report). The maximum and the average accelerations in the FEM model were accordingly higher than the test results. The baseline FEM model was deemed acceptable for the purposes of the FEV study. Another important measure of the FEM model fidelity was the crash duration time that was 20 ms shorter for the model compared to the test. This difference is noticeable because the overall crash duration of 100 milliseconds. However, for the objectives of the FEM study, the model's crash pulse was deemed acceptable, which for the described project schedule seemed quite reasonable. **Review of the Low Development Vehicle Model** The FEV engineers have used the computational optimization methods based on the response surface formulation in order to determine the distribution of material types and grades that would maximally reduce the weight of the vehicle while maintaining the performance and controlling the cost. The part distribution of the resulting optimized LD design FEM model is shown in Figure 15. It is probably misleading to refer to the resulting FEM model as "Low Development" since it is a product of numerous computational simulations and an in-depth engineering study. The resulting inventory of the material models used in the LD FEM model is listed in Table 2. It is evident that there are numerous duplicates as well as unused materials. It would be prudent to purge the list of material models from the LD FEM model as they may lead to errors. Some of the inconsistencies that were found in the current LD FEM model may very well be a result of this model redundancy. Two model files contain most of the material models: • Venza_master_mat_list_r006.k • Venza_Material_Db_Opt_dk2.k The horizontal black line in Table 2 separates the material model specifications between the two files. These two were unchanged for the last two versions of the FEM models that were downloaded from the project download site. Figures 16-32 below show the stress-strain curves for the materials used in the BIW of the LD FEM model. There are obvious duplicates in the model specifications that would be prudent to eliminate and modify the model accordingly before its public release. In addition, there are some errors in the LD FEM model specifications that need to be

	corrected. **Correction Item 1:** Material ID 9 (Figure 30) has stress-strain curves for different strain rates different strain rate curves intersect which is not acceptable from the physical perspective. Materials with IDs 8000006, 8000007, and 8000008 have elastic properties of lightweight materials such as Aluminum and Magnesium alloys, but they utilize yield stress functions of HSLA 350/450 steel defined in file: Venza_frt_susp_exhaust_30ms.k. Currently, only the material 8000006 is used in the LD FEM model, although in the previous model version material ID 8000008 was also used. **Correction Item 2:** Some material assignments in the LD FEM model are inconsistent which is probably a result of too many material models. The mapping of material IDs on the BIW FEM model reveal several unsymmetrical model assignments. The most obvious discrepancy is marked in Figure 33. Here, where one model part is modeled using the mild steel while its corresponding symmetrical counterpart is modeled using the HSLA 350/450 steel. Additional unsymmetrical material assignments are pointed with arrows in Figures 34-37. Two possible outcomes of not pairing the symmetrical components with the same material ID are illustrated in Figures 36-37. In Figure 36 the two different parts have different material assignments, which eventually refer to different material properties. In case of the marked parts in Figure 37, the material IDs are different but because of the repeated material models with different IDs, they eventually refer to the same material properties. The above inconsistencies need to be corrected before the models are released into to the open domain. **Correction Item 3:** Another area of concern is the number of through thickness integration points for the shell elements in the current LD FEM model. As it can be seen in Figure 38, almost all shell elements have just 2 integration points through the thickness. This is

	clearly inadequate from the accuracy standpoint and may be responsible for some of the issuable simulation results shown in the following figures. **Correction Item 4:** Figure 38 shows the thickness distribution in the LD FEM model of the BIW. In general, the thickness distribution is symmetrical with respect to the centerline of the vehicle. However, a closer inspection reveals some asymmetries in thickness assignments. The arrows in Figures 40-41 show the parts that do not have symmetrical assignment of the values with respect to the centerline of the vehicle. I have not checked the extent of the differences, but it something nonetheless that needs to be corrected. **Concern Item 1:** The following Figures 42-45 show some results that may warrant more investigation by the project engineers. Figures 42-43 show the deformation of the main front rails for the baseline vehicle during the NCAP test simulation. The overall deformation is symmetrical. In the case of the LD FEM model, as shown in Figures 44-45, the deformation is markedly different from the baseline and unsymmetrical. The cause for that may be in the unsymmetrical material assignments for the main rails that were present in the previous LD FEM model release and the simulations may have been based on that version. As I was only using the simulation files, I could not tell if that was actually the case. However, I strongly suggest following up on this point as these rails are extremely important for the crash energy management. **Concern Item 2:** One of the modeling aspects that is usually not considered in conventional mild steel vehicle designs is modeling of material fracture/failure [24]. However, in the case of the high strength materials, such as the AHSS, the material fracture is a real possibility that needs to be included in the models. One of the easiest failure models to implement is to specify equivalent strain threshold for the material failure. Once this threshold is reached during crash simulation it leads to gradual element deletion, which simulates crack formation. I would suggest consideration of such a simple model enhancement that, while not comprehensive enough for production design, is probably sufficient for the purposes of the FEV study. The strain rate sensitivity of the material models would help with the regularization of the strain localization and related numerical problems [25].

If you are aware of better methods employed and documented elsewhere to help select and analyze advanced vehicle materials and design engineering rigor for 2017-2020 vehicles, please suggest how they might be used to improve this study.	**[Joost]** This is not my area of expertise. **[OSU – Glenn Daehn]** Everything appears to be well-done and in accord with the state of the art. **[OSU – Tony Luscher]** None known.

ADDITIONAL COMMENTS:

[OSU – Kristina Kennedy] FE Meshing Tool, ANSA. Did a quick Google search and did not find this product. Am familiar with ANSYS and others, but is ANSA an industry-standard tool? Just confirming the wide-use of such a tool out of curiosity.

[Richman] The team of FEV, EDAG and Munro is an outstanding coalition of industry experts with the unique skills and expertise necessary to meet the objectives of this project.

Mass reduction efforts were organized into two segments: body and non-body. Body mass reduction focused on selection of materials (steel, aluminum, plastics and magnesium), grades and gauges. Baseline Venza body design was not changed. Non-body mass reduction efforts examined all vehicle systems for potential cost effective mass reduction opportunities. FEV utilized technical support from two recognized, technically qualified and highly respected engineering services organizations: EDAG and Munro and Associates.

EDAG focused on body structural engineering and cost modeling. They conducted detailed reverse engineering study the baseline Venza to establish baseline vehicle mass and structural characteristics and develop CAE, FE and collision simulation models. Calibrated FE models were used to develop an optimized Venza body structure. EDAG Engineering analysis is thorough and reflects the high level of vehicle engineering expertise and know-how within the EDAG organization. Modeling and simulation technologies utilized by EDAG are state-of-the art and EDAG has recognized competencies in effectively deploying those tools.

The EDAG work presents a realistic perspective of achievable vehicle structure mass reduction using available design optimization tools, practical engineering materials and available manufacturing processes. EDAG cost modeling of the baseline and reduced mass vehicle structures.

Munro lead the process of identifying, analyzing, screening and selecting cost effective mass reduction opportunities in all vehicle systems. Munro is a highly respected engineering organization specializing in benchmarking and lean product design. Munro process for achieving product mass and cost optimization is well developed and highly effective. They utilize a creative mix of functional analysis, competitive benchmarking, cross industry comparisons, advanced materials and manufacturing process knowledge and sound engineering analysis. This segment of the study identified a significant number of practical mass reduction concepts in all 20 vehicle sub-groups. The majority of mass reduction technologies selected for the final design are in some current level of volume production and appear cost effective and realistically achievable by 2017.

FEV decomposed the total vehicle into 20 sub-systems. Each sub-system was aggressively examined to identify realistically achievable and cost effective mass reduction opportunities. Majority of mass reduction achieved (90%) is concentrated in (7) vehicle sub-systems:

	Mass Reduction
Body	68 Kg
Suspension	69
Interior	42
Brakes	41
Engine	30
Transmission	19
Frame, Mounts	17

These 7 sub-systems account for over 90% of the cost increases and decreases in this project.

This reviewer has experience in light weighting of body, suspension and engine systems. Comments in the following sections are limited to those vehicle sub-groups.

A significant number of creative and innovative mass reduction ideas were developed and selected for the remaining (17) sub-systems not discussed in this report. Many of the ideas appear to be appropriate consideration as part of a total vehicle efficiency improvement effort.

Body Optimization Overview

Body Sub-system includes: Body-in-White (BIW), Closures, Hood, Doors, Lift Gate, Fenders. This sub-system is the highest mass sub-group at 529 Kg, 31% of total vehicle mass. Body group design and material selection have a dominant influence on vehicle NVH and collision performance. For that reason, optimization of the body structure is a major focus of this project.

Body sub-system –	BIW, Closures, Bumper, Fenders
Optimization results -	71 Kg mass reduction
	$230 cost increase

FEV body mass reduction 68 Kg. (21 % of total vehicle mass reduction)

Baseline Toyota Venza body elements (BIW, closures, bumpers) are predominantly a mix of mild steel (48%) and HSS (49%) with a resulting mass of 529 Kg (31% of total Venza mass). This mix of materials represents a comprehensive use of automotive grade steels available when the Venza was originally designed.

Body related mass reductions from this baseline are indicative of improvements made possible by advances in materials technology.

Venza baseline BIW structure was used for both the Lotus "Low Development" and EDAG material optimization analysis. Both studies reduced BIW mass by similar amounts, Lotus LD: 61 Kg, EDAG: 54 Kg. Differences between Lotus and EDAG structures include: specific material grades and gauges and joining technology. Lotus LD structure used conventional resistance spot welding while the EDAG structure included continuous laser welding for structurally significant joints. BIW mass for the two structures are similar:

BIW Structure Mass	
Baseline	386 Kg
Lotus Venza LD	325 Kg (- 15.8%)
EDAG Venza	332 Kg (- 14 %)

Significant difference bending and torsional stiffness between the Lotus and EDAG structures (20%) do not appear to be fully explained by the relative difference in mass between the structures. Structural stiffness for a constant shape is dependent on material gauge and modulus and not influenced by strength properties. Auto body stiffness can be increased by improving attachment integrity. It would be helpful to understand the influence of laser seam welding on body NVH and collision performance.

Body Optimization

Body optimization was accomplished using EDAG body mass optimization process. The calibrated Venza FEA model was used. In this process alternate material type, grade and gauge were evaluated for NVH and collision performance. Baseline Venza body structure was not altered. Materials evaluated include advanced high strength steels (AHSS), aluminum, magnesium, plastics. Material gauges were selected based on component part requirements (NVH, Collision) and properties of specific materials. The body mass optimization process explored the potential of HSS, AHSS, aluminum, magnesium and plastics.

Optimized body structure content summary:

	Baseline Mass	Optimized Mass	Mass Reduction	Materials Change
BIW	386.0 Kg	324.0	51.0 Kg (13.2%)	HSS, AHSS, Gauge

Doors	95.7	95.6	0	---------
Hood	17.8	10.1	7.7 (43%)	Aluminum
Lift Gate	15.1	7.7	7.2 (48%)	Aluminum
Fenders	6.8	4.9	1.9 (28%)	Aluminum
Bumpers	7.5	7.5	0	
	528.9 Kg	457.7 Kg	71.2 Kg (13.5%)	

BIW Optimization

The EDAG optimized BIW is predominantly HSS and AHSS with appropriate gauge reductions. Baseline Venza is composed of 78% mild steel and 22% HSS. This material mix is representative of a comprehensive use of available materials at the time this Venza model was designed. The optimization process selected HSS and AHSS for over 80% of structure.

This study provides insight into practical BIW mass reductions achievable with recent and anticipated near term future advancements in automotive steels. Using AHSS aggressively with resultant gauge reductions achieved an 13.2% reduction in BIW mass (3% reduction in total vehicle mass). This finding is consistent with similar investigations on the part of OEM organizations in North America and Europe.

Aluminum was selected for the hood, lift gate and fenders. Mass reduction achieved for those components were: Hood: 43%, Lift gate: 48% and Fenders: 28%. Selection of aluminum for these body components is consistent with OEM production experience and several independent organization studies. The magnitude of mass reduction achieved in this body group is also consistent with production experience.

Body Modeling – Comments

The following observations are submitted in the interest of completeness and do not diminish validity of findings and conclusions of the overall project.

Body Modeling – Service Loads

Vehicle models developed in this study are valid and useful for the intended scope of this project. Models addresses overall bending and torsional stiffness, free body modal frequencies, roof strength, and four crash test load cases. These are good indicators and cover many of the primary structural performance concerns.

This analysis does not address what are commonly referred to as "service loads," including jacking, twist ditch, pothole impacts, 2G bumps, towing loads, running loads, etc. Running loads are typically suspension loads for a variety of conditions to address strength, stiffness and fatigue durability of the body and suspension attachment structures and points. Without these other considerations, the optimization process could may unrealistically reduce mass in components that have little effect on overall body stiffness or strength, yet are important for durability.

Body Modeling – Deformable Barrier

Modeling of deformable barriers has historically been an issue. Source, nature or origination of the deformable barriers (moving and fixed) used in this project are not explained. In the offset deformable barrier crash test load cases, overall deformations, including barrier deformations are reported. The reporting does, however, raise a modeling concern. Barrier deformations of over 515 mm are reported for the offset tests. The IIHS deformable barrier has 540 mm thickness of deformable material. It is not expected to compress completely. Excessive barrier deformation has the potential to change the overall acceleration and deformation scenarios reported and influence the mass optimization process.

Body Modeling – Average Acceleration

Overall acceleration issues are not reported in a format normally used by collision development engineers. Charts of unfiltered acceleration pulses are shown and comparisons are made by evaluation of peak accelerations. "Average accelerations" are referred to, but in this report average is the average of left and right side peak accelerations.

Average acceleration as represented by the slope of the filtered velocity/time curve is commonly used to evaluate relative collision performance of a structure. Common practice is to try to steepen the curve in the early portion of the crash sequence (up to perhaps 50 ms) and to try to flatten the curve in the later parts. The logic has to do with the motions of a restrained occupant within the structure. In addition, total velocity change, including rebound, is typically reviewed. As an example, increasing front structure strength can increase restitution and rebound, which increases the overall change in velocity, or Delta-V, and can have adverse effects on overall occupant performance. While peak accelerations are useful, unfiltered peaks can be misleading due to the noise/vibration effect, and at best represent only a partial analysis.

Body Modeling - Stiffness in Collision Simulation

In evaluating the performance of the optimized body structure, the analysts in general considered "less deformation" of the body structure to equate to "better performance." Less deformation may be an index of structural stiffness but is not necessarily an indication of better collision performance. Less deformation generally equates to higher decelerations and resulting forces on the occupant. It is likewise generally desirable to efficiently use as much of the allowable free crush space as possible, not less.

Body Modeling – Door Opening

Part of the rear impact analysis includes an analysis of rear door opening deformation and an estimate of door openability post-crash. While this is an interesting and useful analysis, it is not explained why it is done. It is not a required aspect of the regulations. Since it is in the report, a similar analysis should probably be done for the front door openings in the front crash test load cases. Most if not all manufacturers have an in-house requirement that front doors must be openable following a standard front crash test.

Non-body Design Optimization

This project included a major engineering effort to identify practical mass reduction opportunities in non-body component groups. A rigorous process was followed to identify potential mass reduction concepts. This process selected a extraordinary number of technologies that were judged to be practical, cost effective and in volume production now or will be in production by 2017. A few of the larger mass reduction ideas are discussed in the following sections.

Non-body mass reduction ideas selected for the final FEV vehicle design resulted in a 21% reduction in non-body sub-group mass reduction. A portion of the mass reduction achieved in this area was the result of vehicle mass reduction (engine, wheels, tires). The majority of non-body mass reductions are independent of other reductions in vehicle mass.

Suspension

Suspension sub-system – Wheels, Tires, Shock Absorbers,

Steering Knuckles, Control Arms, Springs, …

Optimization results - 69 Kg mass reduction

$0 cost increase

Major mass reductions in this group are:

Wheels and Tires	32.8 Kg	Resized to new weight
Shock absorber	14.1	New light weight design
Front Control Arm	1.9	Convert to Aluminum
Front and Rear Knuckle	12.6	Conversion to Cast Aluminum
Front and Rear Sta. Bar	7.0	Innovative Al tube concept
Other	0.6	

<u>Wheels</u>

Downsizing wheels and tires (5) for the 317 Kg (18.5%) reduction in total vehicle mass is appropriate and is a normal consideration in OEM weight reduction programs. Wheel and tire combinations selected represent a 22% mass reduction from the reduction for these components. This magnitude of mass reduction is potentially achievable, but must be considered somewhat aggressive.

<u>Knuckles</u>

Conversion of steering knuckles to cast aluminum is a proven strategy. Estimated mass reduction by conversion to aluminum is 38% of knuckle mass. Approximately 35% of knuckles on vehicles built in North America use aluminum knuckles. Mass reduction achieved in those programs range from 35% to 45%

depending on knuckle configuration. Knuckle mass reduction assessment in this study is achievable.

Control Arms

Conversion of the front control arm to forged aluminum results in a vehicle mass reduction of 2 Kg. Baseline Venza control arm design is typical of a design used widely throughout the industry. A significant proportion of these arms are produced in aluminum. Mass reduction estimates for conversion of this component is typical of the reductions seen in similar production programs.

Shock Absorber, Sway Bars

Reduced mass shock absorber/strut designs and the tubular sway bars are innovative concepts. Cost reduction of $58 is attributed to the reduced mass shock absorber concept. Production viability and cost of this ideas is not known to this reviewer.

System Cost

Total cost for mass reductions in this group is estimated to be net $0. Cost savings resulting from downsized wheels and tires ($79) and low mass shock absorbers ($58) offset cost increases for low mass arms, knuckles and stabilizer bars.

Engine

Optimization results -	30.4 Kg mass reduction
	$ 43.96 cost reduction

Main sources of engine mass reduction:

Downsizing - constant performance	10.4 Kg (2.7 L to 2.4 L)
Cylinder Block – Al Mg Hybrid, liners	7.1
Valve train – Al castings, power metal	3.7
Cooling system – plastic housings	2.6
Timing Drive – Plastic covers	1.5
Other	5.1

Engine - Downsizing

Largest mass (10.4 Kg) reduction came from downsizing the engine to a smaller displacement to maintaining baseline Venza performance levels. Assessing appropriate engine weight for a downsized engine is a complex task. Changing displacement within a basic engine achieves small incremental mass reductions. A broader perspective was used in this study. Based on competitive engine technology assessments, an engine was selected representing mass optimization for the 2.4 L displacement. Mass of the new engine was adjusted based on sound engineering analysis to meet packaging and performance parameters of the baseline engine-vehicle package. This approach represents an innovative, thorough and well-engineered approach to estimating optimized engine mass reduction resting from vehicle mass reduction.

Developing a new engine involves massive investments in design, development and manufacturing. Production engines are designed for use in a broad range of vehicles and for a period of time spanning several vehicle design cycles. Manufacturers may not have the opportunity to provide a mass optimized engine for a specific vehicle.

The majority of engine mass reduction ideas selected for the FEV Venza exploit recent advances in materials and/or manufacturing technologies. Many small gains were made converting cast iron housings to cast aluminum, and cast aluminum covers and brackets to cast magnesium or plastic. Most of the engine mass reduction ideas selected have been proven in multiple high volume applications over several years. A few engine Ideas have less proven high volume field experience and were identified by FEV as “D” level selection candidates.

3. **VEHICLE CRASHWORTHINESS TESTING METHODOLOGICAL RIGOR (CAE only)**	**COMMENTS**
Please comment on the methods used to analyze the vehicle body structure's structural integrity (NVH, etc.) and safety crashworthiness.	**[Joost]** The baseline testing and comparison process (pgs. 67-128) is very thorough. The team establishes credibility in the proposed design by performing an initial baseline comparison against the production Venza – this suggests that the modeling techniques used can reasonably predict the performance of the lightweight design. It is unfortunate that the deformation mode comparisons could not be made quantitative (or semi-quantitative) somehow. Comparing how the model and test look after a crash gives an indication of deformation mode, but the comparison seems subjective. For example, image D-28 (pg 95) seems to show slightly different failure mechanisms in the CAE model versus the real test. The report notes that the bushing mountings were rigid in the model while they likely failed in the real vehicle. I would expect that these failures are designed into the vehicle to support crash energy management. The results crash pulses (pg 98) for the model and test look fairly similar, but it is unfortunate that this crash energy mechanism was not captured. The intrusion correlation for the baseline model is very good. This again adds credibility to the modeling approach used here. On page 386 the report states that the Mg CCB was not included in the crash or NVH analysis. Replacing a steel CCB with Mg is likely to have a significant impact on both crash and NVH performance. The technology is viable (and has been used on production vehicles as stated) however the crash energy management and NVH performance must be offset by adding weight elsewhere in the vehicle. The CCB plays a role in crash and a major role in NVH so I do not think that it is appropriate to suggest that the material replacement will have the reported results in this case. My suggestion is to leave the CCB as steel in the weight analysis (or go back and redo the crash and NVH modeling, which I suspect is not viable). **[Richman]** 1) LS-Dyna and MSC-Nastran are current and accepted tools for this kind of analysis. FEM analysis is part science and part art. EDAG has the experienced engineers and analysts required to generate valid simulation models and results. 2) EDAG was thorough in their analysis, load-case selections and data for evaluation

	3) The handling of acceleration data from the crash test simulations is a bit unusual, and further analysis of the data is recommended. **[OSU – Tony Luscher]** Trifilar suspension apparatus was used to find the CG and moments of inertia of the engine and other major components. The dynamic FEA modal setup was run using NASTRAN. Vibration modes were analyzed by the CAE model and then compared with physical test data in order to correlate the FEA model to the physical model. Five different load case configurations with appropriate barriers were placed against the full vehicle baseline model. Models were created with high detail and fidelity. **[Simunovic]** The correlations and modifications of the baseline vehicle FEM model to the experimental results were primarily done on the measurements of vibrational and stiffness characteristics of the BIW. Once the stiffness of the BIW model was tuned to the experimental results, it was considered to be sufficiently accurate to form the foundation for the crash model. The vehicle crash FEM model was then correlated to the NCAP and MDB side impact. The correlations were primarily based on the deformation modes and the FEM model was found to be satisfactory for the purposes of the FEV study. Comparison of the deformation in the NCAP crash in Figures 46-49 shows very good correlation of the deformation modes. The deformation of the subframe shown in the Figures 48-49 also shows very high fidelity of the simulated deformation compared to the experiment. In summary, the correlation of the baseline FEM model with the NCAP test is quite satisfactory. The correlation with the side MDB test was not elaborated in the report. However, the side impact is perhaps the most important and limiting design aspect for the lightweight vehicles. The side impact is almost exclusively a structural problem that does not compound the benefits of the reduced mass, as is the case of the frontal impact. A documented correlation of the baseline FEM model with the side impact experiment will in my opinion be a very beneficial technical addition to the FEV project that would significantly support the findings of the technical feasibility of the lightweight opportunities in the existing vehicle design space.
Please describe the extent to which state-of-the-art crash simulation testing methods have been employed as well as the extent to which the associated analysis exhibits strong technical	**[Joost]** This is not my area of expertise. **[Richman]** 1) CAE modeling guidelines used appear to provide a rigorous and logical technical approach to the development of the FE and the methods of analysis.

rigor.	2) Method of evaluating and comparing acceleration levels in the various crash test scenarios is a bit unusual, a more accepted method of comparing velocity/time plots and average accelerations is suggested. **[OSU – Tony Luscher]** Global vehicle deformation and vehicle crash behaviors were analyzed and compared to the deformation modes of test photographs. Fidelity was good. A few notes on these comparisons are noted on this page in the additional comments section. **[Simunovic]** The FEV Low Development vehicle study has been reviewed following the instructions by the US EPA. It has been found that the FEV study followed most of the current technical guidelines and the state-of-the-art practices for computational crash simulation and design. Several inconsistencies were found in the developed FEM models that need to be addressed and corrected before the FEM models are released for the general use.
If you have access to FMVSS crash setups to run the model under different scenarios in LS-DYNA, are you able to validate the FEV/EDAG design and results? In addition, please comment on the AVI files provided.	**[Joost]** N/A **[OSU – Tony Luscher]** This reviewer has expertise in crash simulation. However due to time constraints the model was not run under different scenarios in LS-DYNA. No AVI files were found.
If you are aware of better methods and tools employed and documented elsewhere to help validate advanced materials and design engineering rigor for 2017-2020 vehicles, please suggest how they might be used to improve the study.	**[Joost]** N/A **[Richman]** Methods and tools were appropriate. **[OSU – Tony Luscher]** None found.
ADDITIONAL COMMENTS: **[OSU – Kristina Kennedy]** "Bending and torsional stiffness values did not provide acceptable performance (when replacing with HSS)". This is an "of course" comment, right? HSS would absolutely produce worse results when replacing steel. These results were expected, correct? **[OSU – Tony Luscher]** The caption on Figures 1.8.13 to 1.8.14 state that they are at 100 ms although the previous paragraph lists them as occurring at 80 ms. The muffler deformation looks quite different in Figure 1.8.14.	

Figure 1.8.33 is unclear and cannot be seen.

4. **VEHICLE MANUFACTURING COST METHODOLOGICAL RIGOR (CAE BIW and Vehicle)**	**COMMENTS**
Please comment on the methods used to analyze the mass-reduced vehicle body structure's manufacturing costs.	**[Joost]** Overall, the costing methods used in this study seem to be very thorough. The details of the approach provide considerable credibility to the cost estimates, however there will always be concerns regarding the accuracy of cost models for systems where a complete, detailed engineering design has not been established. I believe that this report does a good job of representing the cost penalties/benefits of the technologies but I would still anticipate negative response from industry. There a few examples where I believe that the cost was underestimated or where additional data could be helpful in corroborating the results: The engine cost comparison suggests that the 2.4L engine will cost less than the 2.7L engine due to reduced material content (smaller engine). The analysis goes on to say that the remaining costs (manufacturing, install, etc.) would be about the same for both engines. This seems credible, but is it possible to compare the price of both engine types as well? It may be possible to find prices for both of these engines from a Toyota dealer, and while price is certainly different than cost, it would be helpful in establishing that the cost differential estimate is reasonably accurate. Regarding the cylinder head subsystem (pg 211), the report notes that a switch from Mg to plastic for the head covers introduces engineering challenges related to the cam phaser circuitry. While the report identifies two production examples of this change, these are for high cost engines. It seems unlikely that the designs would achieve the quoted cost savings given that this has only been applied to high cost engines and there are recognized difficulties in the engineering/design. Regarding the body redesign, the estimated cost increase due to materials and manufacturing ($231.43, pg 333) for a weight savings of 67.7kg produces a weight reduction penalty of about $3.42/kg-saved which seems appropriate for the materials and assembly processes suggested in the report. I don't find the cost estimates for the seats to be credible (pg 378). If it's possible to reduce the weight of the seats (which represent a significant portion of vehicle weight) while saving significant cost, why would there be any steel seats in production? These are "bolt on" parts that are provided to the OEMs by suppliers so this would be a relatively easy change to make if the cost/weight trade-off shown in this report is true. The report should, at the very least, address why these kinds of seats are not more prevalent in current vehicles.

	Why is there a cost savings for the front axle hub (pg 555)? If you are proposing to scallop the hub during forging then you will still need the same amount of input material – some of it will be removed during scalloping, but you will not get a cost savings. Also, it's not made explicitly clear that the current hub is forged. If you are proposing to move from a cast hub to a forged hub then the cost will most certainly increase. If the cost savings here is due to the estimated weight savings in the final part (i.e. pay for less material) then this indicates that the model is not correctly capturing the yield from the process. **[Richman]** Body structure mass optimization was conducted by EDAG. Body structure was not altered form the baseline structure. Mass optimization process examined an appropriate range of material types, grades and gauges. Material properties used appear valid for the respective materials and grades. NVH and collision performance results appear consistent and logical with no significant dis-continuities of inconsistencies. In general the process used is excellent and the results appear realistic and valid. Costing models were maintained by EDAG. A complete baseline vehicle cost model was developed and calibrated to the estimated cost of the current Venza. The baseline model was used to track cost changes driven by mass reduction technologies. Cost estimates for mass reduction technologies are based on detailed analysis of the products, materials and process utilized. Estimating costs for new or emerging technologies is a challenging process. Advanced technology cost estimates are based on a combination scaling from known products if available, benchmarking from similar products, material supplier costs, analysis of advanced manufacturing cost, and expert estimates. Labor rates and manufacturing overheads are maintained at documented industry typical levels. This cost tracking approach is fundamentally sound and valid. Cost estimates for new technologies are subject to validity of cost estimates and engineering judgments in the estimate. This project included rigorous engineering assessments of all mass reduction technology costs. For most mass reduction technologies selected, cost estimates appear realistic and are consistent with current production costs and prior vehicle mass reduction studies. In the area of body sheet materials there appears to be some assumptions that result in estimated technology costs as much as 25% higher than volume production experience would suggest. This are is discussed in more detail in this report. Costs attributed to optimization of the body are reported as: Mass Reduction Cost | $/Kg saved BIW | $ 110 | $ 2.19 | HSS, AHHS

Hood	$ 39	$ 5.08	Aluminum
Lift Gate	$ 30	$ 4.16	Aluminum
Fenders	$ 22	$10.93	Aluminum
Total	$ 210	$ 3.20	

Cost increases projected for HSS and AHSS are marginally higher than have been reported in analytical studies and OEM experience in volume production. Production vehicle studies of AHSS in auto body applications have suggested cost impact of reduced body mass can offset a majority of the cost premiums associated with these materials.

Cost increases projected for aluminum sheet application are significantly higher than has been seen in prior studies and in production OEM experience. The optimized body includes three aluminum components: Hood, Fenders and Lift Gate. Mass reductions attributed to these three product areas are consistent with OEM production experience. Estimated cost increases are significantly higher than have been seen in production experience.

Using the hood as an example, total cost of the baseline hood is estimated to be $43 while total cost of the aluminum hood is estimated to be $93. Mass savings with the aluminum hood is 7.7 Kg resulting in a net cost per Kg mass reduction of $6.49. Production program experience with aluminum hoods typical find a cost premium below $4.50 per Kg mass reduction. Processing costs for a steel or aluminum hood should be similar. That similarity is reflected the EDAG cost model. The main cost difference between hoods is in material cost. Examining the EDAG cost model it appears aluminum sheet products were assessed a base metal cost and a grade premium. The two factors appear to be combined in the cost model results a raw material cost substantially higher than actual market price for these materials.

EDAG cost models for auto body sheet materials (AHSS and aluminum) appear to be overstating raw material costs. A review of the costing models and correlation with market prices for the materials and how raw material cost for sheet products is established in the models may be appropriate.

[OSU – Tony Luscher] Mass reduction was analyzed first on a system level and then by a component level basis. Mass reduction concepts were based upon a very comprehensive literature review of new materials and manufacturing processes and alternative designs ideas that appear in the open literature and at trade shows. An assessment of these was made in terms of technological readiness, fitness for use in mass production, risk, and cost. In addition there were consultation with industry and experts.

[Simunovic] This is not my area of expertise.

Please describe the extent to which state-of-the-art costing methods have been employed as well as the extent to which the associated analysis exhibits strong technical rigor.	**[Joost]** This is not my area of expertise. **[Richman]** Costing models are thorough covering all elements of total production cost (material, processing, equipment, tooling, freight, packaging, …). Baseline cost model was calibrated to baseline vehicle cost projection. The basic model is complete and sound. Cost estimates for mass reduction technologies are the result of a rigorous engineering process utilizing benchmarking data, material and component costs from suppliers and detailed analysis of manufacturing costs. Sound creative engineering analysis was used to scale product cost to this specific vehicle application. Accuracy of new technology cost estimates is dependent on the knowledge, skill , experience and engineering judgment of the individuals making the estimates. Munro Associates conducted this segment of the project. Munro is a highly respected organization with strong qualifications in product cost analysis. It is reasonable to assume cost estimates in this study are valid estimates for the mass reduction technologies. One area of cost estimate concern is reduced mass sheet products. In this area, material and equipment costs attributed to the reduced mass technologies are significantly higher than actual production experience would support. Source of the discrepancy is not clear form the information in the project review documents. **[OSU – Tony Luscher]** The impact of costs, associated with mass reduction, was evaluated using FEV's methodology and tools as previously employed on prior powertrain analyses for EPA. Cost reduction assumptions are clearly laid out and are reasonable. The report does a good job of realizing the inherent challenges and risks in applying any new technology, let alone lightweight technology, to a vehicle platform. FEV describes the component interactions both positive and negative in its recommendations. The actual values in the EXCEL files were not checked. **[Simunovic]** This is not my area of expertise.
If you are aware of better methods and tools employed and documented elsewhere to help estimate costs for advanced vehicle materials and design for 2017-2020 vehicles, please suggest how they might be used to improve this study.	**[Joost]** This is not my area of expertise. **[Richman]** Process methodology and execution used is one of the best this reviewer has seen. **[OSU – Tony Luscher]** None found. **[Simunovic]** This is not my area of expertise.

ADDITIONAL COMMENTS:

[Joost] The change from a cast Al engine block with cast Fe liners to a cast-over Mg/Al hybrid with PWTA coated cylinders is very interesting, but the cost penalty estimate seems low relative to what I would expect. Previous work exploring the use of Mg intensive engines (which did not include the added complexity of cast-in Al liners) suggests a cost penalty of $3.89 per pound saved (see http://www1.eere.energy.gov/vehiclesandfuels/pdfs/lm_08/3_automotive_metals-cast.pdf report B) versus this report which suggests a cost penalty of $3.51 per kilogram saved, about half as expensive. The cited study was performed on a 2.5 L engine, comparable to the Venza. The primary difference is that the Venza study includes downsizing which would save on material costs, but I'm not confident that the savings would be as substantial as indicated in this report. It seems that something has been underestimated.

There are several examples where a cost savings has been calculated by reducing the size of a component, despite using more expensive material. For example the Front Rotor/Drum and Shield subsystem shows a savings for the caliper subsystem and a modest increase in the cost of the rotor and shield. Some of the cost savings here is due to reducing the size of the system (scaling to the 2008 Toyota Prius). However, there would still be a weight savings (albeit lower) if the conventional cast iron materials were used and downsized to the 2008 Toyota Prius – this is the likely outcome in a real automotive environment. Given the option to choose a more expensive, exotic, untested system that saves significant weight versus a conventional low cost system that saves less weight, it seems like an OEM would choose the conventional solution. In this case the suggested weight savings are technically possible but would never happen in a practical automotive environment.

[Richman] A review of cost development for reduced mass sheet product should be reviewed. Current model would lead to de-selecting some low mass sheet based solutions due to unrepresentative cost assessment.

[OSU – Kristina Kennedy] Table 1.7.1: NVH Results Summary. The "Weight Test Condition" and "Weight BIW" are ALSO outside of limits (> 5%), but not noted in results. Only those highlighted in red are noted as "failures". All failures (> 5%) should be called out specifically since that was their target.

[OSU – Tony Luscher] There are many typos and fragmented sentences in these sections. These should be corrected. Bookmark references do not all work.

5. CONCLUSION AND FINDINGS	COMMENTS
Are the study's conclusions adequately backed up by the methods and analytical rigor of the study?	**[Joost]** Yes. I identified various areas where the analysis or report could be improved, but overall the methods used here provide a credible and reasonable estimate of the potential for weight savings. Based on some of my earlier comments I would expect that actual costs to be somewhat higher than predicted in this study. Additionally, real vehicles share components across platforms so using vehicle-specific components would add additional cost. It is possible that the cost curve would cross $0/lb-saved at a lower total weight savings than suggested here. **[Richman]** Study conclusions and findings are well supported by the analytical rigor, tools used and expertise of the organizations involved. EDAG conducted a detailed reverse engineering process to define baseline Venza component mass and structural performance. The process included: vehicle teardown, identification of component mass and material composition and component scanning to create digital models of structural components. Part connections (spot weld, seam weld, laser weld), dimensions (location, weld diameter, weld length), and characteristics were documented during scanning process. Material property data was obtained by coupon testing part samples. Scan data, part weight and material information were used to create a CAE model of the vehicle structure. A finite element (FE) model was created from the CAE model using ANSA mesh software. The FE model was used to evaluate NVH characteristics (bending, torsion, modal analysis) of the structure using NASTRAN. Model results were compared and calibrated with analytical test results to establish the baseline analysis model. CAE crash performance simulations (LS-DYNA) were conducted to verify model correlation with actual vehicle crash test performance in National Highway Traffic Safety Association (NHTSA) regulatory performance testing. Model results were calibrated to actual Venza crash performance data. The correlated crash model became the baseline crash model for the remaining load cases. EDAG is widely recognized as highly competent and experienced in vehicle structural modeling, NVH and collision simulation and structural engineering. LS-Dyna, MSC/Nastran and ANSA are valid and widely-used simulation tools, commonly used and accepted within the engineering community and the industry to perform this analysis. The approach used by EDAG to develop Venza structural models is a state-of-the art methodology utilizing proven modeling tools. Structural models developed in this project were calibrated to physical test results of actual vehicle structures. Simulation results appear reasonable and logical, building confidence in the fidelity of the analysis. Models have excellent correlation to actual vehicle performance. FMVSS crash results are consistent with bending and torsional stiffness properties. There is no apparent reason to question results of this modeling and simulation effort. These models would be expected to be

	valid for comparison of design alternatives. These models would be expected to provide reliable assessments of NVH and collision performance of the Venza structure. Report conclusions with regard to NVH and collision performance do not substantially overreach the capability and results of the analysis. In some relatively minor areas, assessment to of the "optimized" structure is not fully supported by generally recognized measures of structural performance. These few relatively uncertainties do not diminish the overall conclusion that the modeling and simulation efforts are well done and the major conclusions are valid useable. **[OSU – Glenn Daehn]** At the time of review, Section G "Conclusions and Recommendations" is unavailable. We hope that in this section FEV will point out the most promising actions that auto makers may take to reduce mass while conserving cost. **[OSU – Tony Luscher]** The report's conclusions are based on sound engineering principals of good rigor.
Are the conclusions about the design, development, validation, and cost of the mass-reduced design valid?	**[Joost]** Yes. As above, there is reason to believe that the true cost will be higher than predicted here, but I think this analysis provides a useful estimate. **[Richman]** Design development and validation conclusions are well supported in this study. Cost model is valid and cost conclusions are generally realistic. There appears to be a systematic discrepancy in cost modeling of low mass sheet products. This discrepancy has a minor impact on conclusions of this study. **[OSU – Glenn Daehn]** This study is carefully crafted with excellent attention to engineering detail. It is important to note that the overall environment for vehicle design, manufacture and use is continually changing. See the "Additional Comments" section of this document for further development of the implications of this. **[OSU – Tony Luscher]** This reviewer found the overall work to be thorough and well documented. Therefore the conclusions are well supported and validated by the engineering and modeling in the report.
Are you aware of other available research that better evaluates and validates the technical potential for mass-reduced vehicles in the 2017-2020 timeframe?	**[Joost]** I have not seen a report as thorough as this. There are several examples of resources that provide useful information regarding weight reduction potential such as Cheah, L.W. Cars on a Diet: The Material and Energy Impacts of Passenger Vehicle Weight Reduction in the U.S. Joshi, A.M. Optimizing Battery Sizing and Vehicle Lightweighting for an Extended Range Electric Vehicle Lutsey, N. Review of technical literature and trends related to automobile mass-reduction technology **[Richman]** This reviewer has monitored automotive mass reduction studies in North America and Europe for several

	years. This study is the best evaluation of mass reduction opportunities and associated costs this reviewer has seen. **[OSU – Glenn Daehn]** There are no more comprehensive or detailed studies that we are aware of. This is an excellent compilation of ideas for practical vehicle mass reduction and fuel efficiency improvement. **[OSU – Tony Luscher]** None found.

ADDITIONAL COMMENTS:

[OSU – Glenn Daehn] The study does an excellent job within its scope. As this reviewer sees the scope, the driving question is: Can a well-engineered relatively modern vehicle (2010 Toyota Venza) have its mass reduced by 20% or more, without significant cost penalty and while maintaining crashworthiness. The answer to that question is a clear "YES". Further, this conclusion is backed with rigor and attention to detail. This is in my mind, very clear, well-done and technically rigorous.

This reviewer believes that there are a few other important questions that were not asked. These include:

1) Will the proposed changes in design pose any other important risks in manufacture or use? This can include: warranty exposure, durability, increased noise, vibration and harshness, maintenance concerns, etc., etc.

2) Will increasing regulatory constraints and/or consumer expectations require increases in vehicle mass, opposing the mass reductions provided by the improved practices outlined in this study?

Both these issues will make vehicle light weighting more difficult than this report suggests. With respect to issue 1) there are a number of materials and design substitutions that may produce concerns with durability, manufacturability and warranty claims. For example when substituting polymers for metals, there are new environmental embrittlement modes that may cause failure and warranty claims. Also, if substituting aluminum for steel, multi-material connections may cause galvanic corrosion problems. When using thinner sheets of higher strength steel, formability may be reduced and springback may be more problematic. Both these issues may preclude the use of the stronger material with a similar design and may also increase the time and cost involved with die development. Lastly there are always risks in any new design. For example, when using new brake designs, pad wear and squeal may be more pronounced. All of these issues may cause a manufacturer to avoid the new technology.

There are also local constrains on material thicknesses that are outside this review methodology. For example while a roof rail may meet crash and stiffness criteria, it may deflect excessively or permanently if a 99th percentile male pulls on it exiting a vehicle. Similarly, parking lot and hail dents may require greater thickness gauges than this study may indicate.
The problem of vehicle light-weighting and improved fuel economy is seen here through the lens as being an engineering problem to be solved. And in many

ways it is. However, the forces of consumer expectations and behaviors are an essential part of the problem. As an interesting anecdote, the Model T Ford had a fuel economy of about 20 MPG, very similar to the average fuel economy of vehicles on the road today. No modern consumer would choose a Model T for many obvious reasons. Our cars have become extensions of our living rooms with many electrical motors driving windows, mirrors, seats and complex and costly HVAC and infotainment systems. All of these systems add weight, complexity and use power. Further increased complexity of engines to improve emissions and increase fuel economy has increased engine mass.

This study shows that with good engineering we can reduce vehicle mass of an existing vehicle by 20% with little to no increased cost or adverse consumer reaction. Based on our current course, it is just as likely this benefit will be taken by improved mandated safety and emission features as well as improved creature comforts.

Much can be gained through enlightened consumer behavior (assuming the average consumer wants to reduce energy use and carbon footprint). While much of this is outside the scope of this report, in particular it would be useful if the average consumer would understand the lifecycle environmental impacts of vehicle choice and of varied vehicle design, and would adopt a 'less is more' ethic and see their transportation systems as that, simply transportation. A more minimalist ethic that would move against increasing vehicle size and the creep of multiple motors for seats, mirrors, windows, etc., would reduce acquisition cost, maintenance cost and energy cost. This is in addition, of course, to the usual advice to reduce fuel consumption (limit trips, limit speed, tire pressure, carpooling, etc. etc.) is still valuable.

It should also be noted that there are other potentially low-cost actions that can be easily adopted to reduce greenhouse gas emissions and reduce dependence on foreign oil. One of these is widespread adoption of natural gas fuels for personal transportation. Use of Compressed Natural Gas (CNG), has lower fuel cost than gasoline, produces less pollution and greenhouse gas emission per energy used, and requires only very modest changes to conventional vehicle architecture, with no significant increases in complexity. The cost and size of a CNG tank and the development of refueling infrastructure are the main barriers to adoption of a technology that could have important and positive societal benefits.

This is an excellent and useful study. It is important however to recognize the limitations of purely engineering solutions. And even within the engineering realm, there are many reasons that the implementation of the solutions in this paper study will require much effort to become part of mainstream automobiles.

[OSU – Kristina Kennedy] With respect to measuring powertrain CG and moment of inertia, notes "oscillation as an undamped" condition. Just confirming, this means no dynamic dampers were used in the engine room modeling? Is this realistic? Acceptable practice?

6. OTHER POTENTIAL AREAS FOR COMMENT	COMMENTS
Has the study made substantial improvements over previous available works in the ability to understand the feasibility of 2017-2020 mass-reduction technology for light-duty vehicles? If so, please describe.	**[Joost]** Yes. Other studies have reviewed the mass saving potential of various technologies individually, or imagined the impact of combining many technologies. However I am not aware of a design study that takes an existing vehicle and assesses each piece with the thoroughness used here. **[Richman]** Yes. Overall objectives) of the project (20% mass reduction, less than 10% cost increase) are timely and consistent with industry interests in the short term. Retaining the OEM designed and field proven body structure eliminates uncertainty related to evaluation of novel and un-proven structures. This analysis clearly identifies body mass reduction achievable with new and near term future grades of HSS and AHSS. An exhaustive list of non-body mass reduction concepts are evaluated in this study. Some of these technologies are well known and understood in the industry, other are new, creative and innovative. Each technology is reviewed from an engineering and cost perspective and scaled to the specific application. The technology selection process was analytical, rigorous and un-biased. Majority of technologies selected are appropriate for the mass reduction and cost objectives of the project. This information provides helpful information to industry engineers considering mass reduction alternatives for other vehicle programs. **[OSU – Glenn Daehn]** Without question. The only similar study also targeted the Venza. This provides much additional analysis and many additional ideas beyond the Lotus study. **[OSU – Glenn Daehn]** The major contribution of this study was to pull together and evaluate all of the current proven concepts that are applicable to a lightweight vehicle in the 2017-2020 timeframe. It is successful in this regard.
Do the study design concepts have critical deficiencies in its applicability for 2017-2020 mass-reduction feasibility for which revisions should be made before the report is finalized? If so,	**[Joost]** No – I would not say that any deficiencies here are "critical". **[Richman]** Major findings of the project appear practical for implementation by 2017-20. Two technologies selected for inclusion in the final vehicle concept appear "speculative" for 2017-20, Co-cast magnesium/aluminum block and MMC brake rotors. Both technologies are identified as "D" level for implementation.

please describe.	Designing, developing and establishing production capacity for a new engine block is a time consuming and costly process. Investments would be required by OEM manufactures and casting suppliers. It is not clear the level of human resources and capital investment required for this technology could be justified the basis of the mass reduction potential of (7 Kg). Aluminum MMC brake rotors were selected for inclusion in the final vehicle configuration. In the judgment of this reviewer, this technology is the most speculative technology selected for the final vehicle configuration. MMC rotors have been in development for over 25 years. Development experience with these rotors has generally not been acceptable for typical customer service. The minimum mass MMC rotor design selected in this project is a radical (by automotive standards) multi piece bolted composite design with an MMC rotor disc. This design is identified as a "D" rated technology and a mass savings of 9 Kg. The aluminum MMC portion of the mas reduced rotor assembly would be regarded as "speculative" at this time. Cost models used to assess low mass sheet product may have some questionable assumptions. For this project, adjustment in the cost model is unlikely to influence he material selection process. Correction in this area would have a greater impact on technology screening and selection to achieve mass reductions above 20%. **[OSU – Glenn Daehn]** Conclusions and recommendations section is missing. This is an important opportunity to reinforce the most important actions that automakers can take. The report still lacks the ability to trace some technical details all the way back to the source. This is described previously.
Are there fundamentally different lightweight vehicle design technologies that you expect to be much more common (either in addition to or instead of) than the one Lotus has assessed for the 2017-2020 timeframe (Low Development)?	**[Joost]** Not in the 2017-2020 time frame. Switching to an advanced steel dominant body with a few instances of Mg and Al seems appropriate for the time frame. The considerable use of lightweight plastics is also in line with my expectations for available technology in this time frame. **[Richman]** No. The result of his study is a logical and cost effective advancement in the development of more efficient passenger vehicles for the 2017-20 time frame. **[OSU – Glenn Daehn]** It seems apparent that vehicles are moving more and more to multi-materials construction and as we move away from steel-based construction, joined primarily by resistance spot welds, there will be need for additional joining technologies. Laser welding is mentioned as one possible replacement for resistance spot welds, but it is expected that over time there will be much more use of structural adhesives, self piercing rivets, conformal joints and other joining strategies for the BIW.
Are there any other areas outside of the direct scope of the analysis	**[Joost]** All of the areas listed here are somewhat concerning, but given the switch to fairly conventional materials I believe that durability, driveability, and NVH should be not be a significant issue. Detailed analysis work in these areas would likely

(e.g., vehicle performance, durability, drive ability, noise, vibration, and hardness) for which the mass-reduced vehicle design is likely to exhibit any compromise from the baseline vehicle?	require some redesign which may add cost or weight, but I don't think it would be overwhelming. **[Richman]** None identified by this reviewer. **[OSU – Glenn Daehn]** Yes. There are many other details with respect to nuances of customer expectations, durability, warranty risks and manufacturability that are discussed elsewhere in this review. This does not diminish the importance of this great work. Just points out there are an enormous amount of detailed work required to build an automobile, and the job is not finished.
ADDITIONAL COMMENTS: **[OSU – Kristina Kennedy]** Overall, well-written and well-done…my conclusion (which they also reached) is YES, NVH WILL SUFFER when replacing steel with HSS and will OF COURSE make the vehicle MORE STIFF. **[Simunovic]** The FEV report is quite exhaustive. I would suggest that it be released in a hypertext format that can allow different navigation paths through it. Also, the dynamic Web-based technologies can be used for effective model documentation, presentation and distribution. I would also recommend that more details on the actual optimization process, including the objective function specification, and the final consolidation of the model, be added to the documentation.	

Peer Review Responses to "*Light-Duty Vehicle Mass-Reduction and Cost Analysis – Midsize Crossover Utility Vehicle (FEV Report)*"

Prepared for

Assessment and Standards Division

Office of Transportation and Air Quality

U.S. Environmental Protection Agency

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EPA Contract Number: EP-C-12-014 WA0-3

August 9, 2012

Peer Review Responses to "*Light-Duty Vehicle Mass-Reduction and Cost Analysis – Midsize Crossover Utility Vehicle (FEV Report)*"

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Executive Summary

In December 2011, EPA contracted with SRA International (SRA) to conduct a peer review of *Light-Duty Vehicle Mass-Reduction and Cost Analysis – Midsize Crossover Utility Vehicle (FEV Report)* developed by FEV and EDAG.

The peer reviewers selected by SRA were William Joost (U.S. Department of Energy), Glenn Daehn, David Emerling, Kristina Kennedy, and Tony Luscher (The Ohio State University), Douglas Richman (Kaiser Aluminum), and Srdjan Simunovic (Oak Ridge National Laboratory). In addition, Srdjan Simunovic and members of the OSU team reviewed various elements of the associated modeling. EPA would like to extend its appreciation to all of the reviewers for their efforts in evaluating this report and the modeling. The reviewers brought useful and distinctive views in response to the charge questions.

The first section of this document contains the final SRA report summarizing the peer review of the *FEV Report*, including the detailed comments of each peer reviewer and a compilation of reviewer comments according to the series of specific questions set forth in the peer review charge. After each section of comments, we provide our response. We have retained the organization reflected in SRA's compilation of the comments to aid the reader in moving from the SRA report to our responses.

TO: Cheryl Caffrey, U.S. Environmental Protection Agency, Office of Transportation and Air Quality (OTAQ)

FROM: Brian Menard, SRA International

DATE: April 26, 2012

SUBJECT: Peer Review of *Light-Duty Vehicle Mass-Reduction and Cost Analysis – Midsize Crossover Utility Vehicle (FEV Report))*, developed by FEV and EDAG.

1. Background

In developing programs to reduce greenhouse gas (GHG) emissions from light-duty highway vehicles, the U.S. Environmental Protection Agency's Office of Transportation and Air Quality (OTAQ) has to evaluate the safety of light weighted automotive designs as well as the methods and costs of proposed technologies to achieve this design.

The 2012 study by FEV, *Light-Duty Vehicle Mass-Reduction and Cost Analysis – Midsize Crossover Utility Vehicle (FEV Report)* is a continuation (i.e., Phase 2 study) of the original Phase 1 Low Development study from Lotus Engineering. The report reviews the amount of mass reduction in the Low Development case ("20%") from the Lotus Engineering Phase 1 study. This is done through analysis of the assumptions for the Body-in-White (BIW), and through an up-to-date re-analysis of light weighting options for all of the other vehicle components of which the Lotus Engineering assumptions are a part. An in-depth cost evaluation of all technologies is included. The FEV Report consists of two parts: In the first part, FEV's contractor, EDAG, has designed and developed the BIW structure in CAE in order to demonstrate that it meets Federal Motor Vehicle Safety Standards (FMVSS) for Light-Duty Vehicles using LS-DYNA. The analysis includes materials, methods, and related costs to assembly and manufacturing. The second part of the report is an in-depth investigation of "other than BIW" vehicle systems based upon discussions with suppliers, Lotus Phase 1 report ideas, and FEV's experience and expertise.

This report documents the peer review of the *FEV Report*. Section 2 of this memorandum describes the process for selecting reviewers, administering the review process, and closing the peer review. Section 3 summarizes reviewer comments according to the series of specific questions set forth in matrix contained in the peer review charge. The appendices to the memorandum contain the peer reviewers' resumes, completed conflict of interest and bias questionnaires for each reviewer, and the peer review charge letter.

2. Description of Review Process

In December 2011, OTAQ contacted SRA International to facilitate the peer review of the *FEV Report*. The model and documentation were developed by FEV and EDAG.

EPA provided SRA with a short list of subject matter experts from academia and industry to serve as a "starting point" from which to assemble a list of peer reviewer candidates. SRA selected three independent (as defined in Sections 1.2.6 and 1.2.7 of EPA's *Peer Review Handbook, Third Edition)* subject matter experts to conduct the requested reviews. SRA selected subject matter experts familiar with automotive engineering and manufacturing, automotive materials, crash simulation, and cost assessment. The coverage of these subject areas is shown below in Table A.

Table A:
Peer Reviewer Experience and Expertise

Name	Affiliation	Coverage					
		Automotive materials	Bonding forming	Manufacturing assembly	Crash simulation	Cost assessment	
Douglas Richman	Kaiser Aluminum	Y	Y	Y	/	Y	
William Joost	US DOE	Y	Y	Y	/	/	
Srdjan Simunovic	Oak Ridge National Laboratory	Y	Y	/	Y	/	
Glenn Daehn et al.	The Ohio State University	Y	Y	Y	Y	Y	

To ensure the independence and impartiality of the peer review, SRA was solely responsible for selecting the peer review panel. A crucial element in selecting peer reviewers was to determine whether reviewers had any actual or perceived conflicts of interest or bias that might prevent them from conducting a fair and impartial review of the *FEV Report*. SRA required each reviewer to complete and sign a conflict of interest and bias questionnaire.

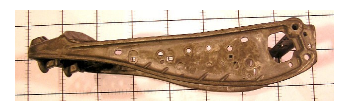
SRA provided the reviewers a copy of the most recent version of the *FEV Report* as well as the peer review charge. The charge included a matrix of questions issues upon which the reviewers were asked to comment. Reviewers were also encouraged to provide additional comments, particularly in their areas of expertise and work experience.

A teleconference between EPA, FEV, EDAG, the reviewers, and SRA was held to allow reviewers the opportunity to raise any questions or concerns they might have about the *FEV Report* and associated modeling, and to raise any other related issues with EPA and SRA, including EPA's expectations for the reviewers' final review comments.

3. Compilation of Review Comments

The *FEV Report* was reviewed by William Joost (U.S. Department of Energy), Glenn Daehn, David Emerling, Kristina Kennedy, and Tony Luscher (The Ohio State University (OSU)), Douglas Richman (Kaiser Aluminum), and Srdjan Simunovic (Oak Ridge National Laboratory). In addition, Srdjan Simunovic and members of the OSU team reviewed various elements of the associated modeling.

1. **ASSUMPTIONS AND DATA SOURCES (CAE BIW and Vehicle)**	**COMMENTS**	**RESPONSE**
Please comment on the validity of any data sources and assumptions embedded in the study. Such items include material choices, technology choices, vehicle design, crash validation testing, and cost assessment that could affect its findings.	**[Joost]** The material selection process used in this study suggests a good understanding of the cost and manufacturing impacts of changing between different steel, Al, Mg, and plastic/composite based materials. Generally the material selections are appropriate for the performance, manufacturing, and cost requirements of the particular systems. Identifying production examples of the materials in similar systems is very important for establishing credibility – the project team did an excellent job identifying production examples of most material replacements. There are, however, a few material selections where additional consideration may be necessary: The transmission case subsystem (pg. 269) features the use of a Sr bearing Mg alloy. Recently, Sn-based alloys have been produced and (I believe) used in production for similar applications. The use of Sn as an alloying ingredient accomplishes many of the same goals (improved high temp creep performance, for example) at a lower cost. It may be worth investigating these new alloys as an opportunity to reduce the cost of the lightweight transmission case subsystem. If not, the selection of a Sr alloy is reasonable.	Thank you. In our study, converting the Case assembly from aluminum to AJ 62 magnesium was based on the functional capabilities of the material. AJ 62 is a powertrain material that brings the gearbox stability and uniformity into a production scenario. It is paramount to the life cycle of a gearbox that creep deformation is kept to a minimum. This product has proven itself in many production transmission applications. There are other potential variants with numerous element additions, such as Sn (tin) coming to the market today and others in the future and we will look at them as they come out of research for light-weight and low-cost material alternatives.

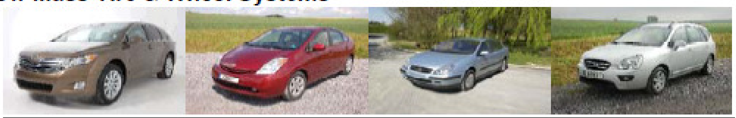
	The feasibility of using hot rolled blanks in the body structure would be further emphasized by providing production examples for vehicles of >200k units per year. Similarly, the use of a 7000 series Al rear bumper is questionable – a production example for a high volume, low cost vehicle should be provided.	The use of hot rolled blanks is now being explored by various OEMs. However, the base material used in the process is a common material and is used throughout the industry. The use of the 7000 series Al rear bumper is the production material used by Toyota in the Venza. Therefore, we chose not to change it for this study.
	The use of Thixomolded Mg seat components should be reconsidered. Thixomolding does have the potential to provide improved ductility compared to die casting; however the process is generally not well regarded in the automotive community due to concerns over limited supply and press tonnage limits (which limit the maximum size of the components that can be manufactured this way). If there is a production example of Thixomolding for >200k unites per year in automotive, then it should be cited in the report. If there is no example then I would suggest switching to die casting (or super vacuum die casting) – the weight reduction and cost will likely be similar.	The boundary conditions for this study were to take into account that the proposed weight reduction idea was to be production ready by 2017. Thixomold is in current production and is a proven technology. In report section F.4B.4.5 there is an example of a prototype back frame showing the weight savings. Other industries use the Thixomolding process, such as Panasonic that uses it to manufacture their 36" TV consoles face. The Venza seat frame fits well into the size limits of the Thixomold size perimeters. The following pictures below of a seat frame in production will be added to the report. The model or OEM cannot be disclosed due to confidentiality.   

	It's not clear how the mass savings were achieved in the wheels and tires. The report states that a 2008 Toyota Prius wheel/tire assembly will be used in place of the stock Venza wheel – however the report also states (pg. 544) that the Prius wheel will be normalized up to the 19"x7" to maintain the original styling of the Venza. The technology employed in the Prius wheel is not different from the stock Venza wheel so why should a scaled-up Prius wheel weigh less than the original Venza wheel? There are also inconsistencies in the report – table F.5-18 references eliminating the spare tire wheel while downsizing the spare tire – why would there be a tire with no wheel? Lastly, if the Prius wheel/tire is scaled up to match the stock Venza size then the spare wheel/tire must also be scaled up – it's not clear that this happened. You are taking significant credit for weight reduction in the wheels and tires (~2% of total vehicle weight) but it's not clear how this is achieved.	The fact the Venza and Prius both share aluminum cast wheels with a spoke design does not reflect the differences that may exist in design methodology for ensuring strength, stiffness and load capacity. The width, thickness and ribbing / webbing methodology in forming the wheels would allow for a similar visual appearance while achieving a different designed component mass. It will require having CAD models or prints of both wheels to fully analyze all physical differences to identify where the mass differences are generated from after the components are scaled to the same relative size for comparison. Yes there is a discrepancy in the table cited showing a previous idea that was not ultimately pursued in the final solution. It should be removed. Yes the spare tire/wheel assembly from the Prius was also a scaled replacement for the Venza and was scaled up due to the two units being basically the same type of design but of different size. A minimal mass savings of only 2kgs was achieved (1kg in each the tire and wheel). By referring to table 10.3.h below, it can be seen that similar vehicle platforms scaled up to the Venza vehicle weight allowing for opportunities for their tire and wheel systems to show reduction in mass as well. This confirms the baseline design of Venza is not optimized for weight efficiency in comparison to these three vehicle systems being scaled by gross vehicle weight. Of these three vehicle platforms, Prius is the lightest one being chosen for the study optimization.

Low Mass Tire & Wheel Systems

The following Table 10.3.h. summarizes low mass production tire & wheel systems. The Prius was selected as the basis for tires and wheels. The mass values were normalized to the Venza mass to define the Low Development baseline.

Table 10.3.h.: Low Mass Tire & Wheel Systems



	2009 Toyota Venza 2.7 FWD	2008 Toyota Prius 1.5 Base	2003 Citroen C5 2.0 HDi Exclusive	2008 Kia Carens 2.0 CRDI Active
	P245/55R19 Al Alloy	P185/65R15 Al Alloy	P195/65R15 Steel	P215/55R16 Al Alloy
Weight	140.165	69.226	70.714	90.13
Curb Mass	1705	1349.1	1342.6	1652.8
Normalized to 1700 kg Curb Mass	140.17	87.49	89.80	92.98

Table 10.5.4.a.: Low Development Tires & Wheels

	Qty	Baseline Mass (2009 Toyota Venza)	New Mass (2008 Toyota Prius)		Cost Impact
Tires & Wheels	1	144.541	108.896	25% Lower	0.96
Road Tire & Wheel		120.989	87.344		0.95
Front	1	60.249	43.672		0.95
Wheel[19 x 6.5]	1	15.300	8.600		0.93
Tire[P225/60R19]	1	14.880	13.200		0.98
Valves	1	0.036	0.036		1.00
RH Wheel & Tire assy	1	30.010	21.836		0.95
Ball bearing hub cover	1	0.023	0.023		1.00
Rear	2	60.740	43.672		0.95

Low mass cast Al wheel (Included in low and high development)
Several vehicles currently in production and several in the Venza price range use lower mass cast aluminum wheel designs. These are shown in Figure 10.4.1.x. along with the Venza wheel. The primary difference was the depth and number of the spokes. The example vehicles indicate the appropriateness of this design for the study vehicle. Applying the ablation casting technique to the Prius wheel would result in an estimated wheel mass of 8.6 kg.

Figure 10.4.1.x.: Venza Wheel shown along with some sample low mass wheel designs.

	Many of the parts in the frame have been changes to a GF Nylon (pg. 667). This may not be unreasonable, but production examples should be provided.	Added production example in section F.8.3.3: This idea has been implemented in current production. The 2012 Chevy Cruze with the 1.4L turbocharged engine and 6-speed automatic transmissions has plastic engine mounts.  
	[Richman] 1) NHTSA crash test data was used for validation of collision simulation models and is an appropriate source. 2) Material property data was supplied by recognized supplier associations and are correct. 3) Cost estimates for reduced mass sheet products seem to include assumption that drive unusually high material and equipment cost. This issue leads to a technology cost effectiveness that is not representative of actual production experience for sheet products.	As mentioned in report section F.4A.11: The vehicle closure aluminum cost in the EDAG portion in the report reflected the revised material cost for sheet aluminum. The cost was reduced from \$4.83/kg in the initial draft of the report to \$4.46/kg in the final report. This value is consistent with the cost utilized for sheet aluminum in the NHTSA paper and at this level the peer reviewer felt, that while it was on the high end of the cost scale, it was within explainable / acceptable limits. Additionally, to further attempt to clarify this the cost estimates for reduced mass sheet products is made up of many factors including manufacturing CO2 emissions, material price (based on the blank size, not the actual part), labor cost, energy cost, equipment cost, tooling, building, maintenance and overhead. However, while all of

	[OSU] **Glenn Daehn** The data and sources appear to be very good; however at the time of this review there are a few items that are unclear. First there some statements that are referenced with superscripts, however there is not a reference list that appears in the document. Second, this report does an excellent job of documenting at a high-level that the finite element analysis is carried out properly, showing agreement with masses, stiffness and crash signatures of baseline vehicles. However, it is important that all of the details be also available to the public, such as the detailed material geometry (mesh files), stress-strain flow-laws used for the materials, weld locations (more than a figure), models used for weld behavior and so on. This can be done by reference or by making the LS-DYNA models public. It is not clear at time of review how this will be done, but it would be a great service to make all this granular detail available. Similar statements can be made regarding the detail for components and materials in the costing models. **Tony Luscher** The data used appears to be valid and appropriate to the tasks that are completed. Vehicle data for the Toyota Venza was obtained by scanning the components and creating the CAD models. Material data was found	these factors were utilized when determining the cost of the optimized vs. the baseline, the major factor driving the increase was the aluminum vs. steel material cost related to the blank size The material and weld data is available in the publicly accessible FEA models (baseline and optimized model). The stress-strain curves are included in the report Appendix for reference. As explained in report section D.10.1. The welds in the model are represented as follows: - Spot welds are represented as solid hexa elements based on LS-DYNA mesh independent weld elements. - Adhesives are represented as continuous solid hexa elements using surface to surface contact. - Laser welds are represented as continuous hexa solid elements.

	from appropriate sources and databases. These were used to create a crash test model for the vehicle and for cost estimation. A thorough search of state-of-the-art vehicle design concepts was used as the basis of mass reduction for the various vehicle systems. **[Simunovic]** This section contains comments on validity of the data sources, material properties, and modeling approaches used in this study. The overall methodology used by the FEV is fundamentally solid and adhere to standard practices of the crashworthiness engineering [5]. However, an in-depth analysis of the model files reveals several areas that may need to be addressed to fully support the findings of the study. Firstly, as a matter of the established procedures for technical documentation, I suggest that the sources for the material properties should be clearly referenced; especially since the authors of the FEV study worked on similar projects for steel industry consortia [6]. Similar projects on concept vehicles [7, 8] also offer guidelines on the reporting. It would also be very helpful to readers to graphically depict mechanical properties such as material stress-strain curves, failure envelopes, etc. Secondly, the technologically important issues with the high strength metallic materials, such as Advanced High Strength Steels (AHSS) [9], are their special processing requirements [10], reduction in ductility, higher possibility of fracture [11-14] (especially under high strain rates [15-17]), and joining [18-22]. Many AHSSs derive their superior mechanical properties from their tailored microstructures, which get strongly affected during welding. Active research in welding of the AHSS shows possibilities of significant reductions of the joint strengths due to the softening processes in Heat Affected Zone (HAZ). Therefore, the strength values for the welds in the current LD model (i.e. SIGY=1550 for MAT_SPOTWELD section in the input files) seems very optimistic, and may need to be reduced or elaborated upon in the report. Several versions of the reports were distributed and I may have very well missed an updated version. In case that joining discussion is indeed restricted to one page as it appears in the current FEV document, I would suggest	In the final report references, material properties and stress vs. strain curves for the materials used are included. As explained in report section D.10.1. Additionally, The suggestion has been reviewed and considering the parent sheet material fracture/failure behavior, the failure option "major in plane strain at failure" (EPSMAJ) of LS-DYNA MAT 123 MODIFIED_PIECEWISE_LINEAR_PLASTICITY_RATE has now been used in the model for materials above 350MPa Yield Stress which are considered High Strength Steels and have less total elongation. LS-DYNA computes the plastic strain in all elements at each time step. When the plastic strain exceeds the failure criterion in an element, that element is eroded, i.e., removed from the finite element model.

	that weld properties and constitutive models be given additional attention in the final report. Third important issue that I would suggest to be addressed is modeling of failure/fracture of the high strength materials in the LD models. Despite long research on the subject, the methods for modeling localization and failure are relatively scarce. There is still no wide consensus on how to model failure in materials. For the FEV study, special attention should be given to the joint areas (spot welds, laser welds) that can experience the degradation of properties due to the thermo-mechanical cycles that they have been exposed to. A simple way of addressing the above points would be to use failure limit strains in plasticity models that are used in the FEV models, i.e., MAT_PIECEWISELINEAR_PLASTICITY. In this approach a limit strain is assigned to material, and after that limit strain is reached in a finite element, the element is gradually removed from the simulation. The values for the failure strains are dependent on mesh and element discretization, where additional simulations should be conducted to correlate energy to failure to the corresponding physical failure process zone for the given problem.	

<table>
<tr>
<td>If you find issues with data sources and assumptions, please provide suggestions for available data that would improve the study.</td>
<td>[Joost] Two plastic technologies are very widely employed in this design: PolyOne and MuCell. It seems that the companies who license/manufacture these technologies were used as the primary source to determine feasibility. However they are likely to be optimistic regarding the capability of their materials. I agree that these materials are appropriate for the indicated applications; however I feel that the credibility would be improved by including other sources (OEMs, Tier 1) or more production examples for existing platforms. With such a large amount of weight reduction attributed to PolyOne and MuCell, it would be beneficial to have a very strong case for capabilities.

[Richman]

[OSU]
<u>Glenn Daehn</u>
See above.

<u>Tony Luscher</u>
None found.</td>
<td>MuCell - As stated on pgs. 371 and 372, the process is currently used by major OEMs such as Audi, Ford, BMW, and VW. On pages 373 through 376 are actual parts and the reduction that they yielded from VW, Ford, and Mercedes Benz.

PolyOne - section on pg. 377 talks about the possibility of up a 30% weight reduction and the conservative approach we took of 10%. PolyOne Corporation provided generic feedback and advice regarding the amount of weight reduction feasible for plastic parts. These CFA application guidelines included considerations for a respective part’s material, geometry, and application. In general, a 10% weight reduction was applied to parts for which a CFA was used. Higher mass reduction may be possible for many components, but would require a detailed analysis on the component and its use in order to safely apply such savings. Instead, a conservative estimate was applied based on PolyOne’s expertise where parts’ properties would not be adversely affected. For parts with a non-Class “A” surface finish, a weight reduction in the 20-30% range is possible.</td>
</tr>
<tr>
<td colspan="2">ADDITIONAL COMMENTS:

[OSU]
<u>Kristina Kennedy</u>
“Building a full vehicle model w/o the use of drawings or CAD data…” Has this method of tear-down + scanning been proven out in industry or in other projects to understand how closely this method would correlate with actual data? Is this basically “reverse engineering” and is that an acceptable method?

<u>Tony Luscher</u></td>
<td>This would be considered the best way to establish a model if the CAD information were not available. This technique of white light scanning is used by many of the automotive OEMs to compare actual component information to CAD information and if needed to actual create CAD data. This technique is highly valued for any reverse engineering project in the industry and with the advanced CAE modeling capabilities and tools available in the market can produce highly correlated models.</td>
</tr>
</table>

Data sources are well documented in the report and will aid if any additional investigation is needed. Several of them were checked for validity. **[Simunovic]** In this document I review the methods, data, and the FEM crash models developed in the FEV study. The models were evaluated based on the analysis of the computational simulation results and on based on the analysis of the actual model files. I want to emphasize that the scope of my review is on the computational simulations of the vehicle crashworthiness and on the modeling approaches employed by the FEV and its contractors. The primary source for my review were the FEV final draft report, the crash animations generated by the FEV, and the computer simulation output files for the NCAP and the ODB crash test configurations. Two vehicle crash models were available, the baseline and the LD model. As it will be shown in the following sections, my review was based to a large extent on the vehicle model files. Very often in the current practice, the actual model files are not sufficiently scrutinized and are evaluated only through the resulting computational simulations. In the case of large complex FEM models, such as car crash models, the model's configuration complexity and its sheer size can obscure the important details of the response and camouflage the sources of errors in the model. That is particularly common when the technology envelope of the state-of-the-art is expanded, as is the case with ever-increasing sizes and complexities of the car crash models.	

2. VEHICLE DESIGN METHODOLOGICAL RIGOR CAE BIW and Vehicle)	COMMENTS	RESPONSE
Please describe the extent to which state-of-the-art design methods have been employed and the extent to which the associated analysis exhibits strong technical rigor. You are encouraged to provide comments on the information contained within the unencrypted model provided by EDAG; the technologies chosen by FEV; and the resulting final vehicle design.	**[Joost]** The report uses a (very thorough) piece-wise approach to weight reduction – each system is broken down and weight reduction opportunities for the individual components are identified. The weight-reduced components are then reassembled into the final vehicle. I believe that this provides a conservative estimate for the weight reduction potential of the Venza, where a vehicle-level redesign would provide greater weight reduction. However, I am also of the opinion that the approach used here is in line with industry practice so; while this may not yield the maximum reasonable weight reduction, it is likely to yield a value more in-line with industry-achievable weight reduction. It is particularly helpful (and credible) to see descriptions technologies that were considered, but abandoned due to performance concerns (e.g., reverting to a timing belt), manufacturing capabilities, (e.g., using a MuCell manifold), and cost (e.g., Mg oil pan). The suspension design process lacks sufficient detail to make the cost and weight estimates credible. Considerable Al is used to replace steel at a very minimal cost penalty. However, as the report indicates, detailed design and validation is necessary to confirm that these changes would be viable for the Venza. For example, changing to a hollow Al control bar is not an industry standard practice and the use of a hollow section may require significant changes to geometry in order to meet the stiffness and strength requirements. While a hollow Al control bar is feasible, I'm not confident that it can be substituted into the design so easily. A $0.40/kg-saved cost penalty for changing a significant number of components from mild steel to Al seems to be an underestimate. **[Richman]** 1) EDAG performed structural modeling. The EDAG organization is widely recognized as technically competent and highly experienced in modeling of auto body structure. Modeling approach appears	 After further discussions and investigation it was decided to move forward with a variation to the first solution proposed. Since no high volume production examples could be readily found for the hollow Al design it was decided to keep the hollow configuration but utilize the material choice of steel instead. This still allows for an adequate weight savings while using a common design choice found in most European and many domestic vehicle applications currently being produced. This reduced the previous mass savings by 2.61kgs and decreased the associated cost by $10.83.

	technically robust and logical. 2) Body structural analysis utilized industry recognized CAE, CAD and collision modeling analysis tools and protocols. Tools used are state-of-the-art and the approach. 3) FE model was validated against physical test data for NVH and collision performance. Model correlation with physical test results is very good. No significant discrepancies or inconsistencies have been identified in the modeling results. 4) Based on these observations, the models would be considered valid and reliable for moderate A:B design comparisons that are the subject of this vehicle study. **[OSU]** **<u>Glenn Daehn</u>** The work is well done and technically rigorous. Again, we encourage making all pertinent detail publicly available. **<u>Tony Luscher</u>** The report does an excellent job of using state-of-the-art design methods. The re-engineering process included vehicle teardown, parts scanning, and data collection of vehicle parts to build a full vehicle CAE model. This raw STL geometry was then translated into an FE meshing tool (ANSA) to create a finite element model. **[Simunovic]** The development of the LD Toyota Venza concept started with the development of the baseline FEM model of the vehicle. The FEM model was developed by a reverse engineering process of disassembly, geometry scanning, component analysis, material characterization and the incremental FEM model development. The turn-around time for this process by the FEV is quite impressive. Equally impressive are the apparent quality of the FEM mesh, the definition of joints and assembly of the overall model. The discretization of the BIW sheet materials uses proportionately sized quadrilateral shell elements, with few triangular elements. The mesh density is mostly uniform and without large variations in the FEM element sizes and the aspect ratios. The BIW model has about 6% of triangular shell elements in the sheet metal, which is a very small amount given the complexities of	

	the vehicle geometry. Figures 1-3 show the geometry and the parts variety for the baseline vehicle model. There are no apparent geometry conflicts in the model and parts are well aligned with compatible geometries and FEM meshes. This is essential for accurate modeling of currently the prevailing joining method for sheet metals, spot welding. The level of geometrical detail in the model is very high and as someone who has been involved with the vehicle crashworthiness modeling for the last twenty years, I think that the developed FEM mesh of the Venza BIW is the current state-of-the-art. Figure 4 shows some details of the BIW FEM mesh that illustrate the prevalence of the quadrilateral shell finite elements, constant aspect ratios and presence of the geometry details that are necessary for an adequate modeling of the progressive structural crush.	
Please comment on the methods used to analyze the technologies and materials selected, forming techniques, bonding processes, and parts integration.	**[Joost]** The forming, joining, and integration techniques used in the report were analyzed only by referencing production examples or companies who produce similar products. Detailed design work would certainly include a more thorough analysis of the manufacturing techniques however for the scope of this report I believe that the level of analysis is appropriate. **[Richman]** 1) Body: Process used to select materials, grades and gauges for the mass optimized body sub-group is technically sound and thorough. Election of laser welding of structurally significant body panels indicates deployment of advanced manufacturing process where appropriate. 2) Non-body: Methodology used to identify, screen and select non-body mass reduction technologies is thorough, detailed and highly effective. Munro Associates lead this segment of the project. Munro is recognized as being technically competent, highly experienced, knowledgeable, and creative in benchmarking and lean engineering of automotive and non-automotive systems. **[OSU]**	To clarify in the report the following will be added : The welds in the model are represented as follows: - Spot welds are represented as solid hexa elements based on LS-Dyna mesh independent weld elements. - Adhesives are represented as continuous solid hexa elements using surface to surface contact. - Laser welds are represented as continuous hexa solid elements.

	<u>Glenn Daehn</u> All is in accord with the state of the art. It is not clear how welds are represented in the FE-Model, without dissection of the LS-DYNA input stacks. **<u>Tony Luscher</u>** The Toyota body repair manual was used to identify the material grades of the major parts of the body structure. These material grades were then validated by material coupon testing. The MSC Nastran solver was used to solve for the bending and torsion stiffness of the body in white model. Good correlation was achieved between physical stiffness testing and FEA stiffness results. **[Simunovic]** The development of the LD Toyota Venza concept started with the development of the baseline FEM model of the vehicle. The FEM model was developed by a reverse engineering process of disassembly, geometry scanning, component analysis, material characterization and the incremental FEM model development. The turn-around time for this process by the FEV is quite impressive. Equally impressive are the apparent quality of the FEM mesh, the definition of joints and assembly of the overall model. The discretization of the BIW sheet materials uses proportionately sized quadrilateral shell elements, with few triangular elements. The mesh density is mostly uniform and without large variations in the FEM element sizes and the aspect ratios. The BIW model has about 6% of triangular shell elements in the sheet metal which a very small amount is given the complexities of the vehicle geometry. Figures 1-3 show the geometry and the parts variety for the baseline vehicle model.	As explained in report section D.10.1. Welding Property: The spot welds on the structure are used with mesh independent hexa solid weld element of LS-DYNA. The mechanical properties use 500MPa Yield Stress which represents the average level strength of the baseline material and candidate material of the optimized structure.

	In the following, I first give the analysis of the baseline FEM model. The baseline FEM model is very adept and can be used for illustration of some shortcomings of the LD model that I think need to be addressed. It is important to note that the LD model is much more complex due to a large number of materials and gages that resulted from the computational optimization process. This complexity and the project time constraints dramatically increase the potential for error. Unfortunately the tools for managing such complex systems are not yet mature, making the development and the evaluation of this complex vehicle model very challenging. Over the years, I have developed several simple programs that can be used to debug FEM models by directly analyzing the model files. The common approach to evaluation of large FEM models is to almost exclusively consider computational simulation results. However, these simple tools allow for evaluations of relationships within the FEM models directly from the model input files, thereby enabling debugging of the models independently from the simulations. **Review of the FEM Model for the Baseline Toyota Venza** The primary material for the BIW of the baseline vehicle, 2009 Toyota Venza, was identified in the Lotus Phase 1 Report as mild steel. Lotus Phase 1 study stated that the BIW also had about 8% of Dual Phase steel with 590 MPa designation, while everything else was commonly used mild steel sheet material. The FEV/EDAG study showed that there was more variety to the baseline design than originally anticipated. Table 1 lists the materials used in the BIW model (file Venza_biw_r006.k) that were modeled using MAT_PIECEWISE_LINEAR_PLASTICITY). Aluminum bumper was modeled using MAT_SIMPLIFIED_JOHNSON_COOK material model in LS-DYNA. The number of material models is relatively small. Most of the CAE tools display the FEM model based on their part identification number (ID). To verify the material model assignment one must then verify material assignment for every part and then sort them accordingly. For large complex models this is a very tedious process that is very error prone. More advanced CAE tools, such as HyperMesh, have	The referenced shortcomings, the material ID 9 which showed an intersecting strain rate curve, the unsymmetrical model assignment, the number of through thickness integration points for the shell elements, and thickness distribution which showed some asymmetries have all been corrected in the final paper.

	options for grouping and displaying model entities by material types and IDs. Figure 5 displays the material assignments for the baseline BIW. The specific assignment of the materials for the BIW and the corresponding stress-strain curves are shown in the figures below. Most of the material models account for strain rate sensitivity of the material. For a given plastic strain, the yield stress is calculated by interpolating stresses between two neighboring stress strain curves based on the applied strain rate. There are established modeling recommendations for modeling strain rate sensitivity effect in crash models. The specified stress strain curves should not intersect. Extrapolated lines from their last specified linear segment should not intersect, as well. The material models should use plastic strain rate [23] instead of the total strain rate as the basis of the strain rate effect calculation. This option (VP=1) was not used in the FEV models although it is highly recommended in practice. Figures 6-10 show the main material systems for the baseline BIW model. The material assignments correspond to the assignments in the project's report. The stress-strain curves for different strain rates in the above figures do not intersect. Their extrapolations however have potential for intersection at high plastic strains in Figures 7and 8. The number of the data points in Figures 9 and 10 are too large and needs to be reduced in order to avoid the interpolation errors by the simulation program. It is obvious that curves in Figures 9 and 10 were developed by analytical fits. Such approach can create undesirable artifacts such as an appearance of the yield point elongation for Dual Phase steel in Figure 10. An interpolation approach with fewer points and curves is recommended. Figure 11 illustrates the optimal piecewise linear interpolation (green curve) of the base (red) curve in Figure 10. The interpolated curve has error of 1% of the value range with respect to the actual curve and uses only 9 points. Next, the BIW sheet material thickness distribution is shown in Figure 12. The colors indicate symmetrical distributions in accordance with the specified thickness distribution in the project report.	In the final paper the material models did use plastic strain rate as the basis of the strain rate effect calculation. The option (VP=1) was used in the final FEV models. The stress vs. strain curves used in this report came from "WorldAutoSteel" and, as such, no attempt was made to manipulate the curves in any manner. The curves were used as received and the algorithm within LS DYNA used the data in the analysis.

	In many situations, the accuracy of the crash simulation is dependent on the shell element formulation (type) used. The basic shell element formulation (reduced integration Belytschko-Tsay, LS-DYNA type 2) is computationally very efficient but has lower accuracy than more complex formulations such as the fully-integrated Bathe-Dvorkin shell element (LS-DYNA type 16). Figure 12 shows the shell element formulations in the BIW model. The current crash modeling recommendation is to use shell element type 16 when possible. The Bathe-Dvorkin shell is 3.5 times more computationally expensive than the Belytschko-Tsay shell so that in order to strike a proper balance between the accuracy and the computational speed element types can be mixed in the model. This is especially true when large number of simulations is conducted, as was the case for computational optimization in the FEV study. As it can be seen in Figure 16, the baseline model employs accurate element formulation in the main structural components, while the Belytschko-Tsay formulation is employed in the remainder of the sheet metal which is an appropriate compromise for the large scale computations. Another important technical aspect of the crash simulations with the shell elements is the employed number of integration points through the thickness of the shells. The default (2 points) is insufficient for the crash analyses. Three points is also inadequate in the current simulation guidelines because it results in a very quick formation of plastic hinges in the sheet metal during crush. A minimum of 5 through-thickness integration points is currently recommended for the crash simulations. Therefore, modification of the model in this regard is suggested for the general release. Another commonly overlooked formulation aspect for the shell elements is the through thickness shear factor. Recommended value is 0.833, which was used only in bumper structures of the current model (Figure 14). Changing the factor to 0.833 is recommended. In summary, the baseline Venza FEM model is developed following most of the recommended development procedures for crash models. The modifications suggested above would meet few additional recommendations that would likely increase the robustness of the model. The NCAP and the	In the final report the fully-integrated Bathe-Dvorkin shell element (LS-DYNA Type-16) was used for the element formulation in the BIW model for the major load path parts. As explained in report section D.10.1. • Integration Points The integration point through the thickness of the sheet metal in this BIW model is used with 5-point integration option for major load path parts. • Transverse Shear Scale Factor The shear correction factor which is commonly used for shell element for isotropic material type has a value assigned of 0.833. As explained in report section D.10.3.2. In analyzing the comparison between the FE model and actual

	side MDB barrier simulation results can be compared with the actual crash tests conducted by NHTSA. The comparison of the simulation and the NCAP test shows somewhat stiffer response of the FEM model with respect to the test (Figure 1.18.18 in the last FEV report). The maximum and the average accelerations in the FEM model were accordingly higher than the test results. The baseline FEM model was deemed acceptable for the purposes of the FEV study. Another important measure of the FEM model fidelity was the crash duration time that was 20 ms shorter for the model compared to the test. This difference is noticeable because the overall crash duration of 100 milliseconds. However, for the objectives of the FEM study, the model's crash pulse was deemed acceptable, which for the described project schedule seemed quite reasonable.	test results the side structure deformation contour is in part dependent on structural interactions between space holders such as seat belt retractors, seat structure, door trim panels, seat cushions, etc. In the FEA model there are major differences from the actual vehicle test conditions such as seat structure model, retractor assembly at B-Pillar lower along with there are no space holders like trim panels, seat cushions, etc. Therefore the load carrying path between side structure, seat and tunnel block in the FEA model is not the same as in the actual test. With these differences the intrusion levels seen are generally found to be larger than the actual test results. The NHTSA test utilized for the comparison was NHTSA Test No. MB5128 for 2009 Toyota Venza 38.5MPH MDB side impact, which provided the intrusion numbers used in the comparison with the baseline model. The intrusions in the area of the "B" pillar mid-levels (Level 2 ~ Level 4) come out larger than the actual test. However, the upper and lower pivot spots (Level 1 & Level 5) show fairly good comparison. For example, in Level 1, side rocker level, shows 133.7 mm which is similar to the test level of 134 mm and level 5, roof rail, shows 6.0 mm which is also similar to the test result of 12.0 mm of intrusion. However, it is felt these differences are more than adequately explained by the lack of actual components in the FE model. The scope of the program did not include attempting to

correlate the intrusion values and the numbers seen demonstrates a reasonable tendency and therefore considered as acceptable.

Since the baseline model was found to trend as expected when compared with actual test results this level of intrusion was established as the base and used to compare further iteration of the models.

Review of the Low Development Vehicle Model

The FEV engineers have used the computational optimization methods based on the response surface formulation in order to determine the distribution of material types and grades that would maximally reduce the weight of the vehicle while maintaining the performance and controlling the cost. The part distribution of the resulting optimized LD design FEM model is shown in Figure 15.

It is probably misleading to refer to the resulting FEM model as “Low Development” since it is a product of numerous computational simulations and an in-depth engineering study. The resulting inventory of the material models used in the LD FEM model is listed in Table 2. It is evident that there are numerous duplicates as well as unused materials. It would be prudent to purge the list of material models from the LD FEM model as they may lead to errors. Some of the inconsistencies that were found in the current LD FEM model may very well be a result of this model redundancy.

Two model files contain most of the material models:

- Venza_master_mat_list_r006.k
- Venza_Material_Db_Opt_dk2.k

The horizontal black line in Table 2 separates the material model specifications between the two files. These two were unchanged for the last two versions of the FEM models that were downloaded from the project download site.

The material ID’s shown in the two model files is a result of including all the potential material selections used in the project. The initial file included the Material ID, Load Curve ID and Material Names for all of the potential materials that were considered while the second file included a shortened list of these materials that was actually considered in the optimization process. The reassignment of Material ID’s, and Load Curve Numbers for the optimized model was done to assist in the optimization process.

	Figures 16-32 below show the stress-strain curves for the materials used in the BIW of the LD FEM model. There are obvious duplicates in the model specifications that would be prudent to eliminate and modify the model accordingly before its public release. In addition, there are some errors in the LD FEM model specifications that need to be corrected. **Correction Item 1:** Material ID 9 (Figure 30) has stress-strain curves for different strain rates different strain rate curves intersect which is not acceptable from the physical perspective. Materials with IDs 8000006, 8000007, and 8000008 have elastic properties of lightweight materials such as Aluminum and Magnesium alloys, but they utilize yield stress functions of HSLA 350/450 steel defined in file: Venza_frt_susp_exhaust_30ms.k. Currently, only the material 8000006 is used in the LD FEM model, although in the previous model version material ID 8000008 was also used. **Correction Item 2:** Some material assignments in the LD FEM model are inconsistent, which is probably a result of too many material models. The mapping of material IDs on the BIW FEM model reveal several unsymmetrical model assignments. The most obvious discrepancy is marked in Figure 33. Here, where one model part is modeled using the mild steel while its corresponding symmetrical counterpart is modeled using the HSLA 350/450 steel. Additional unsymmetrical material assignments are pointed with arrows in	<u>To Correction Item 1:</u> The strain rate curve shown intersecting has been corrected in the final FE model. <u>To Correction Item 2:</u> The inconsistencies and the unsymmetrical model assignments have been corrected and implemented in the final FE model.

<table>
<tr><td></td><td>Figures 34-37.

Two possible outcomes of not pairing the symmetrical components with the same material ID are illustrated in Figures 36-37. In Figure 36 the two different parts have different material assignments, which eventually refer to different material properties. In case of the marked parts in Figure 37, the material IDs are different but because of the repeated material models with different IDs, they eventually refer to the same material properties.

The above inconsistencies need to be corrected before the models are released into to the open domain.</td><td></td></tr>
<tr><td></td><td>Correction Item 3:

Another area of concern is the number of through thickness integration points for the shell elements in the current LD FEM model. As it can be seen in Figure 38, almost all shell elements have just 2 integration points through the thickness. This is clearly inadequate from the accuracy standpoint and may be responsible for some of the issuable simulation results shown in the following figures.</td><td><u>To Correction Item 3:</u>
The number of integration points through the thickness of the sheet metal is a very important technical aspect of the crash simulations and the shell elements. The default number (2 points) of integration points is considered insufficient for most crash analyses. Therefore in the final models 5 through-thickness integration points, which is the current accepted practice, was selected and used for all of the major load path parts.</td></tr>
<tr><td></td><td>Correction Item 4:

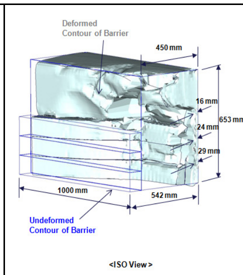
Figure 38 shows the thickness distribution in the LD FEM model of the BIW. In general, the thickness distribution is symmetrical with respect to the centerline of the vehicle. However, a closer inspection reveals some asymmetries in thickness assignments.

The arrows in Figures 40-41 show the parts that do not have symmetrical assignment of the values with respect to the centerline of the vehicle. I have not checked the extent of the differences, but it something nonetheless that needs to be corrected.</td><td><u>RE: Correction Item 4:</u>
As explained in report section F.4A.10:
The material thickness distribution and material selection in the final models have been corrected and the parts now have symmetrical assignment of the values with respect to the centerline of the vehicle.</td></tr>
</table>

	Concern Item 1: The following Figures 42-45 show some results that may warrant more investigation by the project engineers. Figures 42-43 show the deformation of the main front rails for the baseline vehicle during the NCAP test simulation. The overall deformation is symmetrical. In the case of the LD FEM model, as shown in Figures 44-45, the deformation is markedly different from the baseline and unsymmetrical. The cause for that may be in the unsymmetrical material assignments for the main rails that were present in the previous LD FEM model release and the simulations may have been based on that version. As I was only using the simulation files, I could not tell if that was actually the case. However, I strongly suggest following up on this point as these rails are extremely important for the crash energy management.	<u>Answer for Concern Item 1:</u> The non-symmetrical deformation mode behavior is due to the packaging differences on left and right shock tower areas. It is worth noting that the engine compartment packaging is not symmetrical in the base vehicle. The methodology used to determine acceptability of the revised structure was the comparison of the intrusion values and the resulting pulse. The deformation of the structure was not one of the factors reviewed or used in determining acceptability of the revised structure. It was beyond the scope of this project to perform a complete analysis of the structure and the various structural members. The areas that were reviewed were dash intrusion and pulse and the results of both of these areas were considered acceptable in both the baseline and the optimized model so no further investigation into the rail deformation shapes was undertaken. However, it is agreed that if this project was done at an OEM leading to putting these changes into production a complete analysis of the rails would have to be performed.
	Concern Item 2: One of the modeling aspects that is usually not considered in conventional mild steel vehicle designs is modeling of material fracture/failure [24]. However, in the case of the high strength materials, such as the AHSS, the material fracture is a real possibility that needs to be included in the models.	<u>Answer for Concern Item 2:</u> The suggestion has been reviewed and considering the parent sheet material fracture/failure behavior, the failure option "major in plane strain at failure" (EPSMAJ) of LS-DYNA MAT 123

	One of the easiest failure models to implement is to specify equivalent strain threshold for the material failure. Once this threshold is reached during crash simulation it leads to gradual element deletion, which simulates crack formation. I would suggest consideration of such a simple model enhancement that, while not comprehensive enough for production design, is probably sufficient for the purposes of the FEV study. The strain rate sensitivity of the material models would help with the regularization of the strain localization and related numerical problems [25].	MODIFIED_PIECEWISE_LINEAR_PLASTICITY_RATE has now been used in the model for materials above 350MPa Yield Stress which are considered High Strength Steels and have less total elongation. LS-DYNA computes the plastic strain in all elements at each time step. When the plastic strain exceeds the failure criterion in an element, that element is eroded, i.e., removed from the finite element model.
If you are aware of better methods employed and documented elsewhere to help select and analyze advanced vehicle materials and design engineering rigor for 2017-2020 vehicles, please suggest how they might be used to improve this study.	**[Joost]** This is not my area of expertise. **[Richman]** **[OSU]** **<u>Glenn Daehn</u>** Everything appears to be well-done and in accord with the state of the art. **<u>Tony Luscher</u>** None known. **[Simunovic]**	
ADDITIONAL COMMENTS: **[OSU]** **<u>Kristina Kennedy</u>** FE Meshing Tool, ANSA. Did a quick Google search and did not find this product. Am familiar with ANSYS and others, but is ANSA an industry-standard tool? Just confirming the wide-use of such a tool out of curiosity. **[Richman]** This analysis does not address what are commonly referred to as "service loads," including jacking, twist ditch, pothole impacts, 2G bumps, towing loads, running loads, etc. Running loads are typically suspension		ANSA is used by EDAG along with many of the OEMs and is recognized software throughout the Industry for FE modeling. The analysis of "service loads," while considered extremely important, was not part of the original

loads for a variety of conditions to address strength, stiffness and fatigue durability of the body and suspension attachment structures and points. Without these other considerations, the optimization process could may unrealistically reduce mass in components that have little effect on overall body stiffness or strength, yet are important for durability.	scope of this project. The initial scope of this project was to verify the body weight reduction levels shown in the original Lotus Engineering Report (and subsequent Lotus revisions to the report). This investigation was performed through the development of NVH and crash model load cases. Upon completion of that investigation, the project then included investigation into additional weight saving opportunities utilizing the same methodology used to verify the findings in the Lotus Engineering Report. These load cases were the basis for validating all the additional weight reduction opportunities identified throughout the material optimization studies.
Modeling of deformable barriers has historically been an issue. Source, nature or origination of the deformable barriers (moving and fixed) used in this project are not explained. In the offset deformable barrier crash test load cases, overall deformations, including barrier deformations are reported. The reporting does, however, raise a modeling concern. Barrier deformations of over 515 mm are reported for the offset tests. The IIHS deformable barrier has 540 mm thickness of deformable material. It is not expected to compress completely. Excessive barrier deformation has the potential to change the overall acceleration and deformation scenarios reported and influence the mass optimization process.	The barriers utilized in the CAE studies are commercially available. These are: Front Offset Barrier: LSTC.ODB.Solid 2009 version Side FMVSS 214 Barrier Impact: LSTC 2007 version Rear Impact FMVSS 301: LSTC 2007 version The deformation of the barrier was not unexpected with the maximum deformation localized in areas as can be seen in the picture below. Our review of the crash event does not indicate any concerns in the barrier performance.

	
In evaluating the performance of the optimized body structure, the analysts in general considered "less deformation" of the body structure to equate to "better performance." Less deformation may be an index of structural stiffness but is not necessarily an indication of better collision performance. Less deformation generally equates to higher decelerations and resulting forces on the occupant. It is likewise generally desirable to efficiently use as much of the allowable free crush space as possible, not less.	The statements declaring less deformation are not necessarily indicators of better collision performance or that it is generally desirable to use as much of the allowable free crush space as possible, as both are true. However, structural strength and reduction in cabin intrusion are also key indicators of vehicle performance and occupant safety. Without having all of the interior data and the passive and active restraint system information for the crash models, it was determined for this study that the crash pulse, intrusion numbers, and deformation modes / appearance would be used to establish baseline values and that all future iterations would be compared to these parameters in an attempt to judge whether the performance of the various iterations were similar in nature to the established baseline. Therefore, these values were felt to be in the acceptable range.
Part of the rear impact analysis includes an analysis of rear door opening deformation and an estimate of door openability post-crash. While this is an interesting and useful analysis, it is not explained why it is done. It is not a required aspect of the regulations. Since it is in the report, a similar analysis should probably be done for the front door openings in the front crash test load cases. Most if not all	For the rear crash event the acceptance criteria was established as similar fuel tank performance. The fuel tank integrity was analyzed by its plastic strain plot with no significant risk of fuel system damage being seen as the maximum strain amount was less than 20% of the plastic strain for the entire fuel

manufacturers have an in-house requirement that front doors must be openable following a standard front crash test.	tank system. To further help understand the damageability resulting in the rear crash event, the rear portion of the vehicle was divided into four zones and the deformation of these zones were reviewed. While the ability to open the rear the is not a regulatory requirement the rear door aperture opening does provide an indication into the structural performance of the rear of the vehicle and it was felt that if the this opening was also maintained this would provide further evidence that the fuel tank integrity was in fact being maintained. As explained in report section D.10.4.4. There was no NHSTA rear crash to compare to so EDAG established the baseline from the rear crash of the baseline model. The acceptance criteria established for the rear crash was no damage to the fuel tank. Additionally, to support the conclusion that the tank maintained its integrity throughout the rear crash event, the rear was divided into 4 zones and the amount of deformation of each zone was reviewed to support the fuel tank integrity requirement.

3. VEHICLE CRASHWORTHINESS TESTING METHODOLOGICAL RIGOR (CAE only)	COMMENTS	RESPONSE
Please comment on the methods used to analyze the vehicle body structure's structural integrity (NVH, etc.) and safety crashworthiness.	**[Joost]** The baseline testing and comparison process (pgs. 67-128) is very thorough. The team establishes credibility in the proposed design by performing an initial baseline comparison against the production Venza – this suggests that the modeling techniques used can reasonably predict the performance of the lightweight design. It is unfortunate that the deformation mode comparisons could not be made quantitative (or semi-quantitative) somehow. Comparing how the model and test look after a crash gives an indication of deformation mode, but the comparison seems subjective. For example, image D-28 (pg. 95) seems to show slightly different failure mechanisms in the CAE model versus the real test. The report notes that the bushing mountings were rigid in the model while they likely failed in the real vehicle. I would expect that these failures are designed into the vehicle to support crash energy management. The results crash pulses (pg. 98) for the model and test look fairly similar, but it is unfortunate that this crash energy mechanism was not captured. The intrusion correlation for the baseline model is very good. This again adds credibility to the modeling approach used here.	The scope of this project did not include modeling all of the necessary components required to build a fully functional and correlated crash model. Rather, the original intent was to validate the Lotus Engineering study and provide additional weight reduction opportunities. The strategy employed to accomplish this was to develop a correlated NVH model, static and dynamic modes, and from that model build a crash model. The results of the crash model would then be compared to the actual crash test to ensure the results looked similar. However, there was no attempt to analyze the differences and to correlate the results. For this project, the results of the baseline CAE crash model would be used to compare all future model results. The bushings are modeled as rigid solid elements; however, the mount attachments (generalized spot weld) are modeled with the appropriate failure time constraints (TFAIL option of LS-DYNA). This same technique was used to compare the results of all of the model iterations.

	On page 386 the report states that the Mg CCB was not included in the crash or NVH analysis. Replacing a steel CCB with Mg is likely to have a significant impact on both crash and NVH performance. The technology is viable (and has been used on production vehicles as stated) however the crash energy management and NVH performance must be offset by adding weight elsewhere in the vehicle. The CCB plays a role in crash and a major role in NVH so I do not think that it is appropriate to suggest that the material replacement will have the reported results in this case. My suggestion is to leave the CCB as steel in the weight analysis (or go back and redo the crash and NVH modeling, which I suspect is not viable).	Some general assumptions were initially applied to convert the CCB from steel to magnesium. In particular, the gauge of the material was doubled to account for the reduced strength magnesium exhibits compared to steel. Magnesium's yield strength is in the 200-275 MPa range depending on the alloy used. A common steel used for a CCB is HSLA 420, which exhibits a yield strength of around 420-550 MPa. For the rough assumptions in this analysis, the increase in thickness of the magnesium CCB would increase its moment of inertia, thereby making up for the relatively low strength of magnesium compared to steel. In order to validate this, mathematical modeling would need to be conducted based on the testing requirements for the CCB. Such an engineering analysis was beyond the scope of this study. In light of this, the benchmarking results were cross-referenced. The Dodge Caliber's magnesium beam is 5.6 kg and the BMW X5's is 5.8 kg. In reality, the magnesium CCB will take a much different shape than the baseline steel one as illustrated in the pictures in the previous sections. It was determined that using the mass of existing magnesium CCBs would be a secure approach as opposed to the mass that resulted using the thickness increase assumptions. Therefore, an average of these two numbers was used for the Venza's redesigned CCB resulting in a final mass of 5.7 kg, saving approximately 4 kg versus the baseline steel beam. The magnesium CCB was not considered in the NVH or crash analyses performed. The NVH analysis provided in the report does not include the Cross Car Beam (CCB). The dynamic and static modes did not include "bolted" on parts

	[Richman] 1) LS-Dyna and MSC-Nastran are current and accepted tools for this kind of analysis. FEM analysis is part science and part art. EDAG has the experienced engineers and analysts required to generate valid simulation models and results. 2) EDAG was thorough in their analysis, load-case selections and data for evaluation 3) The handling of acceleration data from the crash test simulations is a bit unusual, and further analysis of the data is recommended. **[OSU]** **<u>Tony Luscher</u>** Trifilar suspension apparatus was used to find the CG and moments of inertia of the engine and other major components. The dynamic FEA modal setup was run using NASTRAN. Vibration modes were analyzed by the CAE model and then compared with physical test data in order to correlate the FEA model to the physical model. Five different load case configurations with appropriate barriers were placed against the full vehicle baseline model. Models were created with high detail and fidelity. **[Simunovic]** The correlations and modifications of the baseline vehicle FEM model to the experimental results were primarily done on the measurements of vibrational and stiffness characteristics of the BIW. Once	/ components. Rather, the configuration was the same as actually tested in the NVH Lab. While it is true that the CCB plays a significant role in vehicle level NVH model separation strategy, it was not considered in the BIW structure analysis. The crash models, on the other hand, did include the CCB and it was modeled in steel. Once again based on the scope of the project and using the crash models for comparison it was felt the use of a steel CCB would result in a realistic comparison of the body performance during major crash events.

	the stiffness of the BIW model was tuned to the experimental results, it was considered to be sufficiently accurate to form the foundation for the crash model. The vehicle crash FEM model was then correlated to the NCAP and MDB side impact. The correlations were primarily based on the deformation modes and the FEM model was found to be satisfactory for the purposes of the FEV study. Comparison of the deformation in the NCAP crash in Figures 46-49 shows very good correlation of the deformation modes. The deformation of the subframe shown in the Figures 48-49 also shows very high fidelity of the simulated deformation compared to the experiment. In summary, the correlation of the baseline FEM model with the NCAP test is quite satisfactory. The correlation with the side MDB test was not elaborated in the report. However, the side impact is perhaps the most important and limiting design aspect for the lightweight vehicles. The side impact is almost exclusively a structural problem that does not compound the benefits of the reduced mass, as is the case of the frontal impact. A documented correlation of the baseline FEM model with the side impact experiment will in my opinion be a very beneficial technical addition to the FEV project that would significantly support the findings of the technical feasibility of the lightweight opportunities in the existing vehicle design space.	As explained on page 24 of this report in section "Please comment on the methods used to analyze the technologies and materials selected, forming techniques, bonding processes, and parts integration." Response to **[Simunovic]** comment.
Please describe the extent to which state-of-the-art crash simulation testing methods have been employed as well as the extent to which the associated analysis exhibits strong technical rigor.	**[Joost]** This is not my area of expertise. **[Richman]** 1) CAE modeling guidelines used appear to provide a rigorous and logical technical approach to the development of the FE and the methods of analysis. 2) Method of evaluating and comparing acceleration levels in the various crash test scenarios is a bit unusual; a more accepted method of comparing velocity/time plots and average accelerations is suggested. **[OSU]** **<u>Tony Luscher</u>**	The scope of the project was not based on evaluating acceleration levels or velocity/time plots in the various crash test scenarios, but rather comparing intrusion values between the EDAG baseline model and optimized model. Early on the decision was made to judge the performance of revised structure primarily based on intrusion

	Global vehicle deformation and vehicle crash behaviors were analyzed and compared to the deformation modes of test photographs. Fidelity was good. A few notes on these comparisons are noted on this page in the additional comments section. **[Simunovic]** The FEV Low Development vehicle study has been reviewed following the instructions by the US EPA. It has been found that the FEV study followed most of the current technical guidelines and the state-of-the-art practices for computational crash simulation and design. Several inconsistencies were found in the developed FEM models that need to be addressed and corrected before the FEM models are released for the general use.	values since we could not reasonable assess injury criteria without having additional interior / restrain system information. The inconsistencies that were highlighted during the review have been corrected. The recommendations are incorporated into the final report.
If you have access to FMVSS crash setups to run the model under different scenarios in LS-DYNA, are you able to validate the FEV/EDAG design and results? In addition, please comment on the AVI files provided.	**[Joost]** N/A **[Richman]** **[OSU]** **Tony Luscher** This reviewer has expertise in crash simulation. However due to time constraints the model was not run under different scenarios in LS-DYNA. No AVI files were found.	
If you are aware of better methods and tools employed and documented elsewhere to help validate advanced materials and design engineering rigor for 2017-2020 vehicles, please suggest how they might be used to improve the study.	**[Joost]** N/A **[Richman]** Methods and tools were appropriate. **[OSU]** **Tony Luscher** None found.	

ADDITIONAL COMMENTS: **[OSU]** **<u>Kristina Kennedy</u>** “Bending and torsional stiffness values did not provide acceptable performance (when replacing with HSS)”. This is an “of course” comment, right? HSS would absolutely produce worse results when replacing steel. These results were expected, correct?	The bending and torsional values were deemed acceptable in the model. The project was based on developing a correlated NVH baseline model and from this model all future iterations needed to be within 5%. These models reflect this. The difference in stiffness values seen between the baseline and the optimized model is a function of the optimization parameters, to be within 5%, then the impact of using HSS. Replacing mild steel with HSS does not affect the modulus of elasticity of structure. Through additional design iterations or changes in the optimization parameters the performance of the structure could have been maintained with the use of HSS materials.
<u>Tony Luscher</u> The caption on Figures 1.8.13 to 1.8.14 state that they are at 100 Ms although the previous paragraph lists them as occurring at 80 Ms. The muffler deformation looks quite different in Figure 1.8.14. Figure 1.8.33 is unclear and cannot be seen.	The frontal impact analyses were run for 80 Ms. The captions were corrected in the final report. Global vehicle deformation and vehicle crash behaviors were analyzed and compared to the deformation modes of the photographs of the actual test. Figures 1.8.9 to 1.8.14 show different views of the comparative deformation mode at 80 Ms (end of crash). From the comparison of the deformation modes, it can be observed the EDAG baseline model shows similar deformation modes. While the deformation is not identical to what is

	seen in the photographs, it was felt the baseline model did represent a reasonable comparison to the actual test and was acceptable for the baseline and for use in all future comparisons.

4. **VEHICLE MANUFACTURING COST METHODOLOGICAL RIGOR (CAE BIW and Vehicle)**	**COMMENTS**	**RESPONSE**
Please comment on the methods used to analyze the mass-reduced vehicle body structure's manufacturing costs.	**[Joost]** Overall, the costing methods used in this study seem to be very thorough. The details of the approach provide considerable credibility to the cost estimates, however there will always be concerns regarding the accuracy of cost models for systems where a complete, detailed engineering design has not been established. I believe that this report does a good job of representing the cost penalties/benefits of the technologies but I would still anticipate negative response from industry. There a few examples where I believe that the cost was underestimated or where additional data could be helpful in corroborating the results:	
	The engine cost comparison suggests that the 2.4L engine will cost less than the 2.7L engine due to reduced material content (smaller engine). The analysis goes on to say that the remaining costs (manufacturing, install, etc.) would be about the same for both engines. This seems credible, but is it possible to compare the price of both engine types as well? It may be possible to find prices for both of these engines from a Toyota dealer, and while price is certainly different than cost, it would be helpful in establishing that the cost differential estimate is reasonably accurate.	Engine assembly service costs were collected from 3 different sources for both engines. Average 2.7L service cost = $10,763 Average 2.4L service cost = $9,023 These costs were scaled based on historical cost data, resulting in estimated savings of $230. The magnitude of savings using this method seems to include other factors. For this reason FEV chose to use the material content method as stated in the white paper.
	Regarding the cylinder head subsystem (pg. 211), the report notes that a switch from Mg to plastic for the head covers introduces engineering challenges related to the cam phaser circuitry. While the report identifies two	Included in the plastic cam cover cost and mass build up are bolt-on aluminum housing that integrates the phaser control valve and plumbing circuitry. The

	production examples of this change, these are for high cost engines. It seems unlikely that the designs would achieve the quoted cost savings given that this has only been applied to high cost engines and there are recognized difficulties in the engineering/design. Regarding the body redesign, the estimated cost increase due to materials and manufacturing ($231.43, pg. 333) for a weight savings of 67.7kg produces a weight reduction penalty of about $3.42/kg-saved which seems appropriate for the materials and assembly processes suggested in the report. I don't find the cost estimates for the seats to be credible (pg. 378). If it's possible to reduce the weight of the seats (which represent a significant portion of vehicle weight) while saving significant cost, why would there be any steel seats in production? These are "bolt on" parts that are provided to the OEMs by suppliers so this would be a relatively easy change to make if the cost/weight trade-off shown in this report is true. The report should, at the very least, address why these kinds of seats are not more prevalent in current vehicles.	plastic cam cover would seal around the bolt-on housing. With detailed design work, an alternative would be a cylinder head with integrated control valve housing. There are magnesium and plastic seat frames in some production vehicles today. Some seat suppliers have been reluctant to the changeover due to a few different reasons; they might have their own stamping facility and assembly equipment that has been paid for through many years of seat production, so to change over would be too costly. Or the cost fluctuation of plastic and Mg and other lightweight materials are too volatile: Mg was over $6 per kg in 2008, as low as $2.1 in 2007, and today it's at $3.1. Also some seat suppliers are not concerned with weight over cost. Companies like Ford are now pulling seat design in-house to get better control over the design and build of more light-weight seats. As new seat suppliers emerge with proven light-weight seat technologies and manufacturing processes, the thought process will change. In the Venza study, steel-to-mag seat frames were a considerable cost increase: for the front drivers and passengers seat frames the cost per kg was in increase of $1.53 per kg and an average $9 cost increase per front seat. With other added weight saving ideas, the cost was brought down to show an overall seat cost and weight savings. Carry over seat construction is another reason that new technologies are not being used. The cost of design and testing can add considerable costs. So, with all of the issues combined, who would

	Why is there a cost savings for the front axle hub (pg. 555)? If you are proposing to scallop the hub during forging then you will still need the same amount of input material – some of it will be removed during scalloping, but you will not get a cost savings. Also, it's not made explicitly clear that the current hub is forged. If you are proposing to move from a cast hub to a forged hub then the cost will most certainly increase. If the cost savings here is due to the estimated weight savings in the final part (i.e., pay for less material) then this indicates that the model is not correctly capturing the yield from the process. **[Richman]** Body structure mass optimization was conducted by EDAG. Body structure was not altered form the baseline structure. Mass optimization process examined an appropriate range of material types, grades and gauges. Material properties used appear valid for the respective materials and grades. NVH and collision performance results appear consistent and logical with no significant dis-continuities of inconsistencies. In general the process used is excellent and the results appear realistic and valid. **[OSU]** **<u>Tony Luscher</u>** Mass reduction was analyzed first on a system level and then by a component level basis. Mass reduction concepts were based upon a very comprehensive literature review of new materials and manufacturing processes and alternative designs ideas that appear in the open literature and at trade shows. An assessment of these was made in terms of technological readiness, fitness for use in mass production, risk, and cost. In addition there were	change? The OEMs have to drive change, and as weight becomes more of an issue to them, they will drive change to the suppliers. Change statement in report section F.6.4.1 The assumption is the hub is forged in scallop feature without additional scalloping process. Scalloped hubs (Image F.6-3) allow for material mass savings with no cost impact, since the material is removed during the forging process.

	consultation with industry and experts. **[Simunovic]** This is not my area of expertise.	
Please describe the extent to which state-of-the-art costing methods have been employed as well as the extent to which the associated analysis exhibits strong technical rigor.	**[Joost]** This is not my area of expertise. **[Richman]** Costing models are thorough covering all elements of total production cost (material, processing, equipment, tooling, freight, packaging …). Baseline cost model was calibrated to baseline vehicle cost projection. The basic model is complete and sound. Cost estimates for mass reduction technologies are the result of a rigorous engineering process utilizing benchmarking data, material and component costs from suppliers and detailed analysis of manufacturing costs. Sound creative engineering analysis was used to scale product cost to this specific vehicle application. Accuracy of new technology cost estimates is dependent on the knowledge, skill, experience and engineering judgment of the individuals making the estimates. Munro Associates conducted this segment of the project. Munro is a highly respected organization with strong qualifications in product cost analysis. It is reasonable to assume cost estimates in this study are valid estimates for the mass reduction technologies. One area of cost estimate concern is reduced mass sheet products. In this area, material and equipment costs attributed to the reduced mass technologies are significantly higher than actual production experience would support. Source of the discrepancy is not clear form the information in the project review documents. **[OSU]** **<u>Tony Luscher</u>** The impact of costs, associated with mass reduction, was evaluated using FEV's methodology and tools as previously employed on prior powertrain	Vehicle Closure Al cost: The vehicle closure aluminum cost in the final EDAG report reflected the revised material cost for sheet aluminum. The cost was reduced from \$4.83/kg in the initial draft of the report to \$4.46/kg in the final report. This value is consistent with the cost utilized for sheet aluminum in the NHTSA paper and (at this level the peer reviewer felt), while it was on the high end of the cost scale, was within explainable / acceptable limits.

	analyses for EPA. Cost reduction assumptions are clearly laid out and are reasonable. The report does a good job of realizing the inherent challenges and risks in applying any new technology, let alone lightweight technology, to a vehicle platform. FEV describes the component interactions both positive and negative in its recommendations. The actual values in the EXCEL files were not checked. **[Simunovic]** This is not my area of expertise.	
If you are aware of better methods and tools employed and documented elsewhere to help estimate costs for advanced vehicle materials and design for 2017-2020 vehicles, please suggest how they might be used to improve this study.	**[Joost]** This is not my area of expertise. **[Richman]** Process methodology and execution used is one of the best this reviewer has seen. **[OSU]** **Tony Luscher** None found. **[Simunovic]** This is not my area of expertise.	
ADDITIONAL COMMENTS: **[Joost]** The change from a cast Al engine block with cast Fe liners to a cast-over Mg/Al hybrid with PWTA coated cylinders is very interesting, but the cost penalty estimate seems low relative to what I would expect. Previous work exploring the use of Mg intensive engines (which did not include the added complexity of cast-in Al liners) suggests a cost penalty of $3.89 per pound saved (see http://www1.eere.energy.gov/vehiclesandfuels/pdfs/lm_08/3_automotive_metals-cast.pdf report B) versus this report which suggests a cost penalty of $3.51 per kilogram saved, about half as expensive. The cited study was performed on a 2.5 L engine, comparable to the Venza. The primary difference is that the Venza study includes downsizing which would save on material costs, but I'm not confident that the savings would be as substantial as indicated in this report. It seems that something has been underestimated.		The Magnesium Powertrain Cast Components Project is a jointly sponsored effort by the US Department of Energy and the US Council for Automotive Research to determine the feasibility and practicality of producing a magnesium-intensive engine. Participants in the study include Ford, GM, and Chrysler as well as a variety of automotive suppliers. FEV consulted with Bob R. Powell to understand the preliminary results of the MPCCP project. Project completion and final report are not expected until the fall of 2012. The cost increased slightly more due to FEV underestimated the cost of the inclusion of all -

	aluminum fasteners. Based on MPCCP meeting with DOE project representative, the following changes were made in our assumptions to line up with MPCCP study: 1. 7% scrap factor was added for Mg die casting process (MPCCP die casting data) 2. 5% scrap factor added for over-molding difficulty 3. Mg cylinder block cost/kg was recalculated assuming spray in cylinder liners on the base aluminum engine block (MPCCP Assumption). After the changes were implemented, engine block $/kg changed to a $5.207 cost hit, whereas prior peer review the $/kg was a $4.063 cost hit. MPCCP study did not include cylinder liners weight impact in their cylinder block calculation. By taking out the cylinder liner weight save, the Cylinder Block $/kg (Mg engine block only) after peer review = $8.08 cost hit, MPCCP Mg engine block $/kg = $3.89/lb*2.205 = $8.58 cost increase.

There are several examples where a cost savings has been calculated by reducing the size of a component, despite using more expensive material. For example the Front Rotor/Drum and Shield subsystem shows a savings for the caliper subsystem and a modest increase in the cost of the rotor and shield. Some of the cost savings here is due to reducing the size of the system (scaling to the 2008 Toyota Prius). However, there would still be a weight savings (albeit lower) if the conventional cast iron materials were used and downsized to the 2008 Toyota Prius – this is the likely outcome in a real automotive environment. Given the option to choose a more expensive, exotic, untested system that saves significant weight versus a conventional low cost system that saves less weight, it seems like an OEM would choose the conventional solution. In this case the suggested weight savings are technically possible but would never happen in a practical automotive environment.	The proposed changes of possible Al/MMC have been changed back to a cast iron material due to the application not being previously validated in high-volume production but instead in only lower volume vehicle applications. The caliper were not changed to an exotic material but were instead changed from cast iron to a cast Al. A material that has been utilized in this specific vehicle application for decades and has been mass produced by nearly all OEM manufacturers in one model or another.
[OSU] **<u>Kristina Kennedy</u>** Table 1.7.1: NVH Results Summary. The "Weight Test Condition" and "Weight BIW" are ALSO outside of limits (> 5%), but not noted in results. Only those highlighted in red are noted as "failures". All failures (> 5%) should be called out specifically since that was their target.	The categories of "Weight Test Condition" and "Weight BIW" do not represent performance categories of the structure, but rather provide the mass of the structure being tested along with the mass of the BIW. The NVH testing includes the BIW weight and all fixed glass. The value shown for "Weight Test Condition and Weight BIW" was provided for reference only. The 5% limit was used for establishing the acceptability of the structure when comparing the NVH performance level of the structure for the multiple material iterations. The 5% limit was used in judging the NVH performance of the structure for both static and dynamic modes. The rational for the 5% target was based on the typical range of variability seen in testing multiple structures of the same design.
<u>Tony Luscher</u> There are many typos and fragmented sentences in these sections. These should be corrected. Bookmark	

references do not all work.	Corrected in Report

5. CONCLUSION AND FINDINGS	COMMENTS	RESPONSE
Are the study's conclusions adequately backed up by the methods and analytical rigor of the study?	**[Joost]** Yes. I identified various areas where the analysis or report could be improved, but overall the methods used here provide a credible and reasonable estimate of the potential for weight savings. Based on some of my earlier comments I would expect that actual costs to be somewhat higher than predicted in this study. Additionally, real vehicles share components across platforms so using vehicle-specific components would add additional cost. It is possible that the cost curve would cross $0/lb-saved at a lower total weight savings than suggested here. **[Richman]** Study conclusions and findings are well supported by the analytical rigor, tools used and expertise of the organizations involved. **[OSU]** **<u>Glenn Daehn</u>** At the time of review, Section G "Conclusions and Recommendations" is unavailable. We hope that in this section FEV will point out the most promising actions that auto makers may take to reduce mass while conserving cost. **<u>Tony Luscher</u>** The report's conclusions are based on sound engineering principals of good rigor.	Added in report section G
Are the conclusions about the design, development, validation, and cost of the mass-reduced design valid?	**[Joost]** Yes. As above, there is reason to believe that the true cost will be higher than predicted here, but I think this analysis provides a useful estimate. **[Richman]** Design development and validation conclusions are well supported in this study. Cost model is valid and cost conclusions are generally realistic. There appears to be a systematic discrepancy in cost modeling of low mass sheet products. This discrepancy has a minor impact on conclusions of this study.	

	[OSU] **<u>Glenn Daehn</u>** This study is carefully crafted with excellent attention to engineering detail. It is important to note that the overall environment for vehicle design, manufacture and use is continually changing. See the "Additional Comments" section of this document for further development of the implications of this. **<u>Tony Luscher</u>** This reviewer found the overall work to be thorough and well documented. Therefore the conclusions are well supported and validated by the engineering and modeling in the report.	
Are you aware of other available research that better evaluates and validates the technical potential for mass-reduced vehicles in the 2017-2020 timeframe?	**[Joost]** I have not seen a report as thorough as this. There are several examples of resources that provide useful information regarding weight reduction potential such as Cheah, L.W. Cars on a Diet: The Material and Energy Impacts of Passenger Vehicle Weight Reduction in the U.S. Joshi, A.M. Optimizing Battery Sizing and Vehicle Light weighting for an Extended Range Electric Vehicle Lutsey, N. Review of technical literature and trends related to automobile mass-reduction technology **[Richman]** This reviewer has monitored automotive mass reduction studies in North America and Europe for several years. This study is the best evaluation of mass reduction opportunities and associated costs this reviewer has seen. **[OSU]** **<u>Glenn Daehn</u>** There are no more comprehensive or detailed studies that we are aware of. This is an excellent compilation of ideas for practical vehicle mass reduction and fuel efficiency improvement. **<u>Tony Luscher</u>** None found.	

ADDITIONAL COMMENTS: **[OSU]** **<u>Glenn Daehn</u>** The study does an excellent job within its scope. As this reviewer sees the scope, the driving question is: Can a well-engineered relatively modern vehicle (2010 Toyota Venza) have its mass reduced by 20% or more, without significant cost penalty and while maintaining crashworthiness. The answer to that question is a clear "YES". Further, this conclusion is backed with rigor and attention to detail. This is in my mind, very clear, well-done and technically rigorous. This reviewer believes that there are a few other important questions that were not asked. These include:	
1) Will the proposed changes in design pose any other important risks in manufacture or use? This can include: warranty exposure, durability, increased noise, vibration and harshness, maintenance concerns, etc., etc.	The statement will be found in report section C.1
2) Will increasing regulatory constraints and/or consumer expectations require increases in vehicle mass, opposing the mass reductions provided by the improved practices outlined in this study?	No impact to vehicle mass. This is outside the scope of this study.
Both these issues will make vehicle light weighting more difficult than this report suggests. With respect to issue 1) there are a number of materials and design substitutions that may produce concerns with durability, manufacturability and warranty claims. For example when substituting polymers for metals, there are new environmental embrittlement modes that may cause failure and warranty claims. Also, if substituting aluminum for steel, multi-material connections may cause galvanic corrosion problems. When using thinner sheets of higher strength steel, formability may be reduced and springback may be more problematic. Both these issues may preclude the use of the stronger material with a similar design and may also increase the time and cost involved with die development. Lastly there are always risks in any new design. For example, when using new brake designs, pad wear and squeal may be more pronounced. All of these issues may cause a manufacturer to avoid the new technology. There are also local constrains on material thicknesses that are outside this review methodology. For example while a roof rail may meet crash and stiffness criteria, it may deflect excessively or permanently if a 99th percentile male pulls on it exiting a vehicle. Similarly, parking lot and hail dents may require greater thickness gauges than this study may indicate. The problem of vehicle light-weighting and improved fuel economy is seen here through the lens as being	

an engineering problem to be solved. And in many ways it is. However, the forces of consumer expectations and behaviors are an essential part of the problem. As an interesting anecdote, the Model T Ford had a fuel economy of about 20 MPG, very similar to the average fuel economy of vehicles on the road today. No modern consumer would choose a Model T for many obvious reasons. Our cars have become extensions of our living rooms with many electrical motors driving windows, mirrors, seats and complex and costly HVAC and infotainment systems. All of these systems add weight, complexity and use power. Further increased complexity of engines to improve emissions and increase fuel economy has increased engine mass. This study shows that with good engineering we can reduce vehicle mass of an existing vehicle by 20% with little to no increased cost or adverse consumer reaction. Based on our current course, it is just as likely this benefit will be taken by improved mandated safety and emission features as well as improved creature comforts. Much can be gained through enlightened consumer behavior (assuming the average consumer wants to reduce energy use and carbon footprint). While much of this is outside the scope of this report, in particular it would be useful if the average consumer would understand the lifecycle environmental impacts of vehicle choice and of varied vehicle design, and would adopt a 'less is more' ethic and see their transportation systems as that, simply transportation. A more minimalist ethic that would move against increasing vehicle size and the creep of multiple motors for seats, mirrors, windows, etc., would reduce acquisition cost, maintenance cost and energy cost. This is in addition, of course, to the usual advice to reduce fuel consumption (limit trips, limit speed, tire pressure, carpooling, etc. etc.) is still valuable. It should also be noted that there are other potentially low-cost actions that can be easily adopted to reduce greenhouse gas emissions and reduce dependence on foreign oil. One of these is widespread adoption of natural gas fuels for personal transportation. Use of Compressed Natural Gas (CNG), has lower fuel cost than gasoline, produces less pollution and greenhouse gas emission per energy used, and requires only very modest changes to conventional vehicle architecture, with no significant increases in complexity. The cost and size of a CNG tank and the development of refueling infrastructure are the main barriers to adoption of a technology that could have important and positive societal benefits. This is an excellent and useful study. It is important however to recognize the limitations of purely engineering solutions. And even within the engineering realm, there are many reasons that the implementation of the solutions in this paper study will require much effort to become part of mainstream automobiles.	

Kristina Kennedy With respect to measuring powertrain CG and moment of inertia, notes "oscillation as an undamped" condition. Just confirming, this means no dynamic dampers were used in the engine room modeling? Is this realistic? Acceptable practice?	The entire powertrain-engine assembly is treated as a rigid body and this is reflected in the FE modeling. The influence of dynamic damping is not considered critical when comparing models for this analysis. Therefore, this approach was considered acceptable.

6. OTHER POTENTIAL AREAS FOR COMMENT	COMMENTS	RESPONSE
Has the study made substantial improvements over previous available works in the ability to understand the feasibility of 2017-2020 mass-reduction technology for light-duty vehicles? If so, please describe.	**[Joost]** Yes. Other studies have reviewed the mass saving potential of various technologies individually, or imagined the impact of combining many technologies. However I am not aware of a design study that takes an existing vehicle and assesses each piece with the thoroughness used here. **[Richman]** Yes. Overall objectives) of the project (20% mass reduction, less than 10% cost increase) are timely and consistent with industry interests in the short term. Retaining the OEM designed and field proven body structure eliminates uncertainty related to evaluation of novel and un-proven structures. This analysis clearly identifies body mass reduction achievable with new and near term future grades of HSS and AHSS. An exhaustive list of non-body mass reduction concepts are evaluated in this study. Some of these technologies are well known and understood in the industry, other are new, creative and innovative. Each technology is reviewed from an engineering and cost perspective and scaled to the specific application. The technology selection process was analytical, rigorous and un-biased. Majority of technologies selected are appropriate for the mass reduction and cost objectives of the project. This information provides helpful information to industry engineers considering mass reduction alternatives for other vehicle programs. **[OSU]** **<u>Glenn Daehn</u>** Without question. The only similar study also targeted the Venza. This provides much additional analysis and many additional ideas beyond the Lotus study. **<u>Tony Luscher</u>**	

	The major contribution of this study was to pull together and evaluate all of the current proven concepts that are applicable to a lightweight vehicle in the 2017-2020 timeframe. It is successful in this regard.	
Do the study design concepts have critical deficiencies in its applicability for 2017-2020 mass-reduction feasibility for which revisions should be made before the report is finalized? If so, please describe.	**[Joost]** No – I would not say that any deficiencies here are "critical". Major findings of the project appear practical for implementation by 2017-20. **[Richman]** Major findings of the project appear practical for implementation by 2017-20. Two technologies selected for inclusion in the final vehicle concept appear "speculative" for 2017-20: Co-cast magnesium/aluminum block and MMC brake rotors. Both technologies are identified as "D" level for implementation. Designing, developing and establishing production capacity for a new engine block is a time consuming and costly process. Investments would be required by OEM manufactures and casting suppliers. It is not clear the level of human resources and capital investment required for this technology could be justified the basis of the mass reduction potential of (7 Kg). Aluminum MMC brake rotors were selected for inclusion in the final vehicle configuration. In the judgment of this reviewer, this technology is the most speculative technology selected for the final vehicle configuration. MMC rotors have been in development for over 25 years. Development experience with these rotors has generally not been acceptable for typical customer service. The minimum mass MMC rotor design selected in this project is a radical (by automotive standards) multi piece bolted composite design with an MMC rotor disc. This design is identified as a "D" rated technology and a mass savings of 9 Kg. The aluminum MMC portion of the mas reduced rotor assembly would be regarded as "speculative" at this time. Cost models used to assess low mass sheet product may have some questionable assumptions. For this project, adjustment in the cost model is unlikely to influence he material selection process. Correction in this area	This is a reasonable concern as justification would likely have to assume this technology and investment would benefit future engines and provide a strategic advantage for the OEM willing to take the investment risk. The proposed changes of a possible Al/MMC rotor have been changed back to a cast iron material due to the application not being previously validated in high-volume production, but instead in only lower volume vehicle applications. Given more time and high volume manufacturing development beyond 2017, this technology could be considered again for future applications as it continues its development.

	would have a greater impact on technology screening and selection to achieve mass reductions above 20%. **[OSU]** **<u>Glenn Daehn</u>** Conclusions and recommendations section is missing. This is an important opportunity to reinforce the most important actions that automakers can take. The report still lacks the ability to trace some technical details all the way back to the source. This is described previously.	Add in report section G Updated in report
Are there fundamentally different lightweight vehicle design technologies that you expect to be much more common (either in addition to or instead of) than the one Lotus has assessed for the 2017-2020 timeframe (Low Development)?	**[Joost]** Not in the 2017-2020 time frame. Switching to an advanced steel dominant body with a few instances of Mg and Al seems appropriate for the time frame. The considerable use of lightweight plastics is also in line with my expectations for available technology in this time frame. **[Richman]** No. The result of his study is a logical and cost effective advancement in the development of more efficient passenger vehicles for the 2017-20 time frames. **[OSU]** **<u>Glenn Daehn</u>** It seems apparent that vehicles are moving more and more to multi-materials construction and as we move away from steel-based construction, joined primarily by resistance spot welds, there will be need for additional joining technologies. Laser welding is mentioned as one possible replacement for resistance spot welds, but it is expected that over time there will be much more use of structural adhesives, self-piercing rivets, conformal joints and other joining strategies for the BIW.	

Are there any other areas outside of the direct scope of the analysis (e.g., vehicle performance, durability, drive ability, noise, vibration, and hardness) for which the mass-reduced vehicle design is likely to exhibit any compromise from the baseline vehicle?	**[Joost]** All of the areas listed here are somewhat concerning, but given the switch to fairly conventional materials I believe that durability, drivability, and NVH should be not be a significant issue. Detailed analysis work in these areas would likely require some redesign which may add cost or weight, but I don't think it would be overwhelming. **[Richman]** None identified by this reviewer. **[OSU]** **<u>Glenn Daehn</u>** Yes. There are many other details with respect to nuances of customer expectations, durability, warranty risks and manufacturability that are discussed elsewhere in this review. This does not diminish the importance of this great work. Just points out there are an enormous amount of detailed work required to build an automobile, and the job is not finished.	
ADDITIONAL COMMENTS: **[OSU]** **<u>Kristina Kennedy</u>** Overall, well-written and well-done…my conclusion (which they also reached) is YES, NVH WILL SUFFER when replacing steel with HSS and will OF COURSE make the vehicle MORE STIFF. **[Simunovic]** The FEV report is quite exhaustive. I would suggest that it be released in a hypertext format that can allow different navigation paths through it. Also, the dynamic Web-based technologies can be used for effective model documentation, presentation and distribution. I would also recommend that more details on the actual optimization process, including the objective function specification, and the final consolidation of the model, be added to the documentation.		Links for all reference material are captured throughout the report. They are not hyperlinked. All cost sheets are in a folder structure at EPA website.

4. References

FEV. *Light-Duty Vehicle Mass-Reduction and Cost Analysis – Midsize Crossover Utility Vehicle*. 2012.

Analysis Report Review

Report Title: **Light-Duty Vehicle Mass Reduction and Cost Analysis – Midsize Crossover Utility Vehicle**

Report Number: **07-069-303**

This Analysis Report has been reviewed and complies with the quality assurance procedures of FEV, Inc.

☐ The Analysis Report is adequate for delivery to the customer.

(Signature)	(Signature)
Print Name: Patrick Hupperich	Print Name: Greg Kolwich
Title: **Vice President**	Title: **Manager, Value Engineering**
Date:	Date: 02/14/2012

Project: Light-Duty Vehicle Mass Reduction and Cost Analysis **Task:** EPA Contract EP-C-07-069 WA3-3	**Project #:** 07-069-303 **Date:** 02/14/12
Client: United Stated Environmental Protection Agency **Contact:** Cheryl Caffrey	
Subject/Objectives: The primary objective of this contract is continue the design concepts of the 2010 ICCT report of the Low Development concept vehicle with 20% vehicle mass reduction along with other recent relevant studies. The contractor should continue the work started on ICCT's research building on the original assessments to prove concept, cost effectiveness and feasibility, manufacturability and crashworthiness that can, at minimum, meet the performance functions (as defined in Scope of Work) of the original baseline vehicle (2009 Venza) while controlling for both variable and in-direct cost to maintain affordability (as defined in cost section of SOW). Specifically, the contractor shall use advanced design, material and manufacturing processes that will likely be available in the time frame of the 2017 model year and beyond for the Low Development concept vehicle to optimize and develop an engineering design with sufficient details such that computer modeling can be performed to demonstrate crashworthiness of the vehicle concept in addition to detailed incremental cost estimate for the design, including both detailed direct (piece) and indirect cost estimates. The Contractor shall assist EPA in discussions with other parties and agencies on this study and document it in the 2017+ NPRM and final rule if necessary.	
Method/Solution: Engineering expertise and state-of-art computer modeling, employed on selected vehicle subsystems, was utilized to generate potential mass reduction ideas for a production stock 2010 Toyota Venza. The target vehicle mass reduction was 20% or approximately 340kg. Selected advanced, alternative, designs, materials and manufacturing processes were based upon a comprehensive literature review and consultation with industry and experts. In addition to mass-reduction calculations the impact of costs, associated with mass reduction, were also evaluated using FEV's detailed and transparent costing methodology and tools. These are the same tools and processed FEV employed on prior powertrain analyses for EPA	

Summary/Results: Revision Date 03/25/2012
Calculated Vehicle Mass Reduction: 316.78 kg
Percent Vehicle Mass Reduction: 18.51% (1711kg Baseline Vehicle Mass)
Calculated Cost Impact for Mass Reduction: $ 92.04 Decrease
Average Cost Per Kilogram: $0.29 Save/Kilogram

Notes:

(1) Mass reduction ideas require packaging, function and performance validation on an application by application basis.
(2) Mass reduction ideas are developed on a subsystem by subsystem basis. As a result the synergistic affect relative to vehicle performance and potential degradation was not evaluated.
(3) Costs presented are direct manufacturing costs
(4) Costs do not include indirect cost factors (e.g. OEM SG&A, ED&T, Tooling, etc.)
(5) Costs are calculated using an established set of boundary conditions (e.g. mass production volumes, competitive market place, mature technology, etc.)
(6) Mass reduction ideas are

Conclusions/Recommendations:

(1) Establish development plan to validate all the proposed technologies
(2) Perhaps this can be a joint effort between the private and public sector.

Light-Duty Vehicle Mass Reduction and Cost Analysis – Midsize Crossover Utility Vehicle

Analysis Report BAV 07-069-303 (3/3)

DRAFT VERSION – NOT FOR DISTRIBUTION

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March 30, 2012

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A. Executive Summary

The United States Environmental Protection Agency (EPA) contracted FEV to perform a Phase 2 analysis on the Lotus Engineering low development portion of the 2010 Phase 1 report. The Phase 1 report, titled "An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Program," was submitted to the Internal Council on Clean Transportation for release during March 2010. The analyses were to include evaluating the mass-reduction opportunities presented in the Lotus report as well as investigate additional mass reduction opportunities. This was to include:

- A detailed finite element analysis of body-in-white (BIW)
- Crash simulation of the entire mass reduced vehicle using sophisticated computer aided engineering tools
- Conducting further investigations into new mass reduction technologies which have been developed since 2009/2010 and redesigning the BIW, if necessary.
- In the event that BIW changes were implemented, verify that the redesigned body meets the major vehicle functional objectives for safety, dynamics, durability and noise/vibration/harshness (NVH).
- Conducting a thorough cost analysis of the mass reduction technologies identified.

The Lotus Engineering low development portion of the Phase 1 report identified mass reduction technologies that achieved a 19% reduction in curb weight, less powertrain, or an 18% curb weight reduction when including a hybrid powertrain with an advanced turbocharged and downsized engine. The goal of the study was to identify mass saving opportunities totaling 20% curb weight while maintaining performance parity relative to the current vehicle. FEV's review of the Lotus Phase 1 low development BIW design showed bending and torsional stiffness to be insufficient in meeting the design target of no expected degradation of ride, handling or NVH. Hence the BIW was redesigned in order to achieve the desired design characteristics. FEV also utilized approximately 40 of Lotus's 150 design ideas for mass reduction in the following vehicle systems: seating, vehicle interior, suspension, and braking. Other mass reduction ideas came from research into various technology sources. This report details FEV's additional work and findings to prove the design concept, cost effectiveness, manufacturing feasibility, and crashworthiness that can meet the function and performance of the baseline vehicle (2010 Toyota Venza). All components and assemblies included in the various Toyota Venza vehicle systems were considered available for potential mass-reduction. Both direct mass-reduction of components (e.g., design and/or material alternatives) and mass-reduction of components via mass-reduction compounding (i.e., the reduction of component mass enabled by reductions in vehicle mass) were regarded as viable options.

After a complete vehicle teardown analysis of a 2010 Toyota Venza to record components and manufacturing processes, FEV and its subcontractors used design, material, and manufacturing processes determined likely to be available by the 2017-2020 model year time frame to evaluate mass-reduction ideas. Lighter weight materials such as high-strength steels, aluminum, engineering plastics, and other materials incorporated into innovative structural designs can produce substantial vehicle weight reduction. Product and manufacturing engineering technical experts identified opportunities at the component and assembly level to reduce mass during the teardown and evaluation process. A combination of research and development benchmark data, production benchmark data, and Toyota Venza specific re-design and development data was used to verify and validate the mass-reduction concepts.

Along with mass-reduction calculations, FEV also evaluated the costs associated with mass reduction, employing detailed and transparent costing methodology and tools. The costing methodology and tools are the same as those successfully utilized on previous EPA advance powertrain incremental direct manufacturing cost studies. Additional details on the costing methodology can be found in the EPA published report EPA-420-R-09-020 “Light-duty Technology Cost Analysis Pilot Study” (http://www.epa.gov/OMS/climate/420r09020.pdf).

To evaluate the impact of costs on the mass-reduced components, cost models linked to comprehensive costing databases for raw material rates, labor rates, manufacturing overhead and burden rates, as well as end item scrap, SG&A (selling general and administration), profit, ED&T (engineering, design, and testing), and packaging were employed.

Key to the costing process is the task of developing a universal set of boundary conditions establishing a constant framework for developing incremental costs. A common framework for all costing allows reliable comparison of costs between the new technology configuration (i.e., mass-reduced components) and the baseline technology configuration (i.e., OEM production components).

In addition, having a good understanding of the analysis boundary conditions (i.e., what assumptions are made in the analysis, the methodology utilized, what parameters are included in the final numbers, etc.), results in a fair and meaningful comparison between results developed from alternative costing methodologies and/or sources.

Cost factors not included in the analysis include OEM indirect costs and learning factors. OEM indirect costs include cost categories such as OEM engineering, design and testing, OEM corporate overhead, OEM warranty, and OEM sales. Cost factors associated with new technology inception (e.g. lower production volumes, lower market immaturity, low market competition) are addressed through the addition of learning factors. Indirect costs and costs associated with learning are addressed outside this analysis and within EPA's modeling protocol.. Within the body of this report readers will be referenced as to where additional details may be found on the development and application of indirect cost multipliers (ICM's) and learning factors.

The mass-reduction and cost analysis process employed in this project is summarized with the following five steps:

1) fingerprint the baseline vehicle;
2) mass-reduction idea generation;
3) mass-reduction optimization (weights vs. costs);
4) selection of mass-reduction level with best value; and
5) detail technology feasibility and cost analysis.

FEV subcontracted with EDAG GmbH to evaluate the Venza body structure system using sophisticated computer-aided design (CAD) and engineering (CAE) tools. EDAG is worldwide engineering firm that provides "ready for production (engineering) solutions" across entire vehicle platforms[1] EDAG applied its standard best practice of re-engineering processes, which included vehicle teardown by skilled body technicians, parts scanning, and data collection of vehicle parts to build a full vehicle CAE model. Part details crucial for building the CAE model (e.g., weight, thickness) were obtained and recorded here in an assembly hierarchy. Through the process of constructing detailed models for critical vehicle systems, EDAG was able to validate that major vehicle level functional objectives were being maintained throughout the mass reduction process.

The Venza breakdown identified 17 major systems (e.g., Engine, Transmission, Suspension, etc.) amassed by a significant number of subsystems and sub-subsystems that were individually evaluated in the course of this study. In **Error! Reference source not found.**, a summary of the calculated mass reduction and cost impact for each major system evaluated is provided. This project recorded a mass reduction of 18.51% with powertrain at a cost savings of $0.29/kg without tooling impact. Shown in **Figure A-1** is an incremental direct manufacturing cost/kilogram vs. vehicle mass-reduction percentage. This curve does not include tooling, ICMs, or Learning Factors. It shows both compounded and non-compounded mass-reduction. All direct mass-reduction of components (e.g., design and/or material alternatives) as well as mass-reduction of components via mass compounding are considered viable options. For this project, mass-reduction compounding refers to the reduction of mass of a given component as the result of a reduction in the mass of one or several other components.

1 EDAG GmbH http://www.edag.de/en/company.html

Description	Baseline Mass "kg"	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Tooling Cost "$" (x1000)	Average Cost/ Kilogram W/O Tooling $/kg	Average Cost/ Kilogram W/ Tooling $/kg	Subsys./ Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
Engine System	172.60	30.35	$43.24	$5,892.20	1.42	1.66	17.58%	1.77%
Transmission System	92.76	18.90	($114.15)	($7,650.80)	(6.04)	(6.53)	20.37%	1.10%
Body System(Group -A-) BIW & Closures	528.88	67.89	($230.66)	($22,900.00)	(3.40)	(3.81)	-	3.97%
Body System(Group -B-) Interior	220.61	42.00	$122.98	$9,966.15	2.93	3.22	19.03%	2.45%
Body System(Group -C-) Exterior	26.57	2.37	$7.59	$0.00	3.20	3.20	9.01%	0.14%
Body System(Group -D-) Glazing & Body Mechatronics	63.46	6.16	($15.25)	$0.00	(2.48)	(2.48)	9.70%	0.36%
Suspension System	265.91	69.45	$135.93	($7,200.97)	1.96	1.83	26.12%	4.06%
Driveline System	33.66	1.50	($0.16)	($160.30)	(0.11)	(0.24)	4.47%	0.09%
Brake System	86.71	40.52	$116.21	($1,426.12)	2.87	2.83	46.73%	2.37%
Frame and Mounting System	43.73	16.50	($3.66)	$4,059.70	(0.22)	0.08	37.73%	0.96%
Exhaust System	26.62	7.52	$2.47	$0.00	0.33	0.33	21.09%	0.44%
Fuel System	24.28	6.80	$3.91	$1,535.50	0.57	0.85	28.03%	0.40%
Steering System	24.23	1.82	$11.05	$1,352.70	6.08	6.99	26.31%	0.11%
Climate Control System	15.66	2.44	$9.34	$386.00	3.83	4.03	15.55%	0.14%
Info, Gage and Warning System	1.90	0.08	$0.19	$0.00	2.45	2.45	4.01%	0.00%
Electrical Power Supply System	18.96	-	-	-	-	-	-	-
In-Vehicle Entertainment System	4.59	1.07	$2.43	$1,175.60	2.27	3.60	23.39%	0.06%
Lighting System	10.04	0.53	($0.76)	$400.00	(1.42)	(0.51)	5.29%	0.03%
Electrical Dis. And Electronic Control System	23.94	0.89	$1.35	$103.50	1.52	1.66	22.43%	0.05%
Fluid & Misc.	26.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vehicle	1711.38	316.78 (Decrease)	$92.04 (Decrease)	($14,466.84) (Increase)	0.29 (Decrease)	0.24 (Decrease)	-	18.51%

Table A-1: Mass-Reduction and Incremental Direct Manufacturing Cost Impact for each Vehicle System Evaluated

Similar to the boundary conditions established in the Phase 1 Lotus analysis, the proposed mass-reduction efforts maintain function and performance of the baseline Venza vehicle. Again, the mass-reductions were selected to be available by the 2017 model year. The proposed design is also commercially feasible for high-volume production (~200,000 units per year) and the new technologies are expected to be completely phased in and incorporated into vehicle design by MY2017.

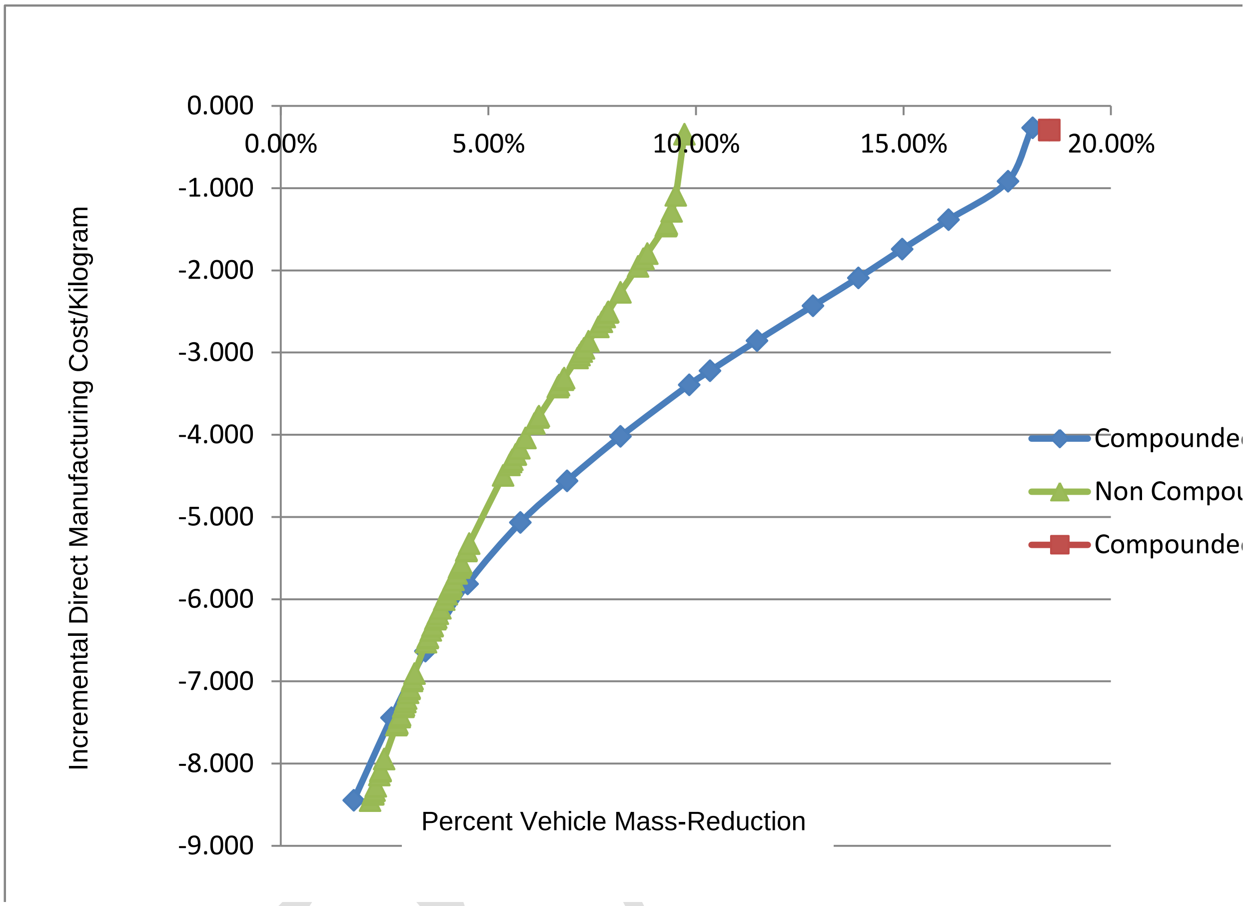


Figure A-1: Toyota Venza Mass-Reduction Cost Curve

B. Introduction

B.1 Project Overview

B.1.1 Background for Studying Mass-Reduction

Vehicle manufacturers are currently modifying the architecture and design of their entire product lineups to better respond to regulatory actions curbing greenhouse gas emissions (GHG) and to meet consumer demands for substantial improvements in vehicle fuel economy while maintaining vehicle functionality and performance attributes. Accordingly, manufacturers are planning to rapidly expand implementation of advanced vehicle, powertrain and engine technologies. These technologies include engine downsizing, turbocharging, direct injection, variable valve timing & lift, automated manual transmissions, automated start-stop systems, electric-hybridization and other technologies.

Another promising technology for reducing vehicle GHG emissions, and the focus of this work, is reduction of vehicle weight. Weight reduction can be accomplished without compromising vehicle interior volume and utility by combining lightweight materials and innovative vehicle design. Many mass reduction techniques are already being applied by vehicle manufacturers such as the use the use of lighter weight materials. These materials include engineering plastics, high strength steels, aluminum, magnesium, and other materials incorporated into innovative structural designs can yield substantial reductions in vehicle weight. Appropriate light-weight vehicle designs can maintain or improve current vehicle characteristics such as safety, NVH control, durability, handling and load carrying capacity. For example, HEV battery pack enclosures could be integrated within the vehicle structure to better optimize body strength and weight compared to current HEVs that are essentially derivatives of conventional vehicles. New materials could be utilized in suspension components that are lightweight but lower in cost than aluminum. Reduction in unsprung mass and improvements in suspension geometry can reduce suspension loads on the chassis allowing synergistic reductions in weight. Use of advanced Computer Aided Engineering (CAE) such as finite element analysis can optimize load paths through the chassis and body by simultaneously maintaining NVH and crashworthiness while achieving weight reduction.

While the vehicle architectures being investigated for this timeframe (2017-2020 production) must achieve low greenhouse gas emissions, the designs must also be cost effective for consumers, meet or exceed current and planned safety requirements, meet consumer expectations for vehicle performance (e.g. acceleration, towing, load carrying, handling) and durability.

B.1.2 Mass-Reduction Evaluation – Phase 1, Background Information

The analysis work covered in this report is a continuation of work previously completed for by Lotus Engineering for the International Council on Clean Transportation. In the initial analysis (also referred to as the Phase 1 analysis) Lotus Engineering performed a mass-reduction evaluation and cost assessment on a current production 2009 Toyota Venza. The Toyota Venza is a 4-door, 5-passenger vehicle available in all wheel drive or front wheel drive configurations and has the physical attributes normally associated with a Cross-over Utility Vehicle (CUV). The Toyota Venza (vehicle example shown in **Image B-1**) is representative of current CUV's in terms of body architecture and powertrains. It achieves five stars (the highest rating) in crash testing, meets current federal safety standards, offers comfortable seating for five with a large storage volume and is rated at 21 MPG city and 29 MPG highway with a 2.7 liter four cylinder internal combustion engine (ICE) and front wheel drive (FWD). Toyota advertises that this is a versatile vehicle for active lifestyles that meets a wide variety of functional requirements.

Image B-1: 2009 Toyota Venza

(Source: http://www.toyotacolors.info/2009-toyota-venza-4x4-v6/)

Lotus began the study with a complete tear-down of the Toyota Venza to establish the mass for each vehicle system. Every part was removed from the Venza vehicle, measured, weighed and the material type recorded. The components were consolidated under the appropriate category, e.g., body, suspension, interior. This work was performed by A2Mac1, an experienced benchmarking specialist subcontracted by Lotus Engineering. This teardown defined the baseline masses and the A2Mac1 database, which includes teardown data on vehicles distributed internationally, was used as a source for selecting lightweight components. Employing Lotus Engineering expertise, best-in-class designs (key selection criteria being mass) were selected to replace existing baseline components.

The scope and deliverables in Phase 1 of the Lotus project included two distinct approaches for production intent lightweight vehicle structures. Specifically, the deliverables were bills of materials (BOM's) representing a Low Development vehicle with a 20% overall mass reduction target that represents approaches that could be implemented by 2017 and a High Development vehicle with a 40% overall mass reduction target, less powertrain, that represented approaches available for model year 2020 vehicles.

The original Lotus Engineering Phase 1 report, “An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Program,” was submitted to the Internal Council on Clean Transportation for release during March 2010. The report can be found at the following Internet address: http://www.theicct.org/sites/default /files/publications /Mass_reduction_final_2010.pdf. In **Appendix H.1** the executive summary from the Lotus report listed above can be found. In summary, Lotus Engineering determined that a 19% (244kg) mass-reduction (no powertrain contribution considered) was possible at a vehicle piece cost impact of a nominal 99% to the baseline Venza vehicle.

B.1.3 Mass-Reduction Evaluation – Phase 2, Purpose and Objectives

As covered in **Section B.1.2** above, the original (Phase 1) Lotus Engineering Low Development mass-reduction and cost analysis had a target of 20% vehicle mass-reduction with production feasibility in the 2017-2020 timeframe EPA contracted with FEV and their contractors a Phase 2 low development mass-reduction analysis to build-on the vehicle mass-reduction efforts previously conducted by Lotus Engineering. The primary objectives can be summarized as follows:

1. Preliminary review and assessment of mass-reduction concepts proposed in Lotus phase 1 analysis.
2. Research and evaluation of potential vehicle mass-reduction ideas to compliment and/or provide additional alternatives to the existing Lotus recommendations. Sources of information include but are not limited to:
    a. OEM and T1 advance production technologies
    b. OEM and T1 advance technologies currently under development
    c. Raw Material Suppliers research and development projects in mass reduction
    d. Existing published studies on the light-weighting of light-duty vehicles (Reference Appendix H3: “Light-Duty Vehicle Mass-Reduction Published Articles, Papers, and Journals Used as Information Sources in the Analysis”)
    e. Alternative industry mass-reduction practices
    f. Mass-reduction idea generated from internal brainstorming.
3. Additional effort in validating Lotus phase 1 ideas and/or any new mass-reduction ideas developed with the scope of the project. The validation methodology was based mainly at three levels:
    a. Surrogate production vehicle benchmark data
    b. Research and Development data from automotive component and material suppliers

   c. Toyota Venza vehicle specific computer aided design (CAD) and engineering (CAE) analysis
4. Ensure most mass-reduction ideas selected are manufacturing feasible and implementation ready for phase-in starting in the 2017 timeframe.
5. Develop detailed incremental direct manufacturing costs for the adoption of the mass-reduced components, with respect to the baseline components, utilizing the same detailed costing methodology employed on previous EPA advance powertrain technologies cost analyses.
6. Develop an incremental tooling cost impact for the adoption of the mass-reduced components, with respect to the baseline components.
7. Develop an incremental direct manufacturing cost versus % vehicle mass-reduction curve.

Basic high level analysis boundary conditions include the following:

1. Target vehicle mass-reduction 20% (340kg) total (baseline Venza approximately 1710kg)
2. Target vehicle direct manufacturing cost impact 0% increase (i.e., cost neutral) with a maximum 10% ($1,671) increase. Manufacturing Suggested Retail Price (MSRP) $25,063, Retail Price Equivalent (RPE) 1.5, vehicle direct manufacturing cost estimate $16,709 ($25,063/1.5).
3. All components and assemblies included in the various Toyota Venza vehicle subsystems and systems are considered available options for potential mass-reduction.
4. All direct mass-reduction of components (e.g., design and/or material alternatives) as well as mass-reduction of components via mass compounding are considered viable options. For this project, mass-reduction compounding refers to the reduction of mass of a given component as the result of a reduction in the mass of one or several other components.
5. No functional or performance degradation permitted from the production stock Toyota Venza.
6. No functional or architecture changes to accommodate alternative engine technologies (this will be done in a separate calculation in EPA's rulemaking modeling). For example:
   a. Downsizing the engine based on adding turbocharging and direct injection
   b. Changing from a traditional I4 internal combustion engine and 6-speed automatic transmission to a hybrid powertrain configuration.

B.1.4 Mass-Reduction and Cost Analysis Process Overview

As previously stated, the Toyota Venza cross-over utility vehicle (CUV) was initially chosen as the baseline vehicle for evaluating mass-reduction opportunities, for both the low- and high-development mass-reduction analyses, in the prior ICCT Phase 1 project. Since the work conducted by FEV and their contractors, is an extension of the original Phase 1 low develop assessment, the Toyota Venza CUV was also evaluated in the phase 2 analysis.

For the Phase 2 analysis, a conscious effort was made to procure a vehicle with a content level similar to the one evaluated in the Phase 1 analysis ensuring optimal continuity between the two studies. For reference the vehicle identification number (VIN) for the 2009 Venza evaluated in the Phase 1 analysis is 4T3ZE11A09U002202. The VIN for the 2010 Venza evaluated in the Phase 2 analysis is 4T3ZA3BB1AU036880

The mass-reduction and cost analysis process overview is defined in five (5) process steps as shown in **Figure B-1**. Additional details on the processes and tools used in each of the steps can be found in Sections C and D.

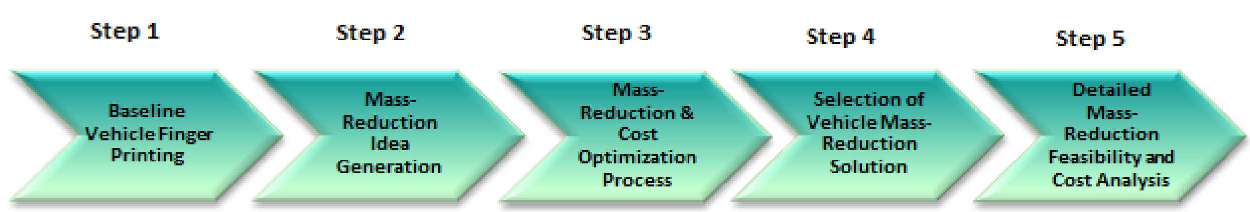


Figure B-1: Key Steps in the Mass-Reduction and Cost Analysis Project

<u>Step 1</u>: "Finger print" the baseline vehicle (i.e., current production Toyota Venza) to gain a thorough understanding of the vehicle content and key attributes. The process involved a systematic disassembly of the vehicle capturing key component information in detailed bill of materials. In addition the finger printing process involved building CAE models of the some of the baseline systems, such as BIW, to establish performance attribute baselines from which new technology configurations could be validated against.

<u>Step 2</u>: Review and analyze the Lotus mass-reduction ideas as well as research new potential mass-reduction ideas. The primary objective in step 2 of the process was to establish a comprehensive list of mass-reduction ideas at a component level. In addition a system was established to grade the mass-reduction ideas in terms of implementation readiness, functionability/performance risk, value (i.e., cost/mass-reduction), etc. For selected systems (e.g. body-in-white structure) preliminary validation work was initiated to support grading of the mass-reduction concept.

Step 3: Utilize an optimization process to determine the best component ideas to move forward with to develop “best value” vehicle solutions. Mass-reduction ideas were sorted and grouped at the component level in terms of their value (i.e., cost/kg). Two sets of rules were established to group components, assemblies/sub-subsystems, subsystems and systems in optimized mass-reduced vehicle solutions. The more conservative approach from a cost perspective was called the “Low Cost Solution”. The approach which supported more emphasis on mass-reduction versus cost was termed the “Engineered Solution”.

Step 4: Evaluate various vehicle solutions in terms of the net mass-reduction, estimated cost impact and comparison of risk. Based on these parameters the team chose a vehicle mass-reduction solution. The solution was a compilation of mass-reduced components, sub-subsystems, subsystems and systems.

Step 5: Develop a detailed mass-reduction feasibility and cost analysis on the vehicle solution selected in step 4. The detailed mass-reduction feasibility analysis focused on developing and refining the component mass-reduction estimates made in step 2 of the process. In addition any validation work required on the mass-reduction ideas was implemented in this step. Once the final details on the component mass-reduction were established incremental cost models were established to determine the direct manufacturing cost differences between the baseline production components and new mass-reduced components. Mass-reduction and incremental direct manufacturing cost values were established starting at the component level building up to a vehicle level.

Additional details on the methodology are coved in **Section D (Mass Reduction Analysis Methodology)** and **Section E (Cost Analysis Methodology).**

C. Mass-Reduction and Cost Analysis Assumptions

C.1 Mass-Reduction Analysis Assumptions

A significant amount of the mass-reduction ideas presented in this report are based on implementation of ready bookshelf technologies. By selecting mass-reduction ideas which are already in production and/or have gone through significant research and development by OEMs, automotive parts suppliers and/or automotive raw material suppliers, the implementation risk and manufacturing feasibility risk are considered far less. The end result is a list of ideas with high probability of implementation success.

The general, sources of information used to develop mass-reduction ideas are shown in **Error! Reference source not found.**. In almost all mass-reduction cases, assumptions were required to take the mass-reduction ideas from surrogate components and transfer them to Toyota Venza specific components. This included normalizing the surrogate parts sizes and weights to Toyota Venza specific parts and making high level engineering adjustments for function and performance differences. Unique for the body-in-white (BIW) structure portion of the analysis, CAE tools were used to develop and model the mass-reduction changes and evaluate these changes against the baseline configuration using some industry recognize evaluation procedures. Note because the Body System - Group A (BIW and Closures) is the largest system contributor to mass-reduction and is the primary system associated with crash safety, the additional CAE work was performed.

Figure C-1: Sources of Information used to develop Mass-Reduction Components

The introduction of any new vehicle technologies for increased function, improved performance, and/or reduction in mass, does not come without inherent challenges and risks. Large dedicated engineering teams at the automotive vehicle manufacturing level and automotive parts supplier levels spend years developing components for vehicle specific application to ensure the designed components meet the component, subsystem, system and vehicle function and performance specifications. A great deal of this work involves accounting for component interactions both positively and negatively [e.g., Noise Vibration Harshness (NVH), durability, corrosion, calibration, etc.]

Due to the nature of this type of project, and the inherent analysis limits (e.g. project duration, resources, facilities, funding, etc.) the level of validation which can be conducted on the components within each vehicle system, as well as with assessing the synergistic impact (both positive and negative) is very limited. Though this doesn't imply the mass-reduction ideas are not viable options. It only suggests that significant engineering (i.e., what is normally required to develop a vehicle) is required to design and develop the mass-reduced components into a vehicle specific application in some cases. In many industries, especially the automotive industry, benchmarking vehicle components and technologies (similar to methodology employed in this analysis) is a significant part of OEM and supplier research and development and a mechanism of incubating new vehicle technologies.

Within the scope of FEV's analysis no consideration is given to the exact quantity and timeframe of new mass-reduced technologies introduced into a vehicle platform. The added complexity, associated risk, time period of phase-in, etc. and associated impact to costs is addressed through the EPA's cost modeling factors (e.g., Indirect Cost Multipliers [ICM], learning factors).

In Section C.2 below addition information on the cost analysis assumptions are covered.

Within the mass-reduction and cost analysis results sections (**Sections E** and **F**) additional details on the mass-reduction assumption made and level of validation are captured.

C.2 Cost Analysis Assumptions

For both the baseline Toyota Venza components and the new mass-reduced replacement components the same universal set of assumptions are utilized in order to establish a constant framework for all costing. The primary assumption is that the OEM and suppliers have the option of tooling up either the baseline components (i.e., production stock Venza components) or the mass-reduced components. The same product maturity levels, manufacturing cost structure (e.g., production volumes, manufacturing locations, manufacturing period), market conditions, etc. exist for either technology. This common framework for costing permits reliable comparison of costs between new (i.e., mass-reduced components) and baseline (i.e., production stock Toyota Venza components) components. In addition, having a good understanding of the analysis boundary conditions (i.e., what assumptions are made in the analysis, the methodology utilized, what parameters are included in the final numbers, etc.), a fair and meaningful comparison can be made between results developed from alternative costing methodologies and/or sources.

Additional details on the costing factors included in the cost analysis can be found in **Section E.**

Table C-1 captures the primary universal cost analysis assumptions which are applicable to both the new and baseline configurations evaluated in the analysis.

Table C-1: Universal Case Study Assumption Utilized in the Mass-Reduction Analysis

Item	Description	Universal Case Study Assumptions
1	Incremental **Direct** Manufacturing Costs (Included in the analysis)	A. Incremental **Direct** manufacturing cost is the incremental difference in cost of components and assembly, to the OEM, between the new technology configuration (i.e., mass-reduced components/assemblies) and the baseline technology configuration (i.e., the production stock Venza components/assemblies). B. This value does not include **Indirect** OEM costs associated with adopting the new technology configuration (e.g. tooling, corporate overhead, corporate R&D, etc.).
2	Incremental **Indirect** OEM Costs (Not included within the scope of this cost analysis)	A. Indirect Costs are handled through the application of **"Indirect Cost Multipliers"** (ICMs) which are not included as part of this analysis. The ICM covers items such as ..... a. OEM corporate overhead (sales, marketing, warranty, etc.) b. OEM engineering, design and testing costs (internal & external) c. OEM owned tooling B. Reference EPA report EPA-420-R-09-003, February 2009, "Automobile Industry Retail Price Equivalent and Indirect Cost Multiplier" for additional details on the develop and application of ICM factors. C. Reference EPA & NHTSA, report EPA-420-D-11-901, November 2011 "Draft Joint Technical Support Document: Proposed Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards & Corporate Average Fuel Economy Standards," for additional details on the develop and application of ICM and learning factors.
3	Incremental Production Tooling Costs (Included in the analysis)	A. Incremental Production Tooling cost is the differential cost of tooling to the OEM, between tooling up the new technology configuration (i.e., mass-reduced components/assemblies) versus the baseline technology configuration (i.e., the production stock Venza components/assemblies). B. Analysis assumes all tooling is owed by OEM C. Tooling includes items like stamping dies, plastic injection mold, die casting molds, weld fixtures, assembly fixtures, gauges, etc.
4	Product/Technology Maturity Level	A. Mature technology assumption, as defined within this analysis, includes the following: a. Well developed product design b. High production volume (200K-450K/year) c. Products in service for several years at high volumes c. Significant market place competition B. Mature Technology assumption establishes a consistent framework for costing. For example, a defined range of acceptable mark-up rates. a. End-item-scrap 0.3-0.7% b. SG&A/Corporate Overhead 6-7% c. Profit 4-8% d. ED&T (Engineering, Design and Testing) 0-6% C. The technology maturity assumption does not include allowances for product learning. Application of a **learning curve** to the calculated incremental direct manufacturing cost is handled outside the scope of this analysis.

Item	Description	Universal Case Study Assumptions
5	Selected Manufacturing Processes and Operations	A. All operations and processes are based on existing standard/mainstream Industrial practices. B. No additional allowance is included in the incremental direct manufacturing cost for manufacturing learning. Application of a **learning curve** to the developed incremental direct manufacturing cost is handled outside the scope of this analysis.
6	Annual Capacity Planning Volume	Toyota Venza Specific Components 200,000 Units Shared Platform Components 450,000 Units
7	Supplier Manufacturing Location	United States of America
8	OEM Manufacturing Location	United States of America
9	Manufacturing Cost Structure Timeframe (e.g. Material Costs, Labor Rates, Manufacturing Overhead Rates)	2010/2011Production Year Rates
10	Packaging Costs	A. Calculated on all Tier One (T1) supplier level components. B. For Tier 2/3 (T2/T3) supplier level components, packaging costs are included in T1 mark-up of incoming T2/T3 incoming goods.
11	Shipping and Handling	A. T1 supplier shipping costs covered through application of the Indirect Cost Multiplier (ICM) discussed above. B. T2/T3 to T1 supplier shipping costs are accounted for via T1 mark-up on incoming T2/T3 goods.
12	Intellectual Property (IP) Cost Considerations	Where applicable IP costs are included in the analysis. Based on the assumption that the technology has reached maturity, sufficient competition would exist suggesting alternative design paths to achieve similar function and performance metrics would be available minimizing any IP cost penalty.
13	Platform Synergies Considerations	No consideration was given (positive or negative) to x-platform synergies. Both the baseline and mass-reduced technology configurations were treated the same. a. Common parts used across different models b. Parts homologated / validated / certified for various worldwide markets
14	Derivative Model Considerations	No consideration was given to derivative models. Both the baseline and mass-reduced technology configurations were treated the same. a. 2 wheel, 4 wheel or all wheel drive applications b. Various engine / transmission options with models c. Various towing / loading / carrying capacities
15	Material Cost Reductions (MCRs) on analyzed hardware	Only incorporated on those components where it was evident that the component design and/or selected manufacturing process was chosen due to actual low production volumes (e.g. design choice made to accept high piece price to minimize tooling expense). Under this scenario, assumptions where made, and cost analyzed assuming high production volumes.
16	Operating and End-of Life Costs	No new, or modified, maintenance or end-of-life costs, were identified in the analysis.
17	Stranded Capital or ED&T expenses	No stranded capital or non-recovered ED&T expenses were considered within the scope of this analysis. It was assumed the integration of new technology would be planned and phased in minimizing non-recoverable expenses.

D. Mass Reduction Analysis Methodology

D.1 Overview of Methodology

As outlined in **Section B.1.4,** there are five (5) major process steps implemented in the mass-reduction and cost analysis project. For each of the five (5) process steps involved in the generic process, two (2) analysis road maps were established based on the type of analysis work and project goals required for each (**Figure D-1**). These two primary project goals can be summarized as:

1. Project Task 1: to review the existing Phase 1 Lotus mass-reduction ideas for all remaining systems evaluated and assess the implementation risk, manufacturing feasibility, and value (cost/mass-reduction). The costs calculations referenced in the value equations to be detailed and transparent similar to previous powertrain cost analyses. In cases where additional or greater value mass-reductions component ideas are identified, include them in the analysis.

2. Project Task 2: to validate the body-in-white (BIW) structural mass-reduction ideas recommended by Lotus Engineering using industry-recognized NVH and crash computer aided engineering (CAE) methods and tools. If the Lotus recommended ideas resulted in degradation to the baseline BIW structure, alternative mass-reduction solutions were investigated and validated using industry recognized tools and methods.

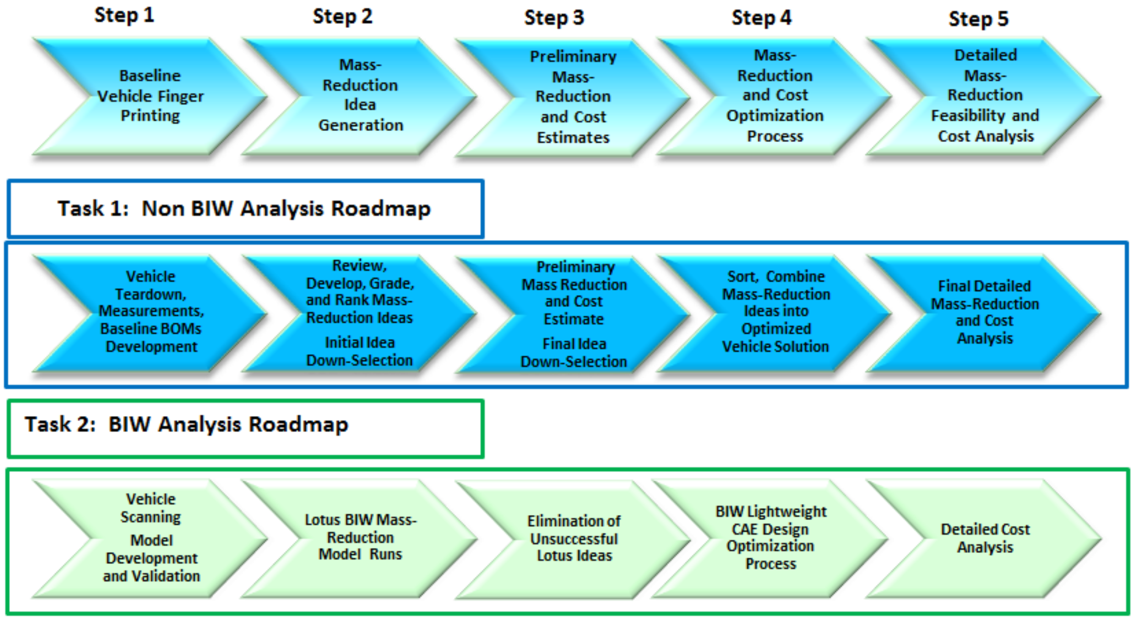


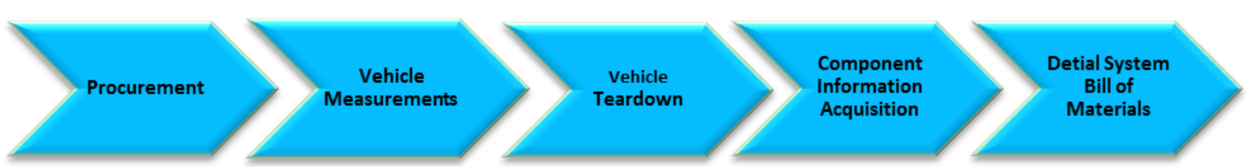
Figure D-1: Project Analysis Roadmaps Based on Project Tacks

Since the mass-reduction objectives were somewhat different for each of the primary project goals, two roadmaps and two teams were developed to support the work. During Project Task 1, FEV were lead and their subcontractor Munro and Associates supported the analysis work; Project Task 2, FEV's subcontractor EDAG took lead on the analysis and FEV supported.

In the methodology discussion which follows, the analysis roadmaps for each task are discussed in detail.

D.2 Project Task One – Non Body-In-White Systems Mass-Reduction and Cost Analysis

D.2.1 Baseline Vehicle Finger Printing



The process started with the purchase of the baseline vehicle (2010 Toyota Venza, VIN 4T3ZA3BB1AU036880). Along with the vehicle acquisition, additional BIW components were purchased upfront due to concerns with damaging the BIW panels during disassembly and while scanning the components.

Before beginning the disassembly process, key vehicle measurements were made, including the four (4) corner vehicle weight, vehicle ground clearance, and positions of key components (e.g., engine, fuel tank, exhaust, etc.) as assembled in the vehicle. The global vehicle component positions were attained through a white light scanning (WLS) process. The same process was used to capture the geometry of the key components required for the BIW NVH and crash analysis. (More discussion on WLS is captured as part of Task 2 methodology, **Section D.3**)

Following the vehicle measurements, a systematic, detailed vehicle disassembly process was initiated. The initial vehicle disassembly process was initially completed at a high level (e.g. engine-transmission assembly, door assemblies, rear-hatch assembly, seats, exhaust assembly). At each stage of the disassembly process, the same order of events took place: (1) WLS when applicable, (2) process mapping of part(s) to capture the part removal process (inverse - part assembly process), (3) photographing of part assembled and removed from the vehicle, and (4) initial part attributes (i.e., part weight and quantity). As each part was removed from the vehicle, it was logged into a general vehicle level comparison bill of materials (CBOM).

After the vehicle was completely disassembled, major modules were further broken down into respective system groups. For example, the components within the front sub-frame module (e.g., brake rotors, brake calipers, drive shafts, suspension struts, springs, etc.) were removed from the module and grouped in their respective systems (**Figure XXX**). A process similar to the vehicle disassembly process was followed ensuring applicable information was captured (e.g., weight, geometric size, process map, photographs, WLS etc.) and recorded for each component. During this step of the process System CBOMs were created. All components belonging to a system (e.g. engine, transmission, body, brakes, fuel, etc.) were physically grouped together and captured together in system CBOM.

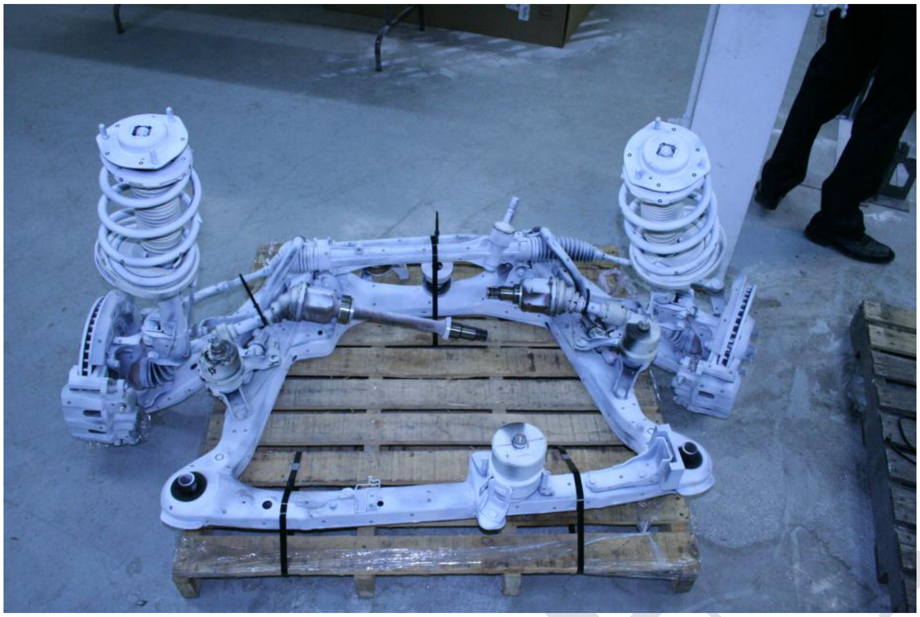
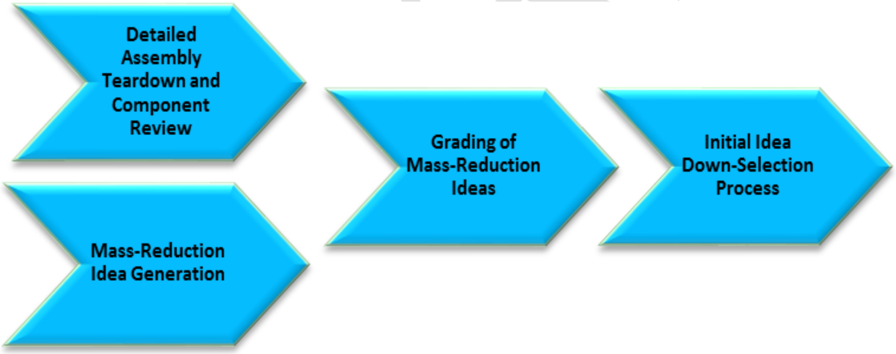


Image D-1: 2010 Toyota Venza Front Subframe Module as Removed During the Teardown Process
(Source: FEV, Inc. photo)

D.2.2 Mass-Reduction Idea Generation



Upon completion of assembly part binning and tracking, a parallel and iterative process of teardown and mass-reduction idea generation was initiated. In general, the assembly level teardown involved a full, detailed disassembly of parts into the lowest level manufactured component forms. This involved both destructive and non-destructive teardown processes. For example, the fuel tank, shown in **Image D-2**, was fully disassembled into the individual manufactured components. From this detailed teardown an accurate assessment of the component materials, weights, hidden design details, and manufacturing processes utilized to manufacture the production stock Venza fuel tank were collected. At all teardown levels, the bill of materials were updated tracking key component information (e.g., parts, quantities, weights, etc.).

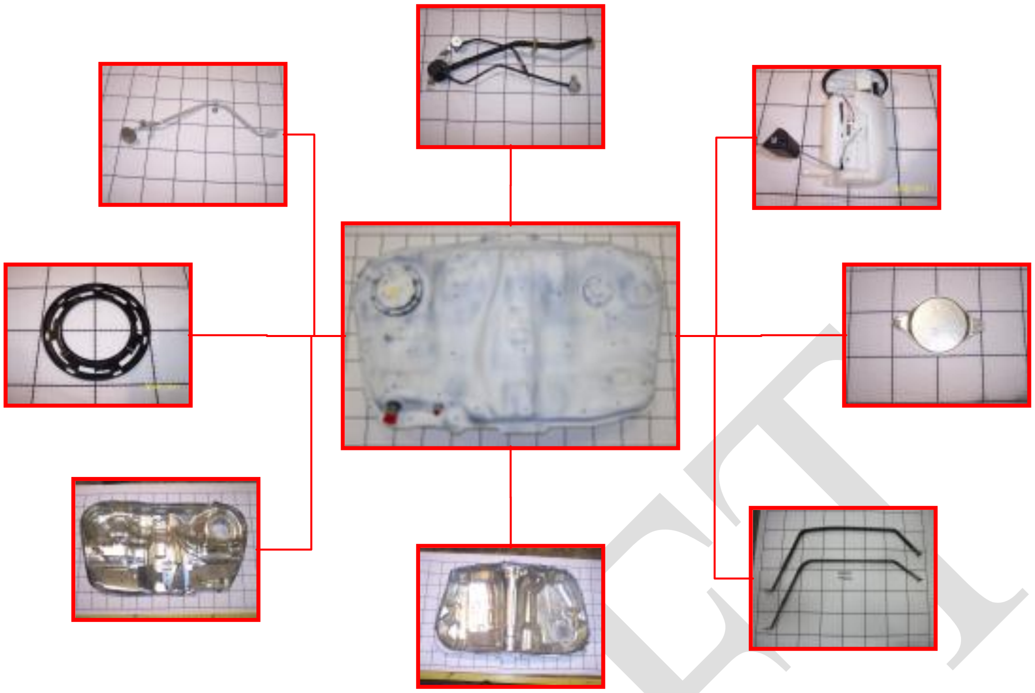


Image D-2: Toyota Venza Fuel Tank Disassembled

In parallel to hardware being disassembled, vehicle system leads (i.e., project engineers responsible for generating mass-reduction ideas for a particular vehicle system) began the mass-reduction idea generation process. The process started by logging the Lotus Engineering Phase 1 report mass-reduction ideas (report name "An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Program") into the FEV Brainstorming Template (FBT). The FBT contains five (5) major sections:

- Part 1: General Part Information Entry
- Part 2: Mass Reduction Idea Entry
- Part 3: Primary Idea Ranking & Down-Selection Assessment
- Part 4: Quantitative Mass-Reduction and Cost Analysis Estimation Entry
- Part 5: Final Ranking and Down-Selection Process Assessment

In this initial idea generation phase of the analysis, Parts 1 and 2 of the brainstorming template are completed. In addition to logging all the Lotus Engineering ideas in the brainstorming template, modified and new ideas were added based on industry research by the vehicle system teams. As shown in **Figure C-1,** several sources were utilized for gathering mass-reduction ideas, including automotive vehicle manufacturers, automotive parts suppliers, raw material suppliers, benchmarking suppliers, and non-automotive part design and manufacturing technologies. The medium for attaining the information came from published articles, papers and journals, supplier websites, supplier published presentation materials, consultation with suppliers, access to benchmark databases (FEV internal, Munro and Associates internal, EDAG internal, A2MAC1 purchased subscription), and internal brainstorming storming sessions. In **Appendix H.3** many of the published documents reviewed and suppliers contacted are listed. Also in **Section F,** "**Mass-Reduction and Cost Analysis Results,"** a significant amount of the details supporting the mass-reduction ideas are captured (e.g., sources of information, applications in production, manufacturing process details, etc.).

All mass-reduction ideas gathered were entered into their respective vehicle system brainstorming templates and connected to the BOMs via a standardized number and naming convention. The process of detailed assembly teardown and generating mass-reduction ideas was an iterative process taking approximately one-third of the overall project duration (four months).

Upon completion of the idea generation phase, the preliminary idea ranking and down-selection process began. In Part 3 of the brainstorming template (***Step 1 in the down selection process)***, the ideas were ranked by the team based on a five- (5-) parameter ranking system: (1) Manufacturing Readiness Risk, (2) Functionality Risk, (3) Estimated Percent Change in Weight, (4) Estimated Change in Piece cost, and (5) Estimated Change in Piece Cost as a Result of Tooling. As shown in **Figure D-2,** there were predefined ranking values for each parameter. The potential ranking values for each parameter were set considering the importance of each parameter within the group. The final idea ranking is the multiple of the five parameter rankings. The best possible score is 1 (i.e., 1x1x1x1x1) which is representative of an idea already in high automotive production, performs equal to or better than the current production Venza part, is expected to yield a 20% mass-reduction, and is cost neutral or a saving relative to the current production piece cost and tooling. The highest achievable value is 10,500 (i.e., 5x10x10x7x3) which represents the opposite extreme. Since one of the boundary conditions for this analysis was low development mass-reduction, the majority of the mass-reduction ideas selected were conservative, thus resulting in a ranking value between 1 and 200.

A ranking of 50 was chosen as the cut-off for the initial down-selection process. Any mass-reduction ideas with a value greater than 50 were removed from the analysis; although, there were a few exceptions, dependent on the number of ideas for a given system.

Primary Idea Down-Select Ranking Process					
Manufacturing Readiness Risk "Possible for 2017 Timeframe"	Functionality Risk (Driveability, Performance, Crash) "Will it work"	Estimated Percent Change In Weight	Estimated Percent Change In Piece Cost	Tooling Cost/Part	Total Ranking
< 1 > High Production Automotive < 2 > High Production Other < 3 > Low Production < 5 > Still In Development/R&D	< 1 > Equal or Better < 2 > Vehicle Ancillary Function Degrade < 5 > Vehicle Minor Primary Function Degrade < 10 > Vehicle Major Primary Function Degrade	< 1 > 20% or Greater Decrease < 2 > 10-20% Decrease < 3 > 0-10% Decrease < 10 > Weight Increase	< 1 > No Change or Decrease < 2 > 0-10% Increase < 3 > 10-25% Increase < 7 > > 25% Increase	< 1 > Same or Decrease < 2 > 0-25% Increase < 3 > >25% Increase	Low Ranking = High Potential Solution High Ranking = Low Potential Solution
1	1	3	2	1	6
1	1	3	2	1	6
					0
2	1	1	3	2	12
3	1	1	7	2	42
1	1	3	3	2	18

Figure D-2: Primary Idea Down-Select Process Excerpt from FEV Brainstorming Template

D.2.3 Preliminary Mass-Reduction and Cost Estimates

Ideas that had an initial ranking of less than 50 were considered as potential high probability mass-reduction ideas. The mass-reduction ideas consisted of ideas from the Lotus Phase 1 report as well as new mass-reduction ideas.

For each of these ideas which made the first cut, the project team then calculated the potential mass-reduction and cost impact of each idea. These calculations were high level calculations based on initial information gathered for each idea. Sources included benchmark data of surrogate lightweight designs, automotive material and part suppliers, and high-level engineering estimates based on material densities, material costs, and anticipated manufacturing cost differences based on processing changes. To reiterate, these are high-level calculations providing a more objective measure of the value (cost/kilogram) for each mass-reduction idea.

The mass-reduction and cost estimates were added beside each relevant idea in the FEV brainstorming matrix (Part 4 of the matrix). Using the estimated mass, estimated cost impact, and Total Ranking (Part 3 of FBT), cost-versus-mass and Total Ranking-versus-mass calculations were made (**Figure D-3**). The calculated values, found in Part 5 of the brainstorming template, were used in the final down-selection process when comparing competing mass reduction ideas on a similar part. For example, several alternative material choices were available for brake caliper pistons (e.g., forge aluminum, cast aluminum, phenolic plastic, titanium) with compatible "Total Ranking" values, which made it difficult to select the best option based on the preliminary ranking process. The preliminary quantitative calculations (i.e., cost impact/mass-reduction, total ranking/mass reduction) provided additional information required to help select the best idea(s) moving forward in the analysis.

	Estimate Weight and Cost Impact on "Best Ranked Idea(s)" (Total Ranking ≤ 50)		Final Idea Down-Selection Using Total Ranking, Unit Weight Save Cost, and Ranking/Incremental Weight Change, Identify Concept for Evaluation			
Total Ranking Low Ranking = High Potential Solution High Ranking = Low Potential Solution	Estimated Incremental Weight Change "kg"	Estimated Incremental Piece Cost Impact "$"	Unit Weight Save Cost "$/kg"	Ranking/Incremental Weight Change "Total Ranking #/kg"	Decision Supporting Information (if Required)	Selected Idea Add "1a,1b,1c,1d,X or D" in box for Selected Concept
6	0.048	-$0.81	-$16.97	125.000		X
6	0.228	-$1.63	-$7.15	26.316		
0	6.064	$0.67	$0.11	0.000	approx = 2009 Toyota Camry (F:11.7-10.8)	1a
12	2.282	-$3.02	-$1.32	5.259	given to Manfred@Munro to investigate: assume hardware costs? machining?	1c

Figure D-3: Estimated Weight and Cost Impact (Part 4) and Final Ideal Down-Selection (Part 5) Excerpt from FEV Brainstorming Template

In many cases team members considered together the preliminary rankings (Part 3 of FBT), the magnitude of the mass-reduction savings (Part 4 of the FBT), and the value of the mass-reduction ideas (Part 5 of the FBT) to determine the final mass-reduction ideas to move forward at the component and assembly level.

Upon completion of the final down-selection process, mass-reduction ideas were grouped/binned together based on their value (i.e., cost/kilogram). There are five (5) cost groups total, plus one group for tracking decontenting ideas that reduce mass, but at the sacrifice of function and/or performance (**Figure D-4**). Decontenting ideas were tracked in the analysis but never included in the final calculations.

At this stage of the analysis, only mass-reduction ideas were captured. These are not necessarily complete mass-reduced component or assembly solutions, as several ideas may have been combined to formulate a component or assembly solution. The process of combining ideas occurs in the next phase of the analysis, which is referred to as the mass-reduction optimization phase.

<u>Mass-Reduction Idea Grouping</u>
●Five cost groups were established to group ideas based on their average cost/kilogram weight save:
Level A: ≤ $0.00/kg (i.e., ideas that either save money or add zero cost)
Level B: >$0.00 to ≤ $1.00
Level C: >$1.00 to ≤ $2.50
Level D: >$2.50 to ≤ $4.88
Level X: > $4.88

● One additional category exists, which is independent of the cost per weight save ratio. This sixth category is referred to as the "Decontenting" category (Level Z) and is reserved for ideas which degrade a systems function/performance by employing the mass reduction idea.

● Decontenting can occur at various functional levels: (1) comfort convenience components (e.g. cup holders, DVD player, storage concealer), (2) secondary support components (e.g. spare tire, jack), or (3) at a primary function level (e.g. downsized engine w/ less horsepower)

Figure D-4: Mass-Reduction Idea Grouping/Binning Bases on Mass-Reduction Value

D.2.4 <u>Mass-Reduction and Cost Optimization Process</u>

The next step in the process was to take the down-selected mass-reduction ideas and find an optimal solution based on mass and cost. The goal was to combine as many mass-reduction ideas to achieve the targeted 20% vehicle mass-reduction, at the lowest possible incremental cost, at the lowest 2017 production implementation ready risk (design and manufacturing).

To achieve an optimized vehicle solution, mass-reduction ideas were combined to formulate mass-reduced components and assemblies (also referred to as sub-subsystems). Mass-reduced components and assemblies were combined into mass-reduced vehicle subsystems; mass-reduced subsystems were combined to create mass-reduced vehicle system solutions; and, finally, mass-reduced vehicle systems solutions were combined to formulate optimized mass-reduced vehicle solutions.

Upfront it is very difficult to predict which components, subsystem, or systems offer the best value relative to mass-reduction until they are evaluated in detail against one another. From the mass-reduction idea level to the vehicle level, all possible combinations were reviewed and compared for the best value.

To help explain the optimization methodology, a mock brake system example will be used as the reference system. The same process is employed for all vehicle systems. The starting point is combining mass-reduction ideas into various component and assembly mass-reduced options. Shown in **Figure D-5**, the front rotor has 10 different ideas which can be combined into several different combinations to create different mass-reduced rotors with different cost impacts (i.e., cost/kilogram). Note, not all ideas can be combined together, as some are alternative options within the same or different cost group. Similar to how mass-reduction ideas are grouped/binned into different value groups, the sample methodology applies to components/assemblies, subsystems, and systems.

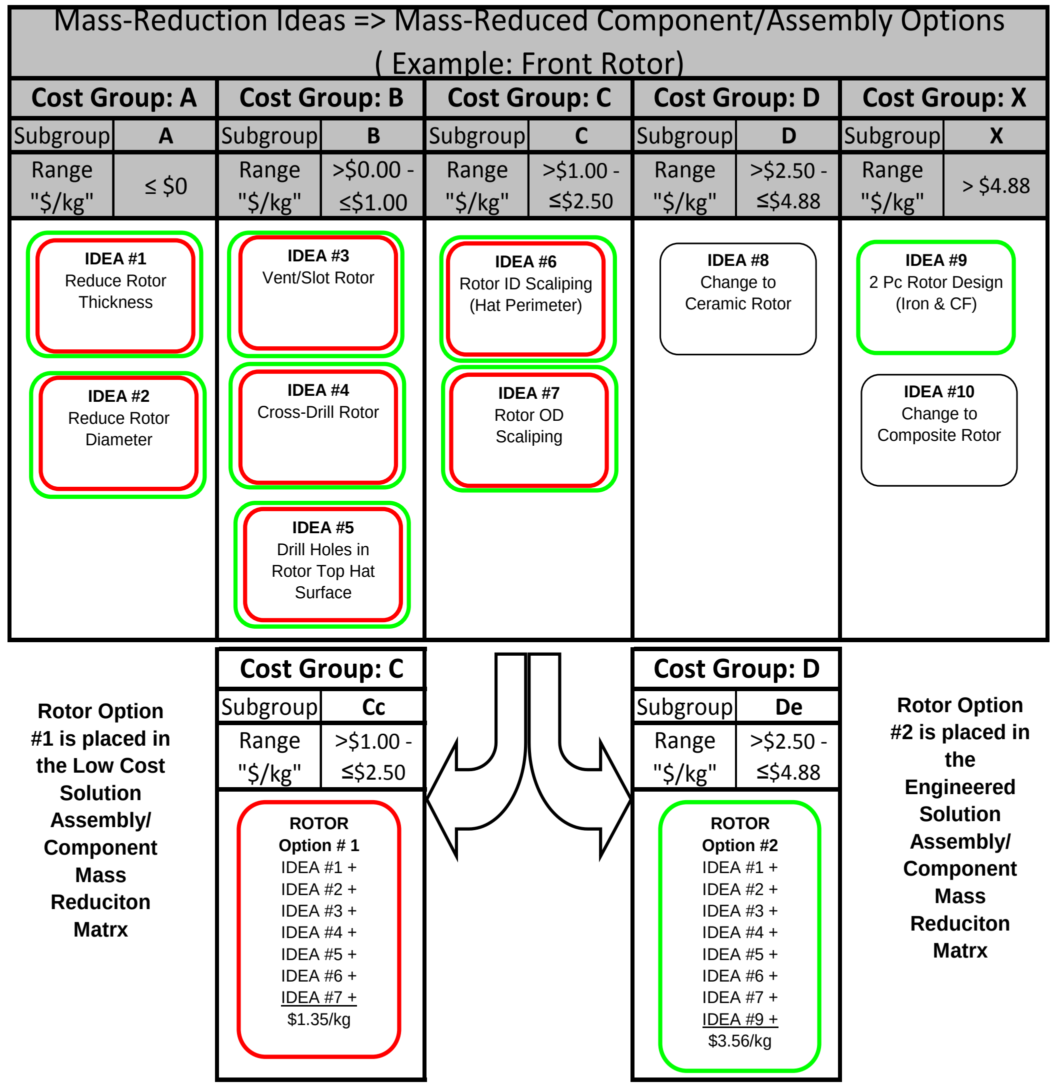


Figure D-5: Component/Assembly Mass-Reduction Optimization Process

Two sets of boundary conditions were established to standardize how mass-reduced ideas were grouped into component/assembly solutions. The first set of boundary conditions drives toward a more cost conscious solution labeled the “Low Cost Solution.” The second set of boundary conditions allows more expensive mass-reduction ideas to be integrated with lower cost ideas and is referred to as the “Engineered Solution.” These same two sets of boundary conditions apply throughout the analysis at all levels (i.e., the subsystem, system, and vehicle level).

The simplest way to explain the difference between the two methodologies is with the aid of **Figure D-5**. In Option #1, Ideas #1 through #7 were summed to develop a mass-reduce front rotor. The cost impact is $1.35/kg, which puts the component solutions into Cost Group C. Because all the ideas included in the combined solution are taken from the cost group bins equal to or lower than Cost Group C (i.e., Cost Group A, Cost Group B and Cost Group C), the final solution is considered a “Low Cost Solution.” In Option #2, Idea #9 is grouped with Ideas #1 through #7 to create a mass-reduced front rotor falling in Cost Group D ($3.56/kg). Because the mass-reduced rotor combines more expensive ideas (Cost Group X) with better value ideas (Cost Groups A, B, and C), the solution is termed an Engineered Solution. An Engineered Solution can include mass-reduction ideas above and below the final solution.

At the completion of idea combining phase of the analysis, various brake subsystems exist (e.g. Front Rotor/Drum and Shield Subsystem, Rear Rotor/Drum and Shield Subsystem, Parking Brake and Actuation Subsystem, Brake Actuation Subsystem) populated with mass-reduced component solutions. Each subsystem has an Engineering Solution matrix and a Low Cost Solution matrix. The Engineering Solution Matrix (**Figure D-6**) has mass-reduced component/assembly solutions built using the Engineered Solution methodology. The intent is to try and have a component mass-reduction solution for every cost group, though this was very difficult within the timing constraints of the project. Conversely, a Low Cost Solution matrix exists, built using the Low Cost Solution methodology.

The same methodology for combining mass-reduction ideas into component/assembly mass-reduced solutions is used for combining components/assemblies into brake subsystems. The only difference, starting at the subsystem build-up level and moving forward, engineered component solutions are used to create engineered subsystem solutions and subsystem engineered solutions are used to create engineered system solutions. The subscript “e” (e.g., Ae, Be, Ce, De, and Xe) identifies the component ideas as Engineered Solutions (**Figure D-6**). The same principles apply for Low Cost Solutions: subscript “c” identifies Low Cost Solutions.

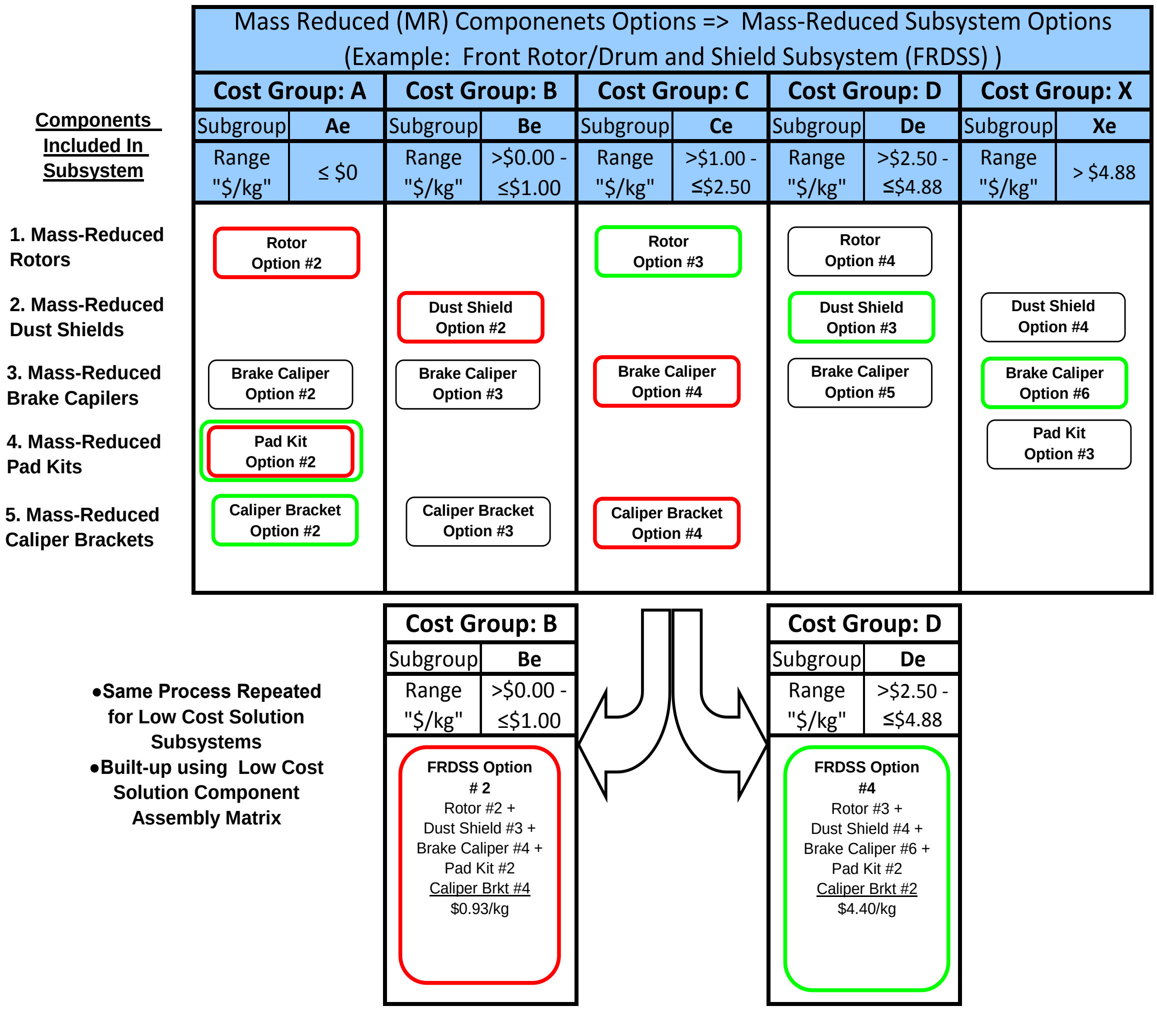


Figure D-6: Subsystem Mass-Reduction Optimization Process – Engineered Solution

At the brake system level, mass-reduced Brake Engineered Subsystem Solutions are grouped to create Brake Engineered System Solutions for several Cost Groups as shown in **Figure D-7**. The same process applies for Low Cost Solutions. The same process was followed for all 17 vehicle systems.

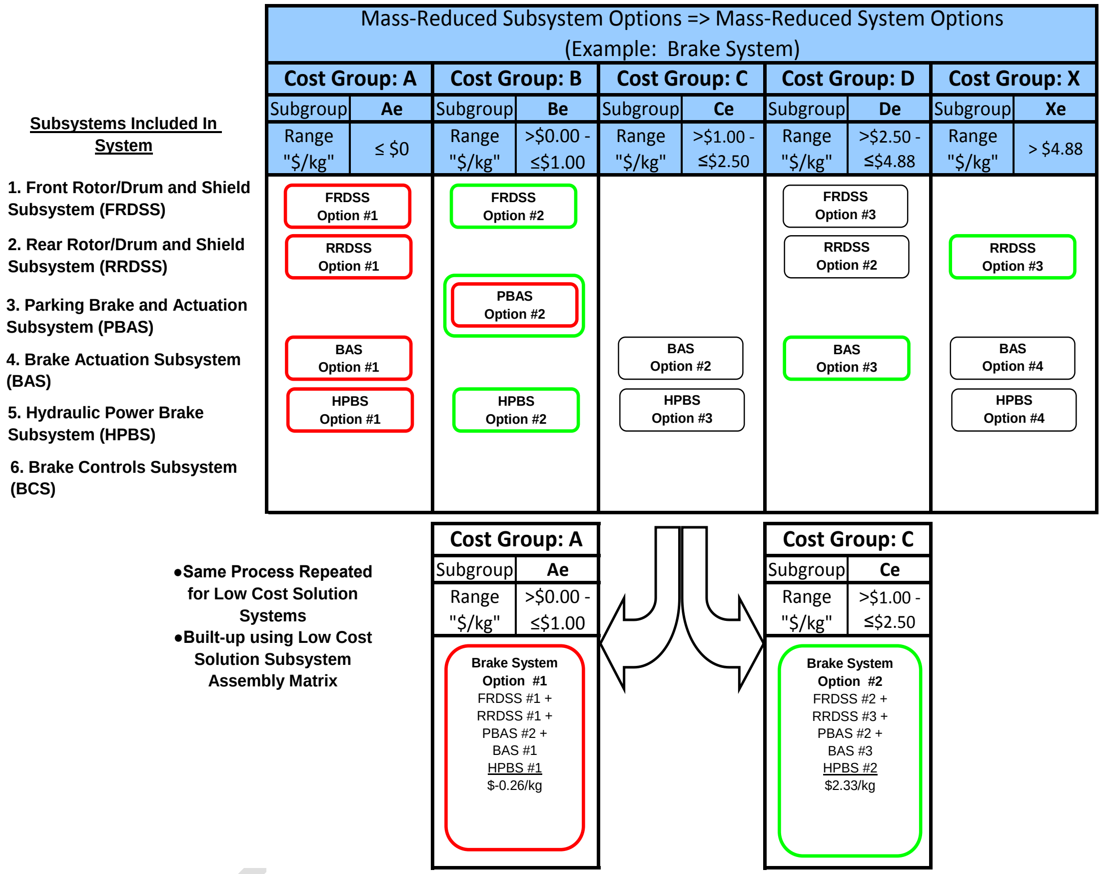


Figure D-7: System Mass-Reduction Optimization Process – Engineered Solution

The vehicle optimization process is completed using a similar methodology as previously detailed. Four different vehicle optimization processes are performed. Similar to the subsystem and system levels above Low Cost Vehicle Optimized Solutions (C) and Engineering Vehicle Optimized (E) Solutions are developed. In addition a Low Cost Vehicle Optimized Solution is developed using system solutions from both the Low Cost systems matrix and Engineering Solution systems matrix; designated Low Cost Vehicle Optimized Solution (C&E) in **Figure D-8**. Similarly an Engineering Vehicle Optimized Solution is developed using system solutions from both the Low Cost systems matrix and Engineering Solution systems matrix.

Figure D-8 shows the various optimized vehicle solutions plotted in terms of cost/kilogram versus %Vehicle mass-reduction. Based on the data, the team chose the Low Cost Vehicle Optimized Solution (C&E), which was estimated to reduce the vehicle mass by 20% at an estimated cost of $0.82/kilogram.

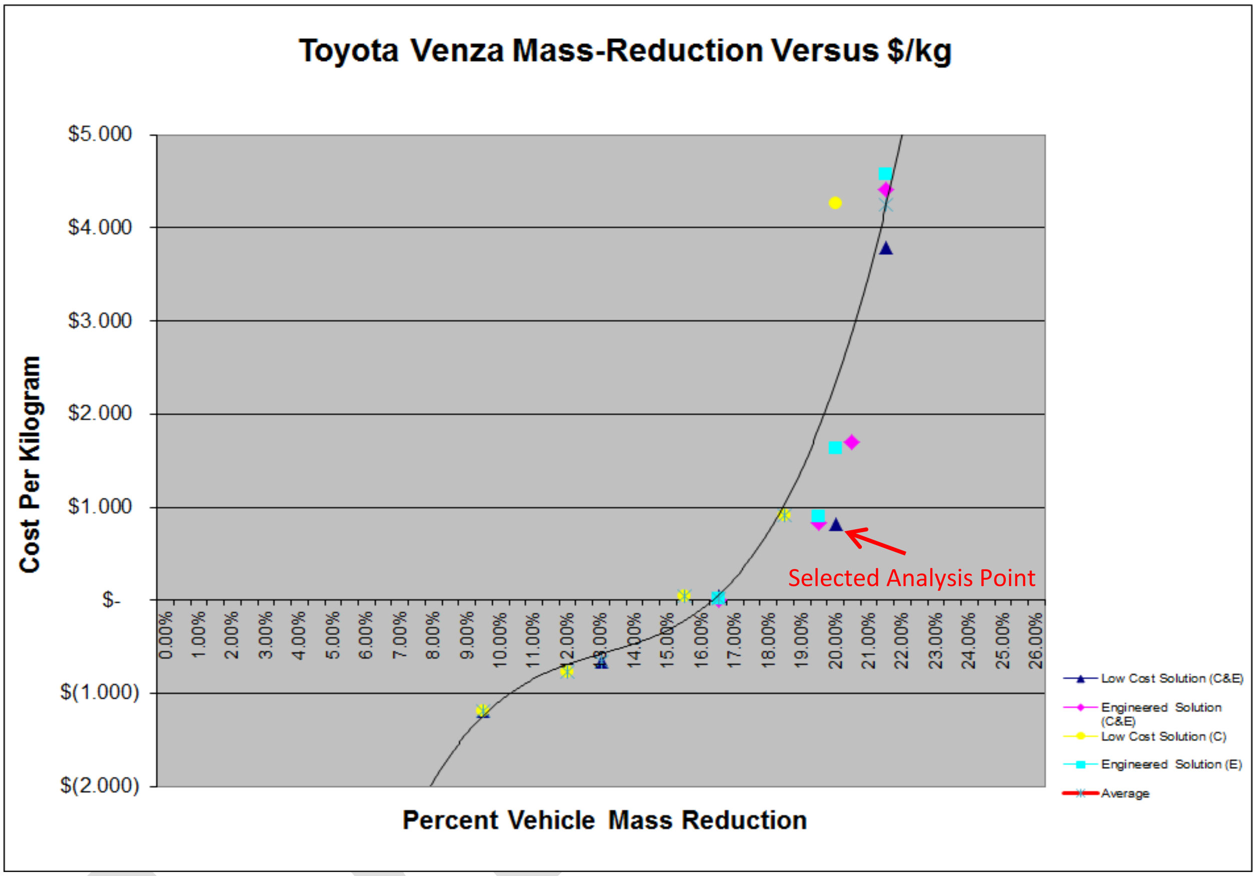


Figure D-8: Potential Mass-Reduction Vehicle Solutions Developed Through the Mass-Reduction Optimization Process

D.2.5 Detailed Mass-Reduction Feasibility and Cost Analysis

Upon the selection of the optimized vehicle solution, and the mass-reduction ideas associated with the optimized vehicle solution, the detail analysis could begin. In the detail mass-reduction feasibility analysis additional engineering work was employed to verify the mass-reduction ideas were feasible both from the design and manufacturing feasibility perspective. The additional work was centered on expanding the supporting portfolio of information gathered on the mass-reduction ideas using the same types of sources and methodology as used in the initial idea generation phase including: researching existing industry published works in mass-reduction, reference data from production benchmark databases, and speaking with material suppliers, automotive part suppliers, and alternative transportation industry suppliers. The research, the partnerships involved in the analysis, study assumptions, and calculations are all discussed in detail in **Section F** ("Mass-Reduction and Cost Analysis Results")**.** This includes the assumptions on those systems (e.g., engine, brakes, suspension, fuel, body-in-white) which took additional mass-reduction credit based on the entire vehicle getting lighter (i.e., mass compounding credit).

In some cases, the ideas originally selected for the detailed analysis did not work out. When this occurred, the team returned to the brainstorming template for similar value mass-reduction ideas to try and ensure their system target mass-reductions and costs were maintained. In other cases new alternative, better value ideas were discovered as part of the detailed analysis. When this occurred, the new, greater value mass-reduction ideas replaced the original lessor value mass-reduction ideas. From a mass-reduction perspective, some systems went up slightly from the original mass-reduction optimization model while others came down by similar amounts. Overall the difference between the originally predicted mass-reduction, from the optimized vehicle solution, to the final detailed model, for all systems other than Body Group -A- (body-in-white, bumpers, closures) was approximately +1% (greater mass-reduction for the detailed analysis).

The original target for the Body Group -A- system analysis was approximately 20% from a system perspective, or 6.2% relative to the total vehicle mass-reduction. With project timing constraints, the Body Group -A- system mass-reduction system target was reduced to 16%, or 5% relative to the vehicle. The achieved Body Group -A- mass-reduction was 12.8% relative to the system, 4% relative to the vehicle. Details on the body-in-white targets can be found in the following section (**Section D.3**).

Complete details on the costing methodology utilized in this analysis can be found in **Section E**. In addition a summary of the costing results can be found in **Section F.1**. Details on the costing assumptions made in the analysis can also be found in the various system, subsystem, and sub-subsystem sections within **Section F** of the report.

In summary, there was a shift in the cost impact between the original optimized vehicle solution and the final detailed solution. The original optimized vehicle solution predicted a cost increase of $0.82/kg for a 20% vehicle mass-reduction. In the final detailed analysis, a 18.5% mass-reduction yielded a $0.29/kilogram savings. The difference is not so surprising as the inflection point in **Figure D-10** is right around the 16% mass-reduction point. At 15%vehicle mass-reduction there is an approximate savings of $0.33/kg. At 18% vehicle mass reduction there is a positive cost impact (i.e., cost increase) of approximately $0.66/kg.

Because many of the detailed costing spreadsheet documents generated within this analysis are too large to be shown in their entirety, electronic copies can be accessed through EPA's electronic docket ID EPA-HQ-OAR-2010-0799 (**http://www.regulations.gov)**.

D.3 Project Task Two – Body-In-White Systems Mass-Reduction and Cost Analysis

The following section deals with detail methodology in developing the mass-reduction for Body Group -A- [body-in-white (BIW) structures, bumpers, and closures]. As mentioned in Section D.1, the portion of the analysis was subcontracted to EDAG due to their vast experience in BIW design and development.

To keep with the integrity of the work performed by EDAG, their report was included in the overall report in its entirety.

D.3.1 Introduction

The team evaluated the body system of a Toyota Venza using computer-aided engineering (CAE). vehicle noise, vibration, and harshness (NVH) and crash load cases were built based on physical NVH test requirements and regulatory crash and safety requirements respectively. CAE baseline models for each of the NVH and crash-load cases were built and simulated to correlate the CAE results with the test results of a similar vehicle (in this case, the 2009 Toyota Venza with panoramic roof). Upon verifying the model quality based on EDAG CAE guidelines and meeting the correlation targets (<5% difference), the EDAG baseline model was treated as the baseline reference for further development of NVH and crash-iteration models and lightweight optimization processes.

A detailed CAE evaluation of the body structure for the lightweight design of the Toyota Venza is described in this section. The weight reduction and cost effect of the lightweight design are also presented, along with the CAE evaluation cases including structural strength (torsion, bending, and modal) and regulatory crash requirements (flat frontal impact FMVSS208/US NCAP; 40% offset frontal Euro NCAP; side impact FMVSS214; rear impact FMVSS301; and roof crush resistance FMVSS216A/IIHS).

D.4 Body System CAE Evaluation Process

A CAE evaluation was conducted based on EDAG's standard best practice of re-engineering process. It includes vehicle teardown, parts scanning, and data collection of vehicle parts to build a full vehicle CAE model without the use of actual design drawings or CAD data. The typical CAE evaluation process followed for this project is shown in **Figure D-9**. Various inputs, outputs, and tools used for the steps in each process are provided in **Figure D-10**.

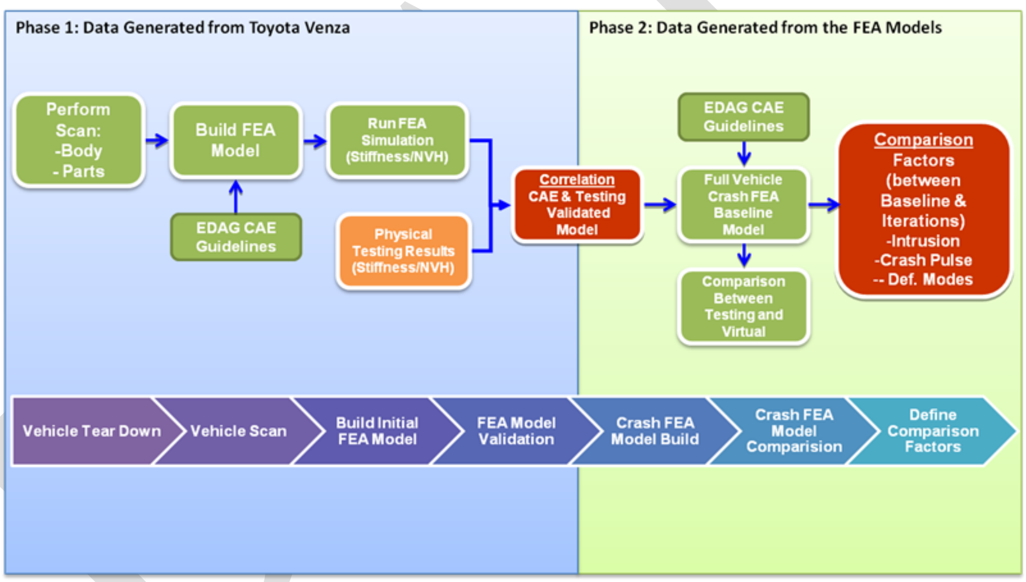


Figure D-9: CAE Evaluation Process and Components

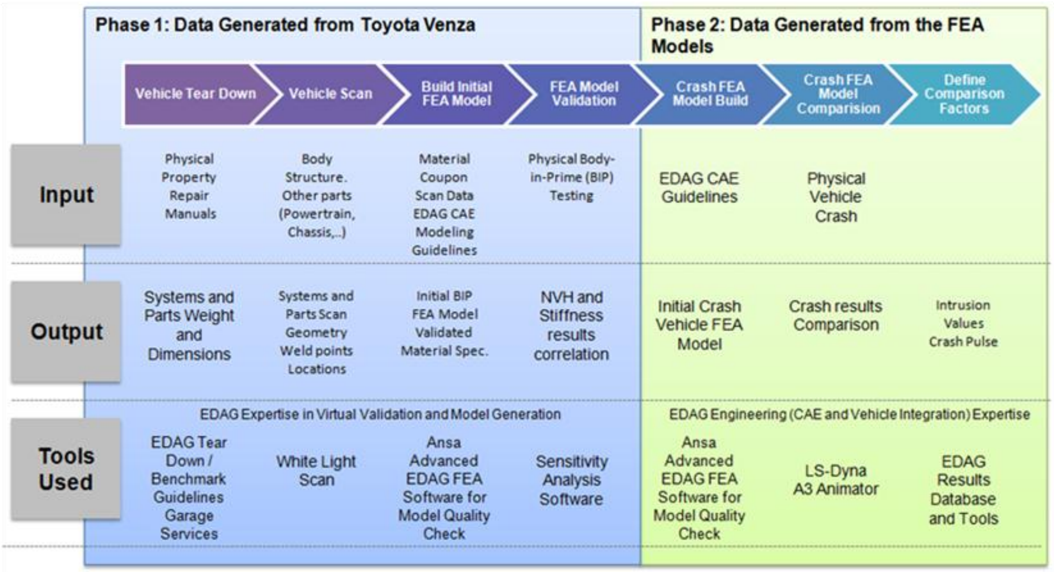


Figure D-10: CAE Evaluation Process Inputs, Outputs, and Tools

D.5 Vehicle Teardown

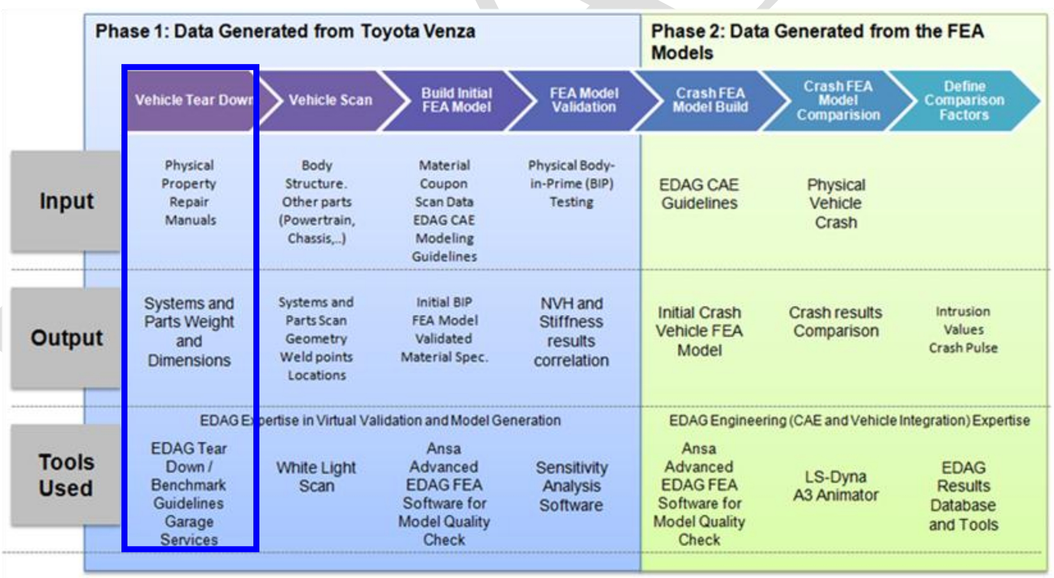


Figure D-11: Vehicle Teardown

A Toyota 2010 Venza was purchased and completely disassembled by skilled body technicians. Toyota body repair manuals were used to aid in disassembly of vehicle. Part details and metadata crucial for building the CAE model (such as part weight and thickness) were obtained and recorded in an assembly hierarchy (see **Figure D-12**).

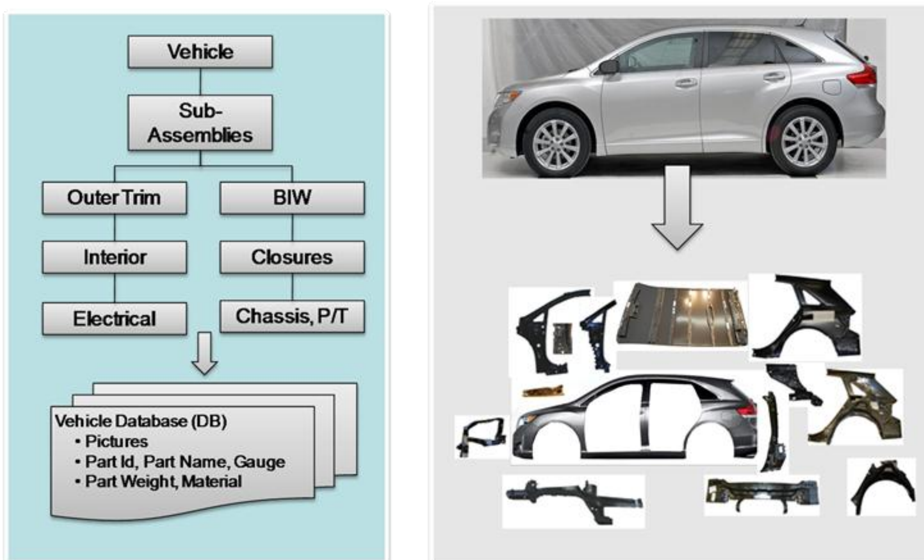


Figure D-12: Vehicle Teardown Process

A few more disassembled body parts used in the CAE model are shown in Appendix A (see Section A.1).

EDAG's project scope was to calculate a reduction in body weight for the EDAG baseline model; major subassembly weights were calculated and tabulated. This information was used as the baseline weights in the CAE evaluation process (**Table D-1**).

Area		Baseline	
System	Sub-system	System Mass	Sub-Total
Closures	Door Frt	53.2	
	Door RR	42.4	
	Hood	17.8	
	Tailgate	15.0	
	Fenders	6.8	
	Sub-Total		135.3
BIW	Underbody Asy	40.2	
	Front Structure	42.0	
	Roof Asy	31.3	
	Bodyside Asy	161.9	
	Ladder Asy	102.6	
	Sub-Total		378.0
BIW Extra	Radiator Vertical Support	0.7	
	Compartment Extra	4.5	
	Shock Tower Xmbr Plates	3.1	
	Sub-Total		8.2
Bumper	Bumper frt	5.1	
	Bumper rear	2.4	
	Sub-Total		7.5
Edag Target System Total			528.9

Table D-1: Baseline Weights

D.6 Vehicle Scanning

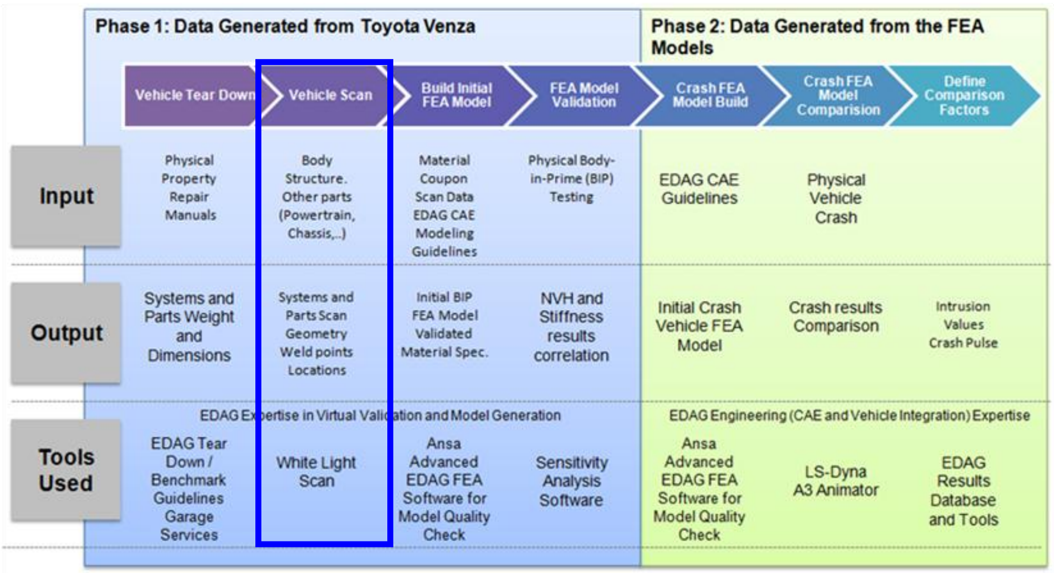


Figure D-13: Vehicle Scanning

One of the most critical inputs for building the finite element analysis model (FEA) was the digital format of the geometry of the body parts. The geometry of each part was obtained by using White Light Scanning (WLS) techniques and stored in stereo lithography (STL) format. As the vehicle was disassembled, the scanning was performed simultaneously with the vehicle teardown process starting with the full vehicle before disassembling, then progressing to the subsystem level, and lastly moving to the component level.

Even though the WLS focused on body parts, it also included the powertrain, chassis, and miscellaneous parts needed for a full vehicle FEA model. The parts required for scanning were determined based on the analysis load cases (NVH and crash) considered for the CAE evaluation. The parts required for scanning were used to determine the FEA model for analyzing the NVH and crash load cases. **Figure D-14** shows a typical methodology of identifying the parts for scanning. In addition to part geometry, the part connection (such as location and type, e.g., spot weld, seam weld, laser weld), dimensions (e.g., weld diameter, weld length), and characteristics (e.g., bushing) were also captured during the scanning process.

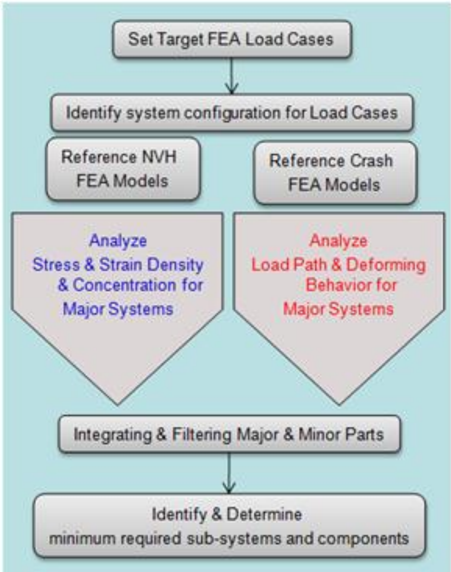


Figure D-14: White Light Scanning Part Identification Methodology

A few sample images of raw STL data of the body structure parts obtained by WLS are shown in Figure A.2.1 in Appendix A. An example of the weld point locations captured from the scanning process is also shown in Figure A.2.2 in Appendix A.

D.7 Initial FE Model

A finite element (FE) model was constructed using finite element mesh (from geometry data), part-to-part connection data, and part characteristics (material data). The geometry and connection data were obtained from the scanning process. The part material data, such as steel grades, were obtained by conducting material tests on the corresponding part samples.

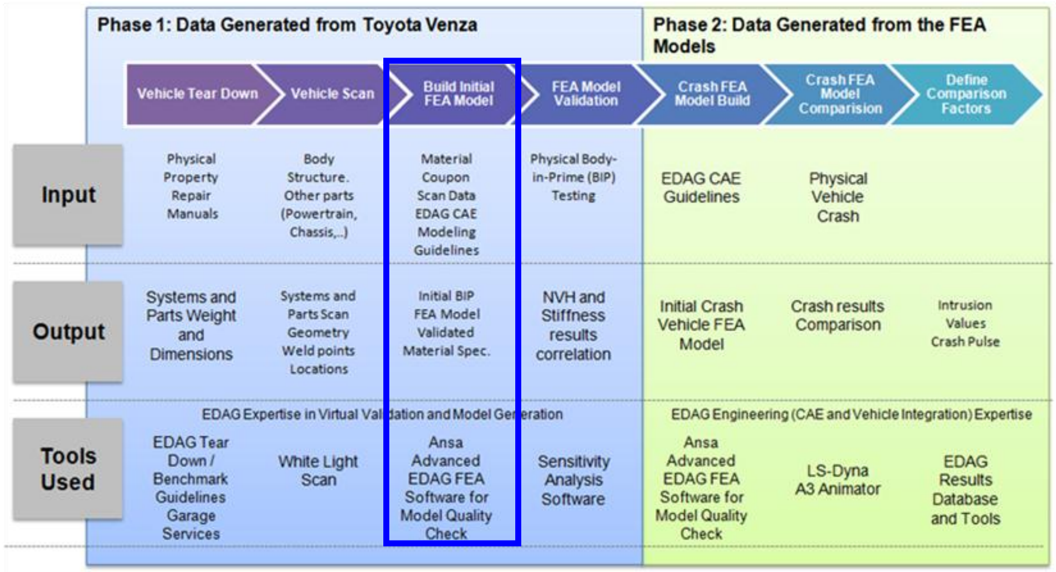


Figure D-15: Initial FE Model

D.7.1 Material Data

The Toyota body repair manual[1] was used to identify the material grades of the major parts of the body structure. The material grades found in the manual were validated by material coupon testing. The material data of the remaining parts were also obtained from coupon testing. A picture of the samples that were taken from the body is shown in Figure A.3.1 in Appendix A.

D.7.2 FE Modeling from Scan Data

A commercially available FE meshing tool (ANSA) was used to generate FE mesh from the raw STL geometry data obtained from WLS. A schematic of the process of meshing from raw STL data is shown in **Image D-3**.

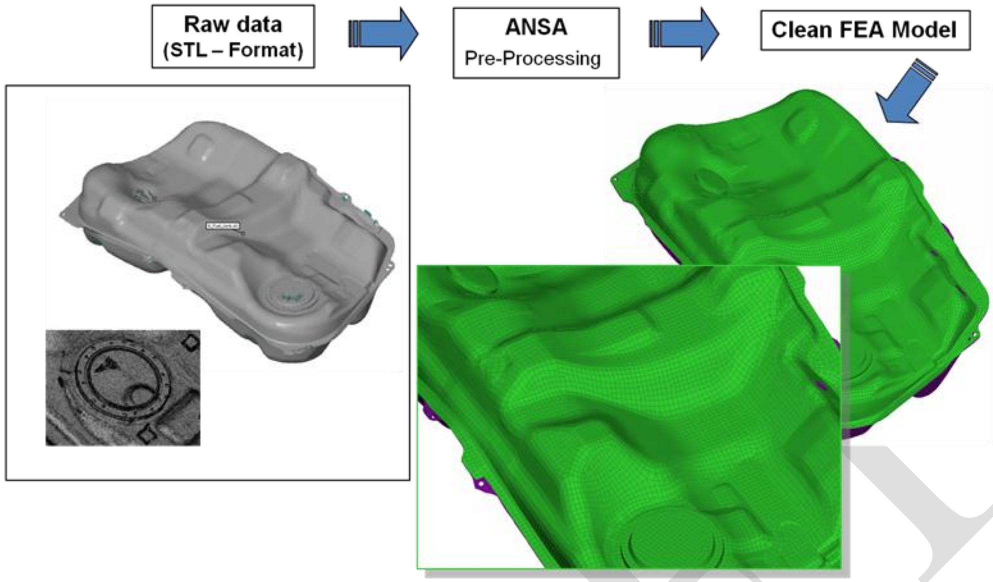


Image D-3: Mesh Generation from STL Raw Data

The raw STL data (e.g., the fuel tank) was imported into the meshing tool. The geometry was then cleaned and meshed as per EDAG meshing quality standards. The meshed parts were assembled by using the connection data captured from the scanning process. EDAG CAE guidelines[2][3] were followed in building the complete vehicle assembly hierarchy. **Image D-4** shows the completely assembled FE model of the Toyota Venza body structure.

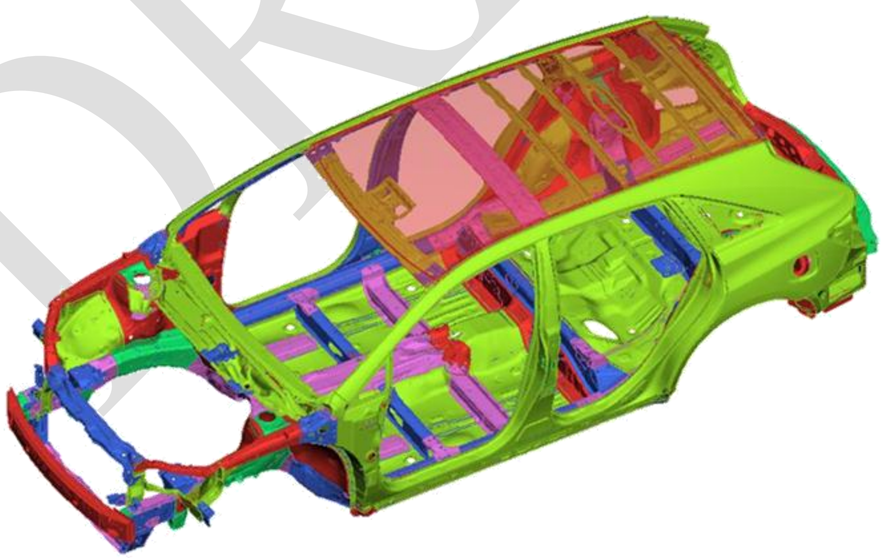


Image D-4: FE Model of Toyota Venza Body Structure

The initial FE model was built with body-in-prime (BIP) assembly for NASTRAN for NVH load cases of bending stiffness, torsion stiffness, and natural frequency modal analysis. It consisted of all the body-in-white (BIW) parts (welded body parts) and a few bolt-on parts needed for NVH analysis. The gauge (thickness) and material data for each part were incorporated into the model accordingly. **Image D-5** represents the gauge map for the BIP. **Image D-6** represents the material grades map for BIP, which, with the exception of the aluminum rear bumper, is made up of all steel components.

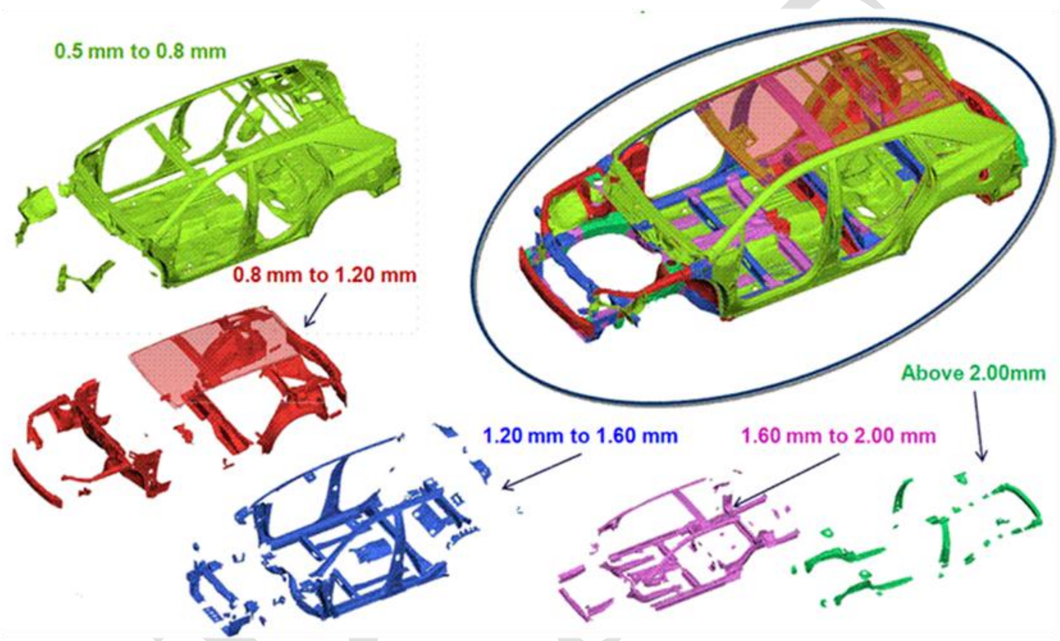


Image D-5: Gauge Map of Baseline BIP Model

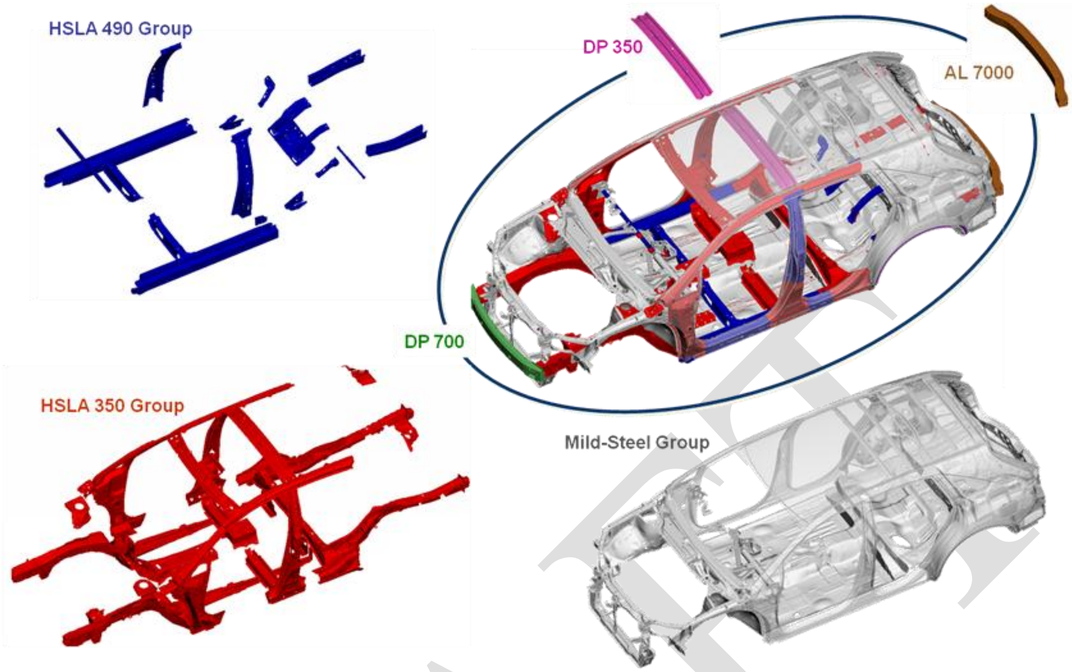


Image D-6: Material Map of Baseline BIP Model

D.8 FEA Model Validation—Baseline NVH Model

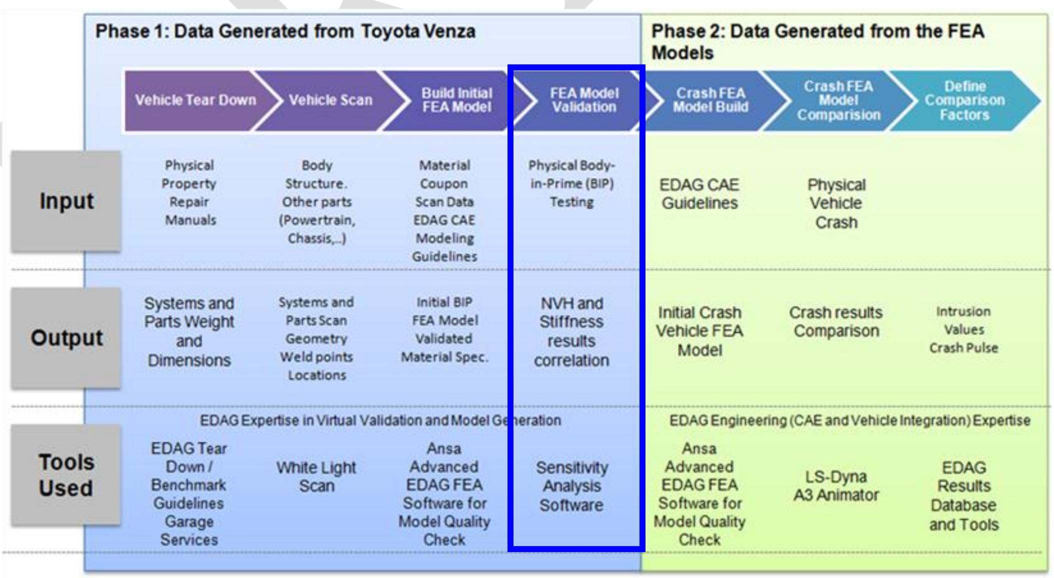


Figure D-16: FEA Model Validation: Baseline NVH Model

The initial FE model needed to be validated in order to obtain a realistic analytical model that represented the real-world test vehicle. The following NVH and static load cases were chosen to validate the initial FE model.

- Static Bending Stiffness
- Static Torsional Stiffness
- Modal frequency

The validation was carried out by correlating the analytical results of each load case against the corresponding physical test results.

D.8.1 Model Statistics

The NVH model consisted of the BIP model including radiator support, glass, front, and rear bumpers. The meshed model of the Toyota Venza baseline model contained 434 parts made up of 720,323 shell elements and 7,913 solid elements.

The necessary load case specific boundary conditions were incorporated into the model using a commercially available pre-post tool and then analyzed using the MSC Nastran solver. The model setup in terms of boundary and load conditions is explained in detail for each of the NVH load cases. **Figure D-7** shows the NVH model before incorporating the boundary and load conditions.

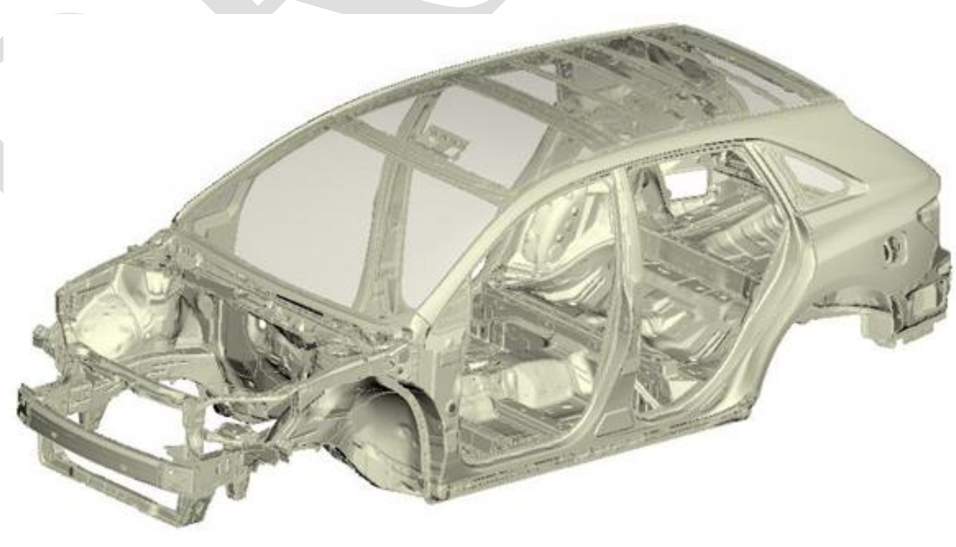


Image D-7: Toyota Venza Initial NVH Model

D.8.1.1 Static Bending Stiffness

In the bending stiffness model, the BIP was constrained and loaded as shown in **Image D-8**. The rear-left shock tower was constrained in the x-, y-, and z-axes; the rear-right shock tower was constrained in the x- and z-axes; the front left shock tower was constrained in the y- and z-axes; and the front right shock tower was constrained in the z-axis. A bending load of 2,224N was applied at the center of the front and rear seats.

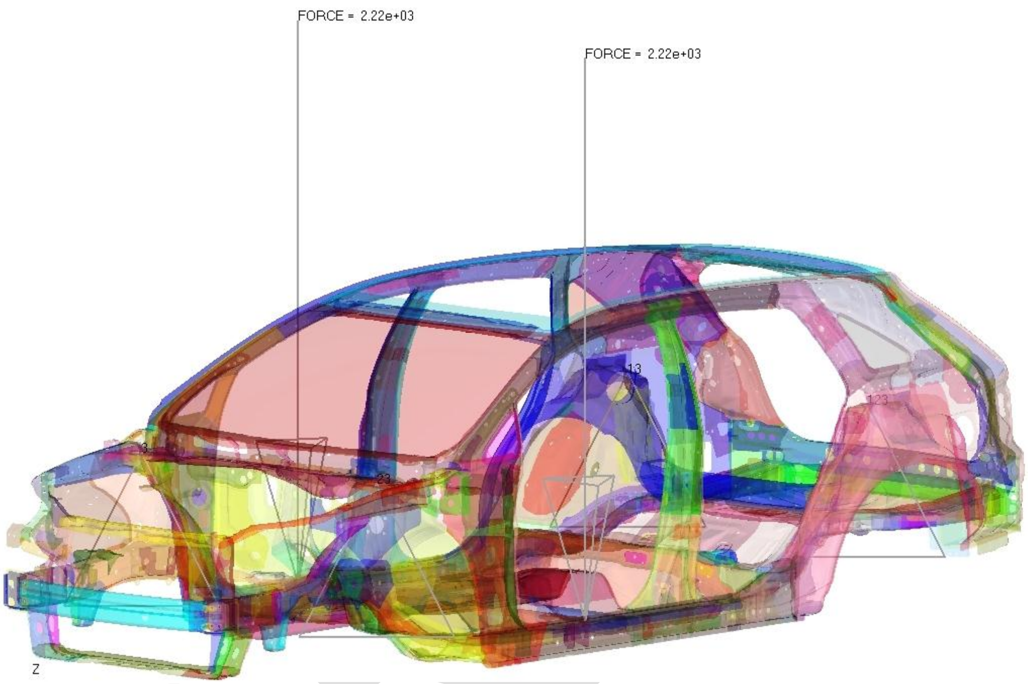


Image D-8: Loads and Constraints on NVH Model For Bending Stiffness

The calculation of bending stiffness was done by measuring Z-displacement in the rocker section area, noting the maximum displacement on each measured location.

$$\text{Bending Stiffness} = \frac{\text{Total Force}}{\text{Maxium Displacement}}$$

D.8.1.2 Static Torsion Stiffness

The torsion stiffness BIP model was constrained and loaded, as shown in **Image D-9**. The rear-left shock tower was constrained in the x-, y-, and z-axes; the rear-right shock tower was constrained in the x and z-axes. Additionally, the center of the front bumper is constrained in the z-direction. Vertical loads of 1,200N were applied in opposite directions on the left and right-front shock towers. Torsional stiffness was calculated from the applied load and deflection.

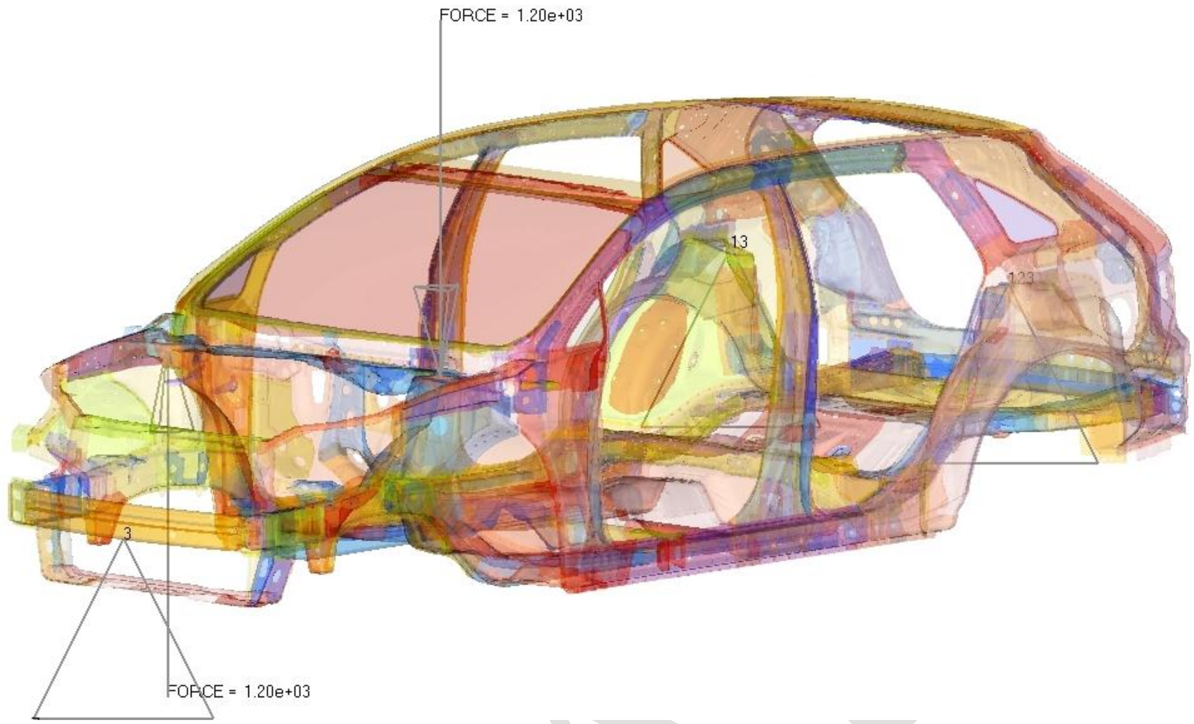


Image D-9: Load and Constraints on NVH Model For Torsional Stiffness

The calculation of torsion stiffness is done by calculating the angular displacement of the BIP. The average of the Z-displacement (Z) at the shock tower is calculated, and then the distance between the shock towers (D) was measured. The angular displacement (w) is calculated as ATAN (Z/D).

$$\text{Torsion Stiffness} = \text{Total Force} * \text{Angular Displacement}$$

D.8.1.3 Modal Frequency

For a vehicle to be dynamically stiff, it is important to have high natural frequencies for the global modes. In the modal frequency analysis model, MSC Nastran SOL 103[4], was used with no boundary conditions. It is a free-free (no boundary condition, no initial condition) natural frequency analysis within a given frequency range of 0-100Hz. This was defined with the help of the NASTRAN PARAM control cards in which the input and output requirements were embedded with the EIGRL card.

D.8.2 FE Model Validation

The validation of the CAE model was carried out in three different steps based on EDAG expertise and engineering knowledge. A summary of the model validation and EDAG CAE baseline model creation is depicted in **Figure D-17**.

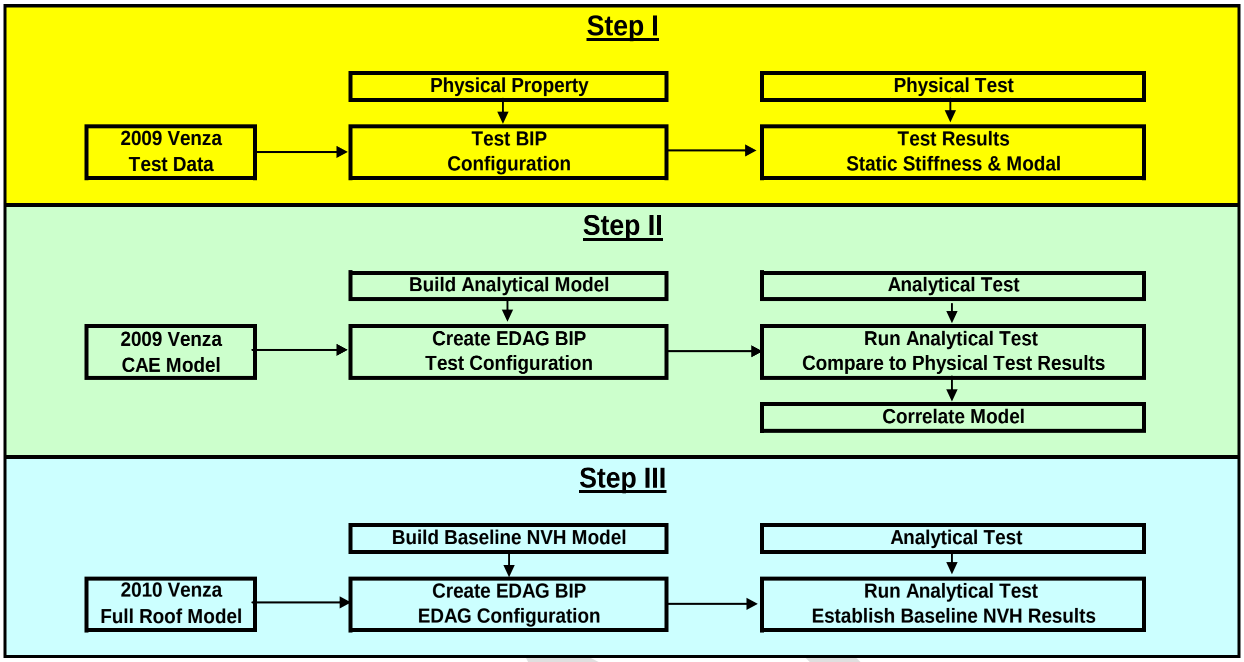


Figure D-17: Process Flow to Build Baseline Model

Step-I: NVH test setup. Collect NVH test results for the 2009 Toyota Venza with panoramic roof.

Step-II: Construction and correlation of NVH model. Correlate the CAE model for the 2009 Toyota Venza with panoramic roof with the test results.

Step-III: EDAG CAE baseline model. Convert the CAE model to a 2010 Toyota Venza with full roof model to build the baseline model.

The model results were then compared with the analytical test results, thus establishing the EDAG CAE baseline model.

D.8.3 Step I: NVH Test Setup

A 2009 Toyota Venza BIW with panoramic roof was setup with the necessary test equipment for static bending, static torsion, and dynamic modal measurements. The testing was conducted at the Ford Motor Company NVH labs.

D.8.3.1. Static Bending Stiffness Test Setup

For testing purposes, the vehicle was instrumented with the necessary deformation measuring gages at the selected locations. The bending test setup is shown in **Image D-**

10. The deformations at different locations were measured by applying a 2,200N force at the left and right rocker sections of the front door opening.

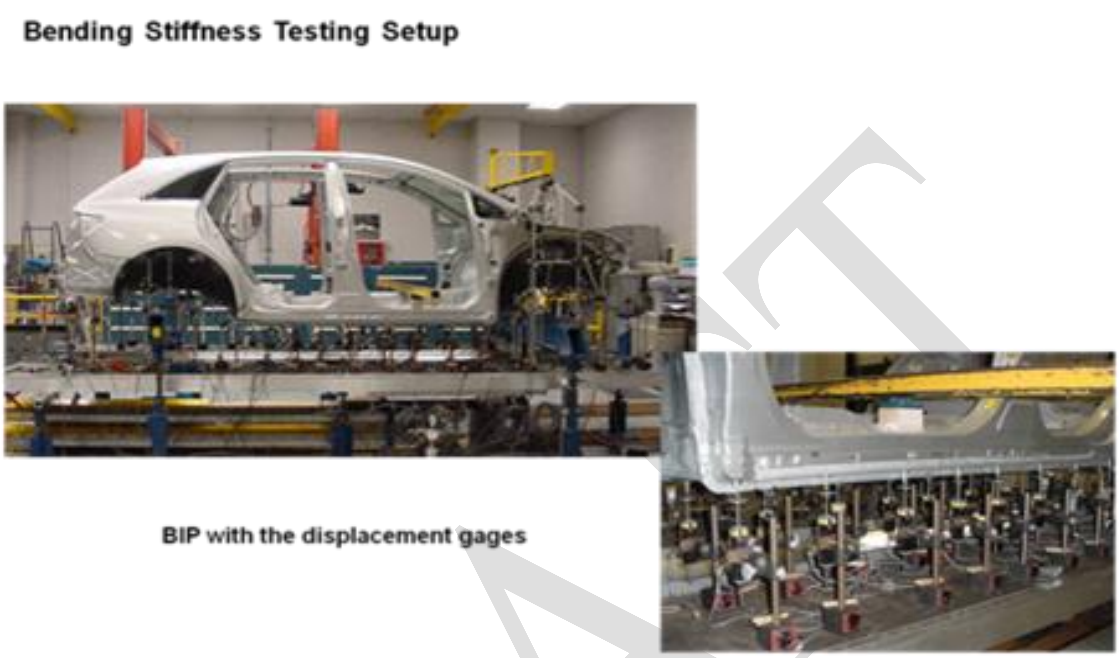


Image D-10: Bending Stiffness Testing Setup

The test vehicle was the 2009 Toyota Venza panoramic roof model. The CAE model was created as an exact replica of the test setup in order to achieve the test correlation. Figure 1.6.2 and **Image D-11** show the static bending CAE setup equivalent to the test vehicle.

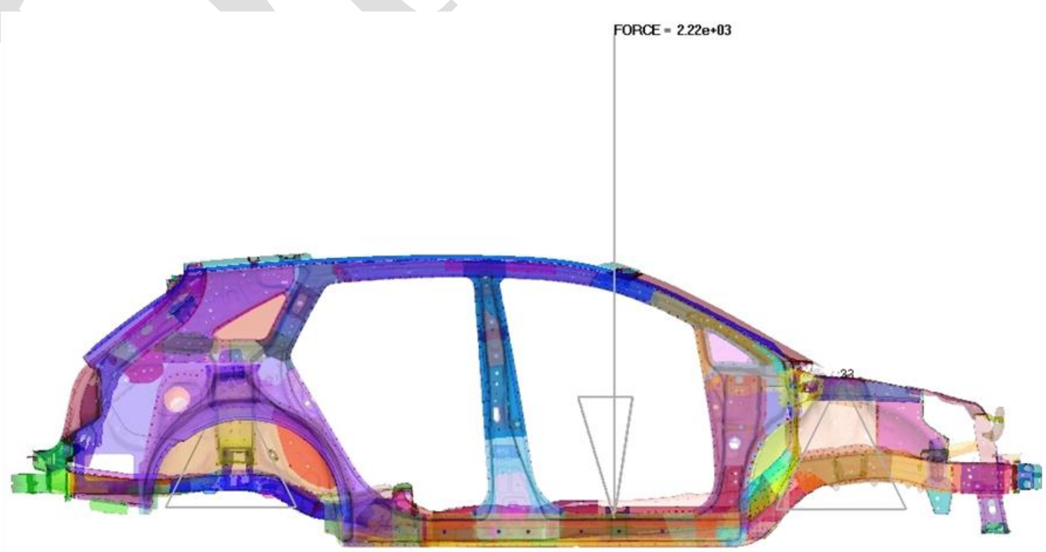


Image D-11: Bending Stiffness CAE Setup

D.8.3.2 Static Torsional Stiffness Test Setup

Similarly, the vehicle was instrumented for measurement of torsion stiffness characteristics as shown in **Image D-12**. The necessary deformations were measured at different test locations by applying 1,200N and **-**1,200N on the left and right shock towers respectively.

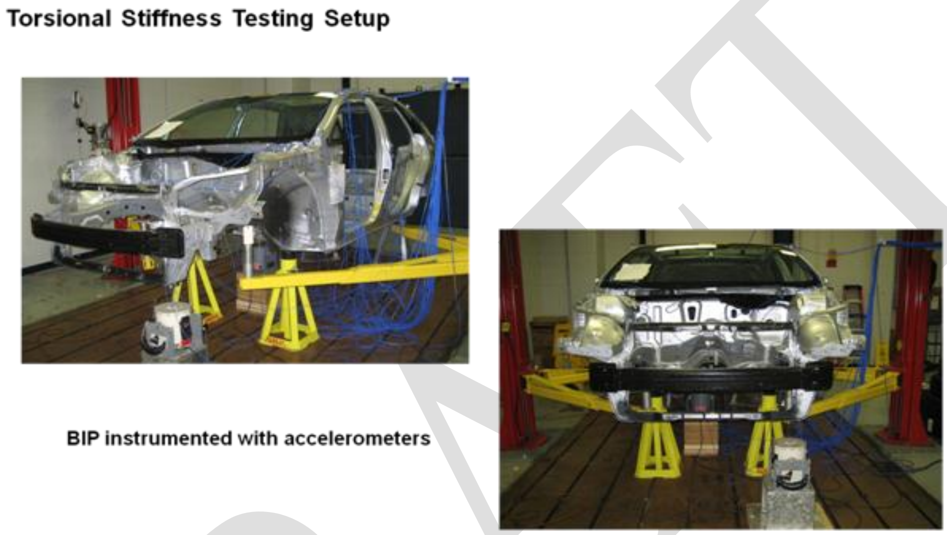


Image D-12: Torsion Stiffness Testing Setup

The CAE model was created by incorporating the same boundary and loading conditions as seen in the physical test setup. **Image D-13** shows the equivalent CAE model for the torsion stiffness test setup.

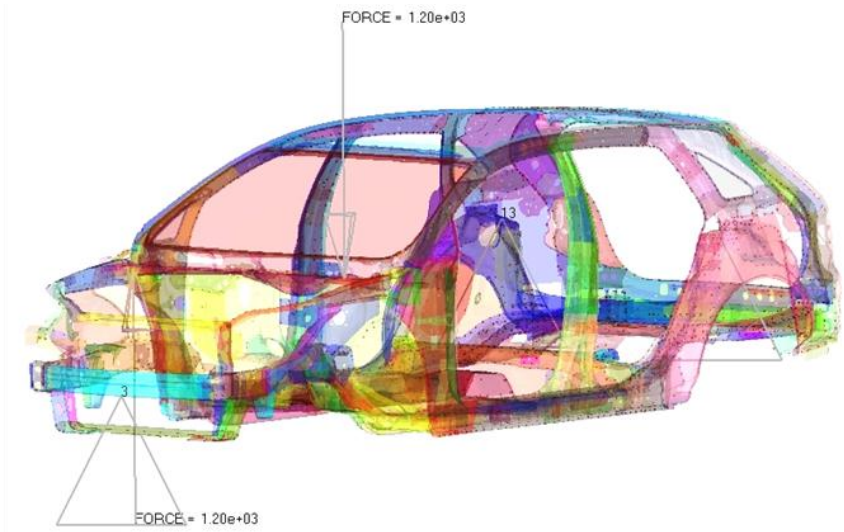


Image D-13: Torsion Stiffness CAE Setup

D.8.3.3 Dynamic Modal Test Setup

In the dynamic modal analysis, MSC Nastran SOL 103 was used with no boundary conditions. It is a free-free (no boundary condition, no initial condition) frequency analysis with a given frequency range of 0-100Hz. This was defined with the help of the NASTRAN PARAM control card in which the input and output requirements are embedded with the EIGRL card.

Once the test data was recorded for the dynamic modal setup, the FEA model was run using NASTRAN. The normal modes were noted in the CAE model and then compared with the test data in order to correlate the FEA model to the physical model.

Image D-14: Dynamic Modal Test Setup

D.8.4 Step II: Construction and Correlation of NVH Model

After the teardown vehicle was scanned and converted to a CAE model, it was converted into a panoramic roof model. This model was then compared with the test model, as shown in **Image D-15**. The various factors that were considered for the correlation were weight of the test vehicle versus the CAE model, modal analysis, torsion stiffness, and bending stiffness.

The NVH models shown in **Figures D-26**, **D-29**, and **D-31** were used to correlate the CAE model. The results are shown in **Table D-3**.

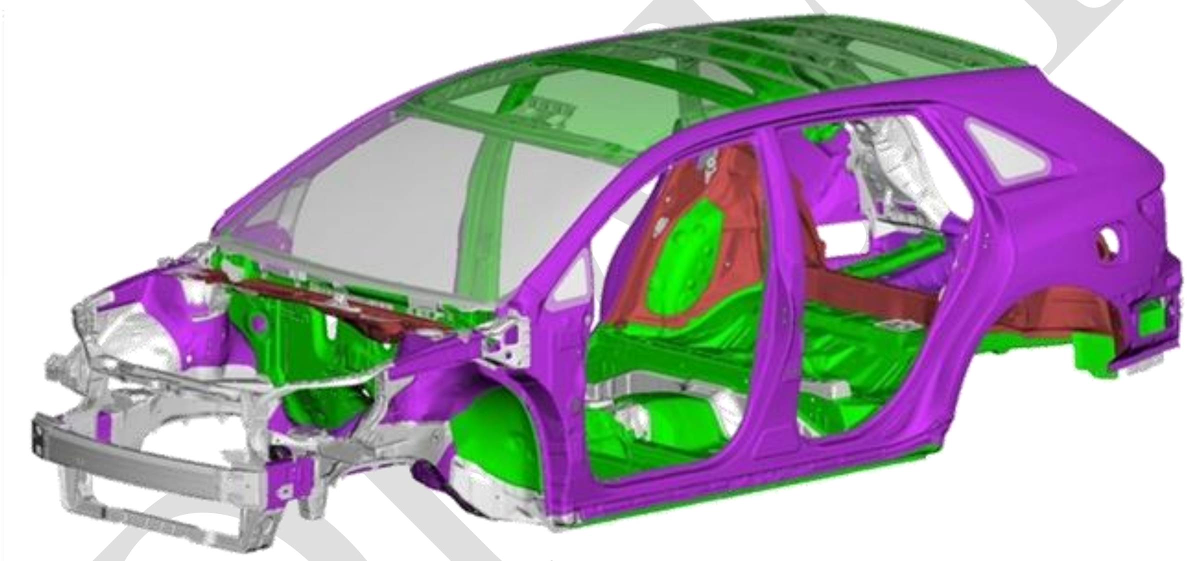


Image D-15: CAE Model for NVH Correlation

D.8.5 NVH Correlation Summary

The MSC Nastran solver (SOL 101 & 103[4]) was used to analyze the NVH load cases. The results of the NVH simulations were studied with respect to the test results. The correlation of the CAE test results of the NVH load cases are shown in **Table D-2**.

Study Description	Overall Torsion Mode (Hz)	Overall Lateral Bending Mode (HZ)	Rear-End Match-Boxing Mode (Hz)	Overall Vertical Bending, Rear-End Breathing Mode (Hz)	Torsion Stiffness (KN.m/rad)	Bending Stiffness (KN/m)	Weight Test Condition (Kg)	Comments
ActualTest Results (Panoramic Roof)	23.0	35.3	36.4	44.5	686.7	17991.0	400.5	Physical Test of 2009 Venza
EDAG CAE Model (Panoramic Roof) Correlation Model	23.0	34.2	35.6	41.9	703.0	17725.7	392.5	CAE Model of 2009 Venza Same Configuration as Test Vehicle
Correlation of CAE Model to Actual Test Results	100.0%	96.6%	97.8%	94.2%	97.6%	98.5%	98.0%	Model Correlation

Table D-2: FEA Model Test Correlation Comparison with Test Data

The data in **Table D-2** shows the initial FE model correlated well with the test vehicle within the 5% target. This model thus qualified to create further EDAG CAE baseline models for the remaining NVH and crash load cases.

D.8.6 Step III: EDAG CAE Baseline Model

The EDAG CAE baseline model for NVH cases was created from the correlated FE model. The correlated FE model was converted to a 2010 Toyota Venza with full roof and simulated for NVH load cases. The results were compared with the test data and the correlated model as shown in **Table D-3**. Note the results of the global torsion mode and torsional stiffness of the baseline model were significantly higher due to the full-roof structure. The other global bending mode and static bending stiffness results showed similar performance with the baseline and correlated models.

Study Description	Overall Torsion Mode (Hz)	Overall Lateral Bending Mode (HZ)	Rear-End Match-Boxing Mode (Hz)	Overall Vertical Bending, Rear-End Breathing Mode (Hz)	Torsion Stiffness (KN.m/rad)	Bending Stiffness (KN/m)	Weight Test Condition (Kg)	Comments
Actual Test Results (Panoramic Roof) Phase I	23.0	35.3	36.4	44.5	686.7	17991.0	400.5	Physical Test of 2009 Venza
EDAG CAE Model (Panoramic Roof) Phase II	23.0	34.2	35.6	41.9	703.0	17725.7	392.5	CAE Model of 2009 Venza Same Configuration as Test Vehicle
EDAG CAE Model (Full Roof) Baseline Model Phase III	54.6	34.3	32.4	41.0	1334.0	18204.5	407.7	CAE Model of 2010 Full Roof Venza Baseline Vehicle

Table D-3: NVH Results Summary for CAE Baseline Model

The baseline model for the NVH cases was correlated and referenced in the project for further NVH load cases. The same NVH baseline model was used to create the crash baseline models. The model setup and load case creations for crash simulations are explained later in this study.

D.9 Lotus Results Validation

The project also included validation of the weight reduction of the Toyota Venza with respect to the Lotus Engineering weight reduction report.[5] Lotus Engineering provided a theoretical study of the weight reduction of the Toyota Venza under two different study levels: a low-development study and a high-development study.

The low-development study primarily included the use of various high-strength steel materials with more focus on substituting existing parts, thus yielding weight savings and resulting cost increases. The high-development study, however, included some design changes, futuristic manufacturing techniques, newly combined assemblies, and production volumes. It primarily featured changes in the body structure of the vehicle.

The scope of this project was to validate the findings of the low-development study, which states that without any major performance degradation, the BIW mass savings would be about 6.55%. **Images D-16** and **D-17** show the material map and the thickness map of Lotus Engineering's optimized low-development study, respectively.

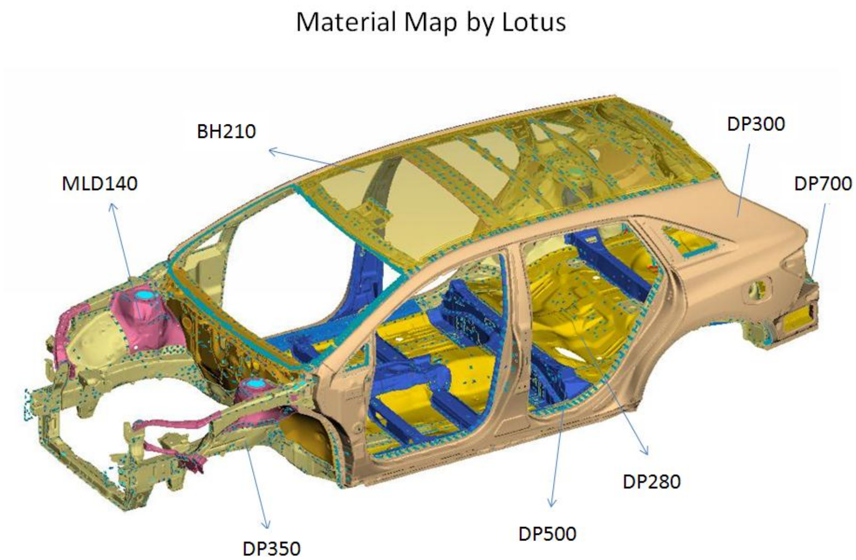


Image D-16: Material Map Based on Lotus Engineering information

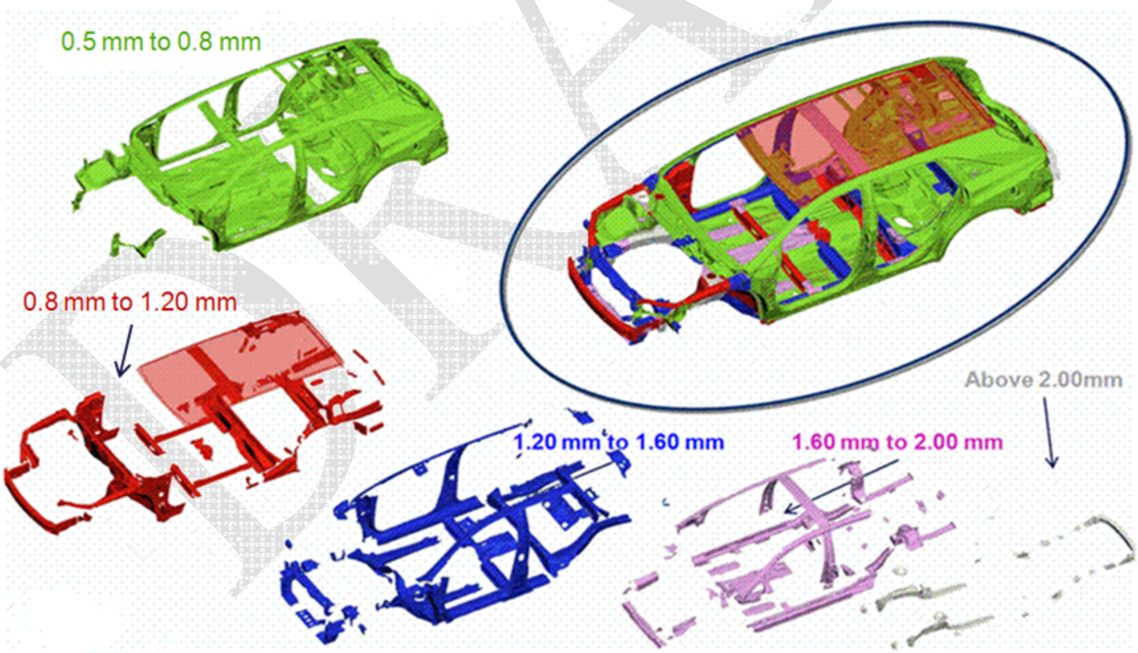


Image D-17: Thickness Map Based on Lotus Engineering information

EDAG validated Lotus Engineering's low-development study for NVH performance using the materials and gauges shown in **Images D-16** and **D-17**. This information was incorporated into the EDAG baseline NVH model. Static stiffness and modal load cases were simulated and compared with EDAG baseline NVH results.

The results of the validation in comparison to the EDAG baseline model are shown in **Table D-4**. The modal analysis results and corresponding weight reduction were comparable, but the bending and torsional stiffness values did not provide acceptable performance. The torsional stiffness is 20.4% less, and the bending stiffness is 20.0% less than the 5% target performance established by EDAG.

Study Description	Overall Torsion Mode (Hz)	Overall Lateral Bending Mode (HZ)	Rear-End Match-Boxing Mode (Hz)	Overall Vertical Bending, Rear-End Breathing Mode (Hz)	Torsion Stiffness (KN.m/rad)	Bending Stiffness (KN/m)	Weight Test Condition (Kg)	Weight BIW (Kg)	Comments
EDAG CAE Model (Full Roof) Baseline Model	54.6	34.3	32.4	41.0	1334.0	18204.5	407.7	378.0	CAE Model of 2010 Full Roof Venza Baseline Vehicle
EDAG CAE Baseline Model with Lotus Recommended Substitutions	53.4	33.7	31.8	39.7	1062.2	14560.0	384.6	352.1	EDAG CAE Model with Lotus Recommendations
Percentage Difference	-2.2	-1.8	-1.9	-3.2	-20.4	-20.0	-5.7	-6.5	Torsion and Bending Outside of the Acceptable Limits

Table D-4: NVH Results Summary for Lotus CAE Model

Further crash validations of Lotus Engineering's study were not conducted, since it did not meet the NVH targeted performance.

D.10 Baseline Crash Model

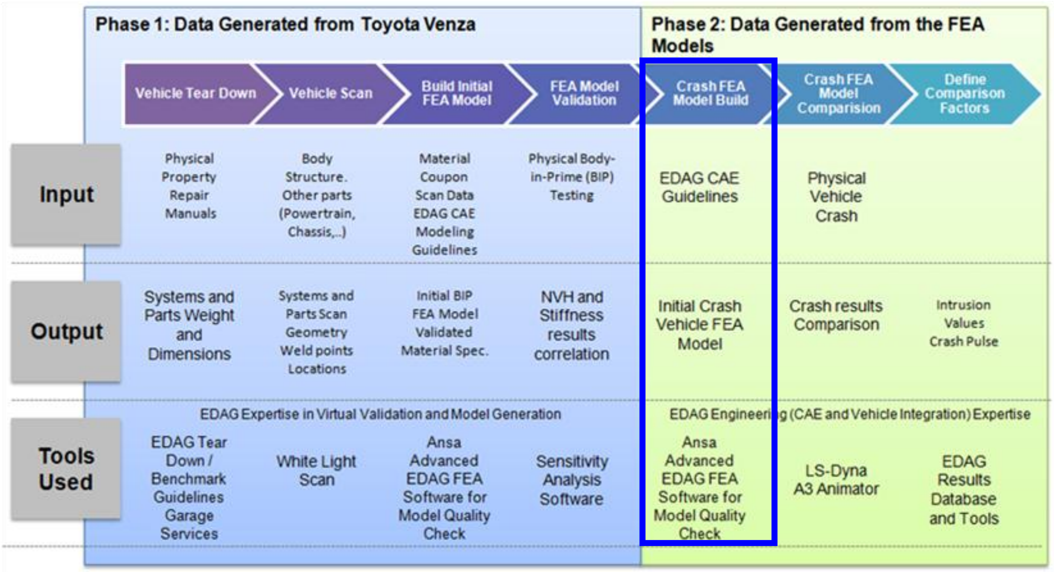


Figure D-18: Baseline Crash Model

As per the scope of the project, CAE crash performance analyses were carried out to verify compliance with the National Highway Traffic Safety Association (NHTSA) regulatory performance targets. For this project, the following Federal Motor Vehicle Safety Standards (FMVSS) and European regulatory test requirements were incorporated into the individual CAE models:

1) FMVSS 208—35 MPH flat frontal crash with rigid wall barrier, same as US New Car Assessment Program (US NCAP)

2) European New Car Assessment Program (Euro NCAP)—35 MPH frontal crash with Offset Deformable Barrier (ODB), same as the Insurance Institute for Highway Safety (IIHS) frontal crash

3) FMVSS 214—38.5 MPH side impact with moving deformable barrier (MDB)

4) FMVSS 301—50 MPH rear impact with moving deformable barrier (MDB)

5) FMVSS 216a—Roof crush resistance (utilizing the higher standard IIHS roof crush resistance criteria)

The structural level performance indices (such as pulse and intrusion) were compared to each of the regulatory targets. In compliance with EDAG common practice, a correlation requirement of >95% (or <5% error) was set for the performance indices.

A baseline crash model was developed and correlated for the frontal and side-impact load cases of testing specifications in FMVSS requirements 1 and 3. The remaining load cases were then carried out using the correlated crash model.

D.10.1 Model Building

D.10.1.1 Major System for Full Vehicle Model

In order to build the full-vehicle crash model, the validated NVH BIP model (from section 1.6.5) was utilized. The crash model included all closure parts (such as hood, doors, and tailgate). Front and rear bumper system structural parts were also included to represent realistic high-speed front and rear-crash scenarios. All parts critical to a high-speed frontal impact scenario were included: powertrain assembly, major engine and transmission parts, radiator assembly, and exhaust subsystem. The fuel tank system parts (critical for rear and side-impact scenario) were also included in the full vehicle crash model. The rear seat system was represented as a lumped mass critical for front and rear-impact scenarios. A carryover FEA seat system was integrated to take into account resistance of seat structure deformation in side-impact scenario. The full-vehicle crash model consisted of a total of 1,300,000 elements. The CAE weight of the model was 1,843.2 kg, in comparison with test vehicle weight of 1,839.9 kg. **Figure D-35** shows the different major systems of the full-vehicle crash model.

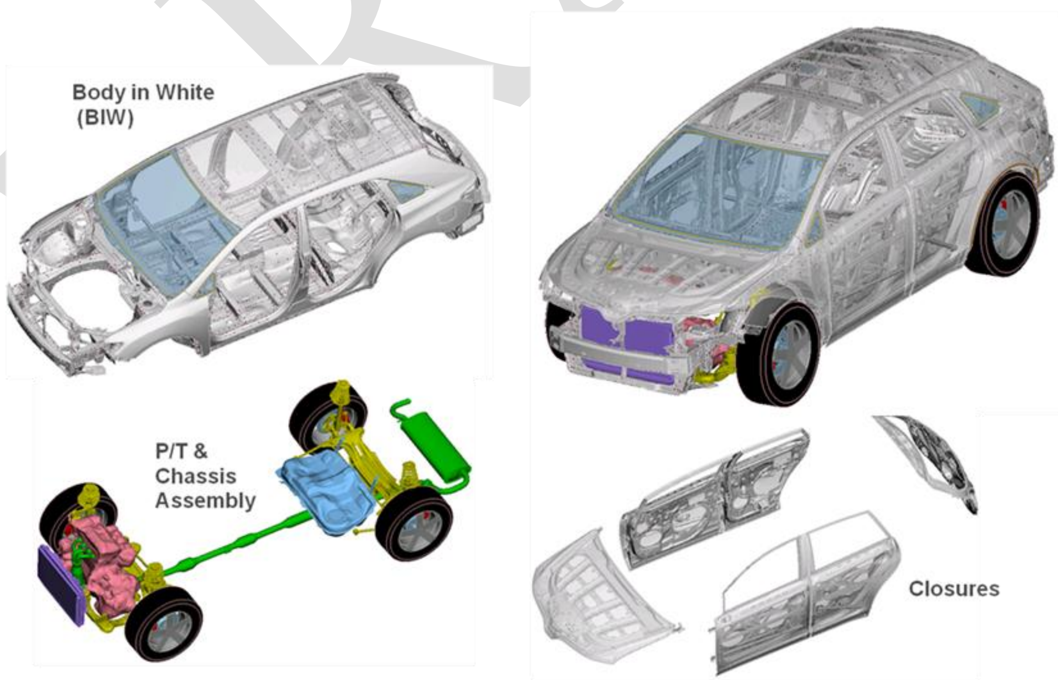


Figure D-35: Major Systems of Full-Vehicle Model

The gauge map and material map of BIP parts (the same as the validated BIP model) are shown in Section 1.5. The gauge and material data for the remaining closure parts were also incorporated accordingly. **Images D-18** and **D-19** represent the gauge map and material grade map of the closure parts.

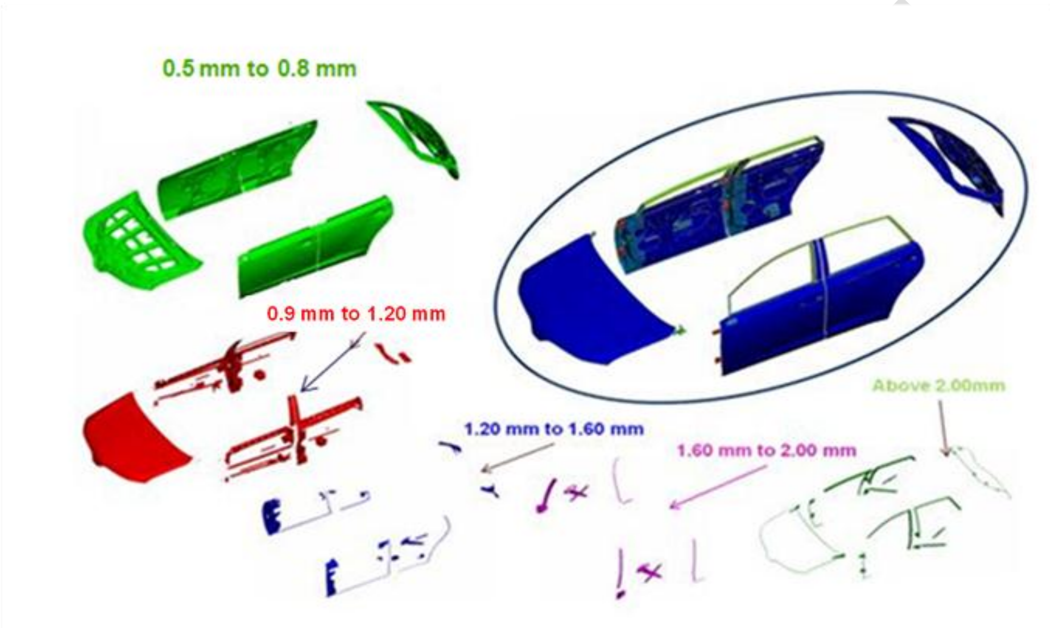


Image D-18: Gauge Map of Closures Models of Baseline

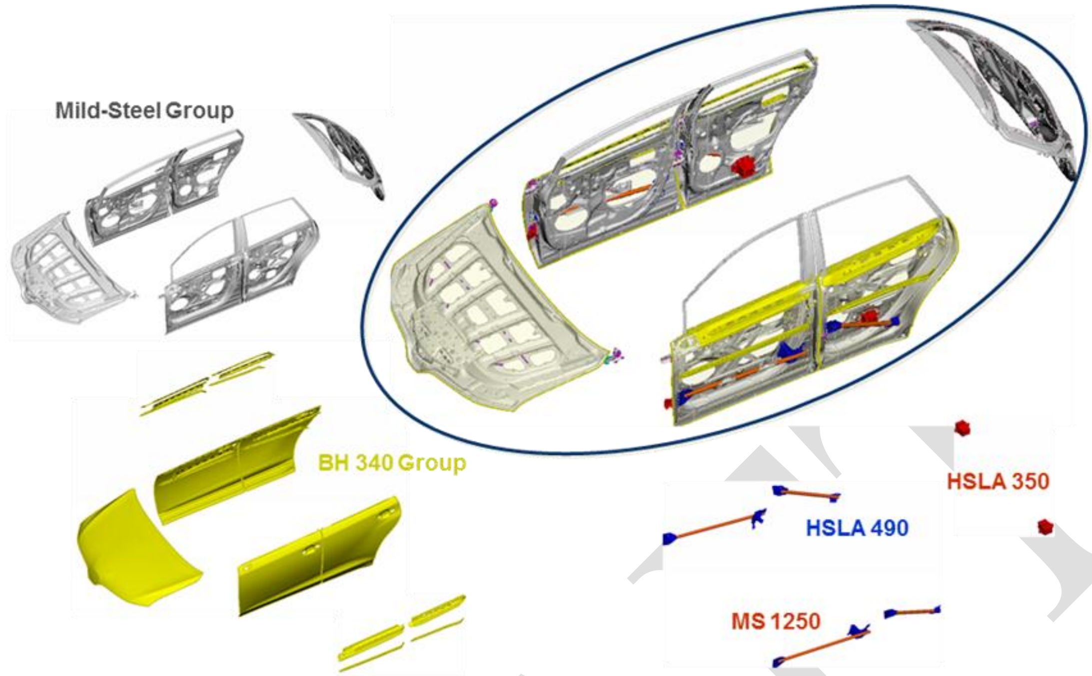


Image D-19: Material Map of Closures Models of Baseline

D.10.1.2 Mass Validation

EDAG standard CAE Modeling guidelines[3] were followed throughout the model building process to be consistent with mass and center of gravity (CG) calibrations. The total vehicle mass was correlated to NHTSA Test No. C95111. Vehicle mass difference was calibrated within 0.5% of test weight. The vehicle CG was calibrated to be within 0.5% of the test measurement.

D.10.2 Powertrain Mass & Inertia Calibration Test

In order to capture correct moment of inertia (MOI) and mass information for the powertrain assembly, an independent swing test was executed. In a full vehicle crash analysis, the characteristics of the powertrain significantly influence the body pulse and engine compartment structural deformation. An accurate representation of the mass and MOI of the engine and powertrain system is therefore a crucial part of the crash simulation.

D.10.2.1 Measuring Powertrain CG & Moment of Inertia

The powertrain and/or engine characteristics, namely, MOI and center of gravity (CG), were measured by conducting an oscillation test on the disassembled powertrain system using trifilar suspension apparatus.[18] Due to the complexity of the measuring process, the following assumptions were made while calculating the MOI and CG:

- Engine mass is evenly distributed across the engine
- The oscillation is assumed to be undamped
- Test frame inertia was subtracted from powertrain inertia

MOI and CG were recorded as per trifilar suspension testing procedures.[18] The CG location is shown in Figure 1.8.4; the powertrain mass and inertia matrix are shown in **Image D-20**.

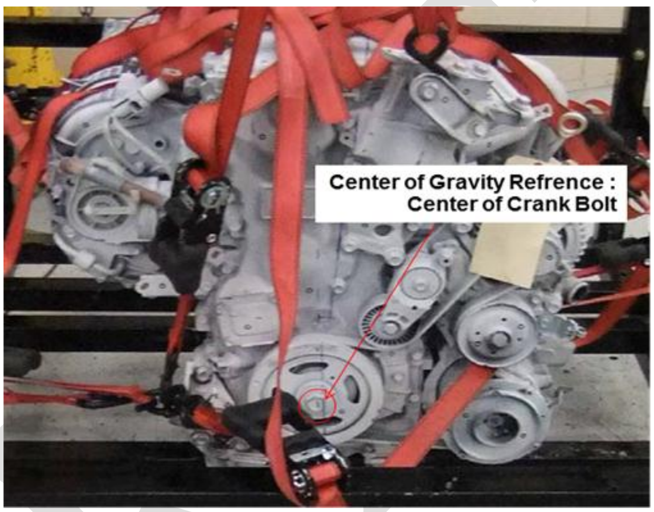


Image D-20: Powertrain and/or Engine Center of Gravity

Powertrain Mass [kg] $\begin{bmatrix} 235.0 \end{bmatrix}$

Center of Gravity (from reference) [m] $\begin{bmatrix} 0.427 & 0.002 & 0.083 \end{bmatrix}$

Inertia Tensor (about CG) [kg·m²]

$$\begin{bmatrix} 10.466 & 1.282 & -4.016 \\ 1.282 & 21.807 & -0.287 \\ -4.016 & -0.287 & 20.284 \end{bmatrix}$$

Principal MOI [kg·m²]

$$\begin{bmatrix} 8.9366 & 0 & 0 \\ 0 & 22.515 & 0 \\ 0 & 0 & 21.106 \end{bmatrix}$$

Principal Directions
(unit vectors relative to original coordinate axis
- displayed in columns of orientation matrix)

$$\begin{bmatrix} -0.940 & -0.196 & -0.280 \\ 0.086 & 0.657 & -0.749 \\ -0.331 & 0.729 & 0.600 \end{bmatrix}$$

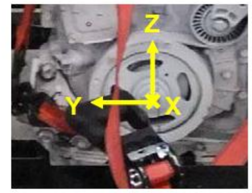


Figure D-19: Powertrain Mass & Moment of Inertia Results

<u>Baseline Crash Model Set-up</u>

The crash load cases considered in this study are

- FMVSS 208—35 MPH flat frontal crash (US NCAP)
- Euro NCAP—35 MPH ODB frontal crash (Euro NCAP/IIHS)
- FMVSS 214—38.5MPH MDB side impact
- FMVSS 301—50 MPH MDB rear impact
- FMVSS 261a—Roof crush (utilizing IIHS roof-crush criteria)

Figure D-19 shows all five different load case configurations with appropriate barriers placed against the full vehicle baseline model.

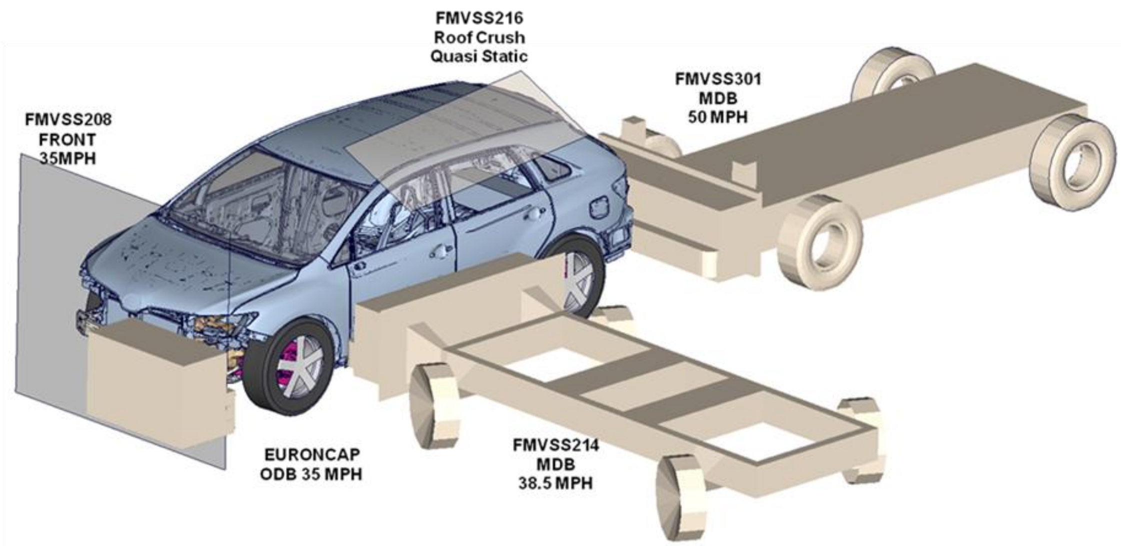


Image D-21: Configuration of All Load Case Set-Ups for Baseline Model

The necessary physical vehicle data obtained during the vehicle teardown phase (e.g., bushings) were included in the crash model. A brief summary of model content statistics is provided in **Table D-5**.

Model Detail	Count
Total number of elements	1,372,930
Total number of nodes	1,374,947
Total number of shell elements	1,275,631
Total number of solid elements	97,099
Total number of beam & discrete elements	91
Total number of part IDs	1157

Table D-5: Contents of EDAG CAE Baseline Model

The crash model correlations with the test results are explained in detail in the following sections.

D.10.3 Baseline Crash Model Evaluation

For reasonable representation of a realistic vehicle crash test, the FE baseline crash model needed to be correlated against physical test data. The FE crash model was correlated using two load cases: frontal impact with flat rigid wall barrier and side impact with moving deformable barrier.

FMVSS 208—35 MPH flat frontal crash (US NCAP)

FMVSS 214—38.5 MPH MDB side impact

The details of these two load cases and correlations of the test results and CAE simulations are explained in the following section.

D.10.3.1 I.FMVSS 208—35 MPH Flat Frontal Crash (US NCAP)

D.10.3.1.1 Model Setup

The frontal impact test of FMVSS 208 (US NCAP) undertaken by the NHTSA, is a full frontal barrier test at a vehicle speed of 35 mph (56 km/h). The corresponding NHTSA Test No. C95111[19] of a 2009 Toyota Venza was referenced to obtain initial crash setup and results. **Image D-22** shows the FMVSS 208 frontal impact test setup of a 2009 Toyota Venza.

Image D-22: FMVSS 208 35 MPH Flat Frontal Crash Test Setup

The CAE model was setup as defined in the FMVSS 208 regulation. The LS-DYNA model was created to represent the exact test initial setup, such as vehicle velocity of 35 mph against a flat rigid wall barrier. The CAE vehicle mass was 1,843.2 kg. This was 3.3kg more than in the test (1,839.9 kg). The weight difference was due to the mesh characteristics of the stamped parts. The CAE vehicle mass included a mass of 38 kg for the purpose of the LS-DYNA mass scaling requirement.[6]

To measure passenger compartment structure integrity, data analysis points as shown in **Image D-23** were measured with respect to a coordinate system reference at the cargo area of the body structure; reference point locations follow IIHS standards. To measure instrument panel (IP) movements, two reference points were taken from the cowl crossmember.

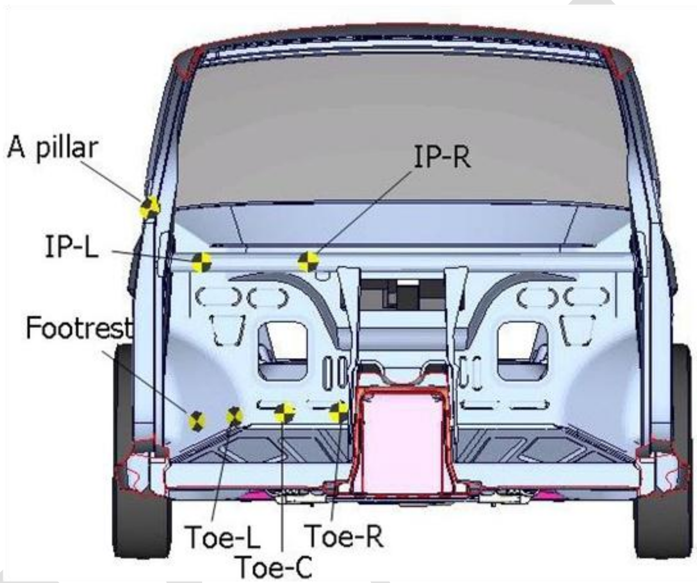


Image D-23: Intrusion Measurement Locations

The LS-DYNA simulation was carried out for an 80 milliseconds (msec) analysis time frame. Following are the results of the analysis and comparison with the test results.

D.10.3.1.2 Deformation Mode Comparison

Global vehicle deformation and vehicle crash behaviors were analyzed and compared to the deformation modes of test photographs. **Images D-24** through **D-29** show different views of the comparative deformation mode at 80 msec (end of crash). From the comparison of the deformation modes, it can be observed the EDAG baseline model showed similar deformation modes.

Image D-24: Deformation Mode Comparison: Right Side View @ 80msec

Image D-25: Deformation Mode Comparison: Left Side View @ 80msec

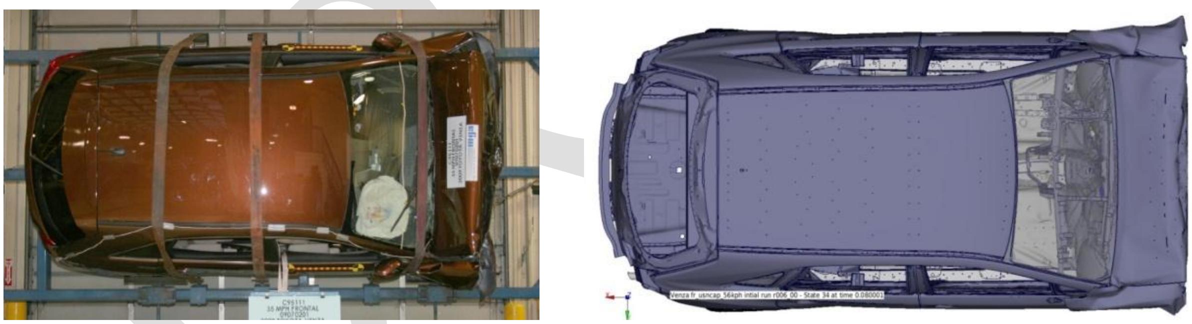


Image D-26: Deformation Mode Comparison: Top View @ 80msec

Image D-27: Deformation Mode Comparison: ISO View @ 80msec

Image D-28: Deformation Mode Comparison: Bottom View Front Area @100msec

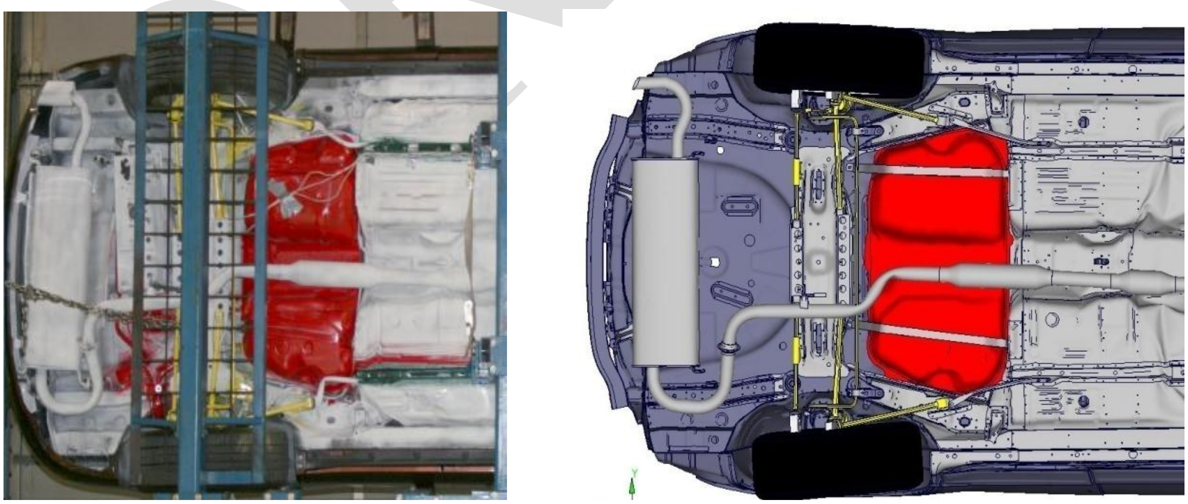


Image D-29: Deformation Mode Comparison: Bottom View Rear Area @100msec

Similarly, the following figures compare the deformation modes at 30 msec. **Image D-30** shows the bottom view of the engine compartment and front cradle deformation. The deformation mode at 46 msec (when the cradle was fully deformed and the impact load was transferred to the lower front dash) was also observed to be well correlated with the test results as shown in **Image D-31**.

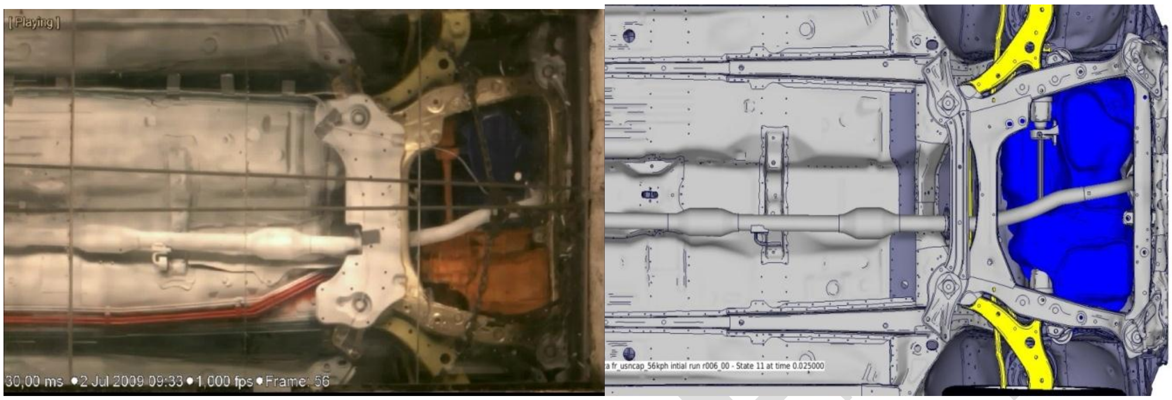


Image D-30: Intermediate Time Front Engine Room and Front Cradle @ 30msec

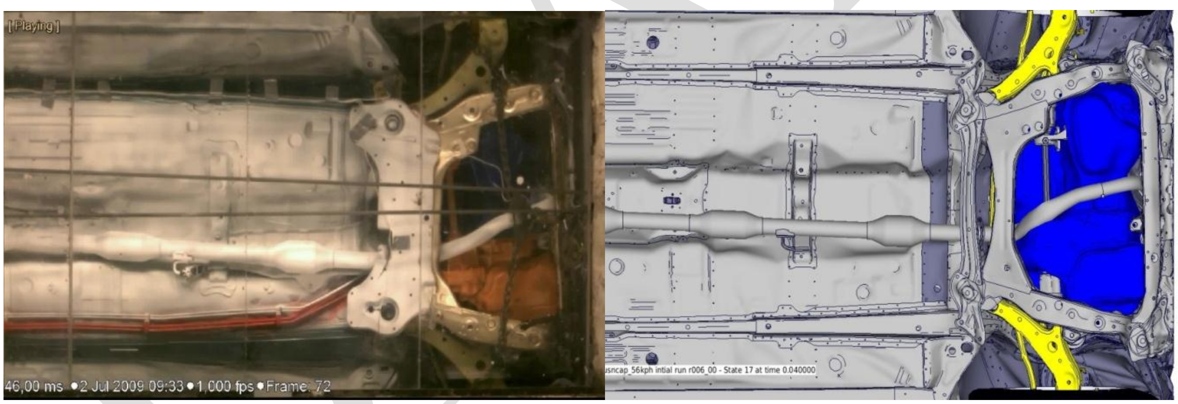


Image D-31: Intermediate Time Front Engine Room and Front Cradle @ 46msec

D.10.3.1.3 Body Pulse Comparison

Another important result was the vehicle acceleration pulse (in G's). The pulse was measured at the undeformed location of the rear-seat crossmember. Figure 1.8.17 shows the location of the pulse data measurement (accelerometer data number 1 & 2) on the test vehicle. The vehicle velocity was measured on the CAE model at the same location (rear-seat crossmember). The velocity was differentiated to obtain the acceleration pulse.

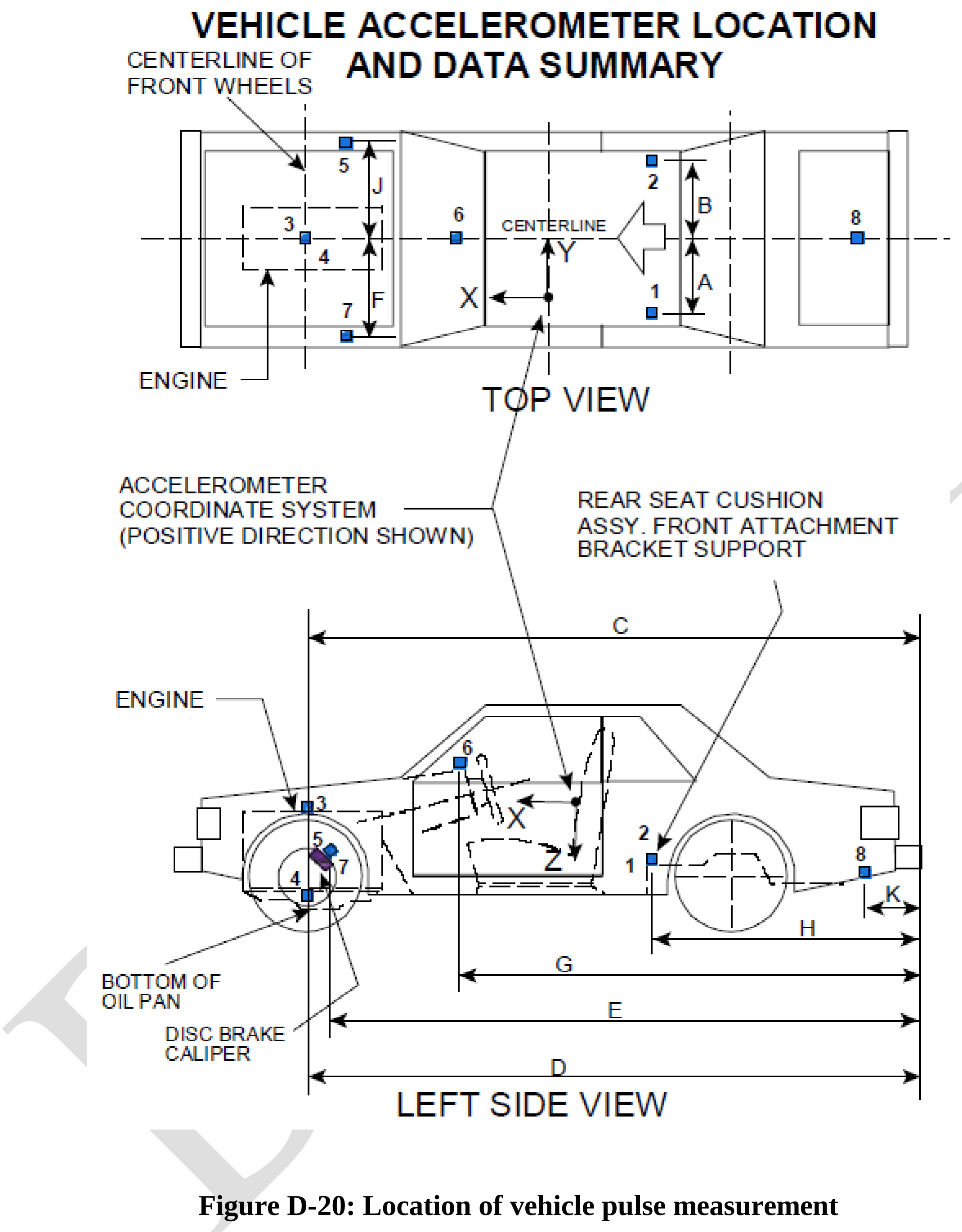
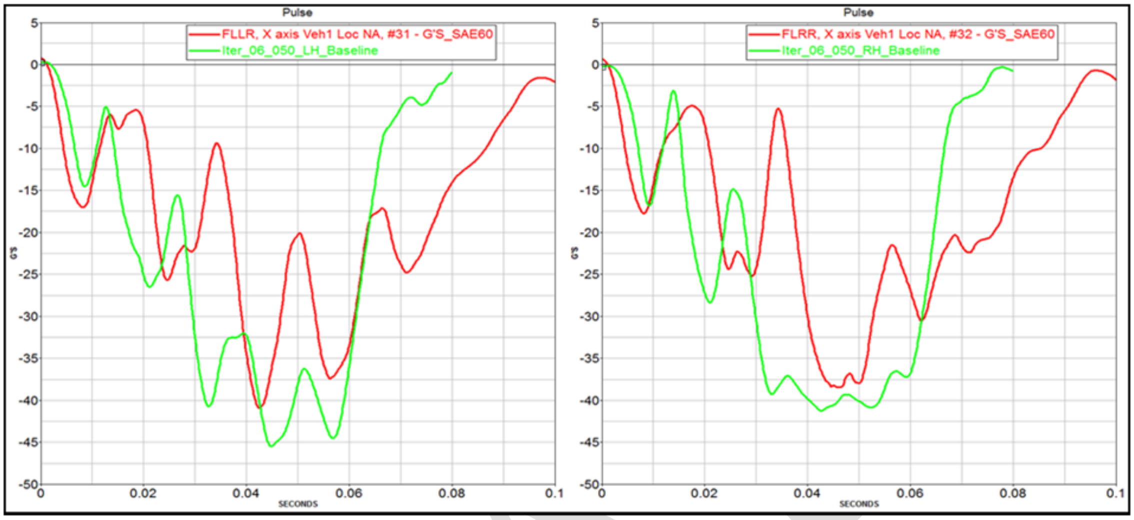


Figure D-20: Location of vehicle pulse measurement

The vehicle acceleration pulse (in G's) for the driver side and the passenger side of the vehicle are shown in Figure 1.8.18. The vehicle pulse of the baseline model is 43.4G, and the test model is 40.9G. When compared to the test results, the vehicle pulse of the CAE simulation is higher by 2.5G. The difference in the vehicle pulse was found to be influenced by the properties of the powertrain mounting bushing. The bushing mountings of the CAE model were represented as rigid connections. In the real test, bushing mountings transfer the crash loads to the engine compartment and under the floor structures: Some of the bushing mountings could fail due to severe deformation of the structure. In this study, since all bushing mountings were rigidly connected to the structure, deformation behavior was treated based on engineering estimates. So the global stiffness of the test vehicle turned out slightly stiffer than the actual vehicle.



Driver side　　　　Passenger side

___ Venza 2010 CAE Baseline (Average pulse 43.4G)
___ Venza 2009 Test (Average pulse 40.9G)

Figure D-21: Body Pulse: CAE Baseline Model vs. Test

Even though the pulse of the CAE baseline model is slightly higher, it is believed to be acceptable for the baseline model. This model gave an excellent frontal crash performance based on an analysis of the dynamic crush and compartment intrusions (explained below).

D.10.3.1.4　Dynamic Crush and Intrusions

Dynamic crush is the total vehicle body deformation at the end of the crash event with respect to the undeformed vehicle. The initial crush of the Toyota Venza baseline was measured to be 605 mm as shown in **Image D-32**.

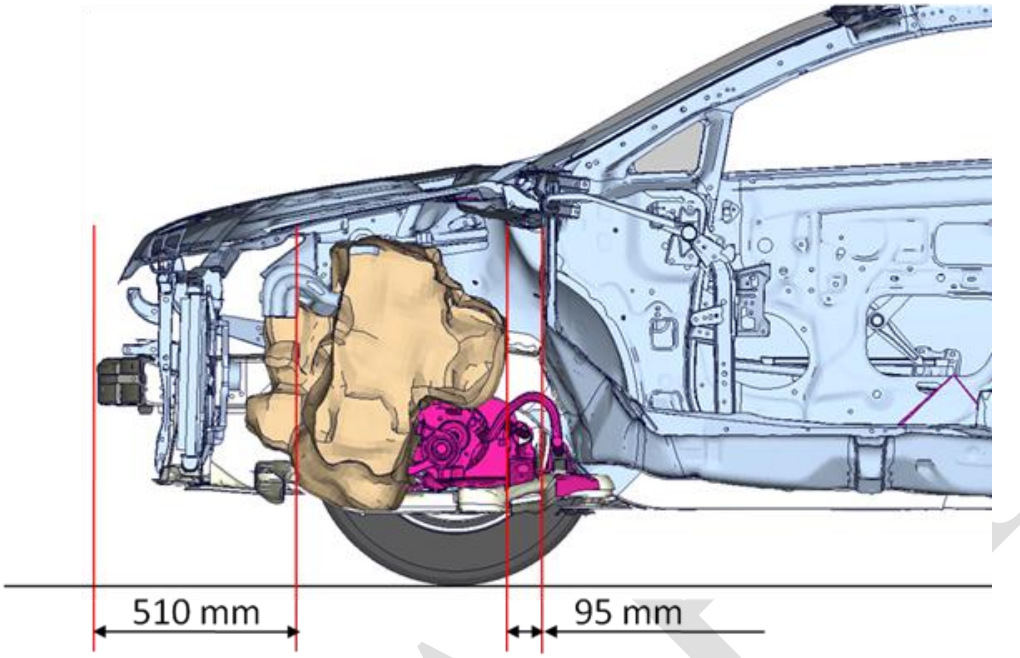


Image D-32: Initial Crush Space

The dynamic crush of flat frontal simulation is plotted in **Figure D-22**.

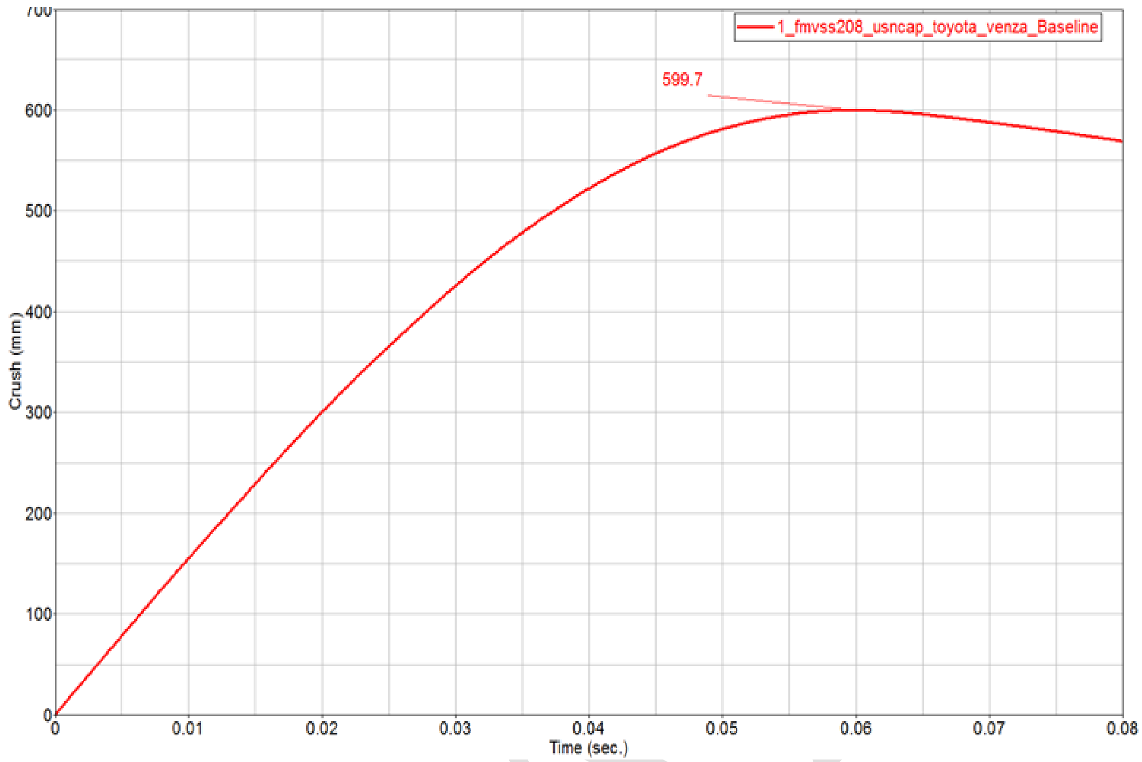


Figure D-22: FMVSS 208 Baseline Dynamic Crush with Barrier Deformation

Figure D-22 shows the maximum vehicle crush of 599.7mm of the baseline model is less than the initial crush space of 605mm. When compared to test results of a maximum crush of 592mm, the baseline model shows a good correlation.

A summary of performance indicators of the baseline model for the flat frontal crash load case is listed in **Tables D-6** and **D-7**.

No.	Frontal crash measurements	Venza 2009 Test Model	Venza 2010 CAE Baseline Model
1	Pulse (G's)	1st peak=17.0 @ 13.8 msec 2nd peak=40.9 @ 84.5 msec	1st peak=7.8 @ 13.8 msec 2nd peak=41.2 @ 84.5 msec
3	Dynamic Crush (mm)	592.0	599.7
4	Weight (kg)	1839.9	1843.2

Table D-6: Pulse and Dynamic Crush

Model	Driver Footwell (mm)	Driver Toe Pan Left (mm)	Driver Toe Pan Center (mm)	Driver Toe Pan Right (mm)
Baseline	58.8	137.1	157.1	102.9

Table D-7: Compartment Dash Intrusion

Table D-7 lists the compartment dash intrusions measured at locations shown in **Image D-23**.

Based on the analysis of the deformation mode, dynamic crush, and compartment intrusions, this model was established as EDAG's baseline target for further frontal offset load case iterations.

D.10.3.2 II.FMVSS 214—38.5MPH MDB Side Impact

D.10.3.2.1 <u>Model Setup</u>

The baseline crash model was correlated using another crash load case of FMVSS 214 side impact with MDB where a moving deformable barrier with a mass of 1,370 kg impacted the vehicle on the driver side with a velocity of 38.5 mph (61.9 km/h). The corresponding NHTSA Test No. MB5128[20] of a 2010 Toyota Venza was referenced to obtain initial crash setup and results. The CAE model was setup as defined in the FMVSS 214 regulation. Full vehicle mass, impact velocity, vehicle height, and barrier position were calibrated accordingly. A typical FMVSS 214 side impact setup with MDB is shown in **Image D-33**.

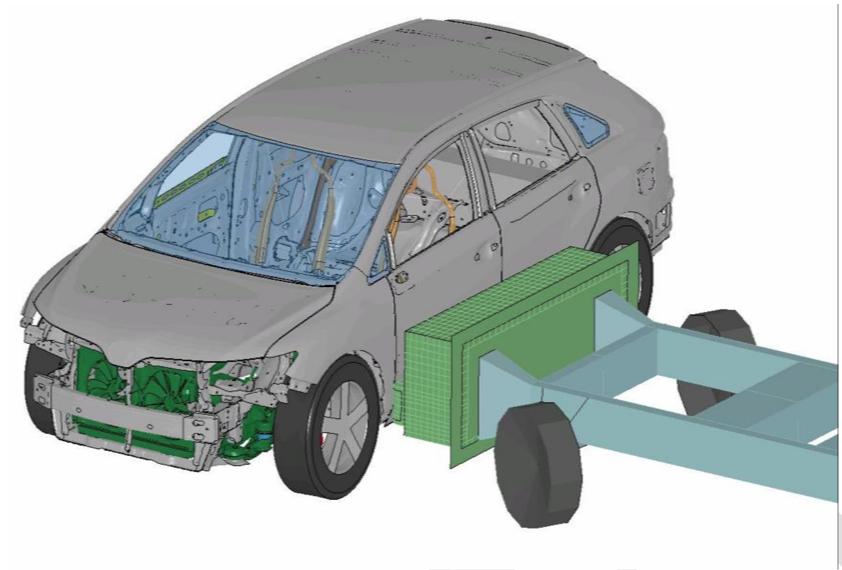


Image D-33: FMVSS 214, 38.5MPH MDB Side Impact CAE Model Setup.

The LS-DYNA simulation was carried out for a 100 msec analysis time frame. The necessary results were analyzed and compared with the test results.

D.10.3.2.2 Deformation Mode Comparison

Side-structure deformation and vehicle crash behaviors were analyzed and compared to the deformation modes of test photographs. **Image D-34** shows the pre-crash conditions for comparison purposes and **Images D-35** through **D-37** show the comparative deformation modes at 100 msec (end of crash) in different views. By comparing the deformation modes, it can be observed the EDAG baseline model shows similar deformation modes.

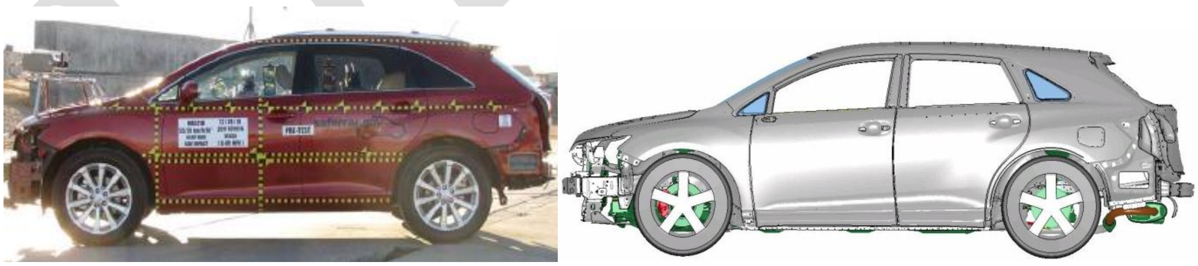


Image D-34: Side Impact: Pre-Crash

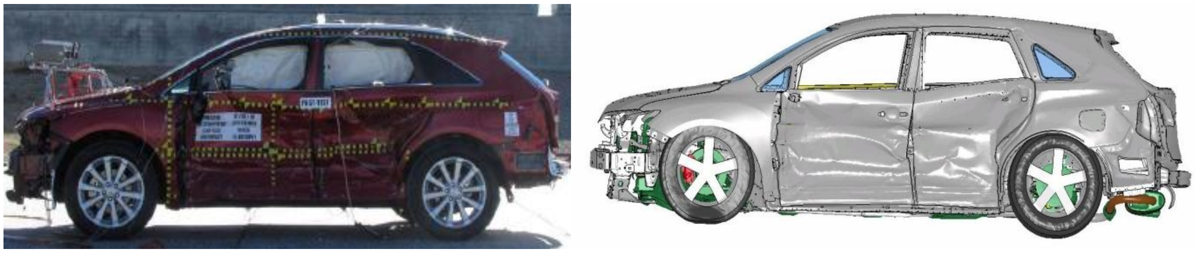


Image D-35: Side Impact: Post-Crash

Image D-36: Doors Deformation Mode Comparison

Image D-37: Rear Door Aperture Deformation Mode Comparison

It is also observed the deformation mode for the doors, especially the rear door aperture deformation, correlated reasonably well with the test as shown in **Image D-37**.

D.10.3.2.3 Intrusion Comparison

Another critical parameter correlated for the side impact case was the B-pillar intrusion levels at the driver-side compartment. The compartment structure intrusions were specified as intrusion numbers (see Figure 1.8.26). The intrusion numbers represent the relative displacement with respect to an undeformed driver-side structure. The accuracy of the intrusions was maintained by using a local vehicle coordinate system at a point on the passenger-side structure. The intrusions were measured at different zones such as zones 1, 2, & 3 to represent B-pillar upper, mid and lower areas. **Figure D-23** shows a section-cut view of the B-pillar intrusion. The gray contour represents the undeformed structure and the red contour represents the deformed structure.

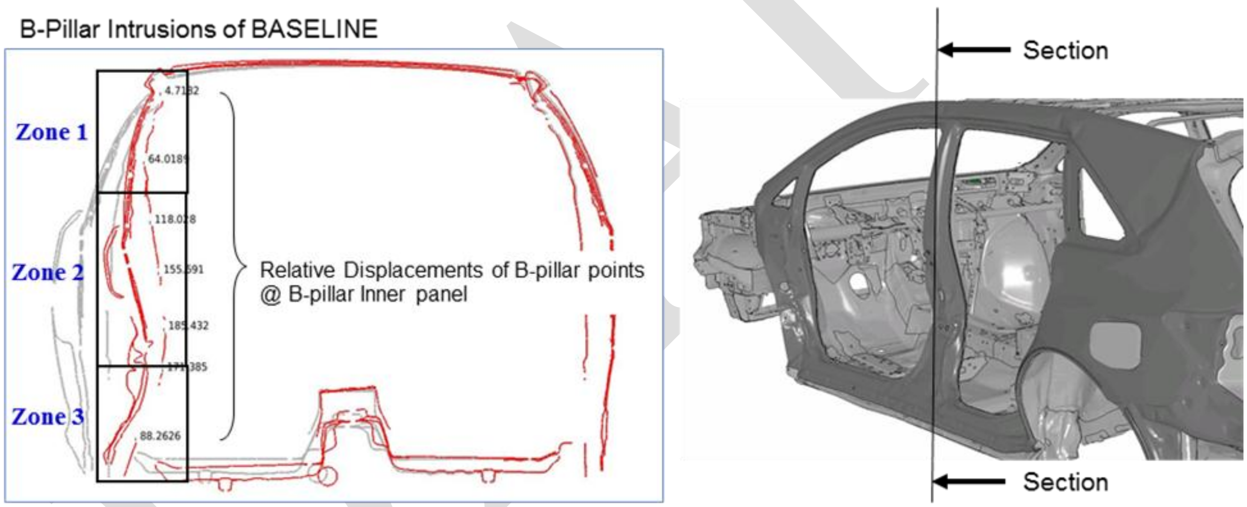


Figure D-23: B-Pillar & Side Rocker Intrusions

A summary of the relative intrusions of the B-pillar of the baseline model is shown in **Table D-8**.

	Zone 1		Zone 2			Zone 3	
Measured Location	Upper	Lower	Upper	Middle	Lower	Upper	Lower
Intrusion (mm)	-4.7	64.0	118.0	155.7	185.4	172.4	88.3

Table D-8: Baseline Model, Relative Intrusions of B-Pillar for FMVSS 214

In analyzing the comparison, the intrusion levels are found to be well correlated to the test results. For example, in zone 2, the maximum intrusion of 185.4mm is in good correlation with the test value of 184 mm[20] (data sheet 12, exterior crush measurements). Since the baseline model is found to be in good correlation with the test result, this intrusion plot is used to compare further iteration models.

D.10.4 Baseline Crash Results

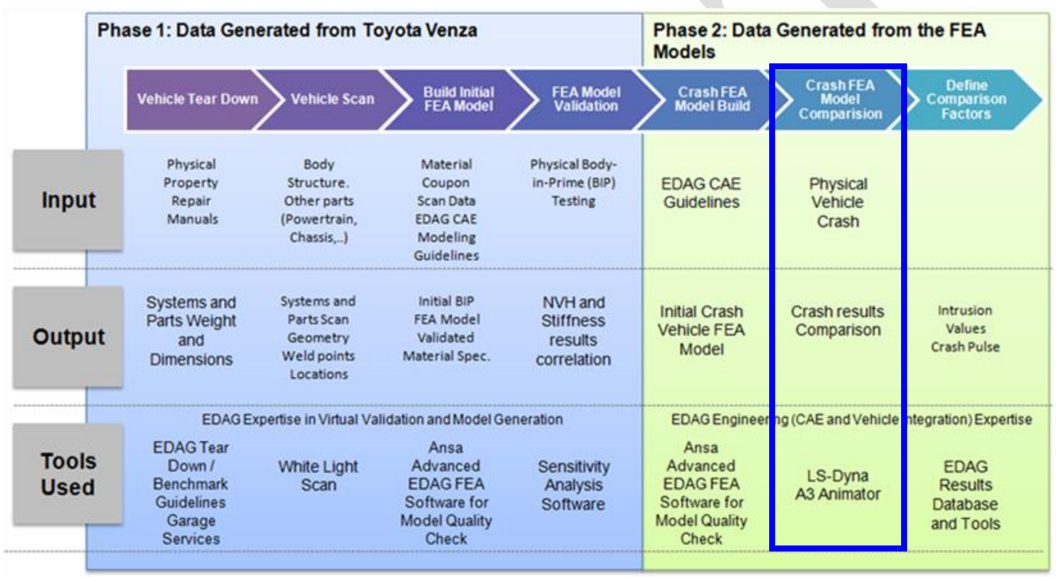


Figure D-24: Baseline Crash Results

The baseline crash results of the FMVSS 208 flat frontal and FMVSS 214 MDB side impact load cases were obtained during the crash model correlation stage (see analysis in Section 1.8.4). The correlated crash model became the baseline crash model for the remaining load cases. By using the correlated baseline model, the remaining 3 crash load cases (listed below and analyzed in the following sections) were simulated to obtain the baseline performance results.

- Euro NCAP—35 MPH ODB frontal crash (Euro NCAP/IIHS)
- FMVSS 301—50 MPH MDB rear impact
- FMVSS 216a—Roof crush resistance (utilizing IIHS roof crush resistance criteria)

These baseline results were treated as performance targets for further iterations.

D.10.4.1 I.FMVSS 208—35 MPH Flat Frontal Crash (US NCAP)

The impact requirements, model setup, and results of the FMVSS 208 flat frontal crash load case have been explained in the model comparison in section 1.8.4.

D.10.4.2 II.Euro NCAP—35 MPH ODB Frontal Crash (Euro NCAP/IIHS)

D.10.4.2.1 Model Setup

For the frontal offset crash load case, the Euro NCAP 35 MPH ODB test execution, as described in the requirements, was used. The CAE model was setup as defined in the Euro NCAP requirements. An offset barrier weighing 233 kg was used. The barrier was positioned with a 40% overlap with respect to the vehicle side-to-side width as per the test requirements. The vehicle impact speed was set at 35 MPH. A typical offset frontal impact model setup with ODB is shown in **Image D-38**.

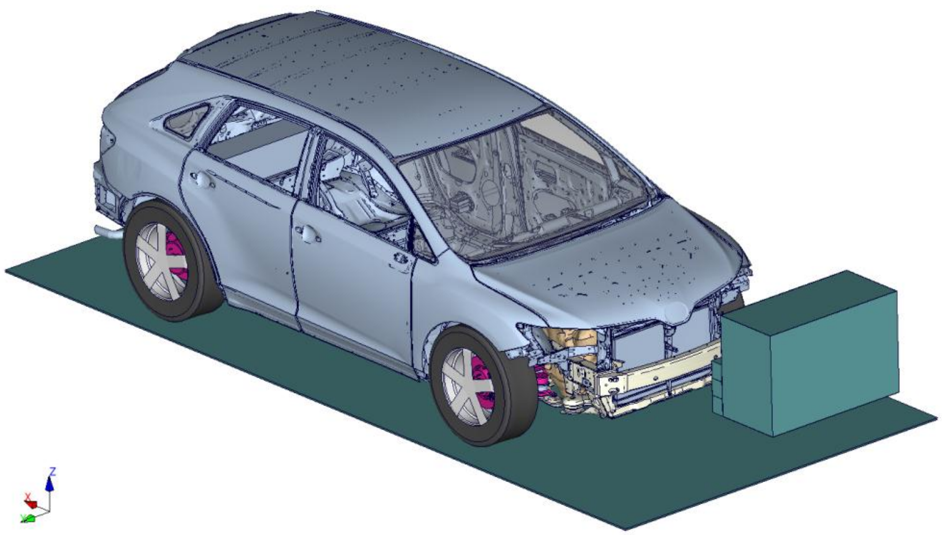


Image D-38: Euro NCAP Baseline Model Setup

To measure passenger compartment structure integrity, data analysis points as shown in **Image D-39** were measured with respect to a coordinate system reference at the cargo area of the body structure; reference point locations follow IIHS standards. To measure instrument panel (IP) movements, two reference points were taken from the cowl crossmember.

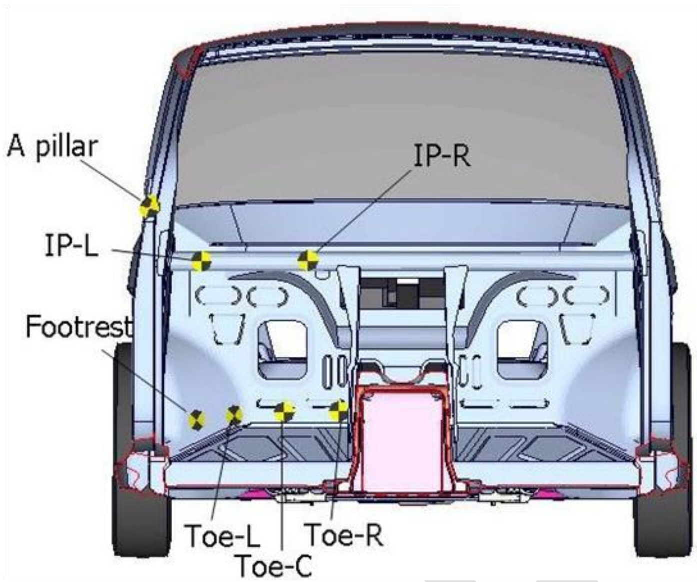


Image D-39: Intrusion Measurement Locations

The LS-DYNA simulation was carried out for a 100 msec analysis time frame. Offset frontal crash test results were not available for this selected Toyota Venza vehicle configuration; therefore, necessary results were analyzed based on the EDAG crash model.

D.10.4.2.2 Deformation Mode

The post-crash vehicle deformation modes of the CAE simulation are shown in **Images D-40** to **D-43**.

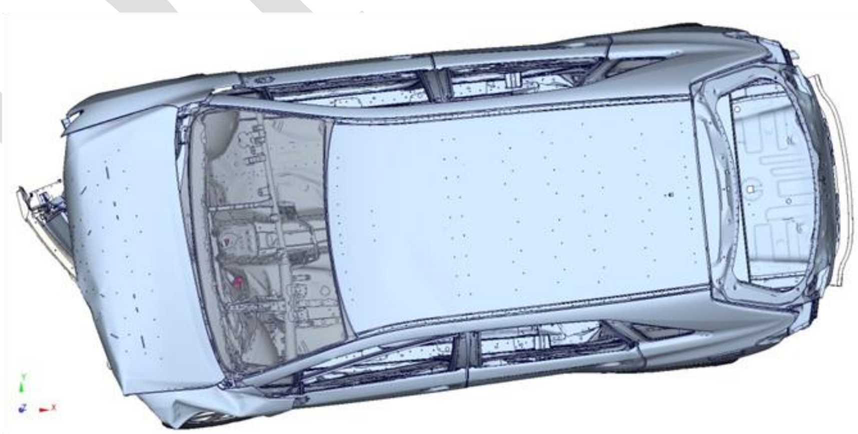


Image D-40: Euro NCAP Baseline Deformation Mode Top View

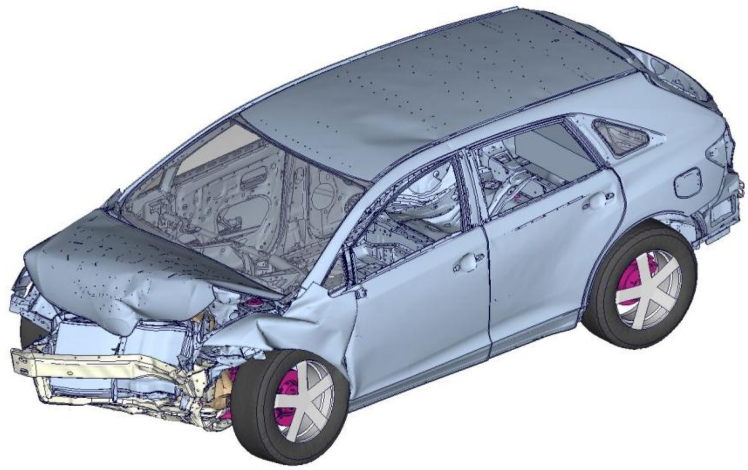


Image D-41: Euro NCAP Baseline Deformation Mode Isometric View

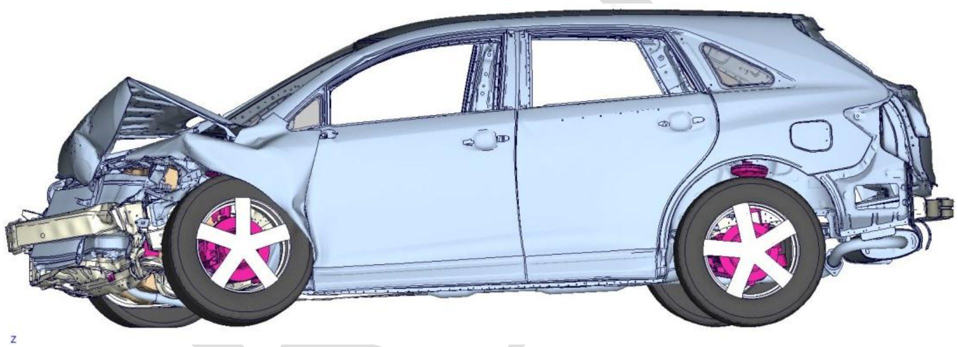


Image D-42: Euro NCAP Baseline Deformation Mode Left Side View

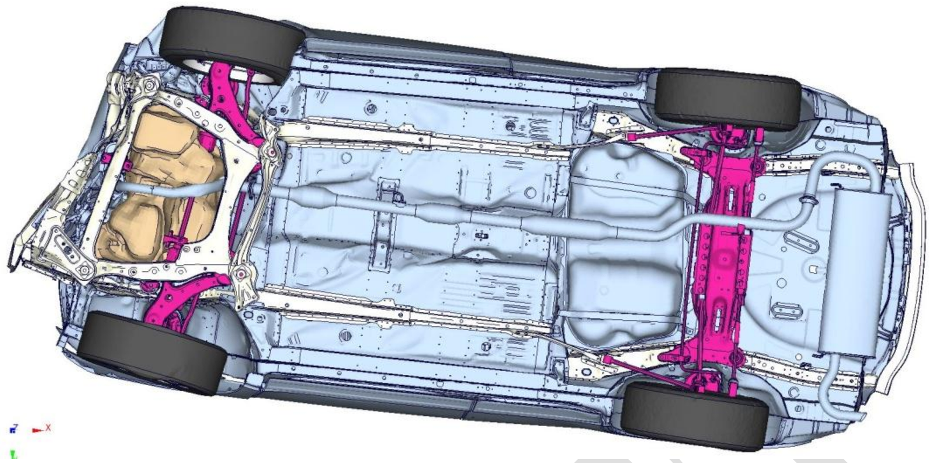


Image D-43: Euro NCAP Baseline Deformation Mode Bottom View

The deformation modes show the impact energy is absorbed by the front bumper and front rail parts without much compartment intrusion. It also reveals the model is integrated well without any connectivity issues.

D.10.4.2.3 Body Pulse, Dynamic Crush, and Intrusion

The vehicle velocity was measured in the x-direction and is shown in **Figure D-25**. The velocity was differentiated to obtain the vehicle acceleration in terms of crash pulse (in G's).

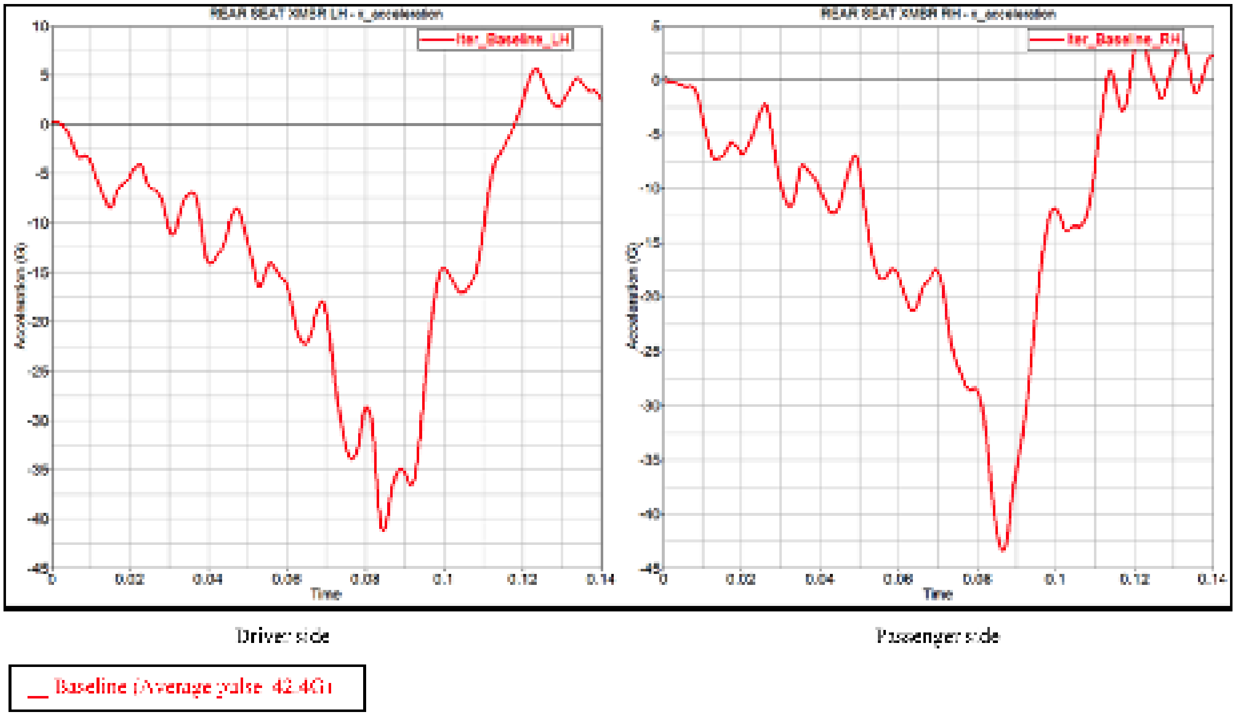


Figure D-25: Euro NCAP Baseline Vehicle Pulse

A crash pulse 35-38G range for the target performance is a conservative value. The CAE simulation shows the crash had a higher pulse of 42.4G but it still gives excellent frontal crash performance when analyzing the dynamic crush and compartment intrusions (explained below). This, coupled with the dynamic crush and compartment intrusion performance, led the engineering team to conclude the performance was sufficient to be the baseline target.

Dynamic crush is the total vehicle body deformation at the end of the crash event with respect to an undeformed vehicle. The initial crush of the Toyota Venza baseline was measured to be 605 mm, as shown in **Image D-44**.

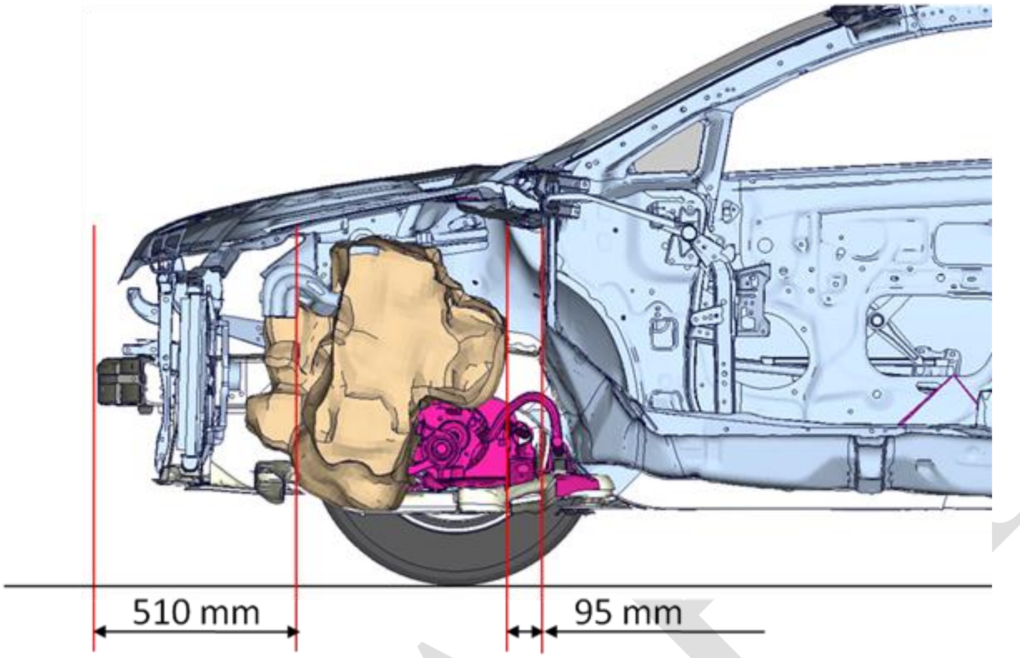


Image D-44: Allowable Crush Space

Graphs of the dynamic crush of frontal offset with and without barrier deformations are plotted in **Figures D-26** and **D-27**, respectively.

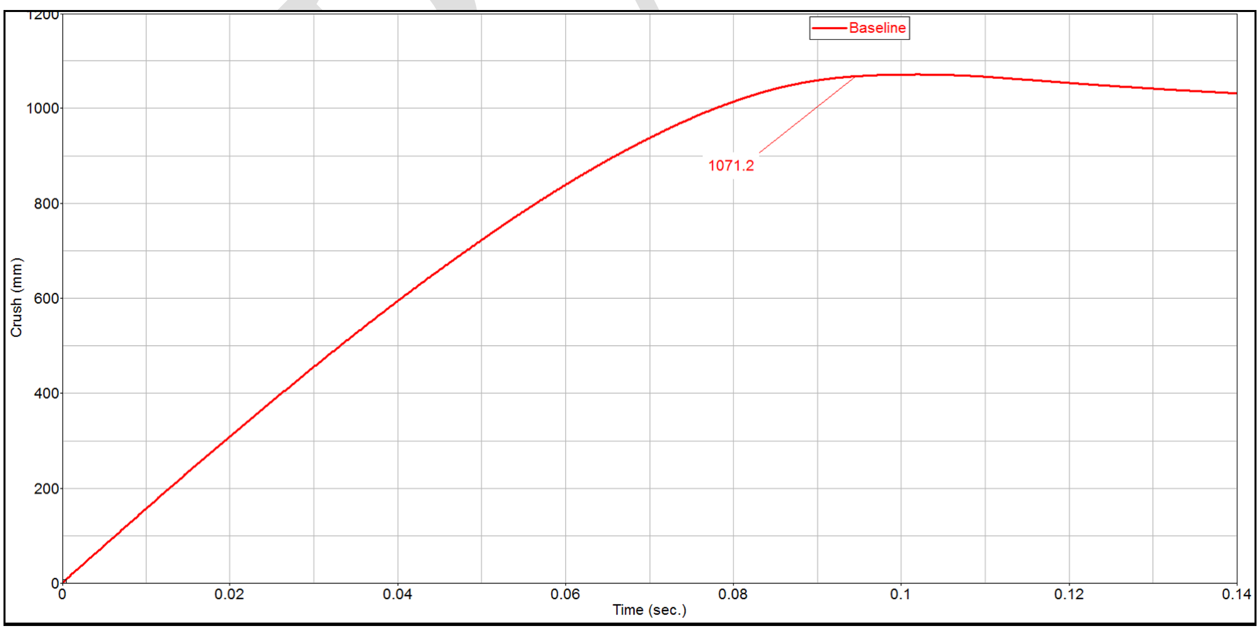


Figure D-26: Euro NCAP Baseline Dynamic Crush with Barrier Deformation

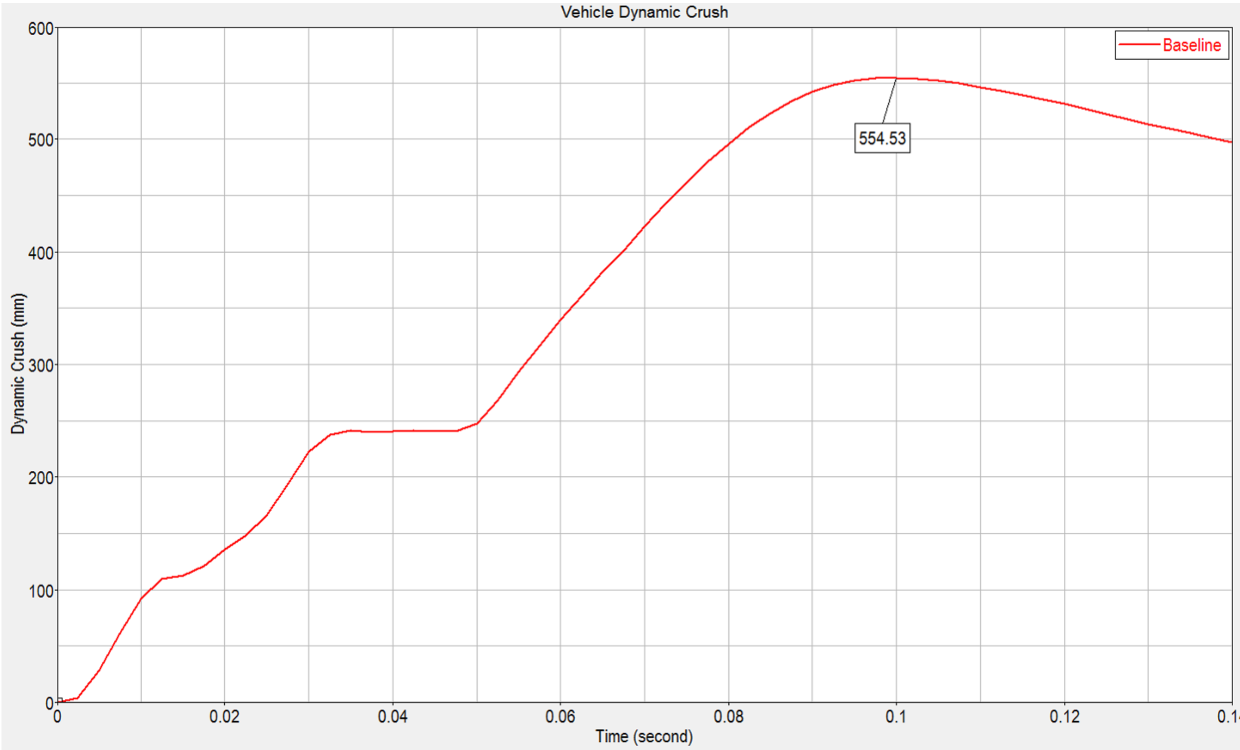


Figure D-27: Euro NCAP Baseline Dynamic Crush Without Barrier Deformation

The dynamic crush shown in **Figure D-26** includes the barrier deformation. Subtracting the barrier deformation, the vehicle crush is 554.5 mm as shown in **Figure D-27**. Therefore, the dynamic crush of the baseline model was within the acceptable range.

Another approach for analyzing the offset frontal crash performance was to plot the passenger compartment intrusions. In the Euro NCAP/IIHS case, the global structural deformation is plotted in terms of intrusion values measured at the compartment dash panel (shown in **Image D-39**). These are rated using different zones: good (green), acceptable (yellow), marginal (orange), and poor (red). The intrusion plot of the CAE baseline simulation is illustrated in **Figure D-28**. The CAE baseline model shows a good rating (green) at the foot well, left and right toe-pan, brake pedal point, and left and right instrument panel crossmember points. The CAE baseline model also shows an acceptable rating at the center toe-pan and door-opening area points.

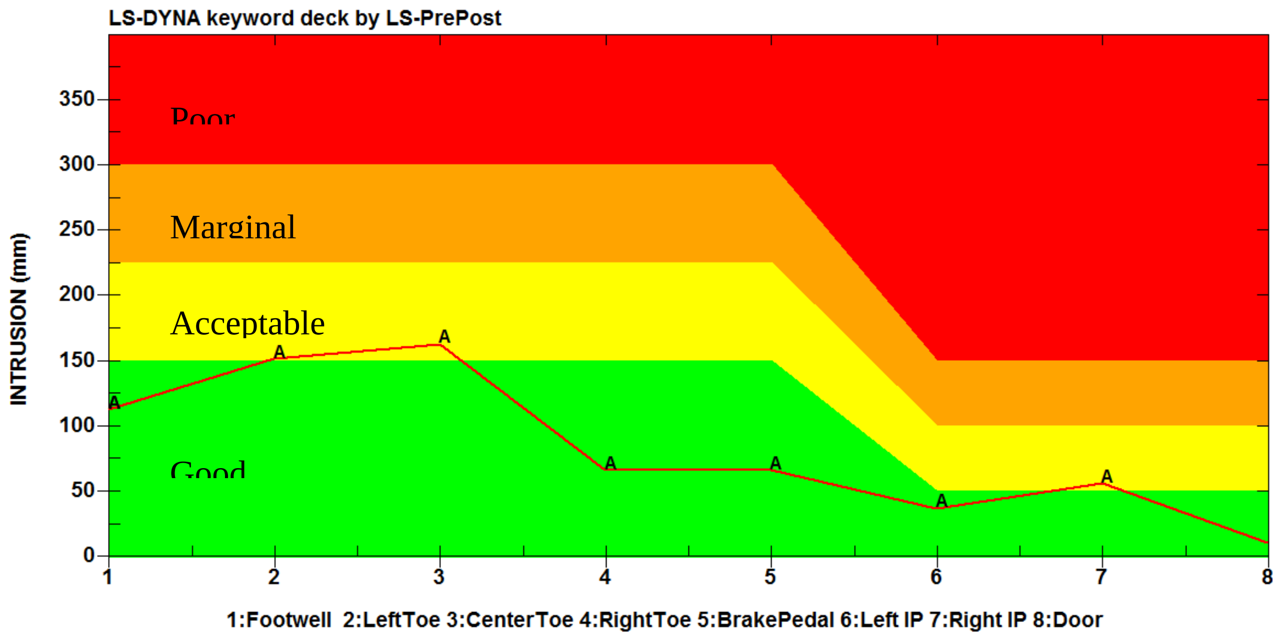


Figure D-28: Euro NCAP Intrusion Plot

A summary of the performance indicators of the baseline model for the offset frontal crash load case is listed in **Tables D-9** and **D-10**.

No.	Frontal crash measurements	Baseline Model
1	Pulse (G's)	1st Peak = 7.8 @ 13.8 ms 2nd Peak = 41.2 @ 84.5 ms
3	Dynamic Crush (mm)	1071.2
4	Weight (kg)	1710.0

Table D-9: Pulse and Dynamic Crush

Model	Driver Footwell (mm)	Driver Toe pan Left (mm)	Driver Toe pan center (mm)	Driver Toe pan Right (mm)
Baseline	133.7	171.2	169.9	75.9

Table D-10: Compartment Dash Intrusion

Based on the analysis of the deformation mode, dynamic crush, and compartment intrusions, this model was established as the EDAG NVH baseline target for further frontal offset load case iterations.

D.10.4.3 III.FMVSS 214—38.5 MPH MDB Side Impact

The impact requirements, model setup, and results of the FMVSS 214 side impact load case have been previously been examined (see Section 1.8.4).

D.10.4.4 IV.FMVSS 301—50 MPH MDB Rear Impact

D.10.4.4.1 Model Setup

FMVSS 301 specifies a moveable deformable barrier (MDB) impact at 50 mph (80 km/h) into a stationary vehicle with an overlap of 70% as shown in **Image D-45**. The MDB used in the test and analysis weighed 1,380 kg.

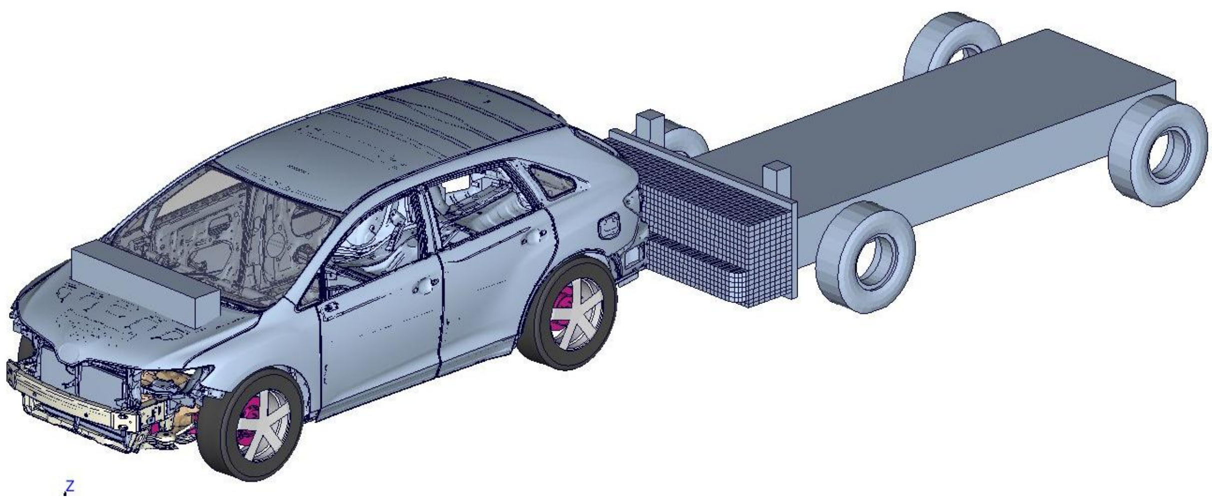


Image D-45: Rear Impact Baseline Model Setup.

The CAE model was setup as defined in the requirements of FMVSS 301. The LS-DYNA simulation was carried out for a 100 msec analysis time frame. FMVSS 301 test results are not available for this selected Toyota Venza vehicle configuration. What follows is an analysis of the results using the EDAG crash baseline model.

D.10.4.4.2 Deformation Mode

The deformation modes of the rear-impact simulation are shown in **Images D-46** to **D-49**. These deformation modes indicate that rear structures protect the fuel tank system during the crash event. In Figure 1.8.39 the rear door area shows no jamming shut of the door opening.

The skeleton view of the rear inner structure deformation in **Image D-47** shows the rear underbody was involved to maximize crush energy absorption and to minimize the deformation of the rear door and the fuel tank mounting areas.

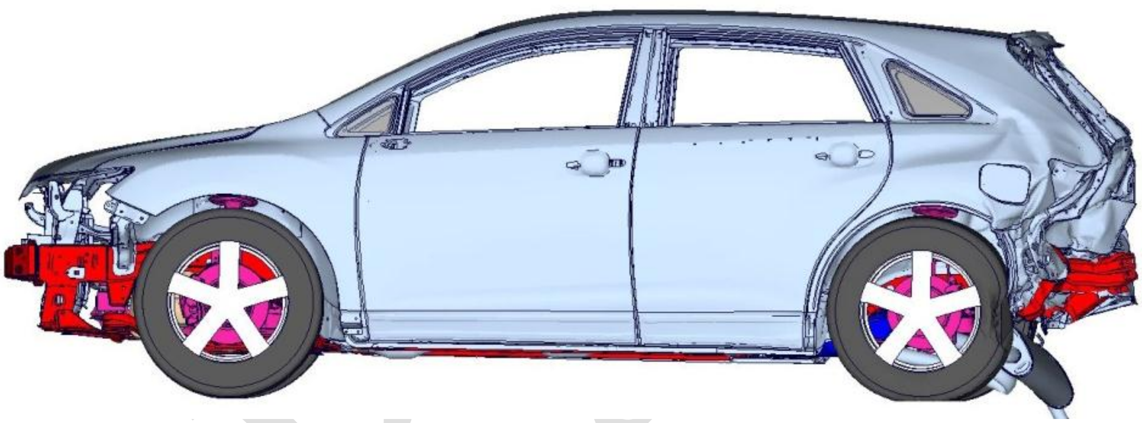


Image D-46: Deformation Mode, Left Side View

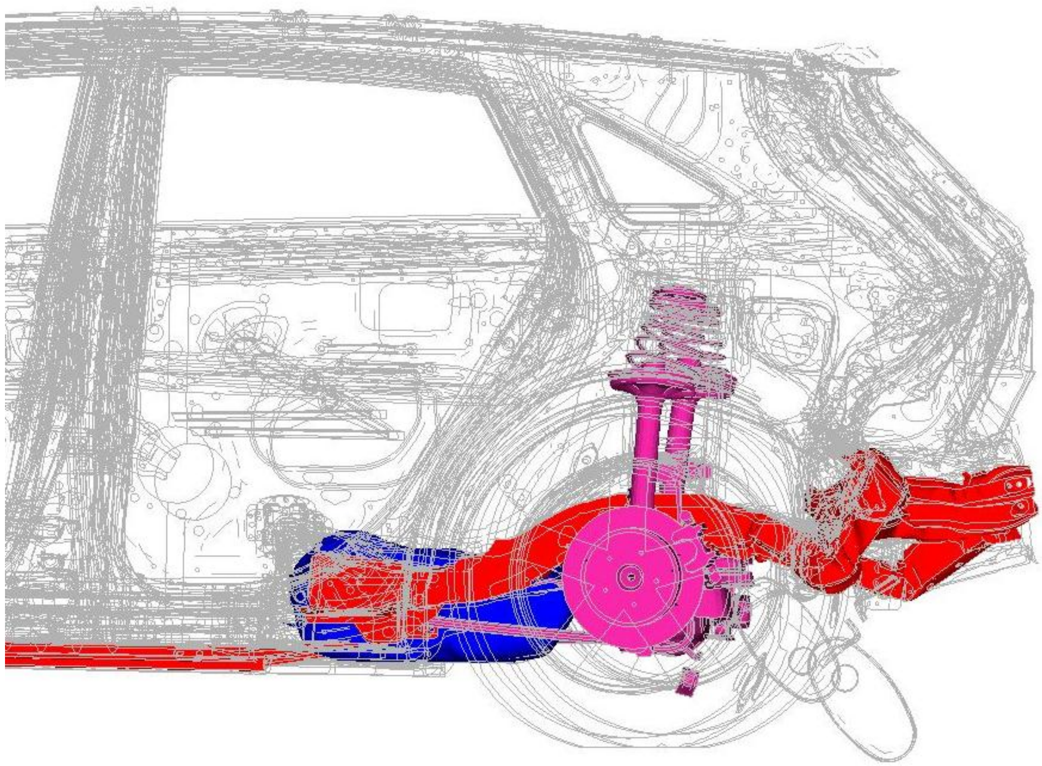


Image D-47: Deformation Mode of Rear Underbody Structure, Left Side View

The bottom view of the rear underbody structure around the fuel tank area at the end of the crash (100 msec) is shown in **Images D-48** and **D-49**. This deformation mode shows the rear rail structure and the rear suspension mounting are intact and that the fuel tank system is protected.

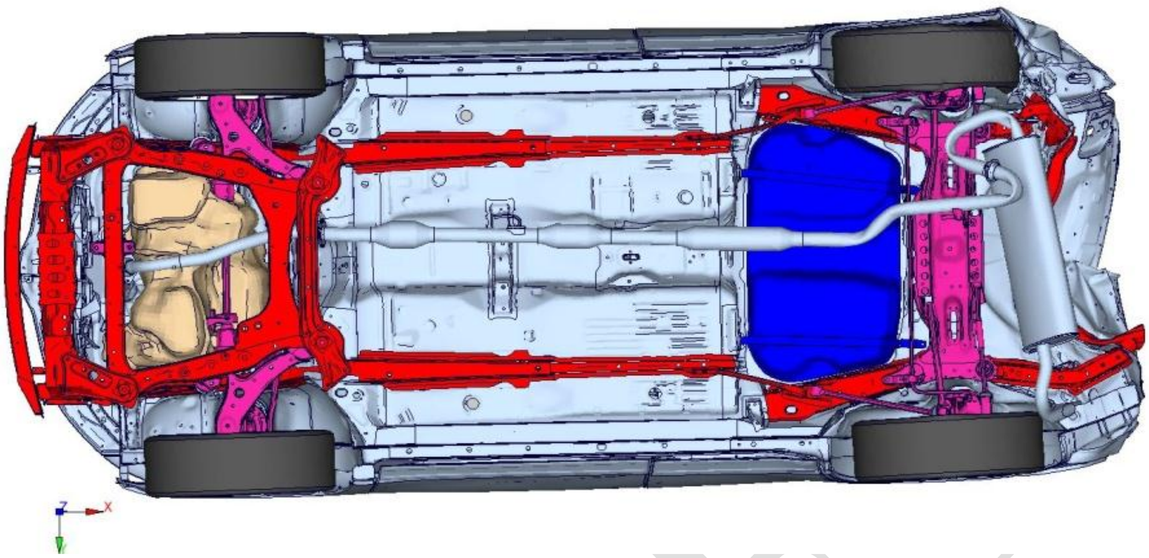


Image D-48: Deformation Mode, Bottom View at 100 msec

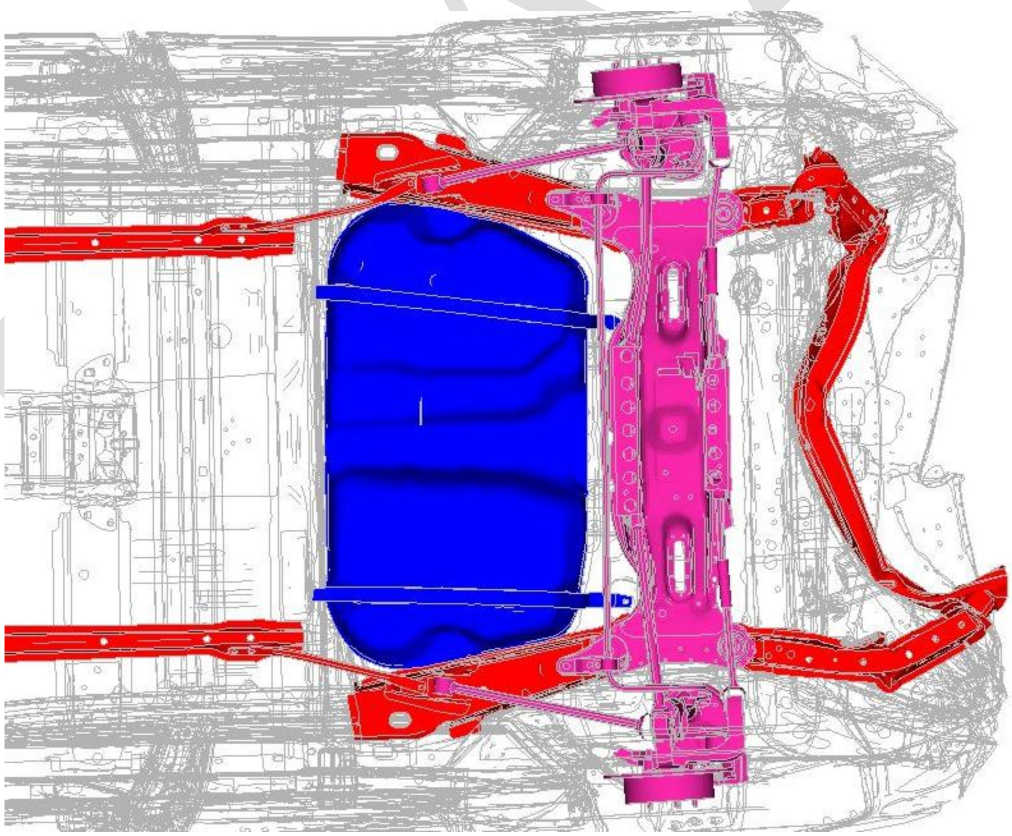


Image D-49: Deformation Mode of Rear Underbody Structure, Bottom View at 100 msec

D.10.4.4.3 <u>Fuel Tank Integration</u>

Fuel tank integrity was further analyzed by its plastic strain plot. The fuel tank system strain plot was monitored as one of the necessary parameters in the rear impact scenario. **Image D-50** and **D-51** show the plastic strain spot of the top and bottom of the fuel tank system at the end of the crash. It indicated no significant risk of fuel system damage as the maximum strain amount is less than 20% of the plastic strain of the entire fuel tank system.

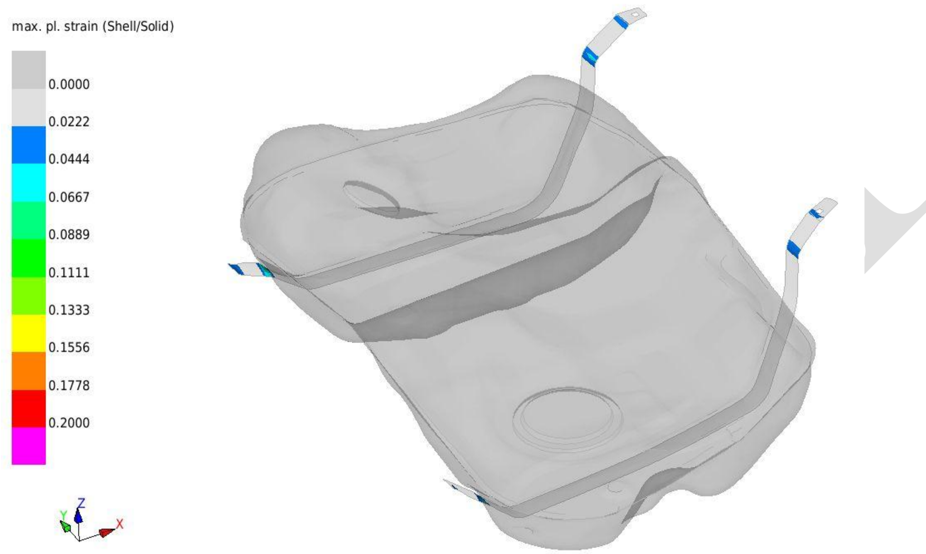


Image D-50: Fuel Tank Plastic Strain Plot of Baseline Top View

Image D-51: Fuel Tank Plastic Strain Plot of Baseline Bottom View

D.10.4.4.4 Structural Deformation

The structural performance of the rear impact is indicated as zonal deformation numbers at each of the deformation zones from the rear end to the front: zone 1—rear bumper area, zone 2—rear trunk structure area, zone 3—rear suspension mounting area, and zone 4—fuel tank mounting area. The deformation measurement locations are shown in **Image D-52**. In addition to the zone deformations, the rear-door opening area deformation was also measured in two more areas: the beltline and the dogleg.

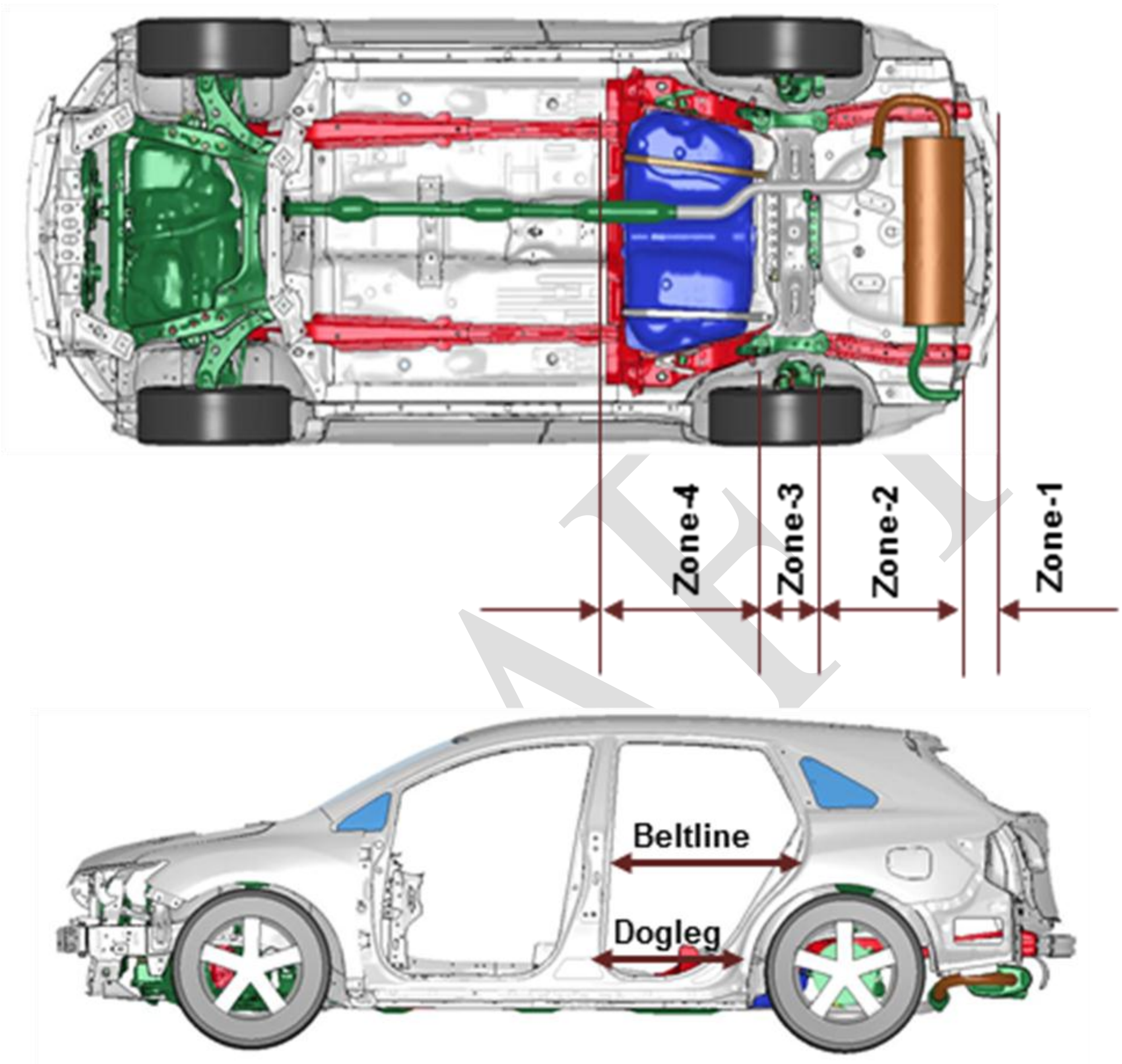


Image D-52: Rear Impact, Structural Deformation Measurement Area

The rear impact deformation measurements of the baseline model are summarized in **Table D-11**.

Model	Under Structure Zone Deformation (mm)				Door Opening (mm)	
	Zone-1	Zone-2	Zone-3	Zone-4	Beltline	Dogleg
Baseline	133.9	301.7	0	0	1.8	0

Table D-11: Rear Impact Structural Performance

Table D-11 shows the door is able to be opened on the baseline model after the crash.

D.10.4.5 V.FMVSS 216a Roof Crush Resistance

D.10.4.5.1 Model Setup

For the roof crash load case, FMVSS 216a roof crush resistance and IIHS roof crush resistance recommendations were used. The FMVSS 216a roof crush resistance test determines the crashworthiness of the vehicle in a rollover. This test requires each side of the passenger compartment roof structure to resist a maximum applied force equal to 3.0 times the unloaded vehicle weight (UVW). The IIHS roof crush resistance test, however, is more stringent and requires the roof structure should resist up to a maximum applied force equal to 4.0 times (rather than 3.0 times) the requirement in FMVSS 216a; it uses the same rigid rectangular platen which is used in the FMVSS 216a roof crush resistance procedure. According to both the FMVSS 216a and the IIHS roof crush resistance tests, the test vehicle will meet the requirements of the standard if each side of the roof structure withstands the maximum applied force prior to the lower surface of the rigid plate moving more than 127 millimeters.

In this project, the driver side roof crush resistance simulation was performed with the assumption of a symmetrical structure for the passenger side. The complete body structure was assembled and clamped at the lower edge of the rocker. The rigid loading device applied the load in a quasi-static manner to the structure by means of a flat rectangular loading platen. LS-DYNA pre-scribed motion[6] was applied in the platen's normal direction. **Image D-53** shows the typical roof crush resistance model setup with the platen positioned on the driver side roof.

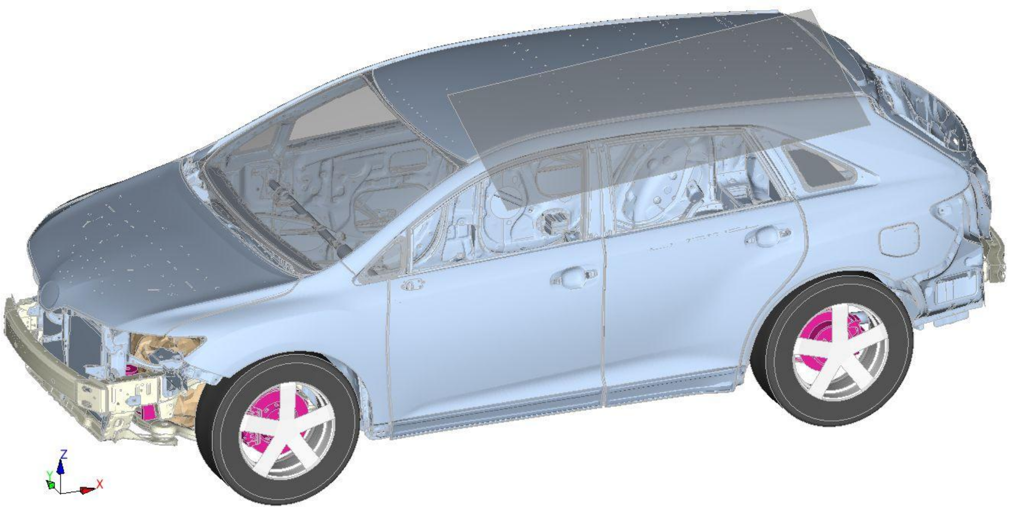


Image D-53: Roof Crush Baseline Model Setup.

The LS-DYNA simulation was carried out for a 140 msec analysis time frame. The strain contour plot of the upper BIP structure and the loading forces were recorded with respect to loaded platen travel.

D.10.4.5.2 Deformation Mode

The roof crush deformation mode at 140 msec after crush event is shown in **Image D-54**. It is noted most of the deformation is concentrated on the roof rail, the A-pillar, and the B-pillar of the load side. The remaining neighboring structures remained undeformed. As a result, a majority of the roof rail and B-pillar deformation modes were analyzed.

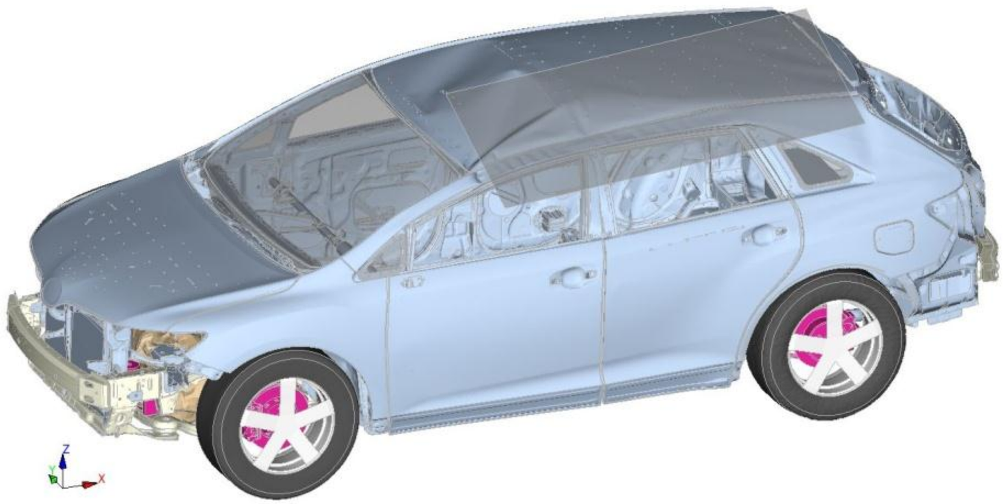


Image D-54: Roof Crush Baseline After Crush View

D.10.4.5.3 Structural Strength

The strength of the roof rail and B-pillar structures in terms of rear passenger head protection during the rollover scenario was determined by a maximum plastic strain plot and a platen force vs. displacement plot. **Image D-55** shows the plastic strain distribution of the roof and B-pillar structures. A 20% limit of the plastic strain was set to analyze the strain distribution. The maximum plastic strain is found to be within the 20% limit over a very few spots, not indicating any failures.

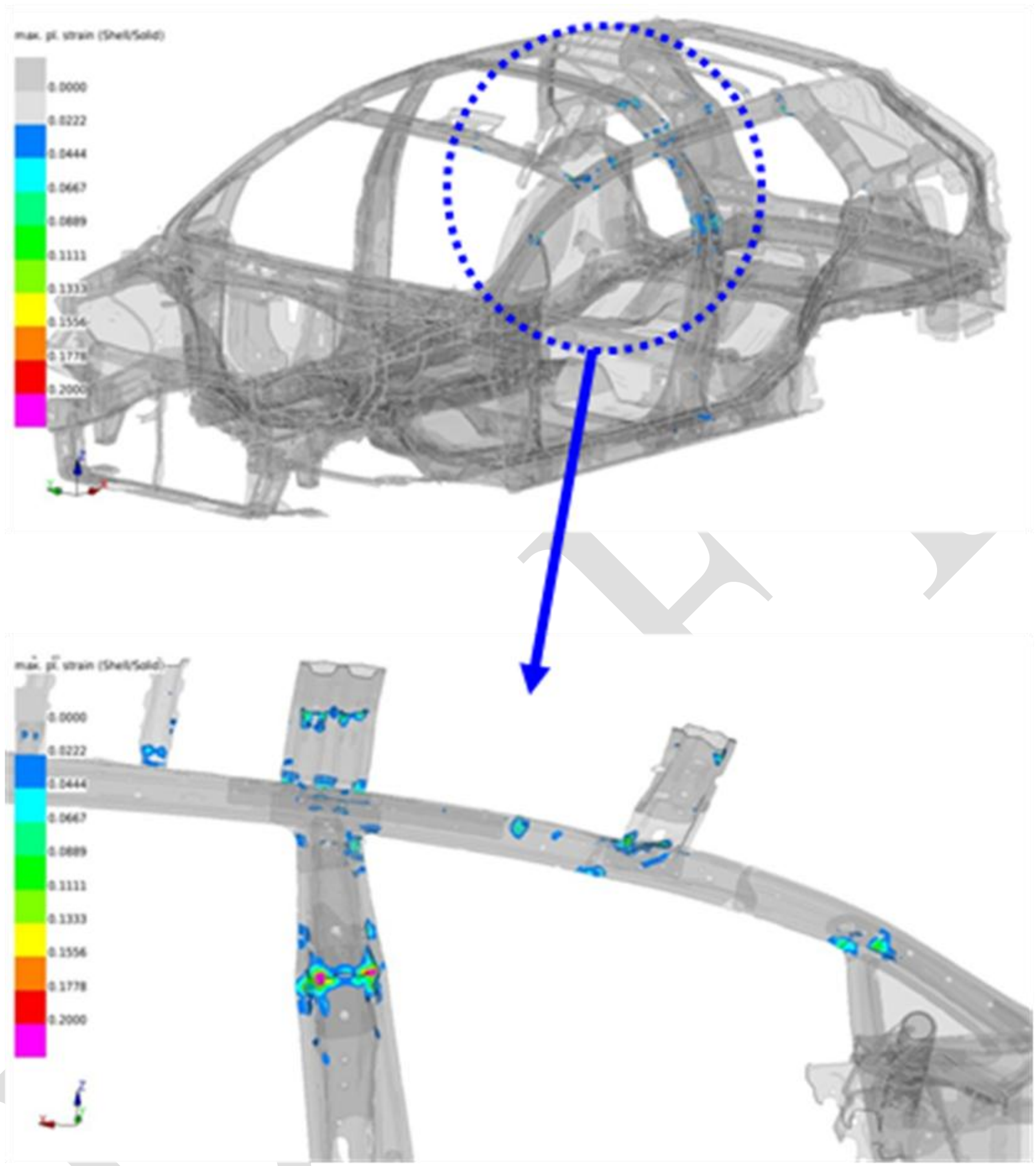


Image D-55: Roof Crush Resistance Baseline After Crush

The ultimate performance of roof crush resistance was determined by the platen force level over the vehicle roof structure. The force vs. displacement curve of the platen is illustrated in Figure 1.8.49.

Figure D-29: Roof Crush Force vs. Displacement Plot of Baseline

A 4 times UVW criterion was used to verify both FMVSS216a and IIHS roof crush resistance requirements. The UVW of the baseline roof crush resistance model is 1,705.5 kg. From **Figure D-29** it is observed the maximum load (86 kN) is greater than 4 times UVW (66.8 kN). Therefore, the baseline model meets both the FMVSS216a and IIHS requirements; it will be treated as the target requirement for further roof crush resistance iterations.

E. Cost Analysis Methodology

E.1 Overview of Costing Methodology

A comprehensive discussion of the costing methodology used to develop the incremental direct manufacturing cost can be found in the EPA published report "Light-Duty Technology Cost Analysis Pilot Study" (EPA-420-R-09-020). In the context of the EPA analysis, incremental direct manufacturing cost is the incremental difference in cost of components and assembly to the OEM, between the new mass reduced technology and baseline technology configurations. The FEV calculated costs for the EPA analyses did not give consideration to any incremental OEM indirect cost with the exception of tooling costs. This portion of the analysis was carried out by the EPA through the application of Indirect Cost Multipliers (ICMs). For additional details on the development and application of ICM factors, reference EPA report EPA-420-R-09-003, February 2009, "Automobile Industry Retail Price Equivalent and Indirect Cost Multiplier" and EPA report EPA-420-D-11-901, November 2011, "Draft Joint Technical Support Document".

The costing methodology is based heavily on assembly teardowns and component analysis of both mass reduced and baseline technology configurations that have similar driving performance metrics. Only components identified as being different, within the two selected technology configurations, as a result of the mass reduced technology adaptation, are evaluated for cost. Component costs are calculated using a ground-up costing methodology analogous to that employed in the automotive industry. All incremental costs for the new technology are calculated and presented using transparent cost models consisting of eight (8) core cost elements: material, labor, manufacturing overhead/burden, end item scrap, SG&A (selling general and administrative), profit, ED&T (engineering, design, and testing), and packaging.

E.2 Teardown, Process Mapping, and Costing

E.2.1 Cost Methodology Fundamentals

The costing methodology employed in this analysis is based on two (2) primary processes: (1) the development of detailed production process flow charts (P-flows), and (2) the transfer and processing of key information from the P-flows into standardize quoting worksheets. Supporting these two (2) primary processes with key input data are the process cost models and the costing databases (e.g. material [price/kg], labor [$/hour], manufacturing overhead [$/hour], mark-up [% of manufacturing cost], and packaging [$/packaging type]). The costing databases are discussed in greater detail in Section E.5.

Process flow charts, depending on their defined function and the end user, can vary widely in the level of detail contained. They can range from simple block diagrams showing the general steps involved in the manufacturing or assembly of an item, to very detailed process flow charts breaking out each process step in fine detail capturing key manufacturing variables. For this cost analysis, detailed P-flows (which will also be referred to as process maps) are used to identify all the steps involved in manufacturing a product (e.g., assembly, machining, welding, forming), at all levels (e.g., system, subsystem, assembly and component).

For example, in a front corner brake system scenario, process flows would exist for the following: (1) at the ***component level***, the manufacturing of every component within the front brake caliper sub-assembly. This would include such components as the caliper housing, caliper mounting bracket, caliper piston, etc. (unless considered a purchase part – ie. Bleeder fitting, brake pads, piston seal, fastening bolts, etc.); (2) at the ***assembly level***, the assembly of all the individual components to produce the caliper assembly module; (3) at the ***sub-subsystem level***, the assembly of the caliper module onto the front knuckle module (including the splash shield, bearing hub, rotor, etc.); and (4) at the ***subsystem level***, the assembly of the front corner brake module onto the vehicle suspension and framing connections. In this example, the front corner brake system is one of several subsystems (e.g., rear brake subsystem, parking brake subsystem, brake actuation subsystem, and power brake subsystem) making up the vehicle overall braking system. Each subsystem, if it is cost in the analysis, would have its own process map broken out using this same process methodology.

In addition to detailing pictorially the process steps involved for a given manufacturing process, having key information (e.g., equipment type, tooling configuration, material type & usage, cycle times, handling requirements, number of operators) associated with each step is imperative. Understanding the steps and the key process parameters together creates the costing roadmap for any particular manufacturing process.

Due to the vast and complex nature of P-flows associated with some of the larger systems and subsystems under analysis, having specialized software which can accurately and consistently create and organize the abundant number of detailed P-flows becomes a considerable advantage. For this cost analysis Design Profit® software is utilized for producing and managing the process flows and integrating key costing information.

Simply explained, the symbols which make up the process map each contain essential pieces of information required to develop a cost for a particular operation or process. For example, in a metal stamping process, the basic geometry of the part, quantity and complexity of part features, material gauge thickness, material selection, etc., are examples of the input parameters used in the calculation of the output process parameters (e.g. press size, press cycle time, stamping blank size). From the calculated press size an overhead rate, corresponding to the recommend press size, would be selected from the manufacturing overhead database. Dividing the equipment rate ($/hour) by the cycle time (pieces/hour) yields a manufacturing overhead cost contribution per part. In a similar fashion a labor contribution cost would be generated. The loaded labor rate for a press operator would be pulled from the labor database. An estimate is made on how many presses the operator is overseeing during any given hour of operation. Dividing the labor rate by number of presses the operator is overseeing, and then by number of pieces per hour, a labor cost contribution per part is derived.

Lastly, using the calculated blank size, material type, and material cost (i.e., price per kilogram) pulled from the material database, a material contribution cost per part can be calculated. Adding all three cost contributors together (e.g., Manufacturing Overhead, Labor, Material) a Total Manufacturing Cost (TMC) is derived. The TMC is then multiplied by a mark-up factor to arrive at a final manufacturing cost. As explained briefly below and in more detail in Section E.7, key data from the process flows and databases are pulled together in the costing worksheets to calculate the TMC, mark-up contribution, and final manufacturing cost.

There are three (3) basic levels of process parameter models used to convert input parameters into output process parameters that can then be used to calculate operation or processing costs: simple serial, generic moderate and custom complex. 1) Simple serial are simple process models which can be created directly in Design Profit®. These process models are single input models (e.g., weld time/linear millimeter of weld, cutting time/square millimeter of cross-sectional area, drill time/diameter vs millimeter of hole depth). 2) Generic moderate process models are more complex than simple serial, requiring multiple input parameters. The models have been developed for more generic types of operations and processes (e.g., injection molding, stamping, die casting). The process models, developed in Microsoft Excel, are flexible enough to calculate the output parameters for a wide range of parts. Key output parameters, generated from these external process models, are then entered into the process maps. 3) Custom complex parameter models are similar to generic moderate models except in that they are traditionally more complex in nature and have limited usage for work outside of what they were originally developed. An example of a custom complex model would be one developed for manufacturing a selected size heat exchanger (radiator) unit for a particular vehicle engine size and body configuration.

All process parameter cost models are developed using a combination of published equipment data, published processing data, actual supplier production data, and/or subject matter expert consultation.

The second major step in the cost analysis process involves taking the key information from the process flows and uploading it into a standardized quote worksheet. The quote worksheet, referred to as the Manufacturing Assumption and Quote Summary (MAQS) worksheet, is essentially a modified generic OEM quoting template. Every assembly included in the cost analysis (excluding commodity purchased parts) has a completed MAQS worksheet capturing all the cost details for the assembly. For example, all the components and their associated costs, required in the manufacturing of a brake caliper module assembly, will be captured in the caliper module assembly MAQS worksheet. In addition, a separate MAQS worksheet detailing the cost associated with assembling the caliper assembly to the vehicle front suspension knuckle, along with any other identified front corner brake sub-subsystem components, would be created.

In addition to process flow information feeding into the MAQS worksheet, data is also automatically imported from the various costing databases. More discussion on the MAQS worksheet, the database interfaces, and it's complete function is captured in **Section E.7**.

E.2.2 Serial and Parallel Manufacturing Operations and Processes

For purpose of this analysis, serial operations are defined as operations which must take place in a set sequence, one (1) operation at a time. For example, fixturing metal stamped bracket components before welding can commence, both the fixturing and welding are considered serial operations within the bracket welding process. Conversely, parallel operations are defined as two (2) or more operations which can occur simultaneously on a part. An example of this would be machining multiple features into a cylinder block simultaneously.

A process is defined as one (1) or more operations (serial or parallel) coupled together to create a component, subassembly, or assembly. A serial process is defined as a process where all operations (serial and/or parallel) are completed on a part before work is initiated on the next. For example, turning a check valve body on a single spindle, CNC screw machine, would be considered a serial process. In comparison, a parallel process is where different operations (serial and/or parallel) are taking place simultaneously at multiple stations on more than one (1) part. A multi-station final assembly line, for assembling together the various components of a vacuum pump, would be considered a parallel process.

As discussed, the intent of a process flow chart is to capture all the individual operations and details required to manufacture a part (e.g., component, subassembly, assembly). This often results in a string of serial operations, generating a serial process, which requires additional analysis to develop a mainstream mass production process (i.e., inclusion of parallel operations and processing). The Manufacturing Assumption section of the MAQS worksheet is where the base assumptions for converting serial operations and processes into mass production operations and processes, is captured.

For example, assume "Assembly M" requires fifteen (15) operations to assemble all of its parts. Each operation, on average, taking approximately ten (10) seconds to complete. In a serial process (analogous to single, standalone work cell, manned by a single operator) consisting of fifteen (15) serial operations, the total process time would be 150 seconds to produce each part (15 operations x 10 second average/station). By taking this serial assembly process and converting it into a mass production parallel process, the following scenarios could be evaluated (Note: rates and assumptions applied below are assumed for this example only):

Scenario #1: 15 serial operation stations, all manned, each performing a single parallel operation.

- Process Time 10 seconds/part, 360 parts/hour @ 100% efficiency
- Labor Cost/Part = [(15 Direct Laborers)*(Labor Rate $30/hour)]/360 parts/hour = $1.25/part
- Burden Cost/Part = [(15 Stations)*(Burden Rate Average (Low Complexity Line) $15/hour/station)]/360 parts/hour = $0.625/part
- Labor + Burden Costs = $1.875/part

Scenario #2: 15 serial operations combined into 10 stations, 5 with 2 parallel automated operations, 5 serial manual operations.

- Process Time 10 seconds/part, 360 parts/hour @ 100% efficiency,
- Labor Cost/Part = [(5 Direct Laborers)*(Labor Rate $30/hour)]/360 parts/hour = $0.42/part
- Burden Cost/Part = [(10 Stations)*(Burden Rate Average (Moderate Complexity Line) $30/hour/station)]/360 parts/hour = $0.83/part
- Labor + Burden Costs = $1.25/part

Assuming a high production volume and a North America manufacturing base (two key study assumptions), Scenario #2 would have been automatically chosen, with the higher level of automation offsetting higher manual assembly costs.

For a component which has a serial process as its typical mass production process (e.g., injection molding, stamping, die casting, selected screw machining), the manufacturing assumption section of the MAQS worksheet requires far less consideration. Analysis is usually limited to determining the total number of equipment pieces required for the defined volume. **Figure E-1** illustrates the fundamental steps incorporated into the cost methodology.

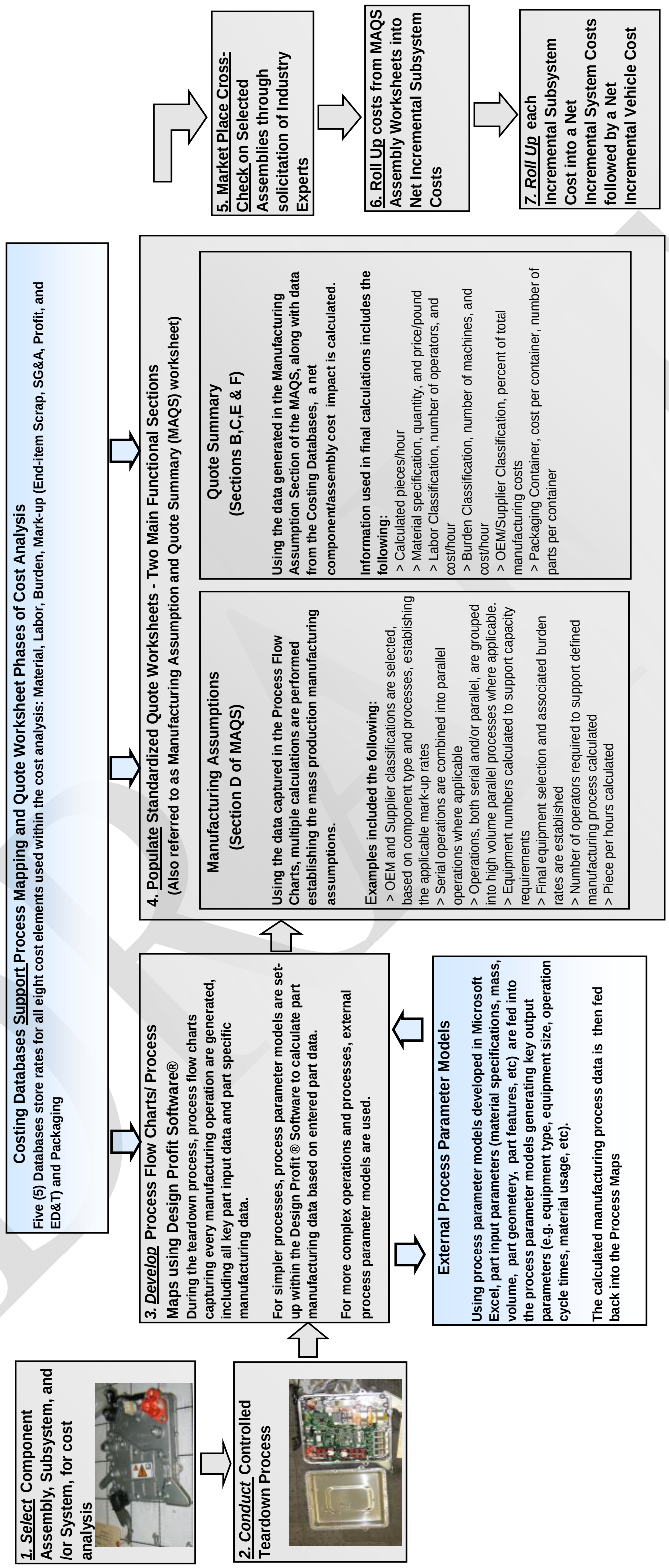


Figure E-1: Fundamental Steps in Costing Process

E.3 Cost Model Overview

The cost parameters considered in determining the net incremental component/assembly impact to the OEM for new technologies are discussed in detail following.

Unit Cost is the sum of total manufacturing cost (TMC), mark-up costs, and packaging cost associated with producing a component/assembly. It is the net component/assembly cost impact to the OEM (generally, the automobile manufacturer). **Figure E-2** shows all the factors contributing to unit cost for supplier manufactured components. Additional details on the subcategories are discussed in the sections that follow.

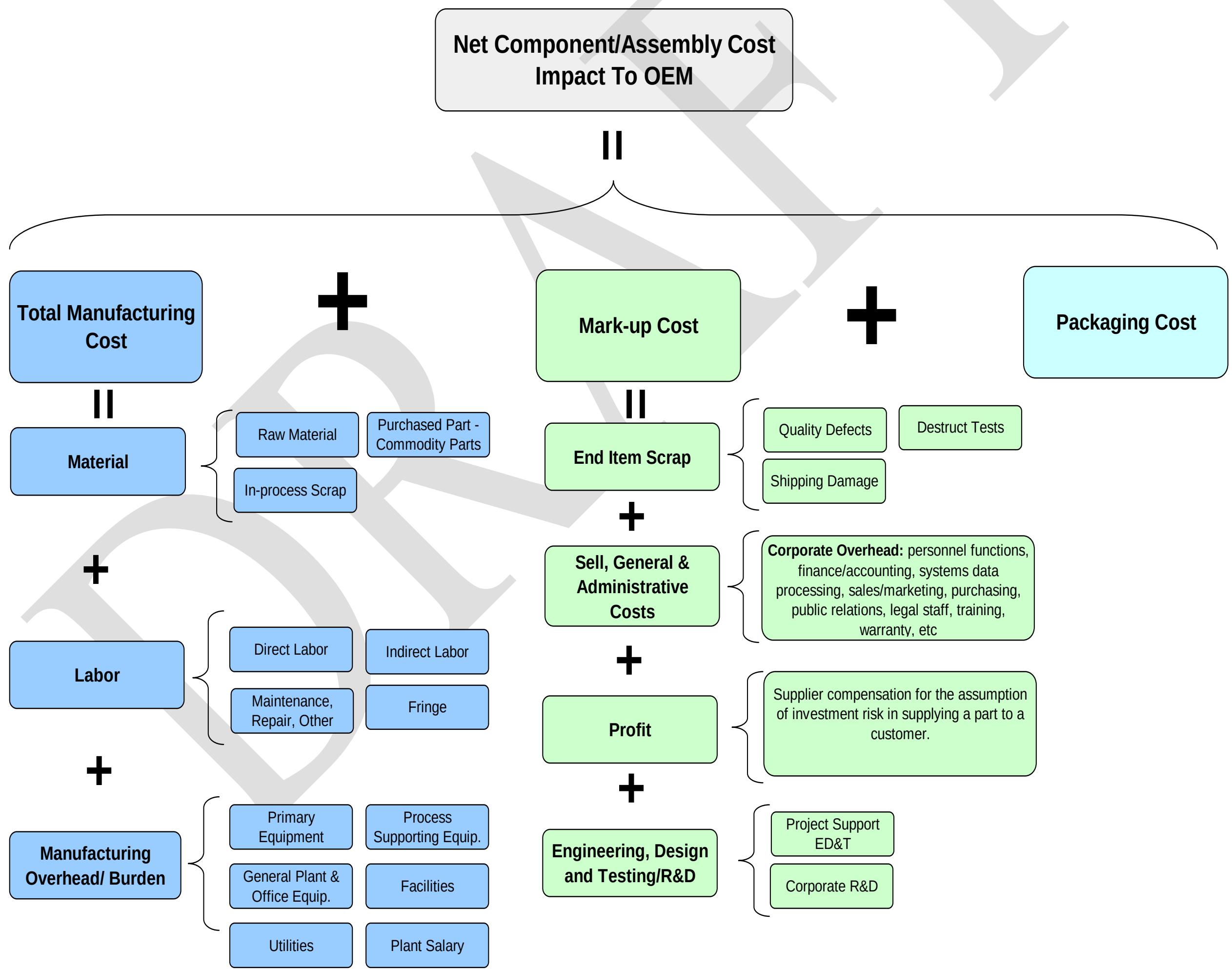


Figure E-2: Unit Cost Model – Costing Factors Included in Analysis

For OEM manufactured components/assemblies, the unit cost is calculated in the same way, except that mark-up is addressed outside the scope of this study through application of indirect cost multipliers (ICM). See Section E.4 for additional details.

Shipping Costs are those required to transport a component between dispersed manufacturing and assembly locations, including any applicable insurance, tax, or surcharge expenses. Shipping costs between T2/T3 and T1 suppliers are captured as part of the mark-up rate (except where special handling measures are involved). For T1 supplier to OEM facilities, the shipping costs are captured using the ICM that replaces mark-up as discussed previously. Additional details on shipping costs are discussed in **Section E.66**.

Tooling Costs are the dedicated tool, gauge, and fixture costs required to manufacture a part or assembly. Examples of items covered by tooling costs include injection molds, casting molds, stamping dies, weld fixtures, assembly fixtures, dedicated assembly and/or machining pallets, cutting tool bodies, torque guns and dedicated gauging. For this analysis, all tooling is assumed to be owned by the OEM. The differential cost impact due to tooling expense is calculated but not included in the incremental direct manufacturing cost in this study. It is however further discussed in **Section E.10**.

Investment Costs are the manufacturing facility costs, not covered as tooling, required to manufacture parts. Investment costs include manufacturing plants (facilities including building structure, flooring & foundations, lighting, water & pneumatic systems, manufacturing equipment (e.g., injection mold machines, die cast machines, machining and turning machines, welding equipment, assembly lines), material handling equipment (e.g., lift forks, overhead cranes, loading dock lifts, conveyor systems), paint lines, plating lines, and heat treat equipment. Investment costs are covered by manufacturing overhead rates and thus are not summed separately in the cost analysis. Additional details on how investments expenses are accounted for through manufacturing overhead can be found in **Section E.5.4**.

Product Development Costs are the ED&T costs incurred for development of a component or system. These costs can be associated with a vehicle-specific application and/or be part of the normal research and development (R&D) performed by companies to remain competitive. In the cost analysis, the product development costs for suppliers are included in the mark-up rate as ED&T. More details are provided in **Section E.5.5.2**. For the OEM, the product development costs are captured in the ICM that replaces mark-up, as discussed previously in the Unit Cost section.

In summary, the two (2) main cost elements (TMC and Mark-up) in the supplier unit cost model defined in **Figure E-2** include considerations for shipping, investment, and product development costs. For the purpose of this study component/assembly packaging costs were considered to be neutral due to the relative size envelope of these parts not changing significantly between the production stock and mass-reduced parts.

Investment costs for the OEM are accounted in the OEM Unit cost model via the TMC. Shipping, tooling, product development and other OEM mark-up costs are accounted for as part of the ICM and are addressed outside the scope of this study.

Lastly, the "Net Incremental Direct Manufacturing Cost" is the incremental difference in cost of components and assembly, to the OEM, between the mass reduced technology configuration and the baseline technology configuration.

A more detailed discussion on the elements which make-up the unit cost model follows in **Section E.5, Costing Databases**.

E.4 Indirect OEM Costs

In addition to the direct manufacturing costs, a manufacturer also incurs certain indirect costs. These costs may be related to production, such as research and development (R&D); tooling; corporate operations, such as salaries, pensions, and health care costs for corporate staff; or selling, such as transportation, dealer support, and marketing. Indirect costs incurred by a supplier of a component or vehicle system constitute a direct manufacturing cost to the OEM (the original equipment (vehicle) manufacturer), and thus are included in this study. The OEM's indirect costs, however, are not included and must be determined and applied separately to obtain total manufacturing costs. These indirect costs are beyond the scope of this study and are applied separately by the EPA staff in their analysis. The methodology used by the EPA to determine indirect costs incurred by auto manufacturers is presented in two (2) studies:

1) Rogozhin, A., et al., "Using Indirect Cost Multipliers to Estimate the Total Cost of Adding New Technology in the Automobile Industry," International Journal of Production Economics (2009), doi:10.1016/j.ijpe.2009.11.031.

2) Gloria Helfand and Todd Sherwood, ''Documentation of the Development of Indirect Cost Multipliers for Three Automotive Technologies,'' Office of Transportation and Air Quality, U.S. EPA, August 2009. This document can be found in the public docket at EPA–HQ–OAR–2010–0799-0064 (www.regulations.gov).

3) EPA & NHTSA, "Draft Joint Technical Support Document: Proposed Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards &

Corporate Average Fuel Economy Standards," for EPA report EPA-420-D-11-901, November 2011, at (http://www.epa.gov/otaq/climate/documents/420d11901.pdf).

E.5 Costing Databases

E.5.1 Database Overview

The Unit Cost Model shown in **Figure E-2** illustrates the three (3) main cost element categories, along with all the core subcategories, that make up the unit costs for all components and assemblies in the analysis.

Every cost element used throughout the analysis is extracted from one of the core databases. There are the databases for material prices ($/kilogram), labor rates ($/hour), manufacturing overhead rates ($/hour), mark-up rates (% of TMC) and packaging ($/packaging option). The databases provide the foundation of the cost analysis, since all costs originate from them, and they are also used to document sources and supporting information for the cost numbers.

The model allows for updates to the cost elements which automatically roll into the individual component/assembly cost models. Since all cost sheets and parameters are directly linked to the databases, changing any of the "Active Rate" cost elements in the applicable database automatically updates the Manufacturing Assumption Quote Summary (MAQS) worksheets. Thus, if a material doubles in price, one can easily assess the impact on the technology configurations under study.

E.5.2 Material Database

E.5.2.1 Overview

The Material Database houses specific material prices and related material information required for component cost estimating analysis. The information related to each material listed includes the material name, standard industry identification (e.g., AISI or SAE nomenclature), typical automotive applications, pricing per kilogram, annual consumption rates, and source references. The prices recorded in the database are in US dollars per kilogram.

E.5.2.2 Material Selection Process

The materials listed in the database (resins, ferrous, and non-ferrous alloys) are used in the products and components selected for cost analysis. The materials identification process is based on visual part markings, part appearance, and part application. Material markings are the most obvious method of material identification. Resin components typically have material markings (e.g., >PA66 30GF<) which are easily identified, recorded in the database, and researched to establish price trends.

For components which are not marked, such as transmission gears, knuckles, body-in-white sheet metal, engine connecting rods, and the like, the FEV and Munro cross-functional team members and Contracted Subject Matter Experts (SME) are consulted in the materials identification. For any materials still not identified, information published in print and on the web is researched, or primary manufacturers and experts within the Tier 1 supplier community are contacted to establish credible material choices.

The specific application and the part appearance play a role in materials identification. Steels commonly referred to as work-hardenable steels with high manganese content (13% Mn) are readily made in a casting and are not forgeable. Therefore, establishing whether a component is forged or cast can narrow the materials identification process. Observing visual cues on components can be very informative. Complex part geometry alone can rule out the possibility of forgings; however, more subtle differences must be considered. For example, forged components typically have a smoother appearance to the grain whereas cast components have a rougher finish, especially in the areas where machining is absent. Castings also usually display evidence of casting flash.

The component application environment will also help determine material choice. There are, for example, several conventional ductile cast iron applications found in base gasoline engines that are moving to Ductile High Silicon - Molybdenum or Ductile Ni-Resist cast irons in downsized turbocharged engines. This is due to high temperature, thermal cycling, and corrosion resistance demands associated with elevated exhaust gas temperatures in turbocharged engines. Therefore, understanding the part application and use environment can greatly assist in more accurate material determinations.

E.5.2.3 Pricing Sources and Considerations

The pricing data housed in the database is derived from various sources of publicly available data from which historical trend data can be derived. The objective is to find historical pricing data over as many years as possible to obtain the most accurate trend response. Ferrous and non-ferrous alloy pricing involves internet searches of several sources, including the U.S. Geological Survey (USGS), MEPS (previously Management Engineering & Production Services), Metal-Pages, London Metal Exchange, estainlesssteel.com and Longbow.

Resin pricing is also obtained from sources such as Plastics News, Plastics Technology Online, Rubber and Plastics News, and IDES (Integrated Design Engineering Systems). Several other sources are used in this research as outlined in the database.

Though material prices are often published for standard materials, prices for specialized material formulations and/or those having a nonstandard geometric configuration (e.g., length, width, thickness, cross-section), are not typically available. Where pricing is not available for a given material with a known composition, two (2) approaches are used: industry consultation and composition analysis.

Industry consultation mainly takes the form of discussions with subject matter experts familiar with the material selection and pricing used in the products under evaluation to acquiring formal quotes from raw material suppliers. For example, in the case of the NiMH battery, much of the material pricing was acquired from supplier quotes at the capacity planning volumes stated in the analysis.

In those cases where published pricing data was unavailable and raw material supplier quotes could not be acquired, a composition analysis was used. This was achieved by building prices based on element composition and applying a processing factor (i.e., market price/material composition cost) derived from a material within the same material family. The calculated price was compared to other materials in the same family as a means to ensure the calculated material price was directionally correct.

Obtaining prices for unknown proprietary material compositions, such as powder metals, necessitated a standardized industry approach. In these cases, manufacturers and industry market research firms are consulted to provide generic pricing formulas and pricing trends. Their price formulas are balanced against published market trends of similar materials to establish new pricing trends.

Resin formulations are also available with a variety of fillers and filler content. Some pricing data is available for specific formulations; however, pricing is not published for every variation. This variation is significant since many manufacturers can easily tailor resin filler type and content to serve the specific application. Consequently, the database has been structured to group resins with a common filler into ranges of filler content. For example, glass filled Nylon 6 is grouped into three (3) categories: 0 to 15 percent glass filled, 30 to 35 percent glass filled, and 50 percent glass filled, each with their own price point. These groupings provide a single price point as the price differential within a group (0 to 15 percent glass filled) is not statistically significant

E.5.2.4 In-process Scrap

In-process scrap is defined as the raw material mass, beyond the final part weight, required to manufacture a component. For example, in an injection molded part, the in-process scrap is typically created from the delivery system of the molten plastic into the part cavity (e.g., sprue, runners and part gate). This additional material is trimmed off following part injection from the mold. In some cases, dependent on the material and application, a portion of this material can be ground up and returned into the virgin material mix.

In the case of screw machine parts, the in-process scrap is defined as the amount of material removed from the raw bar stock in the process of creating the part features. Generally, material removed during the various machining processes is sold at scrap value. Within this cost analysis study, no considerations were made to account for recovering scrap costs.

A second scrap parameter accounted for in the cost analysis is end-item scrap. End-item scrap is captured as a cost element within mark-up and will be discussed in more detail within the mark-up database section, **Section E.5.5**. Although it is worth reiterating here that in-process scrap only covers the additional raw material mass required for manufacturing a part, it does not include an allowance for quality defects, rework costs and/or destructive test parts. These costs are covered by the end-item scrap allowance.

E.5.2.5 Purchase Parts – Commodity Parts

In the quote assumption section of the CBOM, parts are identified as either “make” or “buy.” The “make” classification indicates a detailed quote is required for the applicable part, while “buy” indicates an established price based on historical data is used in place of a full quote work-up. Parts identified as a “buy” are treated as a purchased part.

Many of the parts considered to be purchased are simple standard fasteners (nuts, bolts, screws, washers, clips, hose clamps) and seals (gaskets, o-rings). However, in certain cases, more value-added components are considered purchased when sufficient data existed supporting their cost as a commodity: that is, where competitive or other forces drive these costs to levels on the order of those expected had these parts been analyzed as “make” parts.

In the MAQS worksheet, standard purchase parts costs are binned to material costs, which, in the scope of this analysis, are generally understood to be raw material costs. If the purchase part content for a particular assembly or system is high in dollar value, the calculated cost breakdown in the relevant elements (i.e., material, labor, manufacturing overhead, mark-up) tended to be misleading. That is the material content would show artificially inflated because of the high dollar value of purchase part content.

To try and minimize this cost binning error, purchase parts with a value in the range of \$10 to \$15, or greater, were broken into the standard cost elements using cost element ratios developed for surrogate type parts. For example, assume a detailed cost analysis is conducted on a roller bearing assembly, “Bearing A.” The ratio of material, labor, manufacturing overhead, and mark-up, as a percent of the selling price, can easily be calculated. Knowing the commodity selling price for a similar type of bearing assembly, "Bearing B," along with the cost element ratios developed for Bearing A, estimates can be made on the material, labor, manufacturing overhead, and mark-up costs for Bearing B.

Purchased part costs are obtained from a variety of sources. These include FEV and Munro team members' industry cost knowledge and experience, surrogate component costing databases, Tier 1 supplier networks, published information, and service part cost information. Although an important component of the overall costing methodology, purchase part costs are used judiciously and conservatively, primarily for mature commodity parts.

E.5.3 Labor Database

E.5.3.1 Overview

The Labor Database contains all the standard occupations and associated labor rates required to manufacture automotive parts and vehicles. All labor rates referenced throughout the cost analysis are referenced from the established Labor Database.

Hourly wage rate data used throughout the study, with exception of fringe and wage projection parameters, is acquired from the Bureau of Labor Statistics (BLS). For the analysis, mean hourly wage rates were chosen for each occupation, representing an average wage across the United States.

The Labor Database is broken into two (2) primary industry sections, Motor Vehicle Parts Manufacturing (supplier base) and Motor Vehicle Manufacturing (OEMs). These two (2) industry sections correspond to the BLS, North American Industry Classification System (NAICS) 336300 and 336100 respectively. Within each industry section of the database, there is a list of standard production occupations taken from the BLS Standard Occupation Classification (SOC) system. For reference, the base SOC code for production occupations within the Motor Vehicle Parts Manufacturing and Motor Vehicle Manufacturing is 51-0000. Every production occupation listed in the Labor Database has a calculated labor rate, as discussed in more detail below. For the Toyota Venza CUV mass-reduction and cost analysis study, 2010 rates were used.

E.5.3.2 Direct Versus Total Labor, Wage Versus Rate

Each standard production occupation found in the Labor Database has an SOC identification number, title, labor description, and mean hourly wage taken directly from the BLS.

Only "direct" production occupations are listed in the labor database. Team assemblers and forging, cutting, punching, and press machine operators are all considered direct production occupations. There are several tiers of manufacturing personnel supporting the direct laborers that need to be accounted for in the total labor costs, such as quality technicians, process engineers, lift truck drivers, millwrights, and electricians. A method typically used by the automotive industry to account for all of these additional "indirect labor" costs – and the one chosen for this cost analysis – is to calculate the contribution of indirect labor as an average percent of direct labor, for a given production occupation, in a given industry sector.

The BLS Database provides labor wage data, rather than labor rate data. In addition to what a direct laborer is paid, there are several additional expenses the employer must cover in addition to the employee base wage. This analysis refers to these added employer expenditures as "fringe". Fringe is applicable to all employees and will be discussed in greater detail following.

It should be noted that the BLS motor vehicle and motor vehicle parts manufacturing (NAICS 336100 & 336300) labor rates include union and non-union labor rates, reflecting the relative mix of each in the workforce at the time the data was gathered (2010).

E.5.3.3 Contributors to Labor Rate and Labor Rate Equation

The four (4) contributors to labor costs used in this study are:

Direct Labor (DIR) is the ***mean*** manufacturing labor wage directly associated with fabricating, finishing, and/or assembling a physical component or assembly. Examples falling into this labor classification include injection mold press operators, die cast press operators, heat treat equipment operators, team/general assemblers, computer numerical controlled (CNC) machine operators, and stamping press operators. The median labor wage for each direct labor title is also included in the database. These values are treated as reference only.

Indirect Labor (IND) is the manufacturing labor indirectly associated with making a physical component or assembly. Examples include material handling personnel, shipping and receiving personnel, quality control technicians, first-line supervisors, and manufacturing/process engineers. For a selected industry sector (such as injection molding, permanent casting, or metal stamping), an average ratio of indirect to direct labor costs can be derived from which the contribution of indirect labor ($/hour) can be calculated.

This ratio is calculated as follows:

1. An industry sector is chosen from the BLS, NAIC System. (e.g., Plastics Product Manufacturing NAICS 326100).
2. Within the selected industry sector, occupations are sorted (using SOC codes) into one (1) of the four (4) categories: Direct Labor, Indirect Labor, MRO Labor, or Other.
3. For each category (excluding "Other") a total cost/hour is calculated by summing up the population weighted cost per hour rates, for the SOC codes within each labor category.
4. Dividing the total indirect labor costs by total direct labor costs, the industry sector ratio is calculated.
5. When multiple industries employ the same type direct laborer, as defined by NAICS, a weighted average of indirect to direct is calculated using the top three (3) industries.

Maintenance Repair and Other (MRO) is the labor required to repair and maintain manufacturing equipment and tools ***directly*** associated with manufacturing a given component or assembly. Examples falling into this labor classification include electricians, pipe fitters, millwrights, and on-site tool and die tradesmen. Similar to indirect labor, an average ratio of MRO to direct labor costs can be derived from which the contribution of MRO labor ($/hour) can be calculated. The same process used to calculate the indirect labor ratio is also used for the MRO ratio.

Fringe (FR) is all the additional expenses a company must pay for an employee above and beyond base wage. Examples of expenses captured as part of fringe include company medical and insurance benefits, pension/retirement benefits, government directed benefits, vacation and holiday benefits, shift premiums, and training.

Fringe applies to all manufacturing employees. Therefore the contribution of fringe to the overall labor rate is based on a percentage of direct, indirect and MRO labor. Two (2) fringe rates are used: 52% for supplier manufacturing, and 160% for OEM manufacturing. The supplier manufacturing fringe rate is based on data acquired from the BLS (Table 1009: Manufacturing Employer Costs for Employee Compensation Per Hours Worked: 2000-2010). Taking an average of the "Total Compensation" divided by "Wages and Salaries" for manufacturing years 2008 thru 2010, an average fringe rate of 52% was calculated.

Due to the dynamic change of OEM wage and benefit packages over the last few years (2008-2010), and differences among the OEMs, no updates were made from the original OEM fringe assumptions developed for the initial "Light-Duty Technology Cost Analysis Pilot Study" EPA-420-R-09-020 (http://www.epa.gov/OMS/climate/420r09020. pdf). The OEM fringe rate utilized throughout the analysis was 160%.

E.5.4 Manufacturing Overhead Database

E.5.4.1 Overview

The Manufacturing Overhead Database contains several manufacturing overhead rates (also sometimes referred to as "burden rates," or simply "burden") associated with various types of manufacturing equipment, that are required to manufacture automotive parts and vehicles. Combined with material and labor costs, it forms the total manufacturing cost (TMC) to manufacture a component or assembly, and, subsequently, the cost accounting for considerations such as workers, supervisors, managers, raw materials, purchased parts, production facilities, fabrication equipment, finishing equipment, assembly equipment, utilities, measurement and test equipment, handling equipment, and office equipment. Manufacturing equipment is typically one of the largest contributors to manufacturing overhead, so manufacturing overhead rates are categorized according to primary manufacturing processes and the associated equipment as follows:

1. The first tier of the Manufacturing Overhead Database is arranged by the primary manufacturing process groups (e.g., thermoplastic molding, thermoset molding, castings, forgings, stamping and forming, powder metal, machining, turning, etc.)
2. The second tier subdivides the primary manufacturing process groups into primary processing equipment groups. For example the 'turning group' consists of several subgroups including some of the following: (1) CNC turning, auto bar fed, dual axis machining, (2) CNC turning, auto bar fed, quad axis machining, (3) double-sided part, CNC turning, auto bar fed, dual axis machining, and (4) double-sided part, CNC turning, auto bar fed, quad axis machining.
3. The third and final tier of the database increases the resolution of the primary processing equipment groups and defines the applicable manufacturing overhead rates. For example, within the "CNC turning, auto bar fed, dual axis machining" primary process equipment group, there are four (4) available machines sizes (based on max cutting diameter and part length) from which to choose. The added

resolution is typically based on part size and complexity and the need for particular models/versions of primary and secondary processing equipment.

E.5.4.2 Manufacturing Overhead Rate Contributors and Calculations

In this analysis burden is defined in terms of an “inclusion/exclusion” list as follows:

Burden costs **do not** include:

- manufacturing material costs
- manufacturing labor costs
    - direct labor
    - indirect labor
    - maintenance repair and other (MRO) labor
- mark-up
    - end-item scrap
    - corporate SG&A expenses
    - profit
    - ED&T/ R&D costs expenses
- tooling (e.g., mold, dies, gauges, fixtures, dedicated pallets)
- packaging costs
- shipping and handling costs

Burden costs **do** include:

- rented and leased equipment
- primary and secondary process support manufacturing equipment depreciation
- plant office equipment depreciation
- utilities expense
- insurance costs (fire and general)
- municipal taxes
- plant floor space (equipment and plant offices)
- maintenance of manufacturing equipment (non-labor)
- maintenance of manufacturing building (general, internal and external, parts, and labor)
- operating supplies (consumables)
- perishable and supplier-owned tooling
- all other plant wages (excluding direct, indirect and MRO labor)
- returnable dunnage maintenance (includes allowance for cleaning and repair)
- intra-company shipping costs

As shown in the lists above, burden includes both fixed and variable costs. Generally, the largest contribution to the fixed burden costs are the investments associated with primary and secondary process support equipment. The single largest contributor to the variable burden rate is typically utility usage.

E.5.4.3 Acquiring Manufacturing Overhead Data

Because there is very limited publicly available data on manufacturing overhead rates for the industry sectors included in this analysis, overhead rates have been developed from a combination of internal knowledge and experience at FEV and Munro, supplier networks, miscellaneous publications, reverse costing exercises, and “ground-up” manufacturing overhead calculations.

For ground-up calculations, a generic “Manufacturing Overhead Calculator Template” was created. The template consists of eight (8) sections:

- General Manufacturing Overhead Information
- Primary Process Equipment
- Process Support Equipment
- General Plant & Office Hardware/Equipment
- Facilities Cost
- Utilities
- Plant Salaries
- Calculated Hourly Burden Rate.

The hourly burden rate calculation for a 500 ton (T) injection mold machine is used as an example in the following paragraphs. The General Manufacturing Overhead Information section, in addition to defining the burden title (Injection Molding, Medium Size and/or Moderate Complexity) and description (Injection Molding Station, 500T Press), also defines the equipment life expectancy (12 years), yearly operating capacity (4,700 hours), operation efficiency (85%), equipment utilization (81.99%) and borrowing cost of money (8%). These input variables support many of the calculations made throughout the costing template.

The Primary Process Equipment section (500T Horizontal Injection Molding Machine) calculates the annual expense ($53,139) associated with equipment depreciation over the defined life expectancy. A straight-line-depreciation method, with zero end of life value, is assumed for all equipment. Included in the cost of the base equipment are several factors such as sales tax, freight, installation, and insurance. In addition, a maintenance, repair and other (MRO) expense (other than MRO labor, which is covered as part of the overall labor cost), calculated as a percentage of the primary process equipment cost, is included in the development of the manufacturing overhead.

The Process Support Equipment section (e.g., Chiller, Dryer, Thermal Control Unit-Mold), similar to the Primary Process Equipment section, calculates the annual expense ($6,121) associated with process support equipment depreciation.

The General Plant and Office Hardware/Equipment section assigns an annual contribution directed toward covering a portion of the miscellaneous plant & office hardware/equipment costs (e.g., millwright, electrician, and plumbing tool crib, production/quality communication, data tracking and storage, general material handling equipment, storage, shipping and receiving equipment, general quality lab equipment, office equipment). The contribution expense ($2,607) is calculated as a percent of the annual primary and process support equipment depreciation costs.

The Facilities Cost section assigns a cost based on square footage utilization for the primary equipment ($4,807), process support equipment ($3,692), and general plant and office hardware/equipment ($6,374). The general plant and office hardware/equipment floor space allocation is a calculated percentage (default 75%) of the derived primary and process support equipment floor space. The expense per square foot is $11.50 and covers several cost categories such as facility depreciation costs, property taxes, property insurance, general facility maintenance, and general utilities.

The Utilities section calculates a utility expense per hour for both primary equipment ($9.29/hour) and process support equipment ($3.51/hour) based on equipment utility usage specifications. Some of the utility categories covered in this section include: electricity at $0.10/kW-hr, natural gas at $0.00664/cubic foot, and water at $0.001/gallon. General plant and office hardware/equipment utility expenses are covered as part of the facility cost addressed in the paragraph above (i.e., $11.50/square foot).

The Plant Salary section estimates the contribution of manufacturing salaries (e.g., plant manager, production manager, quality assurance manager) assigned to the indirect participation of primary and process support equipment. An estimate is made on the average size of the manufacturing facility for this type of primary process equipment. There are six (6) established manufacturing facility sizes and corresponding salary payrolls. Each has a calculated salary cost/square foot. Based on the combined square footage utilization of the primary, process support, and general plant and office equipment, an annual salary contribution cost is calculated ($6,625).

The final section, Calculated Hourly Burden Rate, takes the calculated values from the previous sections and calculates the hourly burden rate in three (3) steps: (1) 100%

efficiency and utilization ($30.54/hour); (2) user-defined efficiency with 100% utilization ($35.12/hour); and (3) both user-defined efficiency and utilization ($38.79/hour).

The majority of primary process equipment groups (e.g., injection molding, aluminum die casting, forging, stamping and forming) in the manufacturing overhead database are broken into five (5) to ten (10) burden rate subcategories based on processing complexity and/or size, as discussed in the manufacturing overhead review. For any given category, there will often be a range of equipment sizes and associated burden rates which are averaged into a final burden rate. The goal of this averaging method is to keep the database compact while maintaining high costing resolution.

In the example of the 500T injection molding press burden rate, the calculated rate ($38.79) was averaged with three (3) other calculated rates (for 390T, 610T and 720T injection mold presses) into a final burden rate called "Injection Molding, Medium Size and/or Moderate Complexity." The final calculated burden rate of $50.58/hour is used in applications requiring injection molding presses in the range of 400-800 tons.

The sample calculation of the manufacturing overhead rate for an injection molding machine above is a simple example highlighting the steps and parameters involved in calculating overhead rates. Regardless of the complexity of the operation or process, the same methodology is employed when developing overhead rates.

As discussed, multiple methods of arriving at burden rates are used within the cost analysis. Every attempt is made to acquire multiple data points for a given burden rate as a means of validating the rate. In some cases, the validation is accomplished at the final rate level and in other cases multiple pieces of input data, used in the calculation of a rate, are acquired as a means of validation.

E.5.5 Mark-up (Scrap, SG&A, Profit, ED&T)

E.5.5.1 Overview

All mark-up rates for Tier 1 and Tier 2/3 automotive suppliers referenced throughout the cost analysis can be found in the Mark-up Database, except in those cases where unique component tolerances, performance requirements, or some other unique feature dictates a special rate. In cases where a mark-up rate is "flagged" within the costing worksheet, a note is included which describes the assumption differences justifying the modified rate.

For this cost analysis study, four (4) mark-up sub-categories are used in determining an overall mark-up rate: (1) end-item scrap allowance, (2) SG&A expenses, (3) profit, and

(4) ED&T/R&D expenses. Additional details for each subcategory are discussed following.

The layout of the Mark-up Database is similar to the Manufacturing Overhead Database in that the first tier of the Mark-up Database is arranged by the primary manufacturing process groups (e.g., thermoplastic processing, thermoset processing, casting, etc.). The second tier subdivides the primary manufacturing process groups into primary processing equipment groups (e.g., thermoplastic processing is subdivided into injection molding, blow or rotational molding, and pressure or vacuum form molding). The third and final tier of the database increases the resolution of the primary processing equipment groups and defines the applicable mark-up rates. Similar to the overhead manufacturing rates, size and complexity of the parts being manufactured will direct the process and equipment requirements, as well as investments. This, in turn, will have a direct correlation to mark-up rates.

E.5.5.2 Mark-up Rate Contributors and Calculations

Mark-up, in general, is an added allowance to the Total Manufacturing Cost to cover end-item scrap, SG&A, profit and ED&T expenses. The following are additional details on what is included in each mark-up category:

End-Item Scrap Mark-up is an added allowance to cover the projected manufacturing fall-out and/or rework costs associated with producing a particular component or assembly. In addition, any costs associated with in-process destructive testing of a component or assembly are covered by this allowance. As a starting point, scrap allowances were estimated to be between 0.3% and 0.7% of the TMC within each primary manufacturing processing group. The actual assigned value for each category is an estimate based on size and complexity of the primary processing equipment as shown in **Table E-1**.

When published industry data or consultation with an industry expert improves estimate accuracy for scrap allowance associated with a generic manufacturing process (e.g., 5% for sand casting, investment casting), the Mark-up Database is updated accordingly. In cases where the manufacturing process is considered generic, but the component performance requirements drive a higher fall-out rate (e.g., 25% combined process fallout on turbocharger turbine wheels), then the scrap mark-up rate would only be adjusted in the Manufacturing Assumption Quote Summary (MAQS) worksheet.

Selling, General, and Administrative (SG&A) Mark-up is also referred to as corporate overhead or non-manufacturing overhead costs. Some of the more common cost elements of SG&A are:

- Non-manufacturing, corporate facilities (building, office equipment, utilities, maintenance expenses, etc.)
- Corporate salaries (President, Chief Executive Officers, Chief Financial Officers, Vice Presidents, Directors, Corporate Manufacturing, Logistics, Purchasing, Accounting, Quality, Sales, etc.)
- Insurance on non-manufacturing buildings and equipment
- Legal and public relation expenses
- Recall insurance and warranty expenses
- Patent fees
- Marketing and advertising expenses
- Corporate travel expenses

SG&A, like all mark-up rates, is an applied percentage to the Total Manufacturing Cost. The default rates for this cost analysis range from 6% to 7% within each of the primary processing groups. The actual values, as with the end-item scrap allowances, vary within these ranges based on the size and complexity of the part, which in turn is reflected in the size and complexity of the processing equipment as shown in **Table E-1**. To support the estimated SG&A rates (which are based on generalized OEM data), SG&A values are extracted from publicly traded automotive supplier 10-K reports.

Profit Mark-up is the supplier's or OEM's reward for the investment risk associated with taking on a project. On average, the higher the investment risk, the larger the profit mark-up that is sought by a manufacturer.

As part of the assumptions list made for this cost analysis, it is assumed that the technology being studied is mature from the development and competition standpoint. These assumptions are reflected in the conservative profit mark-up rates which range from 4% to 8% of the Total Manufacturing Cost. The profit mark-up ranges selected from this cost analysis are based on generalized historical data from OEMs and suppliers.

As detailed with the preceding mark-up rates, the actual assigned percentage is based on the supplier processing equipment size and complexity capabilities (**Figure E-2**).

ED&T Mark-up: the ED&T used for this cost analysis is a combination of "Traditional ED&T" plus R&D mark-up.

Traditional ED&T may be defined as the engineering, design and testing activities required to take an "implementation ready" technology and integrate it into a specific vehicle application. The ED&T calculation is typically more straight-forward because the tasks are predefined. R&D, defined as the cost of the research and development activities required to create a new (or enhance an existing) component/system technology, is often independent of a specific vehicle application. In contrast to ED&T, pure R&D costs are very difficult to predict and are very risky from an OEM and suppliers perspective, in that these costs may or may not result in a profitable outcome.

For many automotive suppliers and OEMs, traditional ED&T and R&D are combined into one (1) cost center. For this cost analysis, the same methodology has been adopted, creating a combined traditional ED&T and R&D mark-up rate simply referred to as ED&T.

Royalty fees, as the result of employing intellectual property, are also captured in the ED&T mark-up section. When such cases exist, separate lines in the Manufacturing Assumption & Quote Summary (MAQS) worksheet are used to capture these costs. These costs are in addition to the standard ED&T rates. The calculation of the royalty fees are on a case by case basis and information regarding the calculation of each fee can be found in the individual MAQS worksheets where applicable.

Table E-1: Standard Mark-up Rates Applied to Tier 1 and Tier 2/3 Suppliers Based on Size and Complexity Ratings

Primary Manufacturing Equipment Group	End Item Scrap Mark-up	SG&A Mark-up	Profit Mark-up	ED&T Mark-up	Total Mark-up
Tier 2 /3 – Large Size, High Complexity,	0.7%	7.0%	8.0%	2.0%	17.7%
Tier 2 /3 – Medium Size, Moderate Complexity,	0.5%	6.5%	6.0%	1.0%	14.0%
Tier 2 /3 – Small Size, Low Complexity	0.3%	6.0%	4.0%	0.0%	10.3%
Tier 1 Complete System/Subsystem Supplier (System/Subsystem Integrator)	0.7%	7.0%	8.0%	6.0%	21.7%
T1 High Complexity Component Supplier	0.7%	7.0%	8.0%	4.0%	19.7%
T1 Moderate Complexity Component Supplier	0.5%	6.5%	6.0%	2.5%	15.5%
T1 Low Complexity Component Supplier	0.3%	6.0%	4.0%	1.0%	11.3%

E.5.5.3 Assigning Mark-up Rates

The three (3) primary steps to matching mark-up rates to a given component are:

> **Step 1:** Primary manufacturing process and equipment groupings are pre-selected as part of the process to identify the manufacturing overhead rate.
>
> **Step 2:** Manufacturing facilities are identified as OEM, T1 or T2/T3 (this identification process is discussed in more detail in the Manufacturing Assumption & Quote Summary worksheet section).
>
> **Step 3:** The best-fit mark-up rate is selected based on the size and complexity of the part, which in turn is reflected in the size and complexity of the processing equipment. Note that size and complexity are considered as independent parameters when reviewing a component and the equipment capabilities (with priority typically given to "complexity").

Further details on methodology for developing TMC and supplier mark-up can be found in EPA published report EPA-420-R-09-020 "Light-Duty Technology Cost Analysis Pilot Study" (http://www.epa.gov/OMS/climate/420r09020.pdf).

E.5.6 Packaging Database

E.5.6.1 Overview

The Packaging Database contains standardized packaging options available for developing packaging costs for components and assemblies. In the cost analysis only packaging costs required to transport a component/assembly from a Tier 1 to an OEM facility (or one facility to another at the same OEM) are calculated in detail. For Tier 2/3 suppliers of high- and low-impact components, as well as purchased parts, the Tier 1 mark-up is estimated to cover the packaging as well as shipping expenses. Tier 1 mark-up on incoming Tier 2/3 parts and purchase parts are discussed in more detail in Section E.6.

All core packaging items (e.g., containers, pallets, totes) referenced in the database are considered returnable dunnage. Internal packaging (e.g., tier pads, dividers, formed trays) are also considered returnable with the exception of a few items that are expendable. The cost to clean and maintain returnable dunnage is assumed to be covered by the manufacturing overhead rate.

E.5.6.2 Types of Packaging and Selection Process

Packaging options in the database are limited to a few standard types and sizes to minimize complexity. In general, everything is tailored toward fitting onto a standard automotive pallet (as specified by the Automotive Industry Action Group), which has exterior dimensions of 48 by 45 inches and a base height assumption of 34 inches (although other standard sizes exist in 25, 33 39, 42, 48, and 50 inches in height). A standard transport trailer height of 106 inches is used as the guideline for overall packaging height.

When initially trying to package a component, three (3) typical packaging options are considered:

- standard 48 by 45 by 34-inch palletized container (with tier pads and dividers)
- 48 by 45-inch base pallet with stacked 21.5 by 15 by 12.5-inch totes (48 totes max – and note that totes can have specialized tier pads, dividers, etc.)
- 48 by 45-inch base pallet with vacuum formed dividers strapped together

Considering component attributes such as weight, size, shape, fragility, and cleanliness, one (1) of the packaging options above is selected, along with an internal dunnage scheme. If it is deemed impractical to package the component within one (1) of the primary options, a new package style is created and added to the Packaging Database.

Once the primary packaging type and associated internal dunnage are selected for a component, the assumptions along with the costs are entered into a Manufacturing Assumption Quote Summary (MAQS) worksheet. In the MAQS worksheet, packaging costs along with volume assumptions, pack densities, stock turn-over times, program life, packaging life, and interest expenses are used to calculate a cost-per-part for packaging.

E.5.6.3 Support for Costs in Packaging Database

Primary pallet and container costs are acquired from either Tier 1 automotive suppliers or from container vendors. In some cases, scaling within container groups is performed to quantify the pricing for slightly larger or smaller containers within the same family.

Internal dunnage costs are acquired from either Tier 1 automotive suppliers or calculated based on standard material and processing estimates. When tooling costs are required for packaging, the value of that tooling is added to the total pallet container piece cost, as calculated in the MAQS worksheets. The total value is then amortized to calculate a cost-per-part for packaging.

E.6 Shipping Costs

In the cost analysis, shipping costs are accounted for by one (1) of three (3) factors: (1) Indirect Cost multiplier, (2) total mark-up allowance, or (3) manufacturing overhead. Further, shipping costs are always considered freight on board (FOB) the shipper's dock, with the exception of intra-company transportation. Following are the four (4) shipping scenarios encountered in the cost analysis and how each case is handled.

In the first two (2) cases, OEM and supplier intra-company transportation, shipping costs are accounted for as part of the manufacturing overhead rate. It is assumed that the OEM or supplier would either have their own transportation equipment and/or subcontract for this service. In either case the expense is binned to manufacturing overhead.

The third case is Tier 1 shipments to an OEM facility. As stated previously the shipments are FOB the shipper's dock and thus the OEM is responsible for the shipping expense. The ICM is assumed to cover the OEM's expense to have all parts delivered to the applicable OEM manufacturing facilities.

The final case is Tier 2/3 shipments to the Tier 1 facility. Generally, the Tier 1 supplier is allowed a mark-up on incoming purchased parts from Tier 2/3 suppliers. The mark-up covers many costs including the shipping expenses to have the part delivered onto the Tier 1 supplier's dock. Further, the mark-up can either be a separate mark-up only applied to incoming purchased parts, or accounted for by the mark-up applied to the TMCs. In the former, the purchase part content would not be included in the final mark-up calculation (i.e., Mark-up = (TMC - Purchase Parts cost) x Applicable Mark-up Rate).

For this cost analysis, the latter case is chosen using the same mark-up rate for all Tier 1 value-added manufacturing as well as all incoming purchase parts.

E.7 Manufacturing Assumption and Quote Summary Worksheet

E.7.1 Overview

The Manufacturing Assumption and Quote Summary (MAQS) worksheet is the document used in the cost analysis process to compile all the known cost data, add any remaining cost parameters, and calculate a final unit cost. All key manufacturing cost information can be viewed in the MAQS worksheet for any component or assembly. Additional details on the information which flows into and out of the MAQS worksheet are discussed in more detail in following sections. **Section E.9** discusses how MAQS worksheets are uploaded into subsystem, system, and vehicle summary templates to calculate the net component/assembly cost impact to the OEM.

The fundamental objective of the MAQS worksheet is similar to a standard quoting template used by the automotive industry. However, the format has been revised to capture additional quote details and manufacturing assumptions, improve on transparency by breaking out all major cost elements, and accommodate variable data inputs for the purpose of sensitivity assessments. These features are discussed in more detail in following sections.

For a given case study, all Tier 1 or OEM assemblies, identified in the CBOM as requiring cost analysis, will have a link to a MAQS worksheet. In some cases where high value final assembly Tier 2/3 parts are shipped to a Tier 1 supplier, a separate MAQS worksheet is created for greater transparency. These T2/3 MAQS worksheets are linked to T1/OEM MAQS worksheets, which in turn are referenced back to the CBOM.

Because many of the detailed spreadsheet documents generated within this analysis are too large to be shown in their entirety, electronic copies can be accessed through EPA's electronic docket ID TBD (http://www.regulations.gov).

E.7.2 Main Sections of Manufacturing Assumption and Quote Summary Worksheet

The MAQS worksheet, as shown in **Figure E-3** and **Figure E-4**, contains seven (7) major sections. At the top of every MAQS worksheet is an information header ***(Section A)***, which captures the basic project details along with the primary quote assumptions. The project detail section references the MAQS worksheet back to the applicable CBOM. The primary quote assumption section provides the basic information needed to put together a quote for a component/assembly. Some of the parameters in the quote assumption section are automatically referenced/linked throughout the MAQS worksheet, such as capacity planning volumes, product life span, and OEM/T1 classification. The remaining parameters in this section including facility locations, shipping methods, packing specifications, and component quote level are manually considered for certain calculations.

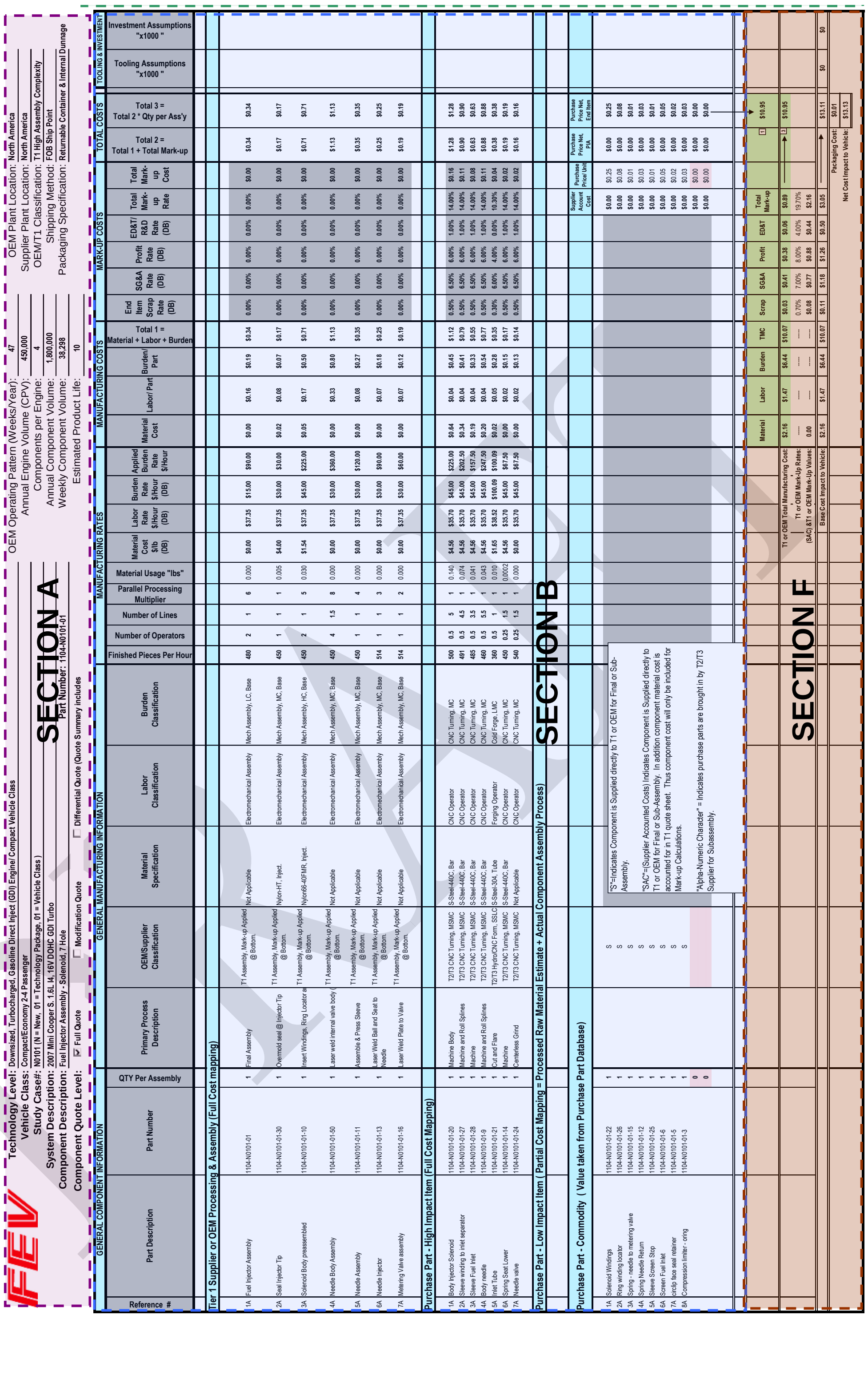


Figure E-3: Sample MAQS Costing Worksheet (Part 1 of 2)

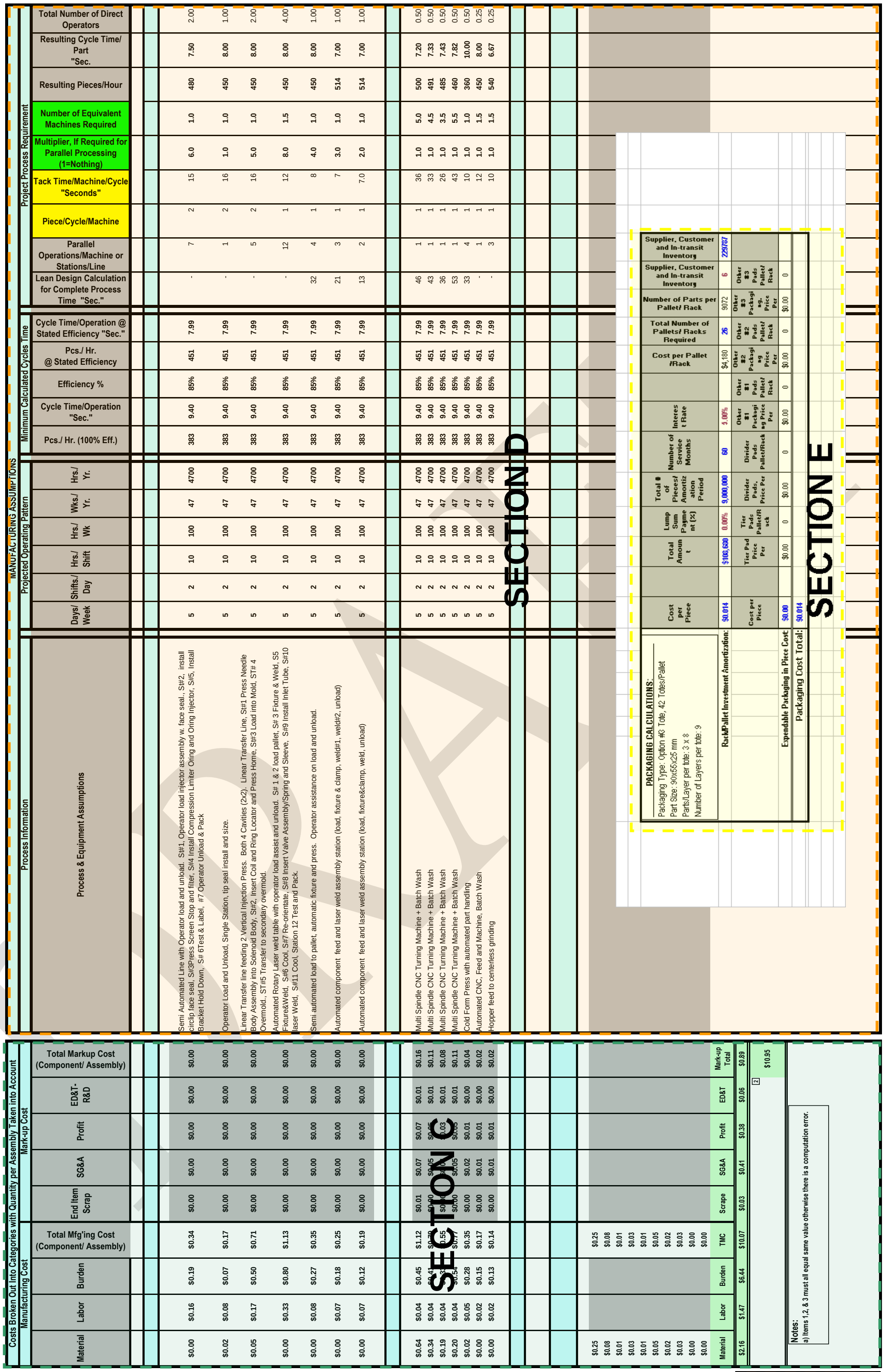


Figure E-4: Sample MAQS Costing Worksheet (Part 2 of 2)

Two (2) parameters above whose functions perhaps are not so evident from their names are the "OEM/T1 classification" and "component quote level."

The "OEM/T1 classification" parameter addresses who is taking the lead on manufacturing the end-item component, the OEM or Tier 1 supplier. Also captured is the OEM or Tier 1 level, as defined by size, complexity, and expertise level. The value entered into the cell is linked to the Mark-up Database, which will up-load the corresponding mark-up values from the database into the MAQS worksheet. For example, if "T1 High Assembly Complexity" is entered in the input cell, the following values for mark-up are pulled into the worksheet: Scrap = 0.70%, SG&A = 7%, Profit = 8.0% and ED&T = 4%. These rates are then multiplied by the TMC at the bottom of the MAQS worksheet to calculate the applied mark-up as shown in **Figure H-H-2**.

The process for selecting the classification of the lead manufacturing site (OEM or T1) and corresponding complexity (e.g., High Assembly Complexity, Moderate Assembly Complexity, Low Assembly Complexity) is based on the team's knowledge of existing value chains for same or similar type components.

OEM Operating Pattern (Weeks/Year):	47	OEM Plant Location:	North America
Annual Engine Volume (CPV):	450,000	Supplier Plant Location:	North America
Components per Engine:	4	OEM/T1 Classification:	T1 High Assembly Complexity
Annual Component Volume:	1,800,000	Shipping Method:	FOB Ship Point
Weekly Component Volume:	38,298	Packaging Specification:	Returnable Container & Internal Dunnage
Estimated Product Life:	10		

TMC

	Material	Labor	Burden	TMC	Scrap	SG&A	Profit	ED&T	Total Mark-up		$10.95
T1 or OEM Total Manufacturing Cost:	$2.16	$1.47	$6.44	$10.07	$0.03	$0.41	$0.32	$0.06	$0.89	→	$10.95
T1 or OEM Mark-Up Rates:	-----	-----	-----	-----	0.70%	7.00%	8.00%	4.00%	19.70%		
(SAC) &T1 or OEM Mark-Up Values:	0.00	-----	-----	-----	$0.08	$0.77	$0.83	$0.44	$2.16		
Base Cost Impact to Vehicle:	$2.16	$1.47	$6.44	$10.07	$0.11	$1.18	$1.26	$0.50	$3.05	→	$13.11
										Packaging Cost:	$0.01
										Net Cost Impact to Vehicle:	$13.13

Figure E-5: Excerpt Illustrating Automated Link between OEM/T1 Classification Input in MAQS Worksheet and the Corresponding Mark-up Percentages Uploaded from the Mark-up Database

The "component quote level" identifies what level of detail is captured in the MAQS worksheet for a particular component/assembly, full quote, modification quote, or differential quote. When the "full quote" box is checked, it indicates all manufacturing costs are captured for the component/assembly. When the "modification quote" box is checked, it indicates only the changed portion of the component/assembly has been quoted. A differential quote is similar to a modification quote with the exception that information from both technology configurations, is brought into the same MAQS worksheet, and a differential analysis is conducted on the input cost attributes versus the output cost attributes. For example, if two (2) brake boosters (e.g., the production stock booster and the mass-reduced booster) are being compared for cost, each brake booster can have its differences quoted in a separate MAQS worksheet (modification quote) and the total cost outputs for each can be subtracted to acquire the differential cost. Alternatively in a single MAQS worksheet the cost driving attributes for the differences between the booster's (e.g., mass difference on common components, purchase component differences, etc.) can be offset, and the differential cost calculated in a single worksheet. The differential quote method is typically employed those components with low differential cost impact to help minimize the number of MAQS worksheets generated.

From left to right, the MAQS worksheet is broken into two (2) main sections as the name suggests, a quote summary ***(Section B)*** and manufacturing assumption section ***(Section D).*** The manufacturing assumption section, positioned to the right of the quote summary section, is where the additional assumptions and calculations are made to convert the serial processing operations from Lean Design® into mass production operations. Calculations made in this section are automatically loaded into the quote summary section. The quote summary section utilizes this data along with other costing database data to calculate the total cost for each defined operation in the MAQS worksheet.

Note "defined operations" are all the value-added operations required to make a component or assembly. For example, a high pressure fuel injector may have twenty (20) base level components which all need to be assembled together. To manufacture one (1) of the base level components there may be as many as two (2) or three (3) value-added process operations (e.g., cast, heat treat, machine). In the MAQS worksheet each of these process operations has an individual line summarizing the manufacturing assumptions and costs for the defined operation. For a case with two (2) defined operations per base level component, plus two (2) subassembly and final assembly operations, there could be as many as forty (40) defined operations detailed out in the MAQS worksheet. For ease of viewing all the costs associated with a part, with multiple value-added operations, the operations are grouped together in the MAQS worksheet.

Commodity based purchased parts are also included as a separate line code in the MAQS worksheet. Although there are no supporting manufacturing assumptions and/or calculations required since the costs are provided as total costs.

From top to bottom, the MAQS worksheet is divided into four (4) quoting levels in which both the value-added operations and commodity-based purchase parts are grouped: (1) Tier 1 Supplier or OEM Processing and Assembly, (2) Purchase Part – High Impact

Items, (3) Purchase Part – Low Impact Items, and (4) Purchase Part – Commodity. Each quoting level has different rules relative to what cost elements are applicable, how cost elements are binned, and how they are calculated.

Items listed in the ***Tier 1 Supplier or OEM Processing and Assembly*** section are all the assembly and subassembly manufacturing operations assumed to be performed at the main OEM or T1 manufacturing facility. Included in manufacturing operations would be any on-line attribute and/or variable product engineering characteristic checks. For this quote level, full and detailed cost analysis is performed (with the exception of mark-up which is applied to the TMC at the bottom of the worksheet).

Purchase Part – High Impact Items include all the operations assumed to be performed at Tier 2/3 (T2/3) supplier facilities and/or T1 internal supporting facilities. For this quote level detailed cost analysis is performed, including mark-up calculations for those components/operations considered to be supplied by T2/3 facilities. T1 internal supporting facilities included in this category do not include mark-up calculations. As mentioned above, the T1 mark-up (for main and supporting facilities) is applied to the TMC at the bottom of the worksheet.

Purchase Part – Low Impact Items are for *higher priced* commodity based items which need to have their manufacturing cost elements broken out and presented in the MAQS sheet similar to high impact purchase parts. If not, the material cost group in the MAQS worksheet may become distorted since commodity based purchase part costs are binned to material costs as discussed previously in **Section E.5.2.5 Purchase Parts – Commodity Parts**. ***Purchase Part – Commodity Parts*** are represented in the MAQS worksheet as a single cost and are binned to material costs.

At the bottom of the MAQS worksheet ***(Section F)***, all the value-added operations and commodity-based purchase part costs, recorded in the four (4) quote levels, are automatically added together to obtain the TMC. The applicable mark-up rates based on the T1 or OEM classification recorded in the MAQS header are then multiplied by the TMC to obtain the mark-up contribution. Adding the TMC and mark-up contribution together, a subtotal unit cost is calculated.

Important to note is that throughout the MAQS worksheet, all seven (7) cost element categories (material, labor, burden, scrap, SG&A, profit, and ED&T) are maintained in the analysis. ***Section C***, MAQS breakout calculator, which resides between the quote summary and manufacturing assumption sections, exists primarily for this function.

The last major section of the MAQS worksheet is the packaging calculation, ***Section E***. In this section of the MAQS worksheet a packaging cost contribution is calculated for each part based on considerations such as packaging requirements, pack densities, volume assumptions, stock, and/or transit lead times. As previously mentioned, for the purpose of this study component/assembly packaging costs were considered to be neutral due to the relative size envelope of these parts not changing significantly between the production stock and mass-reduced parts.

E.8 Marketplace Validation

Marketplace validation is the process by which individual parts, components, and/or assemblies are cross-checked with costing data developed by entities and processes external to the team responsible for the cost analysis. This process occurs at all stages of the cost analysis, with special emphasis is placed on cross-checking in-process costs (e.g., material costs, material selection, labor costs, manufacturing overhead costs, scrap rates, and individual component costs within an assembly).

In-process cost validation occurs when a preliminary cost has been developed for a particular part within an assembly, and the cost is significantly higher or lower than expected based on the team's technical knowledge or on pricing from similar components. In this circumstance, the cost analysis team would first revisit the costs, drawing in part/process-specific internal expertise and checking surrogate parts from previously costed bills of materials where available. If the discrepancy is still unresolved, the team would rely on automotive supplier networks, industry experts, and/or publicly available publications to validate the cost assumptions, making changes where warranted.

Cross-checking on final assembly costs also occurs within the scope of the cost analysis, mainly as a "big picture" check. Final assembly costs, in general cross-checking, are typically achieved through solicitation of industry experts. The depth of cross-checking ranges from simple comparison of cost data on surrogate assemblies to full Manufacturing Assumption and Quote Summary (MAQS) worksheet reviews.

E.9 Cost Model Analysis Templates

E.9.1 Subsystem, System and Vehicle Cost Model Analysis Templates

The Cost Model Analysis Templates (CMAT) are the documents used to display and roll-up all the costs associated with a particular subsystem, system or vehicle. At the lowest level of the hierarchy, the manufacturing assumption quote summary worksheets, associated with a particular vehicle subsystem, are directly linked to the Sub-subsystem CMAT (SSSCMAT). These Sub-subsystem cost totals are then summarized at the next level in the Subsystem CMAT (SSCMAT). All the subsystems cost breakdowns, associated with a particular system, are directly linked to the relevant System CMAT (SCMAT). Similarly, all the system cost breakdown summaries are directly linked to the Vehicle CMAT (VCMAT). The top-down layering of the incremental costs, at the various

CMAT levels, paints a clear picture of the cost drivers at all levels for the adaptation of the advance technology. In addition, since all of the databases, MAQS worksheets, and CMATs are linked together, the ability to understand the impact of various cost elements on the incremental cost can be readily understood. These costing variables can be easily and quickly updated within the various databases to provide a tremendous amount of flexibility in evaluating various costing scenarios and sensitivity studies.

E.10 Differential Tooling Cost Analysis

E.10.1 Differential Tooling Cost Analysis Overview

As part of the mass-reduction and cost analysis project, EPA requested that FEV determine the differential tooling impact for those components that were evaluated for mass-reduction. As stated in **Section E.3**, *Tooling Costs* are the dedicated tool, gauge, and fixture costs required to manufacture a part. Examples of items covered by tooling costs include injection molds, casting molds, stamping dies, weld fixtures, assembly fixtures, dedicated assembly and/or machining pallets, and dedicated gauging. For this analysis, all tooling is assumed to be owned by the OEM.

Tooling costs should not be confused with equipment and facility costs (also sometimes referred to as investment costs or capital investment costs). In the scope of this analysis, ***Investment Costs*** are the manufacturing facility costs, not covered as tooling, required to manufacture parts. Investment costs include manufacturing plants, manufacturing equipment (e.g., injection mold machines, die cast machines, machining and turning machines, welding equipment, assembly lines), material handling equipment (e.g., lift forks, overhead cranes, loading dock lifts, conveyor systems), paint lines, plating lines, and heat treat equipment. Investment costs are accounted for in the manufacturing overhead rates as discussed in **Section E.5.4.2**.The tool cost analysis is an incremental analysis using a similar methodology as established for developing the incremental direct manufacturing costs. For example if a part on the production Venza is injection-molded and the new mass-reduced replacement part is injection-molded using the PolyOne injection mold process, then no further tooling analysis was conducted. The PolyOne process requires no significant tooling modifications relative to traditional injection mold tools. Conversely, if a component went from a stamped part to an injection mold part, the team would then quote the tooling needed for stamping the production stock part as well as the injection-molded mass-reduced part. The tooling cost would be the difference between these two values (+/-).

E.10.2 Differential Tooling Cost Analysis Methodology

Outlined here are the general process steps used by FEV to evaluate the differential tooling impact between the production stock Venza components and the mass-reduced replacement components.

1) Assemble and assign teams of manufacturing expertise

a) Assembled team members have expertise in several key primary and secondary manufacturing processes including stamping, casting, molding and machining.

b) When required, outside consultation resources were also utilized.

c) Assemble and assign teams to vehicle subsystems and systems having a majority of components with fabrication processes matching team's expertise.

2) Establish Boundary Conditions for Tooling Analysis

a) High volume production: 200K units/year Venza specific components (e.g. body-in-white); 450K units/year on cross-platform shared components (e.g. engine, transmission, brakes)

b) Assumed manufacturing life: 5 years

c) Assumed cost of borrowing money: 8%

3) Identify mass-reduced components in the analysis potentially having an incremental tooling impact

a) Evaluate component manufacturing process differences between the production stock and mass-reduced components.

b) Based on the team's assessment, if a significant tooling value difference exists between the production stock and mass-reduced components, a tooling analysis is initiated.

c) If an insignificant incremental tooling difference is identified by the team, a zero value is placed in the Manufacturing Assumption and Quote Summary (MAQS) worksheet for both the production stock component and mass-reduced alternative.

4) Establish tooling costs for components having a potential tooling impact (components which were not evaluated in the analysis for mass reduction were excluded from the analysis up front)

a) Establish tooling line-up for the production Venza components with respect to the mass-reduced components (e.g., types of tools, number of tools)

b) Six (6) standard tooling categories exist to establish the potential tooling line-ups:

i) Primary Manufacturing Tools and Fixtures (e.g., molds, dies, machining fixtures, assembly fixtures, stamping tools)
ii) End of Line Gauges and Testing Fixtures.
iii) Non-Perishable Tooling (e.g., machining cutter bodies, pick-n-place/gantries arms, guide/bushing plates)
iv) Custom & Dedicated Gauges
v) Bulk Processes (e.g., baskets, hangers, custom conveyors or walking arms)
vi) OPTIONAL (to be described w/ comment box if needed)

c) As part of the tooling assessment, consideration is also given to the following:
i) Number of back-up tool sets
ii) Repair frequency, complexity, and costs
iii) Refurbishment frequency, complexity, and costs

d) Tooling costs for each operation included in the component analysis are summed-up and entered in the tooling column of the Manufacturing Assumption and Quote Summary (MAQS) worksheet (**Figure E-6**). The tooling impact is automatically summed-up at the bottom of the MAQS worksheet similar to the direct manufacturing costs for every component evaluated; both the production stock Venza parts (baseline) and mass-reduced Venza parts (new technology configuration).

FEV

Technology Level:	Light Weighting Technology	**OEM Plant Location:**	USA
Vehicle Class:	Mid to Large Size Passenger Vehicle, 4-6 Passengers	**Supplier Plant Location:**	USA
Study Case#:	N0502 (N = New, 05 = Technology Package, 02 = Vehicle Class)	**OEM/T1 Classification:**	T1 High Assembly Complexity
System Description:	Brake System	**Shipping Method:**	FOB Ship Point
Component Description:	Front Rotor/Drum and Shield Subsystem: Front Rotor and Shield Sub-	**Packaging Specification:**	Returnable Dunnage
Component Quote Level:	☑ Full Quote ☐ Differential Quote (Quote Summary includes costing for both Technology Packages)	**EOP:**	2023
		Mean Year Quoted:	2011

Tooling Categories:

1. **Manufacturing Fixtures** (machining, assembly, welding, molds, dies)
2. **Gage & Test Fixtures**
3. **Non-perishable tooling** (machining cutter bodies, pick-n-place/gantries arms, guide/bushing plates, etc)
4. **Gauging** (standard & custom - both variable and go/no-go)
5. **Bulk Process Handling:** baskets, hangers, custom conveyors or walking arms
6. **OPTIONAL** (to be described w/ comment box if needed)

	GENERAL COMPONENT INFORMATION				GENERAL MANUFACTURING INFORMATION			MARK-UP COSTS				TOTAL COSTS		TOOLING & INVESTMENT	
em	Reference #	Part Description	Part Number	QTY Per Assembly	Primary Process Description	Labor Classification						To… Total 2 =	Total 3 = Total 2 * Qty per Ass'y	Tooling Assumptions "x1000 "	Investment Assumptions "x1000 "
													USD	USD	USD
A	Tier 1 Supplier or OEM Processing & Assembly (Full Cost mapping)														
1		Front Brake Rotor (Disc & Hat)		2	Inline gaging	Not Applicable							0.23	$60	
2		Front Brake Rotor (Disc & Hat)		2	Wash	Plating/Coating Operator-332100	Washing Equipment, LMC						0.44	$15	
3		Front Brake Rotor (Disc & Hat)		2	Surface Grind disc surface	Grinding/Polishing Operator-336300	Grinding, MLS, LMC	0.00%	0.00%	0.00%	$0.00	0.64	1.28	$95	
4		Front Brake Rotor (Disc & Hat)		2	Wash	Plating/Coating Operator-332100	Washing Equipment, LMC	0.00%	0.00%	0.00%	$0.00	0.11	0.21	$15	
5		Front Brake Rotor (Disc & Hat)		2	Mechanical Assy	Work Cell Assembly-332100	Mech Assembly, MC, Base	0.00%	0.00%	0.00%	$0.00	0.27	0.54	$58	
6				0				#N/A	#N/A	#N/A	#N/A	#N/A	0.00		
4		Front Brake Rotor (Disc)		2	Wash	Plating/Coating Operator-332100	Washing Equipment, LMC	0.00%	0.00%	0.00%	$0.00	0.12	0.24	$12	
5		Front Brake Rotor (Disc)		2	CNC Machine	CNC Operator-332100	CNC Machining, LC	0.00%	0.00%	0.00%	$0.00	1.79	3.57	$225	
7		Front Brake Rotor (Disc)		2	Trim flash & gates (saw)	Drilling/Boring Operator-331500	SAW, BAND, VERT: 1"Wx1"H - 4"Wx4"H	0.00%	0.00%	0.00%	$0.00	0.05	0.11	$21	
8		Front Brake Rotor (Disc)		2	Sand casting - remove sand	Mold/Cast/Sinter Operator-331500	Sand Cast, Sand Removal, MS	0.00%	0.00%	0.00%	$0.00	0.24	0.48	$0	
9		Front Brake Rotor (Disc)		2	Sand casting - pour cast material	Metal/Pourers/Casters Operator-331500	Sand Cast, Iron, Camshafts	0.00%	0.00%	0.00%	$0.00	24.08	48.16	$0	
					Sand casting - utility energy for										

Figure E-6: Sample Excerpt from Mass-Reduced Front Brake Rotor MAQS worksheet Illustrating Tooling Column and Categories

5) Calculation of Net Differential Tooling Impact

a) Similar to the direct manufacturing cost roll-ups, Cost Model Analysis Templates (CMATs) are used to roll-up the tooling costs at each level of the analysis.

b) Tooling costs are summed-up at the sub-subsystem, subsystem, system level and vehicle level.

6) The Final step is the calculation of "Incremental Tooling Cost per Vehicle" and "Incremental Tooling Cost/Kilogram" of mass-reduction at the final assessed mass-reduced vehicle.

a) Assumptions and calculation shown using the vehicle differential tooling cost and mass reduction value.

b) Additional details on incremental tooling costs by system can be found in Section F.

Assumptions:

- 200K units per year
- Average product/tooling life 5 years
- Cost of money 8%
- Calculated incremental vehicle tooling cost: +$14.5M
- Calculate mass-reduction/vehicle = -316.8kg (18.5%)

Calculations (for the 18.xx% mass reduced vehicle):

- Cost of over 5 years =$+16.2M (constant rate, uniform monthly payments)
- Incremental Tooling Cost per vehicle = $+16.18 ($16,182,335 tooling/[200K units/year x 5 years])
- Incremental Tooling Cost per kilogram = $0.051/kilogram ($16.18/316.8kg)

E.11 Cost Curve - % Mass Reduction vs. Cost per Kilogram

E.11.1 Cost Curve Development Overview

The majority of the Toyota Venza components were reviewed for potential mass reduction as shown in Section Y. While the focus of this study was to obtain 20% mass reduction, it is possible that manufacturers could adopt a portion of these technologies as part of their plan to increase gas mileage over the next decade. EPA's rulemaking calculations utilize a variety of technology feasibility combinations as a part of their rulemaking requirements (e.g. mass reduction, advanced engine technologies, etc.). EPA's current technology packages include estimates of 5%, 10%, 15%, and 20% mass reduction (Reference EPA & NHTSA, report EPA-420-D-11-901, November 2011 "Draft Joint Technical Support Document: Proposed Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards & Corporate Average Fuel Economy Standards,") over a variety of vehicle platforms. The technologies examined by FEV for the Toyota Venza can be grouped such that they achieve these various mass reduction targets.

FEV developed differential costs per component with the assumption that these are the costs when the components are in full production at 200,000 or 450,000 per year as appropriate per sub-subsystem. These values do not include OEM markups for indirect costs – as discussed in **Section E.4,** with the exception of tooling. In the mass-reduction analysis, incremental direct manufacturing costs were calculated with and without assessing the impact of tooling.

E.11.2 Cost Curve Development Overview

FEV utilized their component mass reduction and cost estimates to create a cost per-kilogram per-component. At the sub-subsystem level (which is generally the same as the assembly or module level) all mass-reduced ideas were listed in a table (**Table XXX**) along with key calculated parameters and attributes (e.g., mass deltas, cost deltas, cost/kg impact, and compounded/non-compounded designation). Sub-subsystems were then identified as compounded or non-compounded. Sub-subsystems relying on other vehicle mass-reductions were considered compounded while ideas not relying on a reduction in vehicle mass were considered non-compounded.

All sub-subsystems were then sorted by cost per kilogram in ascending order. Since all compounded sub-subsystems were created with an 18-20% mass reduction in mind, and would not be appropriate to apply to points which only had 5%, 10% or 15% mass reduction, all compounding sub-subsystems were placed at the bottom of the list listed in the order of lowest to highest cost per kilogram structure. Cumulative sub-subsystem cost-per-kilogram values were calculated and the values plotted relative to percent vehicle mass-reduction. Because the compounded mass-reduction sub-subsystem ideas cannot be included in any point other than the 18.5% vehicle mass-reduction point, the line graph stops at approximately 12% (Need to confirm final value) with a single data point at 18.5. Figure XXX illustrates the data shown in Table XXX. Note these values are only incremental direct manufacturing costs and do not include tooling.

To develop data points between the 12% and 18.5% vehicle mass-reduction values, and to determine the potential compounding advantage at values other than at 18.5% vehicle mass-reduction a updated table of data was assembled. By removing the added mass-reduction as a result of compounding for each of the applicable sub-subsystems additional cumulative cost/kg data points were establish for vehicle mass-reductions in the 12-16% range (Table XXX). Using a trend line (Figure XXX) applied to the cumulative cost/kg, non-compounded data, an offset value was established at 18.5% vehicle mass reduction between the cost/kilogram with compounding, and without compounding. Assuming the offset is zero at 0% vehicle mass-reduction, and $X.XX at 18.5% mass-reduction, a curve with compounding considerations at every percent vehicle mass-reduction “x” axis point could be generated.

In **Section F.X** cost curves with and without mass-reduction compounding are shown for percent vehicle mass-reductions of 0% to 20%. In addition the additive impact of tooling at the 5%, 10%, 15% and 20% vehicle mass-reduction data points is included.

F. Mass Reduction and Cost Analysis Results

F.1 Vehicle Results Summary

F.1.1 Assumptions

This analysis used a 2010 model year, 2.7L engine Toyota Venza vehicle. Its purchase price was $25,063.00. Based on the assumption of 1.5 retail price equivalent, the estimated cost to manufacture the Venza vehicle is $16,708.67 (10% vehicle manufacturing cost increase would be $1670.87). The weight of Toyota Venza vehicle is 1711 kg (3771 lbs). The target of this study is to achieve 20% mass reduction which is 342 kg (754lbs). Although Toyota Venza annual volume is 60k units, this analysis considers the volume to be 200k units per year consistent with high volume production assumptions.

The target of this study is to achieve 20% mass reduction (342kg) within 10% cost increase ($1670.87). Five cost groups were established to categorize the mass reduction ideas: A, B, C, D, and X.

- Group A is to reduce mass between 0 and 5% with 10% cost increase. Group A requires an average cost/kilogram ≤$0.
- Group B is mass reduction from 5% to 10% with 10% cost increase. Group B requires an average cost/kilogram between $0 and $1.
- Group C is mass reduction of 10% to 15% with 10% cost increase. Group C requires an average cost/kilogram between $1 and $2.5.

- Group D is to reduce mass 15% to 20% with 10% cost increase. Group D requires an average cost/kilogram between $2.5 and $4.88.
- Group X is de-contenting. All mass reduction ideas providing an average cost/kilogram ≥$4.88 is outside the target of this study.

Level #A Average Cost/Kilogram @ 0-5% Mass Reduction	**≤$0.00**
Level #B Average Cost/Kilogram @ 5-10% Mass Reduction	**>$0.00 to ≤ $1.00**
Level #C Average Cost/Kilogram @ 10-15% Mass Reduction	**>$1.00 to ≤ $2.50**
Level #D Average Cost/Kilogram @ 15-20% Mass Reduction	**>$2.50 to ≤ $4.88**
Level X, De-Contenting 1. No Impact to Daily Operation 2. Impact to Daily Operation (feature, function, performance, etc)	**≤ $4.88**

Table F.1-1: Five Cost Groups to Categorize Mass Reduction Ideas

F.1.2 Baseline Vehicle Mass

Baseline Mass of Vehicle: 1,711 kg (3,771 lbs.)

The vehicle weight was distributed among 23 systems. The body systems take most of the weight, while other major weight contributors included the Suspension, Engine, Transmission, and Brakes systems.

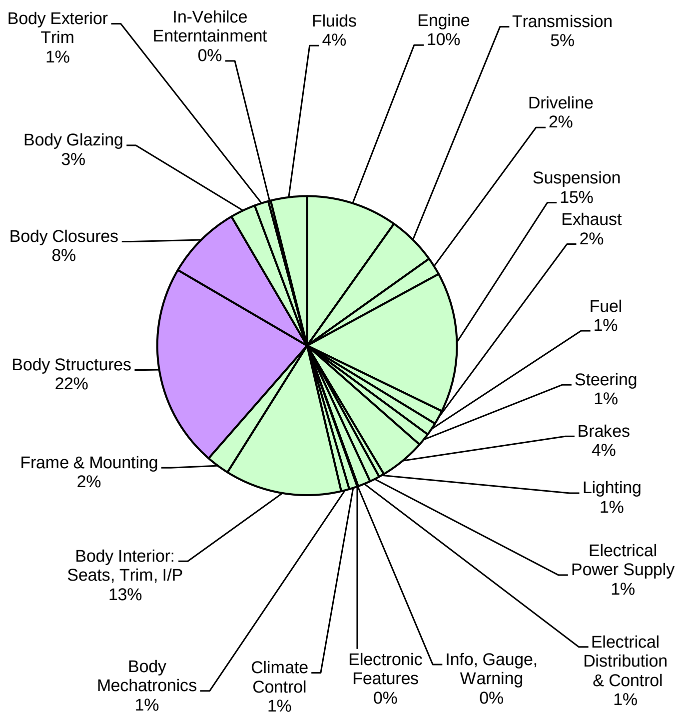


Figure F.1-1: Vehicle Mass System Breakdown

F.1.3 Vehicle Cost Summary

Table F.1-1 is the vehicle mass reduction summary, including the mass reduction and cost impact from each system. The major mass saving systems in the Toyota Venza include: Body system (Group -A-), which saved 3.97% of the vehicle weight; the Suspension system, 4.06%; Brake System, 2.37%; and Body system (Group -B-) at 2.45%. The Engine and Transmission systems reduced vehicle mass by 1.77% and 1.10%, respectively. The entire vehicle achieved 316.78 kg weight reduction and $92.04 cost savings. Average cost per kilogram is $0.29 reductions comparing to baseline vehicle without consider tooling and $0.24 reduction included tooling impact. The table explained the subsystem level details.

Description	System/ Subsystem/ Sub-Subsystem Weight "kg"	Estimate Mass Reduction "+" Mass Decrease, "-" Mass Increase "kg"	Estimated Cost Impact "+" Cost Decrease, "-" Cost Increase "$"	Tooling Cost "$" (x1000)	Average Cost/ Kilogram W/O Tooling $/kg	Average Cost/ Kilogram W/ Tooling $/kg	% System/ Subsystem Mass Reduction "%"	% Vehicle Mass Reduction
Engine System	**172.60**	**30.35**	**43.24**	**5,892.20**	**1.42**	**1.66**	**17.58%**	**1.77%**
Engine System Roll-up ((Eng Down Size))	172.60	10.37	38.42	0.00	3.71	3.71	6.01%	0.61%
Engine Frames, Mounting, and Brackets Subsystem	15.27	1.11	(0.09)	(2,778.60)	(0.08)	(3.11)	7.29%	0.07%
Crank Drive Subsystem	24.73	0.69	6.88	302.80	10.00	10.53	2.78%	0.04%
Counter Balance Subsystem	7.22	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Cylinder Block Subsystem	30.13	7.11	(24.93)	(2,918.00)	(3.51)	(4.01)	23.58%	0.42%
Cylinder Head Subsystem	21.12	1.05	14.04	2,199.60	13.41	15.97	4.96%	0.06%
Valvetrain Subsystem	9.78	3.71	(11.13)	(2,171.00)	(3.00)	(3.72)	37.90%	0.22%
Timing Drive Subsystem	4.31	1.45	4.79	3,522.40	3.29	6.24	33.72%	0.08%
Accessory Drive Subsystem	0.55	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Air Intake Subsystem	13.99	0.51	3.01	1,924.70	5.90	10.49	3.65%	0.03%
Fuel Induction Subsystem	0.54	0.11	2.13	1,533.40	18.51	34.75	21.32%	0.01%
Exhaust Subsystem	7.39	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Lubrication Subsystem	3.34	0.33	(0.20)	26.50	(0.60)	(0.51)	9.97%	0.02%
Cooling Subsystem	14.10	2.59	4.62	2,977.60	1.78	3.18	18.38%	0.15%
Breather Subsystem	0.90	0.22	4.93	1,720.10	22.52	32.07	24.24%	0.01%
Engine Management, Engine Electronic, Electrical Subsystem	2.65	0.39	1.00	341.00	2.57	3.64	14.64%	0.02%
Accessory Subsystems (Start Motor, Generator, etc.)	16.56	0.71	(0.23)	(788.30)	(0.33)	(1.68)	4.28%	0.04%
Transmission System	**92.76**	**18.90**	**(114.15)**	**(7,650.80)**	**(6.04)**	**(6.53)**	**20.37%**	**1.10%**
Transmission System Roll-up	0.00	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
External Components	0.02	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Case Subsystem	24.57	7.75	(11.03)	0.00	(1.42)	(1.42)	31.52%	0.45%
Gear Train Subsystem	41.44	3.49	(119.68)	0.00	(34.29)	(34.29)	8.42%	0.20%
Launch Clutch Subsystem	9.75	4.90	45.16	(7,650.80)	9.21	7.31	50.32%	0.29%
Oil Pump and Filter Subsystem	6.53	1.03	0.90	0.00	0.87	0.87	15.84%	0.06%
Mechanical Controls Subsystem	6.30	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Electrical Controls Subsystem	0.78	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Parking Mechanism Subsystem	0.90	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Driver Operated External Controls Subsystem	2.48	1.73	(29.49)	0.00	(17.08)	(17.08)	69.55%	0.10%
Body System (Group -A-)	**528.88**	**67.89**	**(230.66)**	**(22,900.00)**	**(3.40)**	**(3.81)**	**12.84%**	**3.97%**
Body System (Group -A-)	0.00	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Body Structure Subsystem	386.18	60.30	(189.99)	(22,900.00)	(3.15)	(3.61)	15.61%	3.52%
Body Closures Subsystem	135.25	7.24	(29.96)	0.00	(4.14)	(4.14)	5.35%	0.42%
Bumpers Subsystem	7.45	0.35	(10.71)	0.00	(30.60)	(30.60)	4.70%	0.02%
Body System (Group -B-)	**220.61**	**42.00**	**122.98**	**9,966.15**	**2.93**	**3.22**	**19.04%**	**2.45%**
Body System (Group -B-)	0.00	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Interior Trim and Ornamentation Subsystem	65.20	8.92	37.72	0.00	4.23	4.23	13.69%	0.52%
Sound and Heat Control Subsystem (Body)	4.50	0.27	0.38	0.00	1.40	1.40	5.95%	0.02%
Sealing Subsystem	8.23	2.03	15.70	0.00	7.74	7.74	24.67%	0.12%
Seating Subsystem	92.55	23.39	84.55	14,507.05	3.61	4.37	25.28%	1.37%
Instrument Panel and Console Subsystem	32.69	6.33	(12.49)	(5,317.90)	(1.97)	(3.00)	19.36%	0.37%
Occupant Restraining Device Subsystem	17.44	1.06	(2.88)	777.00	(2.71)	(1.82)	6.08%	0.06%
Body System (Group -C-)	**26.57**	**2.37**	**7.59**	**0.00**	**3.20**	**3.20**	**8.92%**	**0.14%**
Body System (Group -C-)	0.00	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Exterior Trim and Ornamentation Subsystem	13.38	1.15	2.31	0.00	2.01	2.01	8.57%	0.07%
Rear View Mirrors Subsystem	2.76	0.22	0.73	0.00	3.33	3.33	7.90%	0.01%
Front End Modules	5.03	0.49	2.24	0.00	4.56	4.56	9.75%	0.03%
Rear End Modules	5.39	0.51	2.32	0.00	4.52	4.52	9.54%	0.03%

Description	System/ Subsystem/ Sub-Subsystem Weight "kg"	Estimate Mass Reduction "+" Mass Decrease, "-" Mass Increase "kg"	Estimated Cost Impact "+" Cost Decrease, "-" Cost Increase "$"	Tooling Cost "$" (x1000)	Average Cost/ Kilogram W/O Tooling $/kg	Average Cost/ Kilogram W/ Tooling $/kg	% System/ Subsystem Mass Reduction "%"	% Vehicle Mass Reduction
Body System (Group -D-) Glazing & Body Mechatronics	**63.46**	**6.16**	**(15.25)**	**0.00**	**(2.48)**	**(2.48)**	**9.71%**	**0.36%**
Body System (Group -D-)	0.00	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Glass (Glazing), Frame and Mechanism Subsystem	48.01	6.06	(15.67)	0.00	(2.59)	(2.59)	12.63%	0.35%
Handles, Locks, Latches and Mechanisms Subsystem	4.93	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Rear Hatch Lift assembly	4.56	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Wipers and Washers Subsystem	5.96	0.10	0.42	0.00	4.18	4.18	1.68%	0.01%
Suspension System	**265.91**	**69.45**	**135.93**	**(7,200.97)**	**1.96**	**1.83**	**26.12%**	**4.06%**
Suspension System	24.42	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Front Suspension Subsystem	32.89	14.18	(5.74)	(4,828.98)	(0.40)	(0.82)	43.12%	0.83%
Rear Suspension Subsystem	23.58	8.32	4.91	(2,459.05)	0.59	0.23	35.28%	0.49%
Shock Absorber Subsystem	42.94	14.11	57.99	87.06	4.11	4.12	32.86%	0.82%
Wheels And Tires Subsystem	142.07	32.83	78.77	0.00	2.40	2.40	23.11%	1.92%
Driveline System	**33.66**	**1.50**	**(0.16)**	**(160.30)**	**(0.11)**	**(0.24)**	**4.47%**	**0.09%**
Driveline System	0.00	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Rear Drive Housed Axle Subsystem	8.63	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Front Drive Housed Axle Subsystem	6.35	0.73	1.54	(30.00)	2.10	2.05	11.54%	0.04%
Front Drive Half-Shafts Subsystem	18.67	0.77	(1.70)	(130.30)	(2.21)	(2.42)	4.12%	0.04%
Brake System	**86.71**	**40.52**	**116.21**	**(1,426.12)**	**2.87**	**2.83**	**46.73%**	**2.37%**
Brake System	0.00	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Front Rotor/Drum and Shield Subsystem	32.97	17.08	(6.07)	(2,182.66)	(0.36)	(0.51)	51.81%	1.00%
Rear Rotor/Drum and Shield Subsystem	23.44	9.57	6.08	(1,897.51)	0.63	0.39	40.84%	0.56%
Parking Brake and Actuation Subsystem	13.40	9.63	82.98	1,526.28	8.61	8.81	71.88%	0.56%
Brake Actuation Subsystem	5.54	2.98	31.87	1,253.15	10.68	11.19	53.90%	0.17%
Power Brake Subsystem (for Hydraulic)	2.83	1.24	1.35	(125.39)	1.09	0.97	43.89%	0.07%
Brake Controls Subsystem	8.53	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Frame and Mounting System	**43.73**	**16.50**	**(3.66)**	**4,059.70**	**(0.22)**	**0.08**	**49.02%**	**0.96%**
Frame and Mounting System	0.00	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Frame Sub System	43.73	16.50	(3.66)	4,059.70	(0.22)	0.08	37.73%	0.96%
Exhaust System	**26.62**	**7.52**	**2.47**	**0.00**	**0.33**	**0.33**	**28.25%**	**0.44%**
Exhaust System	0.00	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Acoustical Control Components Subsystem	11.74	2.79	(0.21)	0.00	(0.07)	(0.07)	23.75%	0.16%
Exhaust Gas Treatment Components Subsystem	14.87	4.73	2.68	0.00	0.57	0.57	31.79%	0.28%
Fuel System	**24.28**	**6.80**	**3.91**	**1,535.50**	**0.57**	**0.85**	**28.03%**	**0.40%**
Fuel System	0.00	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Fuel Tank And Lines Subsystem	21.02	6.31	2.70	1,439.50	0.43	0.71	30.01%	0.37%
Fuel Vapor Management Subsystem	3.26	0.50	1.21	96.00	2.44	2.68	15.26%	0.03%
Steering System	**24.23**	**1.82**	**11.05**	**1,352.70**	**6.08**	**6.99**	**7.50%**	**0.11%**
Steering System	0.00	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Manual Steering Gear Subsystem	8.82	0.12	0.24	0.00	1.99	1.99	1.39%	0.01%
Power Steering Subsystem	7.48	0.21	0.10	186.80	0.46	1.54	2.81%	0.01%
Steering Column Subsystem	5.08	1.15	10.39	(1,910.00)	9.05	7.03	22.58%	0.07%
Steering Column Switches Subsystem	0.55	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Steering Wheel Subsystem	2.29	0.34	0.32	3,075.90	0.94	12.07	14.69%	0.02%

Description	System/ Subsystem/ Sub-Subsystem Weight "kg"	Estimate Mass Reduction "+" Mass Decrease, "-" Mass Increase "kg"	Estimated Cost Impact "+" Cost Decrease, "-" Cost Increase "$"	Tooling Cost "$" (x1000)	Average Cost/ Kilogram W/O Tooling $/kg	Average Cost/ Kilogram W/ Tooling $/kg	% System/ Subsystem Mass Reduction "%"	% Vehicle Mass Reduction
Climate Control System	**15.66**	**2.44**	**9.34**	**386.00**	**3.83**	**4.03**	**15.55%**	**0.14%**
Climate Control System	0.00	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Air Handling/Body Ventilation Subsystem	12.81	2.03	7.27	146.00	3.58	3.66	15.88%	0.12%
Heating/Defrosting Subsystem	1.03	0.39	2.03	240.00	5.16	5.90	38.03%	0.02%
Refrigeration/Air Conditioning Subsystem	1.33	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Controls Subsystem	0.48	0.01	0.04	0.00	4.21	4.21	1.84%	0.00%
Information, Gage and Warning Device System	**1.90**	**0.08**	**0.19**	**0.00**	**2.45**	**2.45**	**4.01%**	**0.00%**
Information, Gauge and Warning Device System	0.00	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Instrument Cluster Subsystem	1.40	0.08	0.19	0.00	2.45	2.45	5.44%	0.00%
Horn Subsystem	0.50	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Electrical Power Supply System	**18.96**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00%**	**0.00%**
Electrical Power Supply System	0.00	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Service Battery Subsystem	18.96	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
In-Vehicle Entertainment System	**4.59**	**1.07**	**2.43**	**1,175.60**	**2.27**	**3.60**	**23.39%**	**0.06%**
In-Vehicle Entertainment System	0.00	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Receiver and Audio Media Subsystem	3.15	1.02	1.74	1,175.60	1.70	3.10	32.55%	0.06%
Antenna Subsystem	0.16	0.05	0.69	0.00	14.17	14.17	30.82%	0.00%
Speaker Subsystem	1.28	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Lighting System	**10.04**	**0.53**	**(0.76)**	**400.00**	**(1.42)**	**(0.51)**	**5.29%**	**0.03%**
Lighting System	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00%
Front Lighting Subsystem	6.09	0.53	(0.76)	400.00	(1.42)	(0.51)	8.73%	0.03%
Rear Lighting Subsystem	3.83	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Lighting Switches Subsystem	0.13	0.00	0.00	0.00	0.00	0.00	0.00%	0.00%
Electrical Distribution and Electronic Control System	**23.94**	**0.89**	**1.35**	**103.50**	**1.52**	**1.66**	**3.71%**	**0.05%**
Electrical Distribution and Electronic Control Sys.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00%
Electrical Wiring and Circuit Protection Subsystem	23.94	0.89	1.35	103.50	1.52	1.66	3.71%	0.05%
Sub-Total Vehicle Weight =	**1685.10**	**316.78**	**92.04**	**(14,466.84)**	**0.29**	**0.24**		**18.51%**
Weight Reconcile								
Fluids =	68.52							
NVH (Body Mastic) =	8.00							
Misc. =	(50.24)							
Net Calculated Vehicle Weight =	**1711.38**							
Vehicle Weight As Purchased=	**1710.53**							
		(Decrease)	(Decrease)	(Increase)	(Decrease)	(Decrease)		

Table F.1-2: Vehicle Cost Summary

F.1.4 Net Incremental Direct Manufacturing Cost

A summary of the calculated, net incremental, and direct manufacturing costs for producing a Toyota Venza vehicle are presented in **Error! Reference source not found.**. The costs, captured only for vehicle differences having an overall positive or negative cost impact, are broken out for each of the major systems. At the bottom of the table, there is a net incremental cost. From the cost element breakdown within the table, the incremental direct manufacturing costs (i.e., $148.30) are material costs, $109.68 was saved on labor costs, and $80.43 was reduced from overhead costs. Relative to the net incremental direct manufacturing cost of $91.96, approximately 45.46% is total manufacturing costs (i.e., material, labor, overhead). The remaining 54.42% is applicable mark-up.

In the sections which follow, additional details on the components evaluated within each vehicle system and their associated costs will be discussed.

SYSTEM & SUBSYSTEM DESCRIPTION				NEW TECHNOLOGY GENERAL PART INFORMATION:										
				Manufacturing				Markup						
Item	Vehicle	System	Sub-Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	00 Vehicle													
1		01	Engine	614.67	41.94	123.85	780.47	3.21	23.52	20.24	6.43	53.40	0	833.86
2		02	Transmission	261.26	19.48	33.32	314.05	2.20	28.98	20.12	3.30	54.61	0	368.66
3		03	Body System A	780.13	93.56	466.60	1,340.29	0.02	0.35	0.28	0.06	0.70	0	1,343.15
3		03	Body System B	335.28	47.79	111.10	494.18	1.77	29.86	22.55	6.13	60.31	0	554.49
3		03	Body System C	52.07	2.04	8.24	62.35	0.45	6.90	5.47	1.12	13.95	0	76.30
3		03	Body System D	27.90	5.78	114.79	148.48	0.38	7.59	5.09	1.26	14.33	0	162.81
4		04	Suspension System	362.60	81.18	110.72	554.49	4.83	43.78	34.64	9.54	92.79	0	647.29
5		05	Driveline System	16.59	2.84	5.87	25.30	0.34	2.61	2.57	0.95	6.47	0	31.77
6		06	Brake System	151.00	29.27	73.30	253.57	1.30	18.13	15.85	5.29	40.57	0	294.14
7		07	Frame and Mounting System	71.76	10.88	42.55	125.19	0.85	8.95	9.83	4.46	24.09	0	149.28
8		09	Exhaust System	36.97	0.95	0.97	38.88	0.12	1.57	1.45	0.60	3.74	0	42.62
9		10	Fuel System	46.98	5.97	17.74	70.69	0.48	5.28	5.61	2.47	13.84	0	84.54
10		11	Steering System	16.81	4.64	5.57	27.03	0.20	1.35	1.15	0.34	3.04	0	30.07
11		12	Climate Control	17.82	5.39	3.97	27.17	0.07	1.38	0.92	0.23	2.61	0	29.78
12		13	Info, Gage and Warning System	1.70	0.05	0.31	2.07	0.01	0.12	0.14	0.07	0.34	0	2.41
13		14	Electrical Power Supply	-	-	-	-	-	-	-	-	-	-	-
14		15	In-Vehicle Entertainment	1.18	0.64	0.78	2.60	0.01	0.27	0.18	0.02	0.49	0	3.09
15		17	Lighting	10.87	1.23	3.31	15.41	0.04	0.77	0.52	0.13	1.46	0	16.87
16		18	Electrical Distribution and Electronic Control System	7.61	0.62	0.58	8.82	0.03	0.45	0.34	0.05	0.87	0	9.69
17		19	Electronic Features	-	-	-	-	-	-	-	-	-	-	-
	SUBSYSTEM ROLL-UP			2,813.20	354.26	1,123.57	4,291.03	16.33	181.87	146.94	42.45	387.59	0	4,680.78

SYSTEM & SUBSYSTEM DESCRIPTION				BASE TECHNOLOGY GENERAL PART INFORMATION:										
				Manufacturing				Markup						
Item	Vehicle	System	Sub-Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	00 Vehicle													
1			01 Engine	654.08	41.76	119.55	815.40	5.62	26.50	22.64	6.95	61.70	0	877.10
2			02 Transmission	166.53	24.32	30.33	221.17	1.03	17.98	12.23	2.09	33.34	0	254.51
3			03 Body System A	599.94	80.83	428.71	1,109.47	0.02	0.37	0.29	0.06	0.74	0	1,112.48
3			03 Body System B	356.01	99.03	146.46	601.50	2.30	35.83	28.69	9.15	75.97	0	677.47
3			03 Body System C	57.04	2.28	9.30	68.61	0.48	7.57	6.01	1.21	15.28	0	83.89
3			03 Body System D	25.76	6.44	102.31	134.50	0.35	6.91	4.64	1.15	13.05	0	147.56
4			04 Suspension System	429.10	103.60	137.94	670.63	5.96	53.36	41.94	11.32	112.58	0	783.22
5			05 Driveline System	16.79	2.52	5.96	25.26	0.29	2.54	2.55	0.97	6.34	0	31.60
6			06 Brake System	157.80	52.09	143.38	353.27	1.77	27.10	21.98	6.23	57.08	0	410.35
7			07 Frame and Mounting System	77.41	21.22	17.43	116.06	0.99	12.53	11.84	4.19	29.55	0	145.61
8			09 Exhaust System	39.02	0.84	1.05	40.90	0.13	1.75	1.62	0.67	4.18	0	45.08
9			10 Fuel System	28.66	12.35	32.53	73.54	0.51	5.83	6.01	2.55	14.91	0	88.45
10			11 Steering System	18.48	7.84	8.86	35.18	0.38	2.69	2.28	0.59	5.94	0	41.11
11			12 Climate Control	18.12	4.37	13.20	35.70	0.09	1.81	1.21	0.30	3.42	0	39.11
12			13 Info, Gage and Warning System	1.95	0.06	0.22	2.23	0.01	0.13	0.15	0.07	0.37	0	2.60
13			14 Electrical Power Supply	-	-	-	-	-	-	-	-	-	-	-
14			15 In-Vehicle Entertainment	1.46	1.55	1.62	4.62	0.04	0.48	0.32	0.04	0.89	0	5.52
15			17 Lighting	7.91	2.26	4.55	14.72	0.04	0.74	0.49	0.12	1.39	0	16.11
16			18 Electrical Distribution and Electronic Control System	8.92	0.59	0.63	10.14	0.03	0.51	0.34	0.03	0.90	0	11.04
17			19 Electronic Features	-	-	-	-	-	-	-	-	-	-	-
			SUBSYSTEM ROLL-UP	2,664.98	463.94	1,204.00	4,332.91	20.06	204.63	165.24	47.70	437.64	0	4,772.82

SYSTEM & SUBSYSTEM DESCRIPTION				INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE										
				Manufacturing				Markup						
Item	Vehicle	System	Sub-Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	00 Vehicle													
1			01 Engine	39.42	(0.18)	(4.30)	34.93	2.41	2.98	2.40	0.51	8.30	0	43.24
2			02 Transmission	(94.73)	4.84	(2.99)	(92.88)	(1.16)	(11.00)	(7.89)	(1.21)	(21.26)	0	(114.15)
3			03 Body System A	(180.18)	(12.74)	(37.89)	(230.81)	0.00	0.02	0.02	0.00	0.04	0	(230.66)
3			03 Body System B	20.73	51.24	35.35	107.32	0.53	5.97	6.14	3.02	15.66	0	122.98
3			03 Body System C	4.96	0.24	1.06	6.26	0.03	0.67	0.54	0.10	1.33	0	7.59
3			03 Body System D	(2.15)	0.66	(12.48)	(13.97)	(0.03)	(0.68)	(0.45)	(0.11)	(1.28)	0	(15.25)
4			04 Suspension System	66.50	22.42	27.22	116.14	1.13	9.58	7.30	1.79	19.79	0	135.93
5			05 Driveline System	0.19	(0.32)	0.09	(0.04)	(0.05)	(0.07)	(0.02)	0.01	(0.13)	0	(0.16)
6			06 Brake System	6.80	22.81	70.08	99.70	0.46	8.97	6.13	0.94	16.51	0	116.21
7			07 Frame and Mounting System	5.65	10.34	(25.12)	(9.13)	0.14	3.58	2.02	(0.27)	5.46	0	(3.66)
8			09 Exhaust System	2.05	(0.11)	0.08	2.02	0.01	0.19	0.17	0.07	0.44	0	2.47
9			10 Fuel System	(18.32)	6.38	14.79	2.85	0.03	0.55	0.40	0.08	1.06	0	3.91
10			11 Steering System	1.67	3.19	3.28	8.15	0.18	1.34	1.13	0.25	2.90	0	11.05
11			12 Climate Control	0.30	(1.01)	9.24	8.53	0.02	0.43	0.29	0.07	0.81	0	9.34
12			13 Info, Gage and Warning System	0.25	0.01	(0.09)	0.16	0.00	0.01	0.01	0.01	0.03	0	0.19
13			14 Electrical Power Supply	-	-	-	-	-	-	-	-	-	-	-
14			15 In-Vehicle Entertainment	0.28	0.91	0.84	2.02	0.03	0.21	0.14	0.02	0.40	0	2.43
15			17 Lighting	(2.95)	1.03	1.24	(0.69)	(0.00)	(0.03)	(0.02)	(0.01)	(0.07)	0	(0.76)
16			18 Electrical Distribution and Electronic Control System	1.31	(0.03)	0.04	1.32	(0.00)	0.06	0.00	(0.03)	0.03	0	1.35
17			19 Electronic Features	-	-	-	-	-	-	-	-	-	-	-
			SUBSYSTEM ROLL-UP	(148.23)	109.68	80.43	41.88	3.73	22.76	18.30	5.25	50.05	0	92.04

F.2 Engine System

The Base Engine system comprises 10.1% of the total Venza vehicle mass. This system is divided into various subsystems as shown in **Table F.2-1**. Significant mass contributors to the Engine system include Cylinder Block, Crank Drive, and Cylinder Head subsystems. The 2.7 L inline 4-cylinder gasoline engine selected by Toyota is naturally aspirated with no Induction Air Charging subsystem.

System	Subsystem	Sub-Subsystem	Description	System & Subsystem Mass "kg"
01	**00**	**00**	**Engine System**	
01	02	00	Engine Frames, Mounting, and Brackets Subsystem	15.274
01	03	00	Crank Drive Subsystem	24.730
01	04	00	Counter Balance Subsystem	7.218
01	05	00	Cylinder Block Subsystem	30.135
01	06	00	Cylinder Head Subsystem	21.115
01	07	00	Valvetrain Subsystem	9.783
01	08	00	Timing Drive Subsystem	4.312
01	09	00	Accessory Drive Subsystem	0.554
01	10	00	Air Intake Subsystem	13.994
01	11	00	Fuel Induction Subsystem	0.539
01	12	00	Exhaust Subsystem	7.387
01	13	00	Lubrication Subsystem	3.342
01	14	00	Cooling Subsystem	14.098
01	15	00	Induction Air Charging Subsystem	0.000
01	16	00	Exhaust Gas Re-circulation Subsystem	0.000
01	17	00	Breather Subsystem	0.904
01	60	00	Engine Management, Engine Electronic, Electrical Subsystem	2.650
01	70	00	Accessory Subsystems (Start Motor, Generator, etc.)	16.562
			Total System Mass =	**172.598**
			Total Vehicle Mass =	**1711**
			System Mass Contribution Relative to Vehicle =	**10.09%**

Table F.2-1: Baseline Subsystem Breakdown for Engine System

Table F.2-2 summarizes mass and cost savings by subsystem. The systems largest savings results from engine downsizing permitted by a lightened vehicle. The largest subsystem contributors for mass savings are the Cylinder Block and Valvetrain subsystems. Detailed system analysis resulted in 30.3 kg saved and $1.45/kg savings. Lightening the 2.7L Venza Engine system, without the cost and mass benefit of downsizing, results in a cost save of $0.28/kg. Research and development, warranty costs, and NVH were not captured in this analysis. 93% of mass savings claimed for this system have current automotive production examples.

All subsystems were reviewed for mass save opportunity. No opportunities were selected for the Counter Balance, Accessory Drive, Exhaust, and Exhaust Gas Re-circulation subsystems. The Venza engine has no Induction Air Charging system, hence no mass savings for that subsystem.

Lotus used a hybrid approach to address the Venza engine system. This analysis focuses specifically on lightweighting the 2.7L and downsizing based on an equal technology approach. The horsepower requirement determined for the lightened Venza matches what was calculated by Lotus. The components considered as part of the engine system in this analysis do not match what Lotus included. Due to the different approaches in analysis, there will be no further mention of Lotus for this system.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
01	**00**	**00**	**Engine System**						
01	01	00	Engine Assembly Downsize (2.4L)	A	10.365	38.420	$3.71	6.01%	0.61%
01	02	00	Engine Frames, Mounting, and Brackets Subsystem	A	1.114	0.788	$0.71	7.29%	0.07%
01	03	00	Crank Drive Subsystem	A	0.688	$6.88	$10.00	2.78%	0.04%
01	04	00	Counter Balance Subsystem	A	0.000	$0.00	$0.00	0.00%	0.00%
01	05	00	Cylinder Block Subsystem	D	7.106	-24.931	-$3.51	23.58%	0.42%
01	06	00	Cylinder Head Subsystem	A	1.047	14.043	$13.41	4.96%	0.06%
01	07	00	Valvetrain Subsystem	D	3.707	-11.133	-$3.00	37.90%	0.22%
01	08	00	Timing Drive Subsystem	A	1.454	4.792	$3.29	33.72%	0.09%
01	09	00	Accessory Drive Subsystem	A	0.000	0.000	$0.00	0.00%	0.00%
01	10	00	Air Intake Subsystem	A	0.510	2.859	$5.60	3.65%	0.03%
01	11	00	Fuel Induction Subsystem	A	0.115	2.127	$0.00	0.00%	0.00%
01	12	00	Exhaust Subsystem	A	0.000	0.000	$0.00	0.00%	0.00%
01	13	00	Lubrication Subsystem	B	0.333	-0.201	-$0.60	9.97%	0.02%
01	14	00	Cooling Subsystem	A	2.591	4.620	$1.78	18.38%	0.15%
01	15	00	Induction Air Charging Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
01	16	00	Exhaust Gas Re-circulation Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
01	17	00	Breather Subsystem	A	0.219	$4.93	$22.52	0.00%	0.00%
01	60	00	Engine Management, Engine Electronic, Electrical Subsystem	A	0.388	$1.00	$2.57	0.00%	0.00%
01	70	00	Accessory Subsystems (Start Motor, Generator, etc.)	B	0.709	-$0.23	-$0.33	4.28%	0.04%
				A	**30.347** (Decrease)	**43.963** (Decrease)	**1.449** (Decrease)	**17.58%**	**1.77%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.2-2: Mass-Reduction and Cost Impact for Engine System

F.2.1 Engine Assembly Downsize (2.4L)

F.2.1.1 Subsystem Content Overview

The intent of reviewing the engine as an assembly is to propose an engine with less mass yet capable of producing horsepower sufficient to accelerate the lightened Venza with performance equal to base Venza. Since new technologies such as direct injection and turbo charging have been the focus of previous research, only engines of equal technology (dual VVT with no induction) were considered for the downsize.

F.2.1.2 Toyota Venza Baseline Subsystem Technology

The 2.7L inline 4 cylinder engine selected by Toyota (**Image F.2-1**) for Venza is an all Aluminum design with variable valve timing on both the Intake and Exhaust camshafts. The engine has no induction air charging system and utilizes port injection. The intake manifold is a dual runner design, optimizing torque.

Image F.2-1: Venza Base Engine (Toyota 2.7L 1AR-FE)

(Source: www.mr2.com/forums/mk-2-mr2-sw20/Toyota-MR2-20347-some-info-toyota-s-new-6-speed-ea-series-transmissions.html)

F.2.1.3 Mass-Reduction Industry Trends

Mass reduction of passenger car engines has been driven by fuel economy. Valve control technology is one way engines have increased power output. Variable valve timing has become commonplace using hydraulic cam phasers on the intake or intake and exhaust camshafts. Variable valve duration such as in Fiats Multiair has further increased output. Forced induction has also become more popular but comes with additional hardware and associated mass.

F.2.1.4 Summary of Mass-Reduction Concepts Considered

The downsized Venza mass was calculated by assuming a 20% reduced curb weight and maintaining the base payload. The resulting GVWR reduction factor is 84.8%.

Using this Scale factor new horsepower and torque requirements were calculated (**Table F.2-3**). Smaller displacement engines of equal technology were reviewed for power and torque at RMP compatibility.

ENGINE SIZING - BASED ON 20% GVWR REDUCTION		
Toyota Venza Curb Weight (kgs)	1711	
Toyota Venza GVWR (kgs)	2249	
20% Curb Weight Reduction	1369	
Lightened Weight (GVWR)	**1907**	
Power Reduction Factor	0.848	
2.7 Power (kW)	136	
2.7 Torque (N*m)	247	
Reduced-Weight Power (kW)	**115**	
Reduced-Weight Torque (N*m)	**209**	
1AR-FE (Venza) DOHC I4 2672 (kW)	136 @5800	http://en.wikipedia.org/wiki/Toyota_Venza
1AR-FE (Venza) DOHC I4 2672 (N*m)	247 @4200	http://en.wikipedia.org/wiki/Toyota_Venza
2AZ-FE (Matrix) DOHC I4 2362 (kW)	119 @5600	http://en.wikipedia.org/wiki/Toyota_AZ_engine
2AZ-FE (Matrix) DOHC I4 2362 (N*m)	220 @4000	http://en.wikipedia.org/wiki/Toyota_AZ_engine
1AR-FE 2.7L Bore & Stroke (mm)	89.9 x 104.9	
2AZ-FE 2.4L Bore & Stroke (mm)	88.4 x 96	
Engine Downsize Selection - Toyota DOHC I4 2362cc (Avensis, Matrix, …)		

Table F.2-3: Engine Downsize Selection

F.2.1.5 Selection of Mass Reduction Ideas

The Engine selected for the lightened Venza is Toyota's 2.4L 2AZ-FE I4 DOHC (**Image F.2-2**). This Engine (EOP 2009) was featured in cars such as the Camry, Matrix, and Vibe among others. The 2.4L exceeds power and torque requirements at lower engine speeds, indicating that acceleration and drivability would be equal or better. The 2.4L represents a data point for mass and output of a technologically similar power plant. As predecessor to the AR engine, the 2.4L AZ results in a conservative estimate for mass savings.

Image F.2.2: Engine Downsize Selection (Toyota 2.4L 2AZ-FE)

(Source: www.japparts.com.au)

F.2.1.6 Calculated Mass-Reduction & Cost Impact

As shown in **Table F.2-4**, Engine system downsize results in a mass reduction and cost savings.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
01	**00**	**00**	**System downsize (2.7L I4 to 2.4L I4)**						
01	05	01	System downsize (2.7L I4 to 2.4L I4)	A	10.365	$38.42	$3.71	6.04%	0.61%
				A	**10.365** (Decrease)	**38.420** (Decrease)	**$3.71** (Decrease)	**6.04%**	**0.61%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.2-4: Subsystem Mass-Reduction and Cost Impact for Engine Downsize

The 2.4L engine mass was taken from a 2003 Avensis teardown performed by A2MAC1. The 2.7L engine subsystems were matched up with subsystems included in the 2.4L teardown resulting in a 12 kg savings.

New technology mass for the same subsystems was also totaled and compared to the base Venza. The ratio of new technology mass and base technology mass was used to scale down the mass savings for downsizing (**Table F.2-5**). This eliminates duplication of mass savings from further analysis using the 2.7L components as the baseline. The mass savings credited to downsizing was 10.4 kg.

MASS REDUCTION - 2010 VENZA VS. 2003 AVENSIS (A2MAC1)	
2.7L Venza Base Mass *Select Systems* (kg)	129.482
2.4L Avensis Mass *Select Systems* (kg)	117.490
Total Engine Mass Savings 2.7L - 2.4L (kg)	11.992
Venza New Tech Mass *Select Systems* (kg)	111.914
Venza New Tech/Base *Select Systems* (kg)	86.4%
Mass Savings Toyota 2.7L - 2.4L (KG)	**10.365**

Table F.2-5 Engine Downsize Mass Savings Lightweighted

For the sub-systems included in the engine downsize (i.e., engine mounts, pistons, block, head, etc.) the 2.4L mass is 92% of the base Venza mass (**Table F.2-6**). The 2.7L material content for these subsystems was estimated using surrogate cost data.

The mass reduction factor applied to the 2.7L material cost was used to estimate the 2.4L material cost. The difference in material costs results in a $38.42 engine downsize savings. It is assumed that labor and manufacturing burden costs are equal between the 2.7L and 2.4L engines.

ENGINE COST - SAVINGS BASED ON 2.4L TOYOTA REPLACEMENT (HISTORICAL EST)			
2.4L Mass/Base Mass (Downsize Related)		92.0%	
2.7L Cost Estimate (Material Only)	**$**	**480.00**	Material Cost for displacement effected components only (block, crank, pistons, head,..)
2.4L Cost Estimate (Material Only)	**$**	**441.58**	Material Cost for displacement effected components only (block, crank, pistons, head,..)
2.7L - 2.4L Cost Reduction (OEM)	**$**	**38.42**	

Table F.2-6: Engine Downsize Cost Savings

F.2.2 Engine Frames, Mounting, and Brackets Subsystem

F.2.2.1 Subsystem Content Overview

As seen in **Table F.2-7**, the most significant contributor to Engine Frames, Mounting, and Brackets subsystem mass is the Engine Mountings. This subsystem comprises 8.9% of the Engine mass. The Power Train Dampening Element supports the rear of the engine and was categorized with various bolts and fasteners as miscellaneous.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
01	**02**	**00**	**Engine Frames, Mounting, and Brackets Subsystem**	
01	02	01	Engine Frames	0.000
01	02	02	Engine Mountings	12.387
01	02	10	Hanging Eyes	0.000
01	02	99	Misc.	2.887
			Total Subsystem Mass =	**15.274**
			Total System Mass =	**172.598**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**8.85%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.89%**

Table F.2-7: Mass Breakdown by Sub-subsystem for Engine Frames, Mounting, and Brackets Subsystem

F.2.2.2 Toyota Venza Baseline Subsystem Technology

As pictured in **Image F.2-3**, the Venza engine is secured in the vehicle with 3 engine mounts, a Torsion Strut, and Powertrain Dampening Element. Engine mounts (**Image F.2-4**) are constructed from stamped steel weldment with a isolated stud as an attachment point to the engine mounting bracket. The engine mounting brackets are cast iron construction. The engine mount and bracket serve as the link between the engine and vehicle subframe.

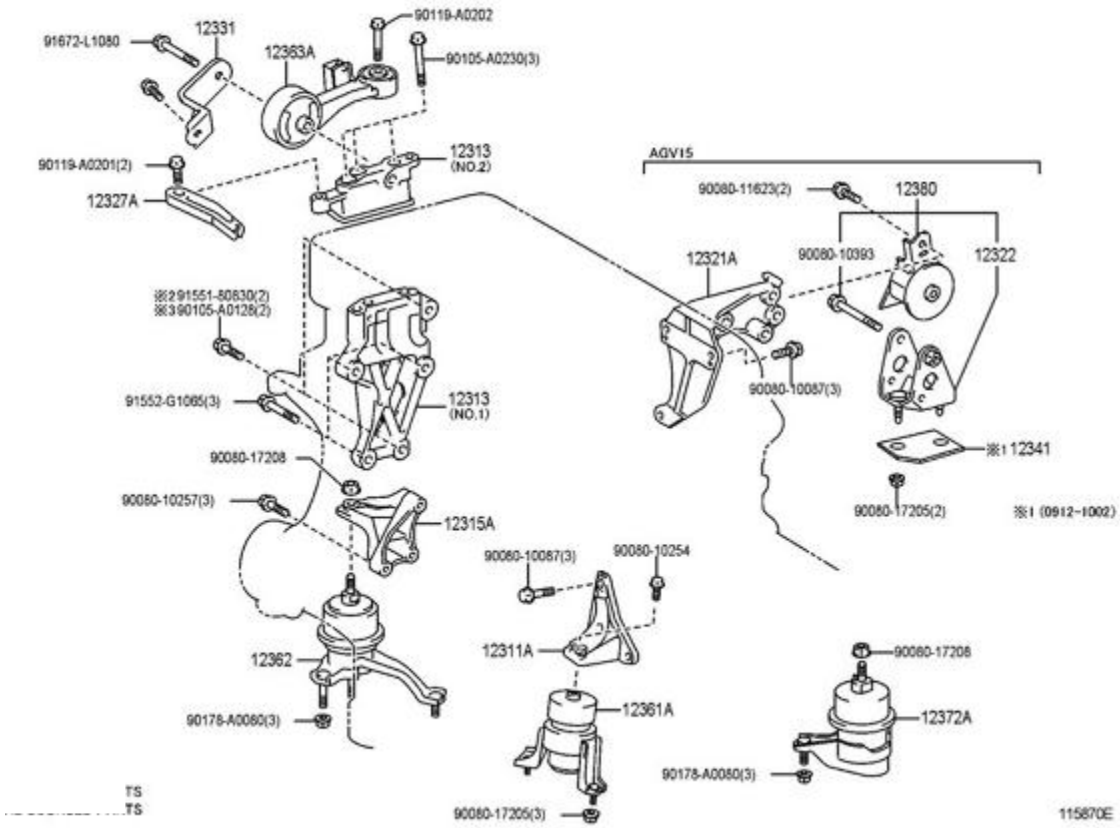


Image F.2-4: Venza Engine Mount Diagram

(Source: www.villagetoyotaparts.com)

Image F.2-5: Venza Engine Mount (Stamped Steel Weldment)

(Source: autopartsnetwork.com)

F.2.2.3 Mass-Reduction Industry Trends

Lightweighting trends for engine mounts include the use of plastic for components traditionally made from metal. Plastic polymer (Polyamide) torque dampeners are current production on Opel and Astra/Insignia (**Image F.2-6**). Polyamide is being tested as a lightweight material for engine mounts (**Image F.2-7**).

Image F.2-6:
Polyamide Torque Dampener

Image F.2-7:
Polyamide Engine Mount

Source: www.contitech.de/pages/produkte/schwingungstechnik/motorlagerung/motorlagerkomponenten_en.html

F.2.2.4 Summary of Mass-Reduction Concepts Considered

Table F.2-8 lists the mass reduction ideas considered for the Engine Frames, Mounting, and Brackets Subsystem. Engine Mount scale down was included in the Engine downsizing calculation and therefore was not credited in this subsystem. Other ideas included material changes for the Engine Mounting Bracket and Torsion Strut Link. The Top Engine Mount Bracket PN12313 shown in **Table F.2-8**, was already a two piece cast iron/Aluminum design and assumed to be partially cast iron for NVH not considered for lightweighting.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Engine Mountings	Scale down engine mounts based on reduced powertrain size and weight reduction	15% mass reduction	Some components may cross other product lines
Engine Mounting Bracket	Material change from steel to Aluminum	50% mass reduction	Increased NVH, FEA required for exact sizing
Torsion Strut Link	Material change from stamped steel to cast Al	50% mass reduction	Simplified processing
Engine Mountings	Polyamide Engine Mounts	50% mass reduction	

Table F.2-8: Summary of mass-reduction concepts considered for the Engine Frames, Mounting, and Brackets Subsystem

F.2.2.5 Selection of Mass Reduction Ideas

Table F.2-9 lists the mass reduction ideas applied to Engine Frames, Mounting, and Brackets subsystem. Polyamide was not selected for the torsion strut application because at the time of the initial investigation no production applications were known.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
01	**02**	**00**	**Engine Frames, Mounting, and Brackets Subsystem**	
01	02	01	Engine Frames	N/A
01	02	02	Engine Mountings	Steel to Aluminum Mounting Bracket & Link
01	02	10	Hangine Eyes	N/A
01	02	99	Misc.	N/A

Table F.2-9: Mass-Reduction Ideas Selected for Engine Frames, Mounting, and Brackets Subsystem.

Image F.2-8 shows the Torsion Strut Assembly as it is featured in the vehicle. **Image F.2-9** shows the Torsion Strut with the bushings removed and NVH pad removed. This stamped steel weldment was changed to die cast Aluminum and 25% volume added to compensate for differences in yield strength.

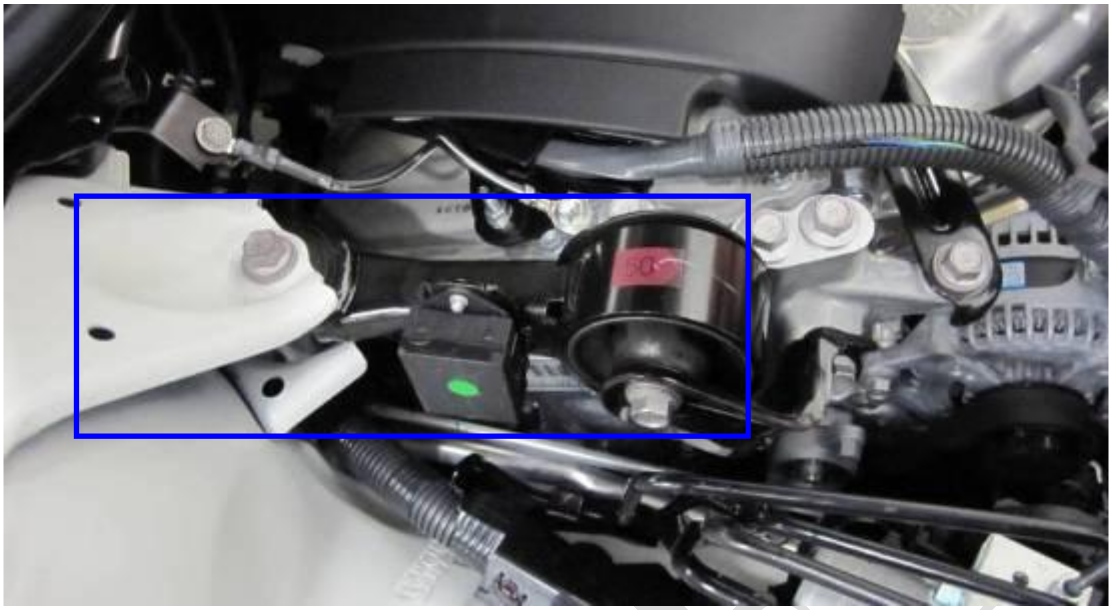


Image F.2-8 Torsion Strut Assembly

Image F.2-9: Torsion Strut Link **Image F.2-10: Lower Engine Mounting Bracket**

(Images F.2-8 – 10 Source: FEV, Inc. photos)

Image F.2-10 is a cast iron Engine Mounting Bracket changed to cast aluminum and 30% volume added for yield strength compensation.

Although not included in this analysis, additional lightweighting opportunity exists for engine mount material substitution. The stamped steel weldment (previous **Image F.2-5**) could be done in aluminum or plastic.

F.2.2.6 Mass-Reduction & Cost Impact

As shown in **Table F.2-10**, engine mountings material change from steel to aluminum results in a mass reduction and cost savings. The Torsion Strut Link was a 55% mass reduction or .355kg and saved $.25. The Lower Engine Mounting Bracket was a 55% mass reduction, or .723kg and saved $.54.

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea					
				Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
01	**02**	**00**	**Engine Frames, Mounting, and Brackets Subsystem**						
01	02	01	Engine Frames		0.000	$0.00	$0.00	0.00%	0.00%
01	02	02	Engine Mountings	A	1.114	$0.79	$0.71	8.99%	0.00%
01	02	03	Hangine Eyes		0.000	$0.00	$0.00	0.00%	0.00%
01	02	04	Misc.		0.000	$0.00	$0.00	0.00%	0.00%
				A	**1.114** (Decrease)	**0.788** (Decrease)	**$0.71** (Decrease)	**7.29%**	**0.07%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.2-10: Mass-Reduction and Cost Impact for Cylinder Head Subsystem

(See Appendix for Additional Cost Detail)

F.2.3 Crank Drive Subsystem

F.2.3.1 Subsystem Content Overview

As seen in **Table F.2-11**, the most significant contributor to the Crank Drive subsystem is the Crankshaft comprising 14.3% of the Engine Mass.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
01	**03**	**00**	**Crank Drive Subsystem**	
01	03	01	Crankshaft	18.185
01	03	02	Flywheel	2.177
01	03	03	Connect Rods (Assemblies: Connecting Rod, Connecting Rod Cap)	2.680
01	03	04	Pistons (Assemblies, Including Pistons, Ring Packs, Piston Pins, Circlips)	1.688
01	03	05	Drive for Accessory Drives (Down force, Flywheel side)	0.000
01	03	10	Drive for Timing Drive (Down force, Flywheel side)	0.000
01	03	15	Adaptors	0.000
01	03	99	Misc.	0.000
			Total Subsystem Mass =	**24.730**
			Total System Mass =	**172.598**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**14.33%**
			Subsystem Mass Contribution Relative to Vehicle =	**1.45%**

Table F.2-11: Mass Breakdown by Sub-subsystem for Crank Drive Subsystem

F.2.3.2 Toyota Venza Baseline Subsystem Technology

The Venza Crankshaft is a forged steel design with a pressed gear to drive the balance shafts and a pressed trigger wheel for crank speed monitoring. The connecting rods are hot forged with fully machined and doweled caps. System components are pictured in **Image F.2-11**.

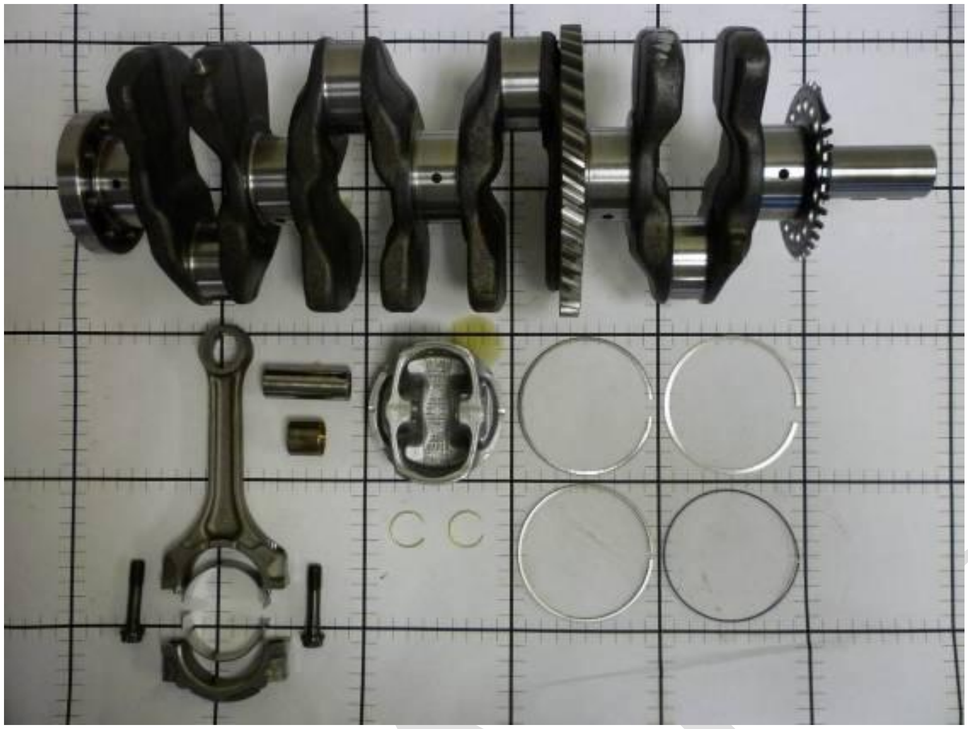


Image F.2-11: Key Components – Crank Drive

(Source: FEV, Inc. photo)

F.2.3.3 Mass-Reduction Industry Trends

Aluminum connecting rods (**Image F.2-12**) are popular in the racing industry and can be purchased from a variety of manufactures. They are typically machined from billet but forged are also available. While lighter aluminum rods contribute to better engine acceleration they have durability and packaging issues not suiting them for production use. Metal Matrix composite has been tested for racing applications and has potential to offset durability issues but at this point is unfeasible for mass production.[1]

Titanium connecting rods are used in racing and production applications. Honda used titanium connecting rods in the Acura NSX in 1990. Other production examples include Corvette (**Image F.2-12**) and the Porsche GT3. Although titanium connecting rods have superior performance at high rpm titanium's cost limits its use to high performance applications.

Image F.2-12
Aluminum Connecting Rod

(Source: www.extremepsi.com)

Image F.2-13:
Titanium Connecting Rod

(Source: http://www.citycratemotors.com)

F.2.3.4 Summary of Mass-Reduction Concepts Considered

Table F.2-12 lists the mass reduction ideas considered for the Crank Drive subsystem. Ideas considered include material substitutions for connecting rods and Flexplate. Aluminum Flexplates are available for aftermarket applications but the gear requires steel for strength and additional fasteners are required to join the Aluminum hub and gear offsetting mass savings and increasing cost. Lightening the connecting rods would likely lead to some savings in the crankshaft, however, quantifying the savings requires design work and was not considered. The Infinity 4.5L V8 has a forged crank with drilled connecting rod journals. This idea, not known during the Venza review, has lightweighting opportunity.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Connecting Rods	Change Material for Connecting Rods (Al/MMC)	30% mass reduction	No proven examples
Connecting Rods	Forged steel carburized connecting rods	25% mass reduction	Feasible Honda S2000 & 1.0L Insight
Crankshaft	process change forged steel to hollow cast iron	15% mass reduction	BMW 745i 4.4L V8 Cast with cored mains 18.8kg Infinity M45 4.5L V8 Forged with drilled conrod journals 23.2 kg
Crankshaft	reduced crankshaft weight due to lighter connecting rods	5% mass reduction	Difficult to quantify
Connecting Rods	split break	0% mass reduction	Cost save only; pair with mass reduction idea for reduced cost/kg
Drive Plate & Ring Gear	Aluminum Flexplate	0% mass reduction	Ring gear requires steel

Table F.2-12: Summary of Mass-Reduction Concepts Considered for the Crank Drive Subsystem

F.2.3.5 Selection of Mass Reduction Ideas

Table F.2-13 lists the mass reduction ideas applied to Crank Drive subsystem.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
01	**03**	**00**	**Crank Drive Subsystem**	
01	03	01	Crankshaft	N/A
01	03	02	Flywheel	N/A
01	03	03	Connect Rods (Assemblies: Connecting Rod, Connecting Rod Cap)	Design optimization and material change
01	03	04	Pistons (Assemblies, Including Pistons, Ring Packs, Piston Pins, Circlips)	Design optimization of pistons & wristpins
01	03	05	Drive for Accessory Drives (Down force, Flywheel side)	N/A
01	03	10	Drive for Timing Drive (Down force, Flywheel side)	N/A
01	03	15	Adaptors	N/A
01	03	99	Misc.	N/A

Table F.2-13: Mass-Reduction Ideas Selected for Crank Drive Subsystem

The connecting rod is one of most highly stressed components of the engine. Its optimization is a delicate balance between reducing rotating mass and catastrophic failure. Mahle, an automotive supplier of power cell units, performed an optimization on a 3.6L V6. The optimized rod design saved 27% mass and is currently in high volume production[1]. The Venza connecting rod, peak combustion pressure (surrogate estimate), and dimensional characteristics were provided to Mahle. After reviewing the connecting rod, the base design was found to be conservative. The base design was coplanar, meaning both the big and small end share the same width. The base Venza rod (**Image F.2-13**) is a plain carbon wrought forged design, requiring full machining and doweling of the cap connection (**Image F.2-14**). The Mahle redesign changes the material to 46MnVs4, providing maximum strength and crack break properties. Crack break eliminates the machining and doweling of the cap connection (**Image F.2-15**).

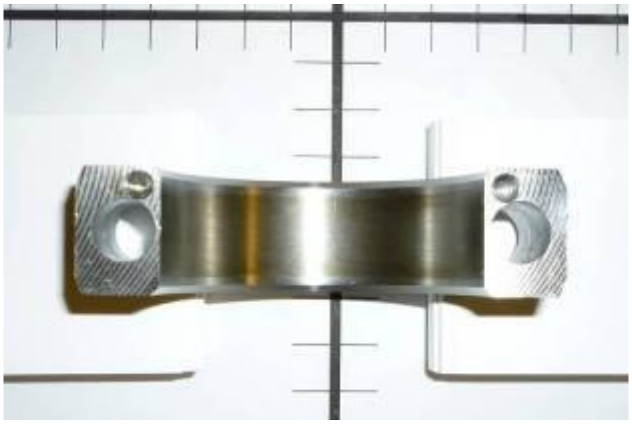


Image F.2-13:
Fully Machined & Doweled Rod Cap

(Source: FEV, Inc. photo)

Image F.2-14:
Crack Break Rod Cap

(Source: www.pirate4x4.com)

Image F.2-16 is a 3D rendering of the lightened Venza rod provided by Mahle. At the small end, the design is stepped, optimizing the pin-bore profile. The pin-bore features forged-in oil pockets (**Image F.2-17**) and eliminates the bushing. The shank cross-section shape was optimized for maximum strength. Mahle downsized the cap and fasteners to save additional weight. Improvements to the connecting rod extend to the wristpin and piston. The piston journals were brought in to meet the narrower small end of the rod which also shortened the wrist pin.

Image F.2-15:
Connecting Rod Assembly (Venza)

(Source: FEV, Inc. photo)

Image F.2-16:
Connecting Rod Assembly (Lightweighted)

(Source: Mahle Engineering)

Image F.2-17:
Forged In Oil Pockets (Lightweighted)

(Source: Mahle Engineering)

Table F.2-14 breaks down the mass savings by component. The Mahle redesign reduced the Connecting Rod Assembly by 23% and the engine mass by .688 kg. While the Mahle redesign impacts the overall vehicle weight, the most significant benefit is reduced friction and improved mechanical efficiency[2].

CONNECTING ROD & PISTON ASSEMBLY	***MAHLE* LIGHTWEIGHTED REDESIGN**			
	Reduction [%]	Base [g]	Mahle [g]	Save [g]
Connecting Rod (46MnVs4)	24%	411	311	100
Connecting Rod Cap (46MnVs4)	14%	155	134	21
Connecting Rod Bolts *Quantity x 2*	25%	64	48	16
ConnectIng Rod Bushing	100%	12	0	12
Piston: (Mahle EvoTec, M174+)	3.4%	298	288	10
Wrist Pin (16MnCr5)	12%	107	94	13
Connecting Rod Assembly	23%	642	493	149
Piston Assembly	6%	405	382	23
Engine *Quantity x 4*				**688**

Table F.2-14: Summary of Mahle Lightweighted PCU components

F.2.3.6 Mass-Reduction & Cost Impact

As shown in **Table F.2-15** Mass reductions for the Crank Drive subsystem save $10/kg. The cost savings for this subsystem is a result of processing savings utilizing split break connecting rod technology.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
01	**03**	**00**	**Crank Drive Subsystem**						
01	03	01	Crankshaft		0.000	$0.00	$0.00	0.00%	0.00%
01	03	02	Flywheel		0.000	$0.00	$0.00	0.00%	0.00%
01	03	03	Connect Rods (Assemblies: Connecting Rod, Connecting Rod Cap)	A	0.596	$6.51	$10.93	22.24%	0.03%
01	03	04	Pistons (Assemblies, Including Pistons, Ring Packs, Piston Pins, Circlips)	A	0.092	$0.36	$3.96	5.45%	0.01%
01	03	65	Drive for Accessory Drives (Down force, Flywheel side)		0.000	$0.00	$0.00	0.00%	0.00%
01	03	66	Drive for Timing Drive (Down force, Flywheel side)		0.000	$0.00	$0.00	0.00%	0.00%
01	03	67	Adaptors		0.000	$0.00	$0.00	0.00%	0.00%
01	03	99	Misc.		0.000	$0.00	$0.00	0.00%	0.00%
				A	**0.688** (Decrease)	**6.878** (Decrease)	**$10.00** (Decrease)	**2.78%**	**0.04%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.2-15: Mass-Reduction and Cost Impact for Crank Drive Subsystem

(See Appendix for Additional Cost Detail)

F.2.4 Counter Balance Subsystem

F.2.4.1 Subsystem Content Overview

Table F.2-16 summarizes the mass contributions for the Counter Balance subsystem. The balance shafts make up the Dynamic Parts sub-subsystem and are the largest contributors to the subsystem.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
01	**04**	**00**	**Counter Balance Subsystem**	
01	04	01	Dynamic Parts	2.583
01	04	02	Static Parts	2.494
01	04	03	Drives	0.000
01	04	99	Misc.	2.141
			Total Subsystem Mass =	**7.218**
			Total System Mass =	**172.598**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**4.18%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.42%**

Figure 5.1-16: Mass Breakdown by Sub-subsystem for Counter Balance Subsystem.

F.2.4.2 Toyota Venza Baseline Subsystem Technology

Common on larger displacement 4-cylinder engines, the 2.7L Venza uses a balance shaft assembly (**Image F.2-18**) to counter vibrations from reciprocating piston mass. The assembly consists of two rotating shafts with offset weights and is housed underneath the crankshaft. A gear on the crankshaft drives the long balance shaft which in turn drives the short balance shaft. A set of oil ported journal bearings were used to support each balance shaft.

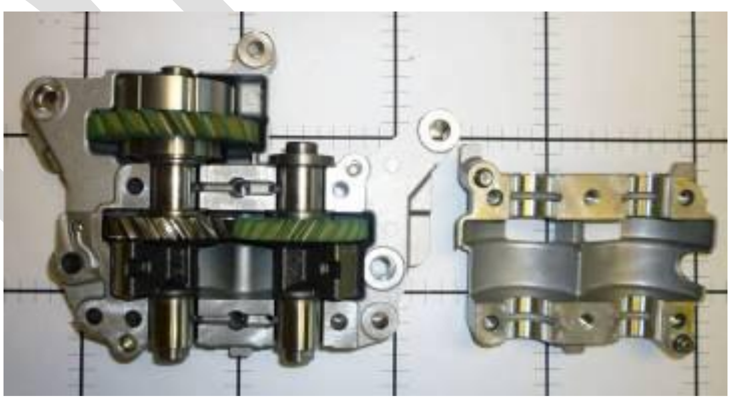


Image F.2-18: Venza Balance Shaft Assembly

(Source: FEV, Inc. photo)

F.2.4.3 Mass-Reduction Industry Trends

Lightweighting trends for balance shafts include the use of nylon drive gears and roller bearings. Development is being done using two mating nylon gears that would further reduce weight and cost.

F.2.4.4 Summary of Mass-Reduction Concepts Considered

Table F.2-17 summarizes ideas considered for balance shaft lighweighting.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Balance Shaft Assembly	roller bearing supports enable weight optimized layout for balancer shafts	10% mass reduction	Reduced system friction
Balance Shaft Drive Gear	Nylon instead of Steel	80% mass reduction	Durability concern, no proven examples at this time

Table F.2-17 Summary of Mass-Reduction Concepts Considered for the Crank Drive Subsystem

Schaeffler AG, winner of the 2011 Pace Awards, was recognized for applying roller bearings to the balance shaft in automotive applications (**Image F.2-19**). Roller bearings require less contact area than the journal bearings used on Venza, allowing for balance shaft mass reductions. Schaeffler's review of the 2.7L balance shaft assembly determined a maximum of .4 kg could be removed from the balance shafts. Replacing the journal bearings with roller bearings would add .330 kg resulting in a system savings of .070 kg. Due to marginal mass savings this idea was not applied.

Roller bearings applied to balance shafts reduce friction by 50% and in production applications have saved 1.5 kW of power. Roller bearings do not require pressurized engine cooling and eliminate the need for oil galleries.

Using nylon for all balance shaft drive gears has potential to save additional weight, but no successful testing or applications have proven an all nylon drive feasible at this time.

Image F.2-19: Schaeffler's Low Friction Roller Bearing Balance Shaft

F.2.4.5 Selection of Mass Reduction Ideas

Downsizing the balance shaft assembly to coincide with the downsized 2.4L engine was selected for the Counter Balance Subsystem.

F.2.4.6 Mass-Reduction & Cost Impact

Mass reduction and cost impact for Counter Balance Subsystem is captured in the engine downsize calculation

F.2.5 Cylinder Block Subsystem

F.2.5.1 Subsystem Content Overview

As seen in **Table F.2-18**, the most significant mass contributor to Cylinder Block subsystem is the cylinder block itself making up two-thirds of the subsystem mass. The Crank Case Adapter makes up 20% of the subsystem mass.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
01	**05**	**00**	**Cylinder Block Subsystem**	
01	05	01	Cylinder Block	19.955
01	05	02	Crankshaft Bearing Caps	3.640
01	05	03	Bedplates	0.000
01	05	04	Piston Cooling	0.138
01	05	65	Crankcase Adaptor	6.172
01	05	66	Water Jacket	0.190
01	05	67	Clinder Barrel	0.000
01	05	99	Misc.	0.040
			Total Subsystem Mass =	**30.135**
			Total System Mass =	**172.598**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**17.46%**
			Subsystem Mass Contribution Relative to Vehicle =	**1.76%**

Table F.2-18: Mass Breakdown by Sub-subsystem for Cylinder Block Subsystem

F.2.5.2 Toyota Venza Baseline Subsystem Technology

The Toyota 2.7L cylinder block assembly incorporates lightweight technology (**Image F.2-20**). The cylinder block is made from lightweight, low-cost die cast aluminum with thin 2.5mm cylinder liners, further reducing weight. The crank case is ladder style with cast iron bearing caps. The Crankcase Adaptor is die cast aluminum, providing added strength to the engine block and integrates the oil filter. The crank case is ladder style with cast iron bearing caps. Oil jets, bolted to the block, provide bottom side piston cooling. A water jacket insert directs coolant flow where it is needed most, evening block operating temperatures.

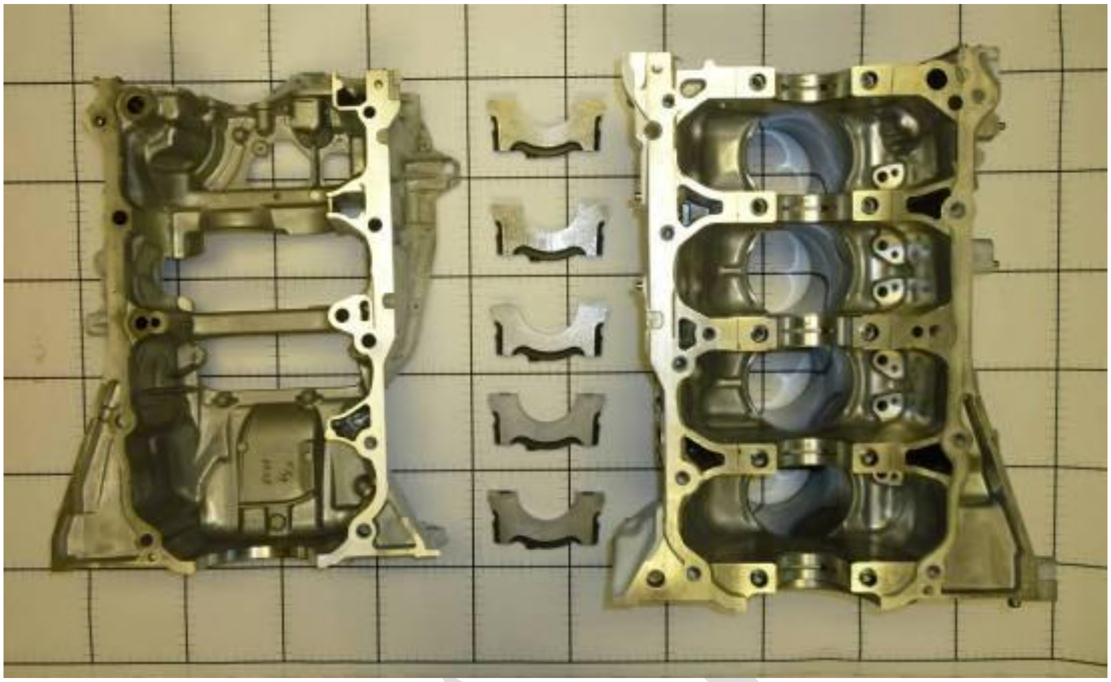


Image F.2-20: Key Components – Cylinder Block Subsystem

F.2.5.3 Mass-Reduction Industry Trends

Grey cast iron is still a popular choice for engine blocks. Among the advantages are strength, wear performance, corrosion resistance, castability, NVH & cost. Compacted Graphite Iron GCI is increasing in popularity for its improved strength over grey cast iron, permitting thinner cross sections and weight reductions over conventional grey cast.[3] GCI is mostly used in European diesel engine applications. Over the past decade, the weight advantage of aluminum has fostered its growth as a material choice for engine blocks and now makes up 60% of engine blocks in production. Under consumer pressure for better fuel economy automakers are now turning their attention to the even lighter magnesium alloys for engine block applications.

Volkswagen has used magnesium cylinders in its 4-cylinder air-cooled boxer engine used in the Beatle and other vehicles for decades. BMW has taken the lead in Magnesium alloy engine block applications. BMW's Z4 Roadster debuted in 2004 as the lightest 3.0 L inline six-cylinder gas engine in the world, made possible by the composite magnesium-aluminum alloy engine. The engines success lead to its implementation in subsequent BMW models exceeding over 300,000 units in 2006[4].

In 2010 a joint effort by GM, Ford, and Chrysler concluded through extensive testing magnesium was a feasible engine block material as tested on the Ford Duratech 2.5L V6.

Changes for successful implementation include ethylene glycol coolant with magnesium protective additives and a new head gasket design to accommodate the aluminum head to Magnesium block interface. Iron bulkheads were also required for added strength and further bulk head development is required to prevent failures. The engine block mass was reduced by 25% without any significant compromises to performance[5].

F.2.5.4 Summary of Mass-Reduction Concepts Considered

Table F.2-19 lists the mass reduction ideas considered for the cylinder block subsystem.

Due to a majority mass contribution, cylinder block was the focus of this subsystem. Carbon fiber was reviewed as a lightweight material for the cylinder block. Composite Castings LLC has a patent-pending molding process used to produce carbon fiber engine blocks for the racing industry. The engine blocks are 45-50% lighter than a comparable aluminum block. Due to extreme cost and only one successful application, carbon fiber is not feasible for lightweighting the engine block. Magnesium, known for its superior specific strength, does have a high-volume production example and presents good opportunity for mass reduction. The main journal caps are constructed from cast iron and are a potential candidate for Metal Matrix Composite but no production examples or testing were identified and therefore questionable technology for the 2017 timeframe.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Cylinder Block	Carbon fiber composite engine block	75% mass reduction	Durability concern, unrealistic cost
Cylinder Block	Aluminum to Magnesium	25% mass reduction	Improved NVH
Main Journal Caps	Cast Iron to Aluminum MMC	50% mass reduction	No proven examples or successful testing at this time
Cylinder Oil Tubes	press in rather than bolt on	50% mass reduction	Reduced oil coverage
Cylinder Block Liner	Plasma sprayed cylinder bores	80% mass reduction	
Crankcase Adapter	Aluminum to Magnesium	65% mass reduction	Reduced elastic modulus & creep resistance

Table F.2-19: Summary of Mass-Reduction Concepts Considered for the Crank Drive Subsystem

Highlighted in an April 2005 edition of MTZ was work performed by Audi on development of a magnesium engine block (**Image F.2-21**). The object of the study was to design, build and test a 1.8L turbo diesel engine with aluminum inserted (**Image F.2-**

22) magnesium engine block. The publication details the many different factors considered in the use of magnesium applied to an engine block. The prototype passed teardown inspection and demonstrated outstanding dampening properties. The magnesium engine weighed 23kg less than its cast iron counterpart and proved a high-strength, closed-deck design can be manufactured from pressure die casting.

Image F.2-21: Audi Lightweight Magnesium Hybrid Engine

(*Source: MOTORTECHNISCHE ZEITSCHRIFT April 2005)*

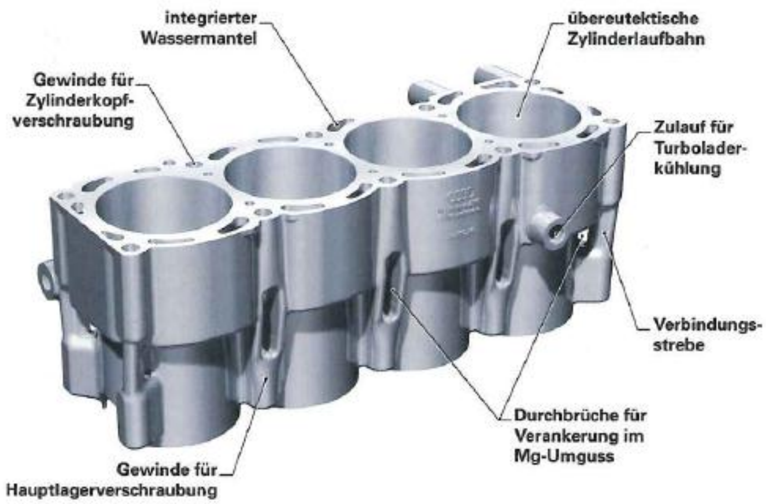


Bild 1: Closed-deck Aluminium-Zylindereinsatz (AlSi17Cu4)
Figure 1: Closed-deck aluminium cylinder insert (AlSi17Cu4)

Image F.2-22 AlSi17Cu4 Gravity Die Casting

(.Source: MOTORTECHNISCHE ZEITSCHRIFT April 2005)

F.2.5.5 Selection of Mass Reduction Ideas

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
01	**05**	**00**	**Cylinder Block Subsystem**	
01	05	01	Cylinder Block	Cylinder Block - Aluminum to Mg/Al hybrid. Cylinder Liner - cast steel to plasma wire arc
01	05	02	Crankshaft Bearing Caps	N/A
01	05	03	Bedplates	N/A
01	05	04	Piston Cooling	Oil Nozzles - bolt on to through bulk head
01	05	65	Crankcase Adaptor	Stiffening Crankcase Housing - Al to Mg
01	05	66	Water Jacket	N/A
01	05	67	Clinder Barrel	N/A
01	05	99	Misc.	N/A

Table F.2-20: Mass-Reduction Ideas Selected for Cylinder Block Subsystem Analysis

F.2.5.5.1 Cylinder Block

Aluminum inserted Magnesium was selected as a replacement to the all Aluminum 2.7L engine block. Like BMW's 3.0L N52 (**Image F.2-23**), a cylinder insert including cooling duct (**Image F.2-24**) is die cast from Aluminum Silicon Alloy (**Image F.2-25**). This Aluminum insert strengthens the critical cylinder bore and bulk head structure while providing a coolant compatible interface. No coolant ever contacts the Magnesium. The insert is then coated with AlSi12 for adhesion and preheated before being inserted into the block die casting tool. The magnesium die casting machine is similar to an Aluminum die casting machine but material conveyance requires a gas cover to prevent contact between molten magnesium alloy and the atmosphere. Magnesium Alloy AJ62 is injected around the Aluminum insert and bonds within 20 seconds then removed and degated (**Image F.2-26**). Components are attached to the Magnesium block with Aluminum fasteners to prevent corrosion from dissimilar metals. High stress fasteners like the cylinder head and crankshaft caps are bolted into the Aluminum insert. Magnesium also requires a specialized rubber coated head gasket to prevent electrochemical corrosion between the sheet steel gasket and magnesium. Magnesium and its alloys are typically treated in aqueous passivating electrolytes to prevent corrosion. All these factors were considered in the differential cost build up. Mass savings was calculated by applying similar water jacket dimensions used by BMW to the 2.7L 1AR-FE and calculating the volume. The remaining volume for the Base engine block was used to calculate the Magnesium content.

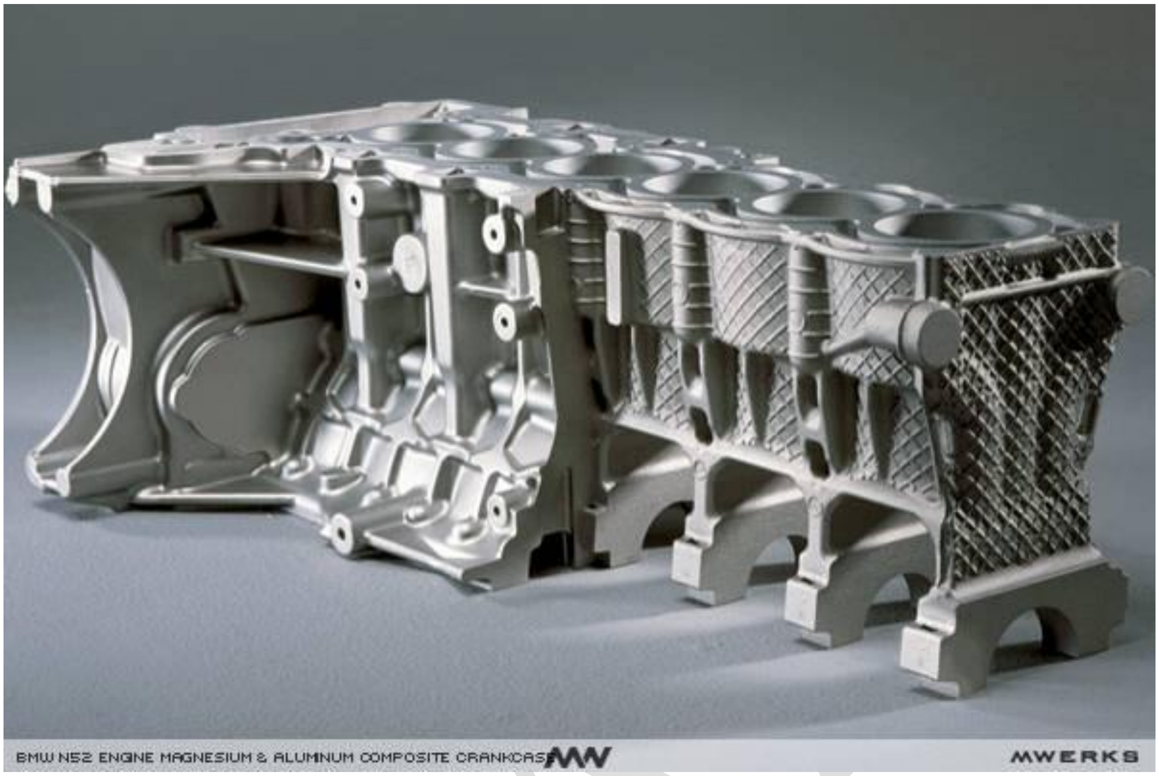


Image F.2-23: BMW N52 Magnesium Aluminum Hybrid Engine Block

(Source: http://www.mwerks.com/artman/publish/features/printer_960.shtml)

Image F.2-24: Aluminum Cylinder Insert with Integrated Water Jacket and Bulkheads

(Source: http://blog.naver.com/PostView.nhn?blogId=zhravlik27&logNo=30080774016)

Image F.2-25: Die Casting - Aluminum Cylinder Insert

Source: http://www.7-forum.com/news/news2004/6zyl/bmw_6zylinder_ottomotor4.php

Image F.2-26: Die Casting - Aluminum Cylinder Insert

(Source: http://blog.naver.com/PostView.nhn?blogId=zhravlik27&logNo=30080774016)

F.2.5.5.2 Cylinder Liner

Toyota's 2.7L uses standard cast iron cylinder liners (**Image F.2-27**). These liners are inserted into the die casting mold prior to filling. Following casting the liners are machined to finish the cylinder bore. Plasma Transfer Wire Arc (PTWA) is a new method of forming an iron surface for the cylinder wall (**Image F.2-28**). The alternative process began development by Ford in the early 1990s and was first implemented on the 2008 Nissan GT-R and the 2011 Shelby Mustang GT500. With PTWA, the aluminum engine block is cast without liners and the aluminum bore is pre-machined to near net size. The bore is then cleaned and fluxed followed by a bonding coat. Low carbon steel wire is continuously fed into the nozzle apparatus and deposited on the cylinder wall. After machining the remaining plasma coating is .070 - .170 mm in thickness. This is roughly 10% of the cast liner thickness found on Toyota's 2.7L. This ultra-thin surface improves heat transfer between the combustion process and the aluminum block.[7] Although Ford has patented their PTWA process, plasma can be used to apply cylinder coatings in a variety of ways. BMW's new N20 engine block uses two iron wires in a similar process. Volkswagen has a cylinder coating process in which steel and Molybdenum powder are applied by a plasma jet. Production applications include Touareg, Lupo, & Van T5. High-Velocity Oxy-Fuel (HVOF) has also been used for the cylinder friction surfaces.

Image F.2-27: [Base Technology]
Cast Iron Cylinder Liners
Source: http://dwolsten.tripod.com/articles/jan96a.html

Image F.2-28: [New Technology]
Plasma Transfer Wire Arc (PTWA)
Source: http://www.greencarcongress.com/2009/05/ptwa-

F.2.5.5.3 Crankcase Adapter

The 2.7L 1AR-FE has cast iron main bearing caps housing the crankshaft. A Crankcase Adapter is used to stiffen the engine block and integrates the oil filter (**Image F.2-29**). BMW's N52 Engine uses a Magnesium Bedplate with integrated bearing caps bolted to the engine block, trapping the crankshaft (**Image F.2-30**). The 2.7L Crankcase Adapter was lightened by using a direct material replacement from Aluminum to Magnesium Alloy.

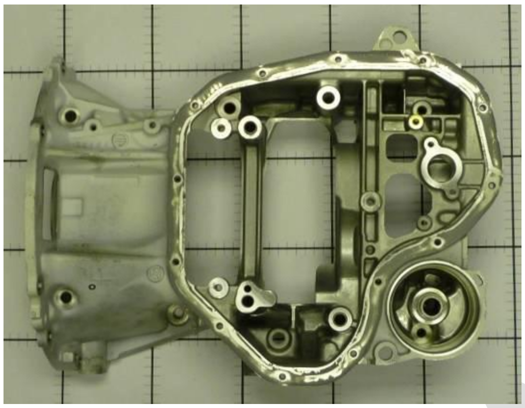


Image F.2-29: [Base Technology] Aluminum Crankcase Adapter

(Source: FEV, Inc. photo)

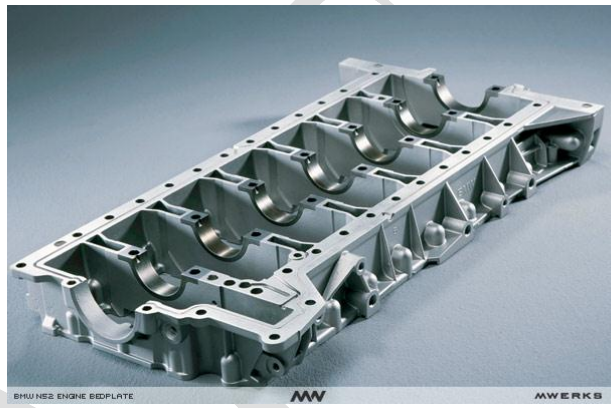


Image F.2-30: [New Technology] Magnesium Bedplate BMW N52

Source:http://www.mwerks.com/artman/publish/features/printer_960.shtml20090529.html

F.2.5.6 Mass-Reduction & Cost Impact

Cylinder Block subsystem results are listed in (**Table F.2-21**). The cylinder block represents the largest mass savings contribution to the engine system. The Magnesium outer block saves 3.3kg over the 2.7L's conventional cast aluminum design. PTWA cylinder liners saved 1.7 kg over cast iron. Substituting magnesium for aluminum in the crankcase adaptor saved 1.9 kg. While magnesium has a considerable weight advantage over aluminum, it comes at a significant cost, resulting in a high cost per kilogram value for the cylinder block subsystem.

System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
				Net Value of Mass Reduction Idea					
01	05	00	**Cylinder Block Subsystem**						
01	05	01	Cylinder Block	D	5.058	-$20.55	-$4.06	25.34%	0.30%
01	05	02	Crankshaft Bearing Caps		0.000	$0.00	$0.00	0.00%	0.00%
01	05	03	Bedplates		0.000	$0.00	$0.00	0.00%	0.00%
01	05	04	Piston Cooling	A	0.124	$0.65	$5.20	89.86%	0.01%
01	05	65	Crankcase Adaptor	C	1.924	-$5.03	-$2.61	31.17%	0.11%
01	05	66	Water Jacket		0.000	$0.00	$0.00	0.00%	0.00%
01	05	67	Clinder Barrel		0.000	$0.00	$0.00	0.00%	0.00%
01	05	99	Misc.		0.000	$0.00	$0.00	0.00%	0.00%
				D	**7.106** (Decrease)	**-24.931** (Increase)	**-$3.51** (Increase)	**23.58%**	**0.42%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.2-21: Mass-Reduction and Cost Impact for Cylinder Block Subsystem

F.2.6 Cylinder Head Subsystem

F.2.6.1 Subsystem Content Overview

As seen in **Table F.2-22**, the most significant mass contributors to the Cylinder Head subsystem are the cylinder head, camshaft carrier and cylinder head cover.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
01	**06**	**00**	**Cylinder Head Subsystem**	
01	06	01	Cylinder Head	13.657
01	06	02	Valve, Guides, Valve Seats	0.000
01	06	03	Guides for Valvetrain	0.280
01	06	06	Camshaft Bearing Housing	1.288
01	06	07	Camshaft Speed Sensor	0.000
01	06	08	Camshaft Carrier	3.077
01	06	09	Other Parts for Cylinder Head	0.464
01	06	20	Cylinder Head Covers	2.349
01	06	99	Misc.	0.000
			Total Subsystem Mass =	**21.115**
			Total System Mass =	**172.598**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**12.23%**
			Subsystem Mass Contribution Relative to Vehicle =	**1.23%**

Table F.2-22: Mass Breakdown by Sub-subsystem for Cylinder Head Subsystem.

F.2.6.2 Toyota Venza Baseline Subsystem Technology

Image F.2-31 highlights the key Cylinder Head subsystem components. The 2.7L cylinder head is a machined aluminum sand casting with dual overhead camshafts housed in a die cast aluminum camshaft carrier. Five independent aluminum camshaft bearing caps trap the camshafts in the carrier. A specialized bearing housing includes integrated pluming for the Cam Phaser hydraulic circuit. The cylinder head cover is made from cast Magnesium and adjoins via an inlay rubber seal. Providing access to the cylinder head cooling cavity is a steel threaded plug.

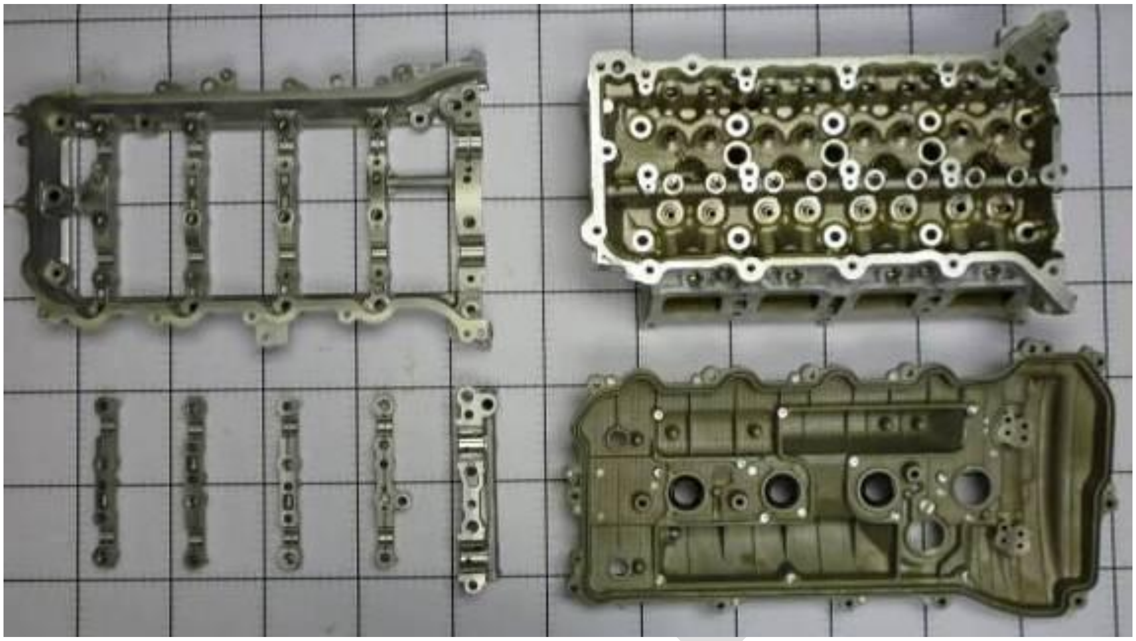


Image F.2-31: Key Components – Cylinder Head Subsystem

(Source: FEV, Inc. photo)

F.2.6.3 Mass-Reduction Industry Trends

Cylinder head industry trends for lightweighting have been limited to the use of aluminum. Magnesium alloy development for cylinder heads is ongoing and aims to resolve stiffness, creep, and corrosion issues. In 2008, the Changchun Institute of Applied Chemistry of CAS and FAW Group successfully developed a magnesium alloy cylinder head for heavy-duty truck. Over 15,000 cylinder heads have been produced from magnesium alloy for heavy-duty truck.[8] A popular choice for lightweight camshaft covers continues to be plastic as well as some use of magnesium.

F.2.6.4 Summary of Mass-Reduction Concepts Considered

As a top subsystem mass contributor, the cylinder head was a focus for mass reduction. Magnesium as a material replacement for aluminum was researched. A production example of a magnesium cylinder head was difficult to find and no passenger car applications were identified. The cam cover, a commonly plastic component, was quickly identified as an opportunity. Hydraulic cam phaser control circuitry through the cam cover was a point of concern for the composite replacement. The latest in valve spring technology offers reduced spring masses as well as reduced spring free lengths, enabling cylinder head height and mass reductions. **Table F.2-23** summarizes ideas considered for cylinder head subsystem.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Cam Cover	Material change from magnesium to composite	28% mass reduction	Cost effective, noise reducing
Cylinder Head Plug Large	Material change from steel to Aluminum	65% mass reduction	
Cylinder Head Plug Small	Material change from steel to Aluminum	65% mass reduction	
Cylinder Head Assembly	Reduced Height	7% mass reduction	Improved packaging
Cylinder Head	Material change from Aluminum to Magnesium	25% mass reduction	Additional cost, no applicable examples

Table F.2-23: Summary of mass-reduction concepts considered for the Cylinder Head Subsystem

F.2.6.5 Selection of Mass Reduction Ideas

Table F.2-24 outlines the mass reduction ideas selected for the Cylinder Head subsystem. As a result of valve spring lightweighting research, an opportunity to save mass on the cylinder head was identified. Optimizing the valve spring includes a shortening of the valve spring free length and creates opportunity to reduce cylinder head height. Although a reduction was assumed feasible and credited as a mass save, design work is required to validate this as an option.

System	Subsystem	Sub-Subsystem	Description	Mass-Reduction Ideas Selected for Detail Evaluation
01	**06**	**00**	**Cylinder Head Subsystem**	
01	06	01	Cylinder Head	Cylinder Head - reduced height for shorter spring
01	06	02	Valve, Guides, Valve Seats	N/A
01	06	03	Guides for Valvetrain	N/A
01	06	06	Camshaft Bearing Housing	N/A
01	06	07	Camshaft Speed Sensor	N/A
01	06	08	Camshaft Carrier	N/A
01	06	09	Other Parts for Cylinder Head	Cylinder Head Plug - Steel to Al
01	06	20	Cylinder Head Covers	Cylinder Head Cover - Mg to Plastic

Table F.2-24: Mass-Reduction Ideas Selected for Cylinder Head Subsystem

The Magnesium Cylinder head cover was changed to plastic as a weight save, cost save, and performance benefit (**Image F.2-32**). Production examples include Chrysler 4.7L V8 and Ford Zetec-R. A plastic cam cover as applied to Venza represents a new challenge due to hydraulic Cam Phaser solenoid actuation. Toyota integrated the valve mounting into the Cam Cover. Plastic may require integration of the solenoids into the Cam Carrier or Camshaft Bearing Cap.

Image F.2-32 Mahle Composite Cam Cover

(Source: www.mahle.com/MAHLE/en/Products/Air-Management-Systems/Engine-and-cylinder-head-covers)

The coolant cavity Access Plug **Images 5.1-33** and **34** was changed from steel to aluminum. Common with the cylinder head, Aluminum is expected to work well for this application. A waxed base polymer applied to the threads was selected to stabilize tightening torques. Aluminum fasteners, common in the Aerospace industry are also being used in automotive. KMAX, a supplier of Aluminum fasteners, was consulted in this application. Production examples include transfer case to transmission bolts on the F150, fasteners on the BMW NG6 engine, and oil pan fasteners used on ZF transmissions.

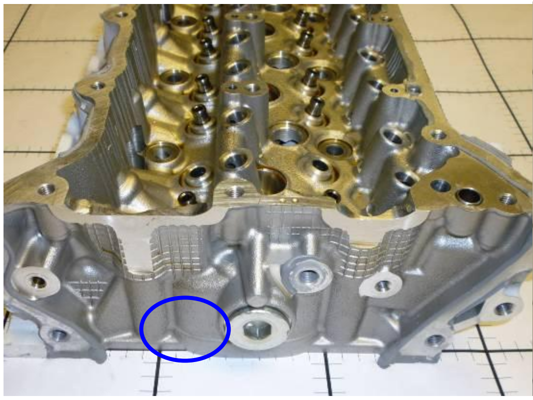


Image F.2-33: Access Plug – Cylinder Head **Image F.2-34: Access Plug – Cylinder Head**

(Source: FEV, Inc. photo)

F.2.6.6 Mass-Reduction & Cost Impact

Table F.2-25 summarizes lightweight activities applied to Cylinder Head subsystem. Among ideas selected, cylinder head height reduction yields the greatest mass savings for the cylinder head subsystem and represents a 7% cylinder head mass reduction. The cost savings of changing the cam cover material from magnesium to composite curbs the entire subsystem cost structure.

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
01	**06**	**00**	**Cylinder Head Subsystem**						
01	06	01	Cylinder Head	A	0.900	$3.49	$3.88	6.59%	0.05%
01	06	02	Valve, Guides, Valve Seats		0.000	$0.00	$0.00	0.00%	0.00%
01	06	03	Guides for Valvetrain		0.000	$0.00	$0.00	0.00%	0.00%
01	06	06	Camshaft Bearing Housing		0.000	$0.00	$0.00	0.00%	0.00%
01	06	07	Camshaft Speed Sensor		0.000	$0.00	$0.00	0.00%	0.00%
01	06	08	Camshaft Carrier		0.000	$0.00	$0.00	0.00%	0.00%
01	06	09	Other Parts for Cylinder Head	A	0.095	$0.00	$0.00	20.56%	0.01%
01	06	20	Cylinder Head Covers	A	0.052	$10.55	$204.24	2.20%	0.00%
01	06	99	Misc.		0.000	$0.00	$0.00	0.00%	0.00%
				A	**1.047** (Decrease)	**14.043** (Decrease)	**$13.41** (Decrease)	**4.96%**	**0.06%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.2-25: Mass-Reduction and Cost Impact for Cylinder Head Subsystem

(See Appendix for Additional Cost Detail)

F.2.7 Valvetrain Subsystem

F.2.7.1 Subsystem Content Overview

As seen in **Table F.2-26**, the most significant subsystem mass contributor is the camshafts. Second to the camshafts, the cam phasers make up a large portion of subsystem mass.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
01	**07**	**00**	**Valvetrain Subsystem**	
01	07	01	Inlet Valves	0.392
01	07	02	Outlet Valves	0.352
01	07	03	Valve Springs	0.544
01	07	04	Spring Retainers, Cotters, Spring Seats	0.160
01	07	05	Valve Actuation Elements: Rockers, Finger Followers, Hydraulic Lash Adjusters,…	1.008
01	07	06	Camshafts	4.898
01	07	08	Camshaft Phaser and/or Cam Sprockets	2.429
01	07	99	Misc.	0.000
			Total Subsystem Mass =	**9.783**
			Total System Mass =	**172.598**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**5.67%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.57%**

Table F.2-26: Mass Breakdown by Sub-subsystem for Valvetrain Subsystem.

F.2.7.2 Toyota Venza Baseline Subsystem Technology

2.7L Valvetrain Assembly can be seen in **Image F.2-35**. Venza baseline technology begins with solenoid actuated hydraulic cam phasers. These cam phasers independently vary the valve intake and exhaust timing events making this a Variable Valve Timing Engine. Toyota distinguishes this cam phaser design from their earlier tandem lobe concept by adding the character (i), meaning with intelligence (VVTi) engine. The cam phasers consist of three main components; the stator, rotor, and drive gear. These components are contructed from sintered iron. The cam phasers directly coupled to the camshafts, drive roller cam followers supported by hydraulic lash adjusters. The roller followers actuate the intake and exhaust valves (**Image F.2-35**). The camshafts on Venza are traditional solid cast design.

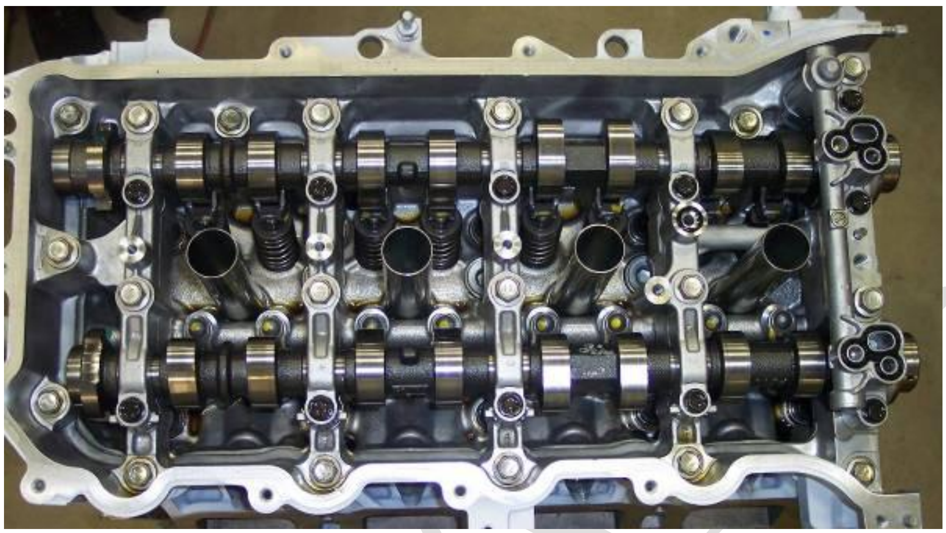


Image F.2-35: Valvetrain Assembly (Phasers removed)

(Source: FEV, Inc. photo)

F.2.7.3 Mass-Reduction Industry Trends

Hollow cast camshafts are a new lightweighting technology that can be found in the Chevy Cruze Ecotec 1.4L turbo. As part of this study a 1.4L camshaft was purchased and a sectioned (**Image F.2-36**). Analysis found that the cored cavity saved 21% mass over the same camshaft cast from solid.

Composite or tubular camshafts used in Europe, are made from tube stock. Cam lobes made from powder metal or forged steel are hydroformed in place. Composite camshafts offer weight savings of up to 50% over traditional solid cast.

Advances in valve spring technology have lead to many new design options, including symmetrical, asymmetrical coiling and tapered springs or beehive springs. All spring types can be made from wire with round or profiled cross sections. Advances in materials and processing techniques now permit lighter spring weights, smaller retaining diameters, and shorter free lengths.

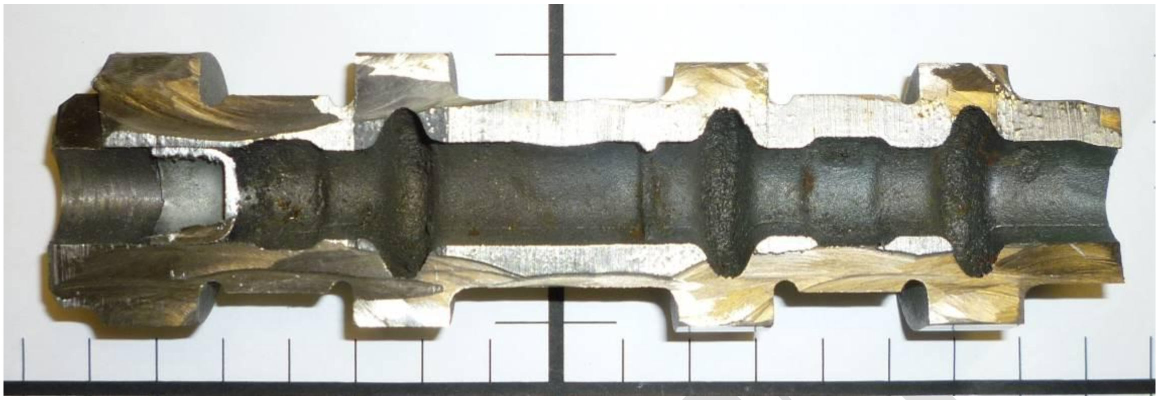


Image F.2-36: Hollow Cast Camshaft – 1.4L Ecotec

(Source: FEV, Inc. photo)

F.2.7.4 Summary of Mass-Reduction Concepts Considered

As seen in **Table F.2-27**, the camshaft, phaser assembly, valve spring, and valve were considered for mass reduction.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Camshaft	Solid cast to tubular composite	46% mass reduction	More expensive, current production examples
Intake Cam Phaser Assembly	Steel to powder metal	66% mass reduction	Current production examples
Exhaust Cam Phaser Assembly	Steel to powder metal	66% mass reduction	Current production examples
Valve Spring Keeper	Reduced size, paired with optimized valve spring	25% mass reduction	Reduced valvetrain inertia
Valve	Laser welded sheet steel	50% mass reduction	cost build-up not feasable for this project
Valve Spring	Design Optimization	26% mass reduction	Current production examples

Table F.2-27: Summary of Mass-Reduction Concepts Considered for Valvetrain

Mubea, a development leader in lightweight vehicle technology supplies composite camshafts to the European passenger car market (**Image F.2-37**). Mubea's process uses internal high pressure fluid to expand the camshaft tube inside servo positioned camshaft lobes. This assembly process opens the range of materials that can be considered for lobe design and concentrates the material to the critical cam lobe region.[9]

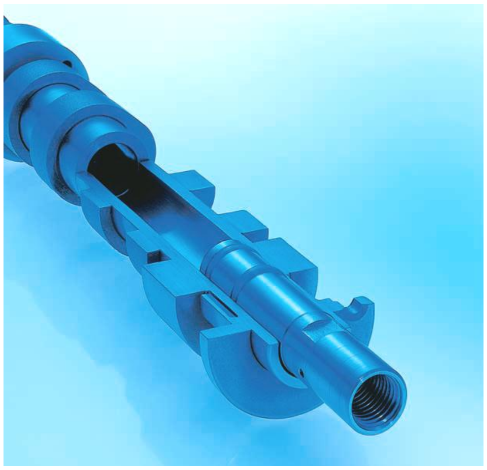


Image F.2-37: Hydroformed Camshaft

Source: http://www.mubea.com/english/

Image F.2-38: Mahle Sheet Steel Valve

Source: http://www.tokyo-motorshow.com/show/2007

The Cam Phaser assembly, made up of many subcomponents can be manufactured from powder metal Aluminum rather than sintered iron. SHW, 2010 award winner for excellence in powder metal, offers this technology in large scale production (700,000 units/year). In this application mass savings is complimented by a performance advantage of reducing valvetrain inertia.[10]

Mahle has developed a new lightweight engine valve with a welded structure made from cold formed steel sheet parts (**Image F.2-38**). The precision laser-welded joint and cold-formed features require no additional processing: only the functional areas are still ground. Sodium can be introduced to the hollow cavity of the exhaust valves reducing valve temperatures. Weight reductions of up to 50% are possible over conventional solid stem valves. Lighter valves enable lighter cam lobes, cam followers, tappets and valve springs.[11]

Mubea offers a lightweight optimized option for valve springs. Not only are the new technology springs lighter than conventional, but they are shorter as well, impacting mating components.

F.2.7.5 Selection of Mass Reduction Ideas

As seen in **Table F.2-28**, the camshaft, phaser assembly and valve springs were selected for mass reduction. Spring Retainers, Spring Seats, and Valve Actuation Elements were not investigated due to limited opportunity mass content.

System	Subsystem	Sub-Subsystem	Description	Mass-Reduction Ideas Selected for Detail Evaluation
01	**07**	**00**	**Valvetrain Subsystem**	
01	07	01	Inlet Valves	Shortened Valve post for shortened spring
01	07	02	Outlet Valves	Shortened Valve post for shortened spring
01	07	03	Valve Springs	Mass & free length reduction; optimized design
01	07	04	Spring Retainers, Cotters, Spring Seats	N/A
01	07	05	Valve Actuation Elements: Rockers, Finger Followers, Hydraulic Lash Adjusters,…	N/A
01	07	06	Camshafts	Solid cast to tubular hydroformed assembly
01	07	08	Camshaft Phaser and/or Cam Sprockets	replace steel components with cast Al
01	07	99	Misc.	N/A

Table F.2-28: Mass-Reduction Ideas Selected for Valvetrain Subsystem

Solid cast camshafts selected by Toyota (**Image F.2-39**) were replaced with Tubular composite camshafts (**Image F.2-40)**. Forged cam lobes hydroformed onto the tube make up the base assembly. Additional details are pressed onto the ends providing geometry for the cam phaser and timing sensor. Production applications for assembled hollow tube camshafts include Fiat 1.8L Diesel, Ford 4.6/5.0/5.4/6.2L V8, Chrysler 3.7L V6 and 8.4L V10.

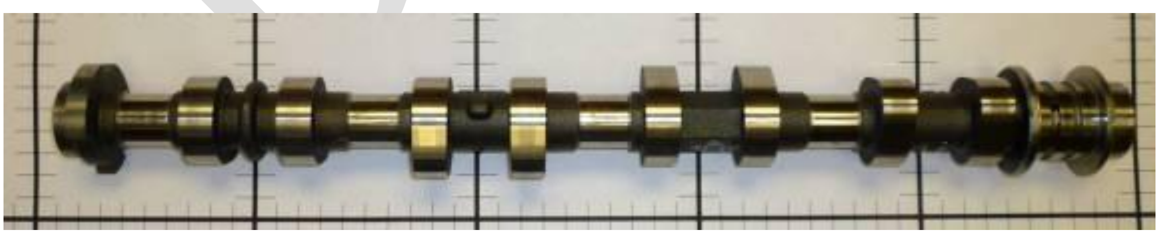


Image F.2-39: [Base Technology] Solid Cast Camshaft

(Source: FEV, Inc. photo)

Image F.2-40: [New Technology] Mubea Hydroformed Camshaft (Fiat 1.8L Diesel)

(Source: FEV, Inc. photo)

Sinter iron cam phasers used on base Venza were lightweighted to Aluminum. **Image F.2-41** shows the sintered iron cam phaser components selected by Toyota and components from a 2008 Mini Cooper. The stator is die cast aluminum and the rotor is sintered powder aluminum (**Image F.2-42**). SHW, located in Aalen-Wasseralfingen, Germany, offers a high silicon alloy Aluminum powder metal sprocket with wear properties sufficient for this roller chain application (**Image F.2-43**). SHW in conjunction with HILITE International, have produced Aluminum cam phaser assemblies, including aluminum sprockets for the BMW N52 & N55.

Image F.2-41: [Base Technology] Sintered Iron Cam Phaser Rotor, Stator, Sprocket

(Source: FEV, Inc. photo)

Image F.2-42: [New Technology]
PM Al Rotor, Die Cast Al Stator

(Source: FEV, Inc. photo)

Image F.2-43: [New Technology]
SHW PM Al Sprocket

(Source: FEV, Inc. photo)

The base valve spring used on Venza is a symmetrical cylinder design with round cross section **Image F.2-44**. Mubea offers an optimized version with two advancements that enable reduced spring length **Image F.2-45**. The Mubea spring features an ovate wire profile. As compared to conventional round, ovate wire reduces the solid height of the spring. The installed height can be reduced proportionally. In addition, Mubea’s spring undergoes a special hardening process after coiling. This optimizes the residual stress profile, resulting in the best possible material properties and enabling a reduced wire diameter. The smaller wire diameter reduces the solid height and resultant installed height. The shorter spring offers a packaging advantage for cylinder head designers that can lead to reductions in cylinder head size and valve length. Further refinements include a honeycomb style or tapered spring that can reduce the valve keeper size. Lighter valve trains mean reduced inertia, less friction, and improved efficiency.

Image F.2-44: [Base Technology] Valve Spring

(Source: FEV, Inc. photo)

Image F.2-45: [New Technology] Valve Spring

(Source: FEV, Inc. photo)

F.2.7.6 Mass-Reduction & Cost Impact

As seen in **Table F.2-29**, the camshaft offers the greatest opportunity for mass reduction. Additional processing associated with tubular camshafts result in higher costs. The optimized valve spring also comes at a cost increase. Valve spring optimization yields mass savings to the cylinder head and the valve itself. New technology applied to the Valvetrain subsystem results in a cost increase.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Estimated Mass Reduction "kg" (1)	Estimated Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
01	**07**	**00**	**Valvetain Subsystem**						
01	07	01	Inlet Valves	A	0.015	$0.17	$11.60	3.81%	0.00%
01	07	02	Outlet Valves	A	0.015	$0.17	$11.60	4.25%	0.00%
01	07	03	Valve Springs	X	0.154	-$1.06	-$6.92	28.24%	0.01%
01	07	04	Spring Retainers, Cotters, Spring Seats		0.000	$0.00	$0.00	0.00%	0.00%
01	07	05	Valve Actuation Elements: Rockers, Finger Followers, Hydraulic Lash Adjusters,…		0.000	$0.00	$0.00	0.00%	0.00%
01	07	06	Camshafts	D	2.133	-$9.25	-$4.34	43.55%	0.12%
01	07	08	Camshaft Phaser and/or Cam Sprockets	B	1.391	-$1.17	-$0.84	57.26%	0.08%
01	07	99	Misc.		0.000	$0.00	$0.00	0.00%	0.00%
				D	**3.707** (Decrease)	**-11.133** (Increase)	**-$3.00** (Increase)	**37.90%**	**0.22%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.2-29: Mass-Reduction and Cost Impact for Valvetrain Subsystem

(See Appendix for Additional Cost Detail)

F.2.8 Timing Drive Subsystem

F.2.8.1 Subsystem Content Overview

As seen in **Table F.2-30**, the most significant mass contributors to the Timing Drive subsystem are the Cover and Guides. Timing Sprockets and Chain make up the remainder of the weight.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
01	**08**	**00**	**Timing Drive Subsystem**	
01	08	01	Timing Wheels (Sprockets)	0.184
01	08	02	Tensioners	0.247
01	08	03	Guides	0.539
01	08	05	Belts, Chains	0.522
01	08	06	Covers	2.820
01	08	99	Misc.	0.000
			Total Subsystem Mass =	**4.312**
			Total System Mass =	**172.598**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**2.50%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.25%**

Table F.2-30: Mass Breakdown by Sub-subsystem for Timing Drive Subsystem.

F.2.8.2 Toyota Venza Baseline Subsystem Technology

Image F.2-46 shows the 2.7L timing drive. Toyoda used a timing chain to drive the valvetrain. A steel gear mounted to the crankshaft translates rotation to the overhead intake and exhaust camshaft sprockets. The action of the chain is contained by a fixed Guide, Vibration Dampener Guide, and Tensioning Guide.

Image F.2-46: Venza Timing Drive System

(Source: FEV, Inc. photo)

F.2.8.3 Mass-Reduction Industry Trends

Timing belts are commonly use in the industry due to cost and quietness of operation. Timing chains, although more durable (service life double that of a belt) began fading out in the 1980s. In recent years, OEMs have trended back due to advances in high-performance chains[12] (**Figure 5.1-1**).

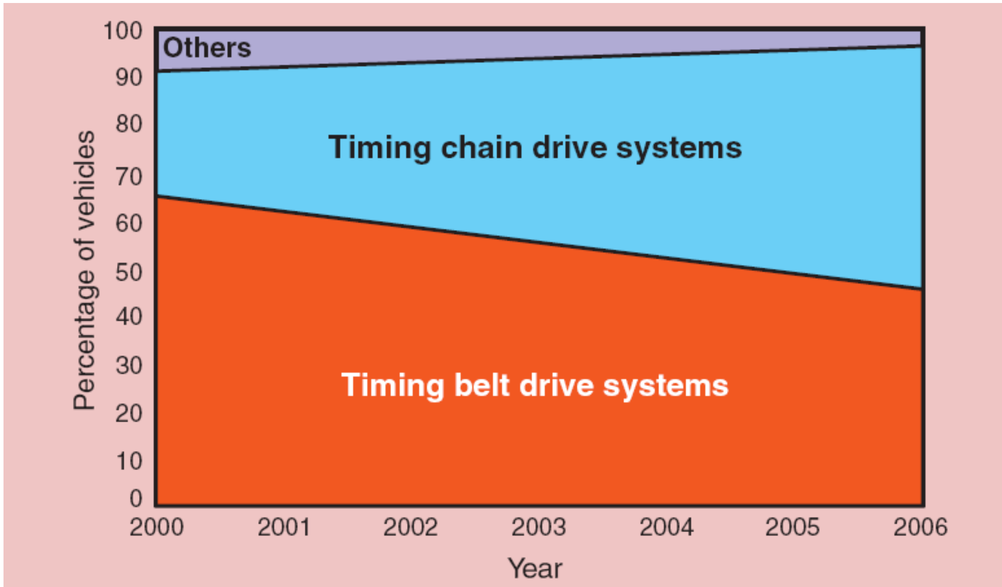


Figure 5.1-1: Industry Trend Timing Belt vs Chain Applications

(Source: http://www.ntn.co.jp/english/products/review/pdf/NTN_TR73_en_P110.pdf)

Front Covers or timing covers have trended to lightweight materials like Magnesium or plastic. Advances in plastic technology have improved thermal resistance and coolant compatibility. Magnesium, although more expensive, has the structural capability to support accessories and mountings. Plastic timing covers are common place on dry belt drive systems. Plastic timing covers on chain drive systems is a developing technology.

F.2.8.4 Summary of Mass-Reduction Concepts Considered

As seen in **Table F.2-31**, many of the timing drive components had opportunity for weight reductions. As largest mass contributor, the Front Cover was reviewed for alternate materials. Magnesium offers a weight advantage over the base aluminum cover, but at a higher cost and still higher weight than plastic. Plastic timing covers have been mass produced for decades on belt drive (dry) systems and offer a substantial weight savings.

The Timing Chain Tensioner Guide for the 2.7L is composed of aluminum. DSM offers production proven plastic solutions for this component saving weight and cost. The Crankshaft Timing Sprocket was reviewed for lightweighting. The loading of this sprocket is higher and it is smaller in diameter than the cam drive sprocket. For these reasons, this component was eliminated as an opportunity for lightweighting.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Front Cover	Material change from Aluminum to composite	34% mass reduction	Cost effective, noise reducing
Timing Chain Tensioner	Material change from Steel to Aluminum	61% mass reduction	Reduced durability
Timing Vibration Dampener	Steel reinforced to all composite	60% mass reduction	Packaging concern
Front Cover Plug	Material change from Steel to Aluminum	66% mass reduction	
Crankshaft Timing Sprocket	Material change from Steel to powder metal	30% mass reduction	Reduced durability
Timing Cover Plate	material change from Steel to Aluminum	66% mass reduction	
Timing Chain Guide	base bracket from steel to Al	66% mass reduction	

Table F.2-31: Summary of Mass-Reduction Concepts Initially Considered for Timing Drive Subsystem

F.2.8.5 Selection of Mass Reduction Ideas

As seen in **Table F.2-32**, the Chain Tensioner, Guide, and Front Cover were all selected for detailed evaluation. The timing chain was not selected due to durability concerns of timing belts, larger pulleys required, and the hydraulic cam phaser design requiring an oiled drive system.

System	Subsystem	Sub-Subsystem	Description	Mass-Reduction Ideas Selected for Detail Evaluation
01	**08**	**00**	**Timing Drive Subsystem**	
01	08	01	Timing Wheels (Sprockets)	N/A
01	08	02	Tensioners	Tensioner Housing - Cast Iron to Al
01	08	03	Guides	Timing Chain Tensioner Base - Al to Plastic
01	08	05	Belts, Chains	N/A
01	08	06	Covers	Front Cover - Al to Plastic. Timing Chain Cover Plate - Steel to Plastic Front Cover Tight Plug - Steel to Al
01	08	99	Misc.	N/A

Table F.2-32: Mass-Reduction Ideas Selected for Timing Drive Subsystem

The 2.7L Tensioning Guide has a nylon contact pad over top an Aluminum base (**Image F.2-47)**. DSM specializes in single piece and two piece plastic timing chain guides. Production examples include the 2007 Honda 1.8L and Chrysler TigerShark I4 (**Image F.2-48**). Stanyl was chosen for this engines timing and balancer drive system due to the hot temperature stiffness, fatigue, and overall efficiency benefit offered by Stanyl.

Image F.2-47
[Base Technology]
Timing Chain Tensioning Guide
(Source: FEV, Inc. photo)

Image F.2-48
[New Technology]
Timing Chain Tensioning Guide
(Source: DSM)

The Timing Chain Tesioner is a ratcheting spring plunger mechanism that applies pressure to the Tensioning Guide. On the Venza, the base construction of this tensioner is cast iron (**Image F.2-49**). Other applications including, 3.6L Pentastar are using aluminum housings (**Image F.2-50**).

Image F.2-49
[Base Technology]
Tensioner Housing – Cast Iron

(Source: FEV, Inc. photo)

Image F.2-50
[New Technology]
Tensioner Housing – Aluminum

(Source: FEV, Inc. photo)

The timing drive system cover, commonly referred to as the Front Cover is made from die cast aluminum (**Image F.2-51**). Mann+Hummel, located in Ludwigsburg, Germany, recently showcased a plastic concept integrating the engine bearing, oil filter and oil cooler (**Image F.2-52**). The Venza Front Cover integrates the oil pump presenting a challenge for plastic. This application was reviewed with DSM and was considered feasible for plastic. A molded insert is required for the oil pump case. Aluminum inserts would be used to support the mounting surface for the Torsion Strut Mounting Bracket and transfer load to the engine block.

Image F.2-51:
[Base Technology]
Front Cover

(Source: FEV, Inc. photo)

Figure 5.1-52
[New Technology]
Front Cover

(Source: http://www.plasticstoday.com/articles)

The Front Cover provides a window for tensioner access. A stamped steel plate was used as a cover. This cover was lightweighted to plastic and a rubber inlayed gasket used to improve sealing. A steel tight plug used for phaser access was changed to aluminum.

F.2.8.6 Mass-Reduction & Cost Impact

As seen in **Table F.2-33**, the Front Cover contributes the most mass savings for the Timing Drive subsystem. The size of this component best leverages the aluminum to plastic density advantage. The material cost per unit volume of plastic offsets other costs in this system resulting in an overall cost savings.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Estimated Mass Reduction "kg" (1)	Estimated Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
01	**08**	**00**	**Timing Drive Subsystem**						
01	08	01	Timing Wheels (Sprockets)		0.000	$0.00	$0.00	0.00%	0.00%
01	08	02	Tensioners	A	0.125	$0.50	$4.00	50.47%	0.01%
01	08	03	Guides	A	0.054	$0.04	$0.72	9.94%	0.00%
01	08	05	Belts, Chains		0.000	$0.00	$0.00	0.00%	0.00%
01	08	06	Covers	A	1.276	$4.25	$3.33	45.24%	0.07%
01	08	99	Misc.		0.000	$0.00	$0.00	0.00%	0.00%
				A	**1.454** (Decrease)	**4.792** (Decrease)	**$3.29** (Decrease)	**33.72%**	**0.08%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.2-33: Mass-Reduction and Cost Impact for Timing Drive Subsystem

(See Appendix for Additional Cost Detail)

F.2.9 Accessory Drive Subsystem

F.2.9.1 Subsystem Content Overview

The Accessory drive pulleys were paired with their associated assemblies and not included in this subsystem. The only components contained in this subsystem are the Accessory Drive Tensioner and Accessory Drive Belt **Table F.2-34**. The Accessory Drive

Tensioner uses lightweight aluminum for the tensioning mechanism and a plastic idler pulley. No lightweighting ideas were identified for this subsystem.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
01	**09**	**00**	**Accessory Drive Subsystem**	
01	09	01	Pulleys	0.000
01	09	02	Tensioners	0.440
01	09	03	Guides	0.000
01	09	05	Belts	0.114
01	09	99	Misc.	0.000
			Total Subsystem Mass =	**0.554**
			Total System Mass =	**172.598**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**0.32%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.03%**

Table 5.1-34: Mass Breakdown by Sub-subsystem for Accessory Drive Subsystem.

F.2.10 Air Intake Subsystem

F.2.10.1 Subsystem Content Overview

As shown in **Table F.2-35**, the leading mass contributor to the Air Intake Subsystem is the Intake Manifold followed by the Throttle Housing Assembly.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
01	**10**	**00**	**Air Intake Subsystem**	
01	10	01	Intake Manifold	7.122
01	10	02	Air Filter Box	1.517
01	10	03	Air Filters	0.181
01	10	04	Throttle Housing Assembly; including Supplies	3.089
01	10	05	Adapters: Flanges for Port Shut-off	0.000
01	10	99	Misc.	2.085
			Total Subsystem Mass =	**13.994**
			Total System Mass =	**172.598**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**8.11%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.82%**

Table F.2-35: Mass Breakdown by Sub-subsystem for Air Intake Subsystem.

F.2.10.2 Toyota Venza Baseline Subsystem Technology

The Air Intake Subsystem consists of a variety of components used to plumb air to the engine. **Image F.2-53** shows the base components used on Venza. The intake manifold is an all plastic vibration welded assembly. The manifold design features vacuum actuated dual runners for a broadened torque curve. A 65mm cast aluminum throttle body meters mass air flow through the intake. The air box and remaining components are injection molded plastic with exception to the EPDM Main Intake Hose. Blow-molded and injection-molded resonators are used, though, the system to muffle engine noise.

Image F.2-53: Air Intake Subsystem Components

(Source: FEV, Inc. photo)

F.2.10.3 Mass-Reduction Industry Trends

Industry trends for air intake lightweighting are focused on the intake manifold. This component, typically made from cast iron, then aluminum is now trending toward plastic. Plastic lends itself well to more complex and more efficient dual runner designs. Aftermarket suppliers offer carbon fiber Intake Tubes. Due to cost and resonator attachment points, carbon fiber was not considered.

F.2.10.4 Summary of Mass-Reduction Concepts Considered

As shown in **Table F.2-36**, plastic components were reviewed for MuCell lightweighting. The Intake Manifold weighing over 7kg was a target for lightweighting. MuCell was reviewed with Trexel and the highly engineered manifold was not a viable candidate. The Aluminum Throttle Body Housing was reviewed for a material change to plastic. The base Venza used fasteners to join the Upper and Lower Air Filter Box segments. Lightweight clips, found in other applications, simplify filter access and were considered for lightweighting.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Air Filter Box	MuCell	9% mass reduction	No thick mold flow sections
Throttle Body Housing	Aluminum to Plastic	40% mass reduction	Metal inserts required
Air Intake Ducting	MuCell	9% mass reduction	No thick mold flow sections
Air Filter Box Fasteners	Redesign for lightweight clips	75% mass reduction	Less expensive design

Table F.2-36: Summary of Mass-Reduction Concepts Initially Considered for Timing Drive Subsystem

F.2.10.5 Selection of Mass Reduction Ideas

Ideas selected to lightweight the Air Intake Subsystem are listed in **Table F.2-37**.

System	Subsystem	Sub-Subsystem	Description	Mass-Reduction Ideas Selected for Detail Evaluation
01	**10**	**00**	**Air Intake Subsystem**	
01	10	01	Intake Manifold	N/A
01	10	02	Air Filter Box	MuCell; redesign for clips, ellimnate bolts
01	10	03	Air Filters	N/A
01	10	04	Throttle Housing Assembly; including Supplies	Throttle Body Housing - Al to Plastic
01	10	05	Adapters: Flanges for Port Shut-off	N/A
01	10	99	Misc.	Air Intake Housing/Cover/Duct/Main Intake Hose - MuCell

Table F.2-37: Mass-Reduction Ideas Selected for Timing Drive Subsystem

The Venza Throttle Body Housing is die cast aluminum (**Image F.2-54**). Plastic applications are now emerging on vehicles like the Mini Cooper (**Image F.2-55**). Aluminum, although still considered lightweight, has nearly twice the density of its plastic counterpart.

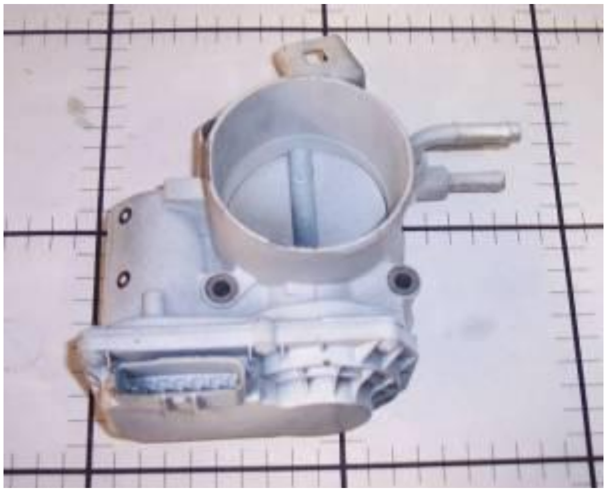


Image F.2-54: [Base Technology]
Throttle Body: Aluminum Housing

(Source: FEV, Inc. photo)

Image F.2-55: [New Technology]
Throttle Body: Plastic Housing

(Source: FEV, Inc. photo)

The fasteners and threaded inserts (**Image F.2-56**) used to joint the upper and lower Air Filter Box were replaced with light weight, low cost, quick clamps (**Image F.2-57**).

Image F.2-56: [Base Technology]
Air Filter Access Fasteners

(Source: FEV, Inc. photo)

Figure 5.1-57: [New Technology]
Air Filter Access Clamp

(Source: FEV, Inc. photo)

After Consulting Trexel, MuCell was applied to all applicable intake components (**Image F.2-58** through **Image F.2-63**). Due to the basic geometry of these components, material delivery webs could not be thinned and a 9% mass reduction was applied.

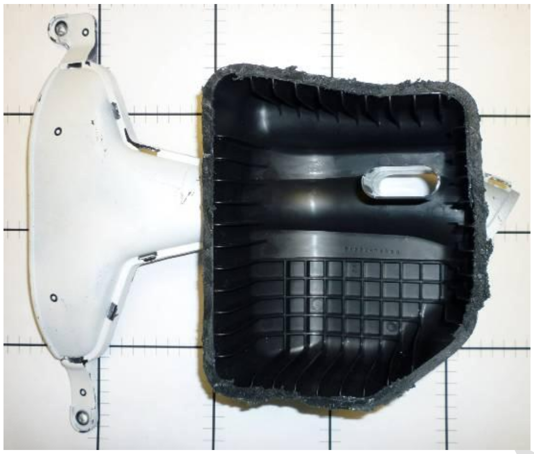


Image F.2-58: Air Intake Housing MuCell - 9% Mass Savings

Image F.2-59: Air Intake Cover MuCell – 9% Mass Savings

Image F.2-60: Air Intake Duct MuCell - 9% Mass Savings

Image F.2-61: Main Intake Hose MuCell - 9% Mass Savings

Image F.2-62: Air Box Upper

Image F.2-63: Air Box Lower

(Images 5.1-58 through 5.1-63 Source: FEV, Inc. photo)

F.2.10.6 Mass-Reduction & Cost Impact

Table F.2-38 shows the weight and cost savings for Air Intake Lightweighting. The Throttle Body cost savings by switching from aluminum to injection-molded plastic drives the $5.60/kg savings for this system.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Estimated Mass Reduction "kg" (1)	Estimated Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
01	**10**	**00**	**Air Intake Subsystem**						
01	10	01	Intake Manifold		0.000	$0.00	$0.00	0.00%	0.00%
01	10	02	Air Filter Box	A	0.144	$0.29	$2.04	9.48%	0.01%
01	10	03	Air Filters		0.000	$0.00	$0.00	0.00%	0.00%
01	10	04	Throttle Housing Assembly; including Supplies	A	0.245	$2.27	$9.29	7.92%	0.01%
01	10	05	Adapters: Flanges for Port Shut-off		0.000	$0.00	$0.00	0.00%	0.00%
01	10	99	Misc.	A	0.122	$0.29	$2.40	5.83%	0.01%
				A	**0.510** (Decrease)	**2.859** (Decrease)	**$5.60** (Decrease)	**3.65%**	**0.03%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.2-38: Mass-Reduction and Cost Impact for Air Intake Subsystem

F.2.11 Fuel Induction Subsystem

F.2.11.1 Subsystem Content Overview

Table F.2-39 details the mass breakdown for the Fuel Induction subsystem. The most significant subsystem mass contributor is the Fuel Rail. The Fuel Injection Pump and regulator were included in the Fuel system and therefore excluded from the Fuel Induction subsystem. At .5 kg, this subsystem has a minimum impact on the overall engine system mass.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
01	**11**	**00**	**Fuel Induction Subsystem**	
01	11	01	Fuel Rails	0.387
01	11	04	Fuel Injectors	0.152
01	11	06	Pressure Regulators	0.000
01	11	07	Fuel Injection Pumps	0.000
01	11	99	Misc.	0.000
			Total Subsystem Mass =	**0.539**
			Total System Mass =	**171.648**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**0.31%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.03%**

Table F.2-39: Mass Breakdown by Sub-subsystem for Fuel Induction Subsystem

F.2.11.2 Toyota Venza Baseline Subsystem Technology

The Venza Fuel Induction system consists of a fuel rail, pulsation damper, and fuel injectors (**Image F.2-64**). The fuel system is returnless, meaning the regulator is located in the fuel tank. A returnless system eliminates the need for a return fuel line and minimizes tank fuel temperature reducing evaporation. The pulsation dampener acts as an accumulator to steady the injector supply pressure in the wake of injection pulse events.

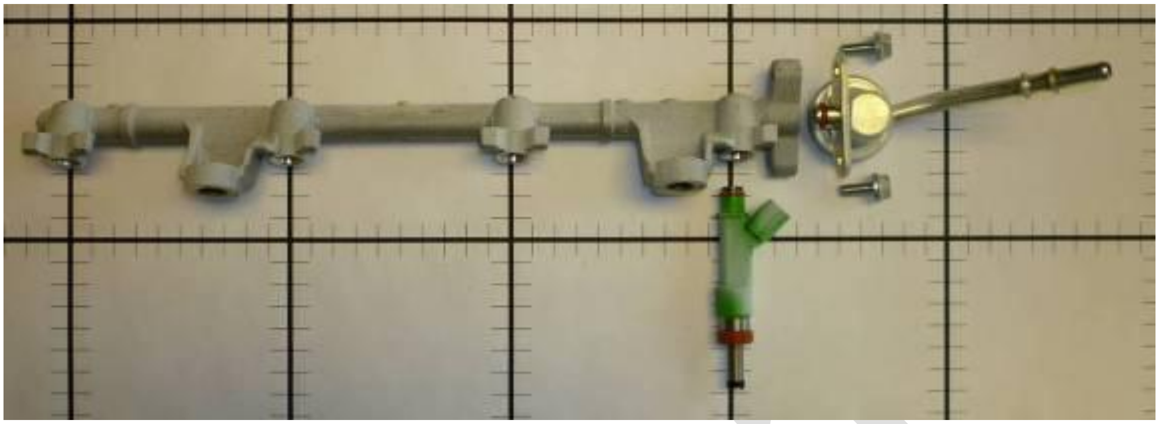


Image F.2-64: Fuel Induction Subsystem Components

(Source: FEV, Inc. photo)

F.2.11.3 Mass-Reduction Industry Trends

Fuel induction lightweighting trends include smaller more efficient fuel injectors and lightweight plastic fuel rails. Some plastic fuel rail designs integrate the pulsation dampener, eliminating mounting hardware and reducing cost (**Image F.2-65**).

Image F.2-65: Fuel Rail with Integrated Pulsation Dampener

(Source: FEV, Inc. photo)

F.2.11.4 Summary of Mass-Reduction Concepts Considered

As seen in **Table F.2-40,** concepts for Fuel Induction Lightweighting include a material change for the Fuel Rail and copper-clad aluminum wire for the Fuel Injector. Disassembly of the Fuel Injector revealed minimal copper content. In addition, to match current carrying capacity copper-clad aluminum wire must be 1.2 times larger in diameter, increasing package size. For these reasons the idea was not feasible.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Fuel Rail	aluminum to plastic	25% mass reduction	Reduced cost
Fuel Injector	Copper Clad Aluminum Wire	5% mass reduction	Larger wire gage for same performance

Table F.2-40: Summary of Mass-Reduction Concepts Considered for Fuel Induction Subsystem

F.2.11.5 Selection of Mass Reduction Ideas

As seen in **Table F.2-41,** the cast aluminum fuel rail was changed to plastic. Production examples include the 3.5L Toyota (**Image F.2-66**). Toyota's reasoning for using plastic in particular engine applications and not exclusively is not understood. Factors such as crash safety may drive metal Fuel Rails.

System	Subsystem	Sub-Subsystem	Description	Mass-Reduction Ideas Selected for Detail Evaluation
01	**11**	**00**	**Fuel Induction Subsystem**	
01	11	01	Fuel Rails	Al to Plastic
01	11	04	Fuel Injectors	N/A
01	11	06	Pressure Regulators	N/A
01	11	07	Fuel Injection Pumps	N/A
01	11	99	Misc.	N/A

Table F.2-41: Mass-Reduction Ideas Selected for Fuel Induction Subsystem

Image F.2-66: Plastic Fuel Rail (Toyota 3.5L)

(Source: FEV, Inc. photo)

F.2.11.6 Mass-Reduction & Cost Impact

As seen in **Table F.2-42**, changing the Fuel Rail from aluminum to plastic saved .115 kg and $2.13.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Estimated Mass Reduction "kg" (1)	Estimated Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
01	**11**	**00**	**Fuel Induction Subsystem**						
01	11	01	Fuel Rails	A	0.115	$2.13	$18.51	29.69%	0.01%
01	11	04	Fuel Injectors		0.000	$0.00	$0.00	0.00%	0.00%
01	11	06	Pressure Regulators		0.000	$0.00	$0.00	0.00%	0.00%
01	11	07	Fuel Injection Pumps		0.000	$0.00	$0.00	0.00%	0.00%
01	11	99	Misc.		0.000	$0.00	$0.00	#DIV/0!	0.00%
				A	**0.115** (Decrease)	**2.127** (Decrease)	**$18.51** (Decrease)	**21.32%**	**0.01%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.2-42: Mass-Reduction and Cost Impact for Fuel Induction Subsystem

(See Appendix for Additional Cost Detail)

F.2.12 Exhaust Subsystem

F.2.12.1 Subsystem Content Overview

As seen in **Table F.2-43,** the Exhaust Manifold and Oxygen Sensor were included in the Exhaust subsystem.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
01	**12**	**00**	**Exhaust Subsystem**	
01	12	01	Exhaust Manifold	7.210
01	12	04	Collector Pipes	0.000
01	12	05	Catalysts	0.000
01	12	06	Particle Filters	0.000
01	12	07	Silencers (Mufflers)	0.000
01	12	08	Oxygen Sensors	0.177
01	12	99	Misc.	0.000
			Total Subsystem Mass =	**7.387**
			Total System Mass =	**172.598**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**4.28%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.43%**

Table F.2-43: Mass Breakdown by Sub-subsystem for Exhaust Subsystem

F.2.12.2 Toyota Venza Baseline Subsystem Technology

Image F.2-67 shows the manifold with integrated catalyst assembled to the Engine. These systems feature time to heat reductions and increase operating temperatures, improving emissions. The tubular weldment with integrated catalyst has a significant weight advantage over its cast counterpart with bolted catalyst.

No mass reduction ideas were identified for the Exhaust subsystem.

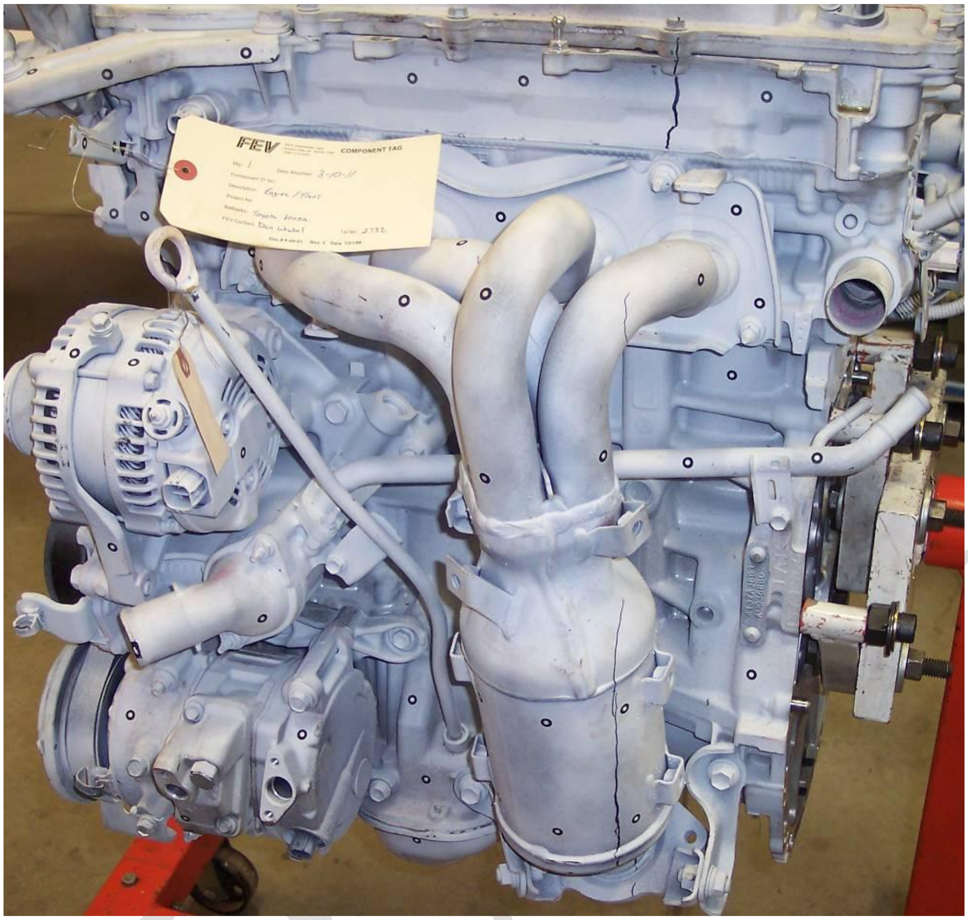


Image F.2-67: Manifold with Integrated Catalyst – 2.7L Toyota

(Source: FEV, Inc. photo)

F.2.13 Lubrication Subsystem

F.2.13.1 Subsystem Content Overview

As seen in **Table F.2-44**, the largest contributor to the Lubrication subsystem is the Oil Pan. Included within the Miscellaneous sub-subsystem is the dipstick assembly.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
01	**13**	**00**	**Lubrication Subsystem**	
01	13	01	Oil Pans (Oil Sump)	1.754
01	13	02	Oil Pumps	1.036
01	13	05	Pressure Regulators	0.099
01	13	06	Oil Filter	0.305
01	13	99	Misc.	0.148
			Total Subsystem Mass =	**3.342**
			Total System Mass =	**172.417**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**1.94%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.20%**

Table F.2-44: Mass Breakdown by Sub-subsystem for Lubrication Subsystem

F.2.13.2 Toyota Venza Baseline Subsystem Technology

The Venza oil pump is a rotor type design. The Inner Rotor is driven on center with the Crankshaft and the Outer Rotor is housed in the Front Cover. The Oil Pump Cover houses the Pressure Regulator. A Baffle Plate mounted under the counter balance system reduces oil turbulence. The Oil Pan is a simple stamping and integrates no other features. Other components include the Oil Strainer, Dip Stick assembly, and Oil Filter Cap (**Image F.2-68**).

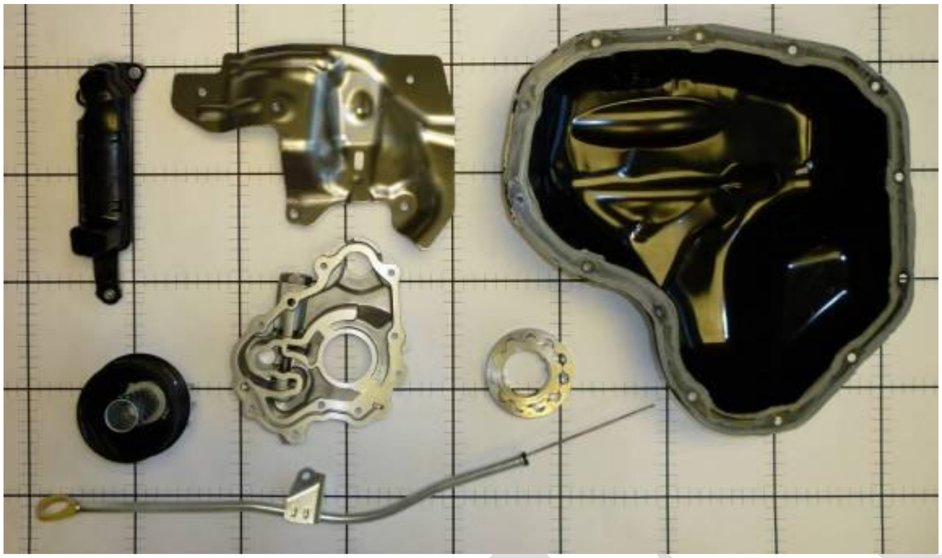


Image F.2-68: Lubrication Subsystem Components

(Source: FEV, Inc. photo)

F.2.13.3 Mass-Reduction Industry Trends

Lightweighting trends for lubrication are metal to plastic applications. Common components include Oil Pans, Baffle Plates, and Dip Stick Cases. Plastic presents the best advantage when multiple components can be integrated into one, like the oil filter mount and the oil pan.

F.2.13.4 Summary of Mass-Reduction Concepts Considered

Table F.2-45 summarizes ideas considered for the Lubrication subsystem. The Oil Pan was considered for plastic or magnesium, but the simple steel stamping is low cost and the pans size limits savings opportunity. The stamped steel oil pan Baffle Plate requires less draw than the oil pan and was considered for an aluminum stamping. The oil pump inner and outer rotors were considered for powder metal aluminum but the severity of failure and lack of production examples discontinued the idea.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Oil Pan	Mg or plastic instead of stamped steel	35% mass reduction	Increased cost, reduced durability
Oil Pan Baffle Plate	steel to plastic or Al	65% mass reduction	
Oil Pump	Steel to PM Al	50% mass reduction	Durability Concern
Dip Stick Tube	steel to plastic	50% mass reduction	

Table F.2-45: Summary of Mass-Reduction Concepts Considered for Lubrication Subsystem

F.2.13.5 Selection of Mass Reduction Ideas

Table F.2-46 summarizes the Ideas Implemented for the Lubrication subsystem.

System	Subsystem	Sub-Subsystem	Description	Mass-Reduction Ideas Selected for Detail Evaluation
01	**13**	**00**	**Lubrication Subsystem**	
01	13	01	Oil Pans (Oil Sump)	Oil Pan Baffle Plate - Steel to Al
01	13	02	Oil Pumps	N/A
01	13	05	Pressure Regulators	N/A
01	13	06	Oil Filter	N/A
01	13	99	Misc.	Dip Stick Tube - Stamped Steel to Plastic

Table F.2-46: Mass-Reduction Ideas Selected for Lubrication Subsystem

The stamped steel Oil Baffle Plate (**Image F.2-69**) is used in the oil pan to reduce turbulence and fluid restriction of moving parts. Preventing unintended grabbing of pan oil helps keep the oil pick submerged particularly at high RPM. This plate was changed to Aluminum.

Image F.2-69: Oil Pan Baffle Plate **Image F.2-70: Oil Pan Baffle Plate Assembled**

(Source: FEV, Inc. photos)

Austrian supplier, Schneegans Silicon GmbH, supplies a plastic Dip Stick Tube for BMW's 2L diesel engine (**Image F.2-71**). Water-injection technology and DuPont™ Zytel® nylon produce a lightweight economical alternative to steel. Plastic also allows easy integration of surrounding components. The Venza Dip Stick Tube is constructed from steel (**Image F.2-72**). The Dipstick Tube was lightweighted by a material change to plastic and scaling the volume up by 2.5.

Image F.2-71: Plastic Dip Stick Tube (BMW 2L Diesel)

(Source: FEV, Inc. photo)

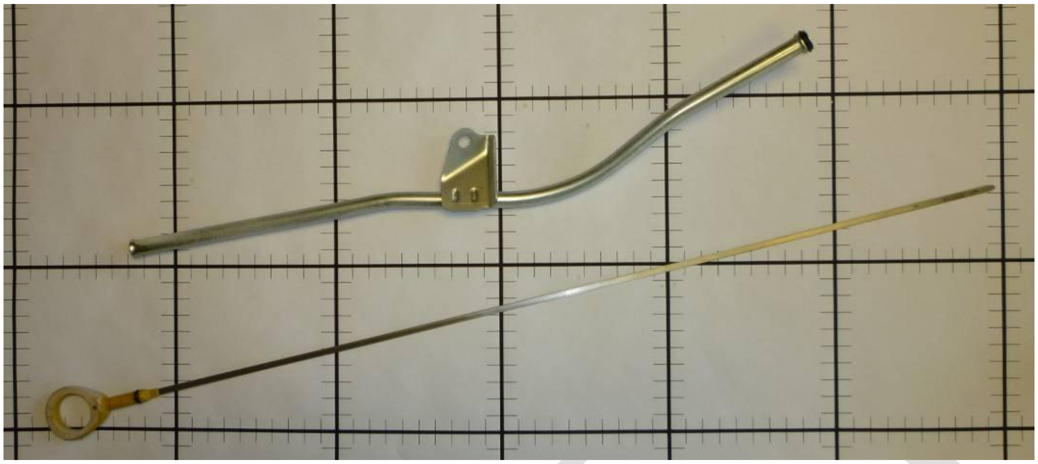


Image F.2-72: Steel Dip Stick Tube (Venza)

(Source: FEV, Inc. photo)

F.2.13.6 Mass-Reduction & Cost Impact

As seen in **Table F.2-47**, lightweighting ideas applied to the Lubrication subsystem saves one-third of a kg and has little impact on cost. Results for the Oil Pan Baffle Plate are summarized in the Oil Pans sub-Subsystem. The Dip Stick Tube is in the Miscellaneous sub-subsystem.

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea					
				Idea Level Select	Estimated Mass Reduction "kg" (1)	Estimated Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
01	**13**	**00**	**Lubrication Subsystem**						
01	13	01	Oil Pans (Oil Sump)	A	0.167	$0.09	$0.57	9.51%	0.01%
01	13	02	Oil Pumps		0.000	$0.00	$0.00	0.00%	0.00%
01	13	05	Pressure Regulators		0.099	$0.00	$0.00	0.00%	0.01%
01	13	06	Oil Filter		0.000	$0.00	$0.00	0.00%	0.00%
01	13	99	Misc.	D	0.067	-$0.30	-$4.39	45.40%	0.00%
				B	**0.333** (Decrease)	**-0.201** (Increase)	**-$0.60** (Increase)	**9.97%**	**0.02%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.2-47: Mass-Reduction and Cost Impact for Lubrication Subsystem

(See Appendix for Additional Cost Detail)

F.2.14 Cooling Subsystem

F.2.14.1 Subsystem Content Overview

Table F.2-48 summarizes the mass breakdown for the Cooling subsystem. The largest mass contributor is the Radiator. Included in the Heat Exchanger sub-system is the AC Condenser.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
01	**14**	**00**	**Cooling Subsystem**	
01	14	01	Water Pumps	2.872
01	14	02	Thermostat Housings	0.205
01	14	04	Heat Exchangers	9.543
01	14	05	Pressure Regulators	0.030
01	14	06	Expansion Tanks	0.282
01	14	99	Misc.	1.166
			Total Subsystem Mass =	**14.098**
			Total System Mass =	**172.417**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**8.18%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.82%**

Table F.2-48: Mass Breakdown by Sub-subsystem for Cooling Subsystem.

F.2.14.2 Toyota Venza Baseline Subsystem Technology

The Venza radiator (**Image F.2-73**) uses standard aluminum heat transfer element with plastic end caps on top and bottom. The water pump is aluminum and has integrated mounting features for the thermostat, belt tensioner, and alternator. The Impeller Cover supports the Impeller Shaft and Drive Belt load. The Water Pump Pulley is steel. The Venza Thermostat Housing is already lightweight plastic.

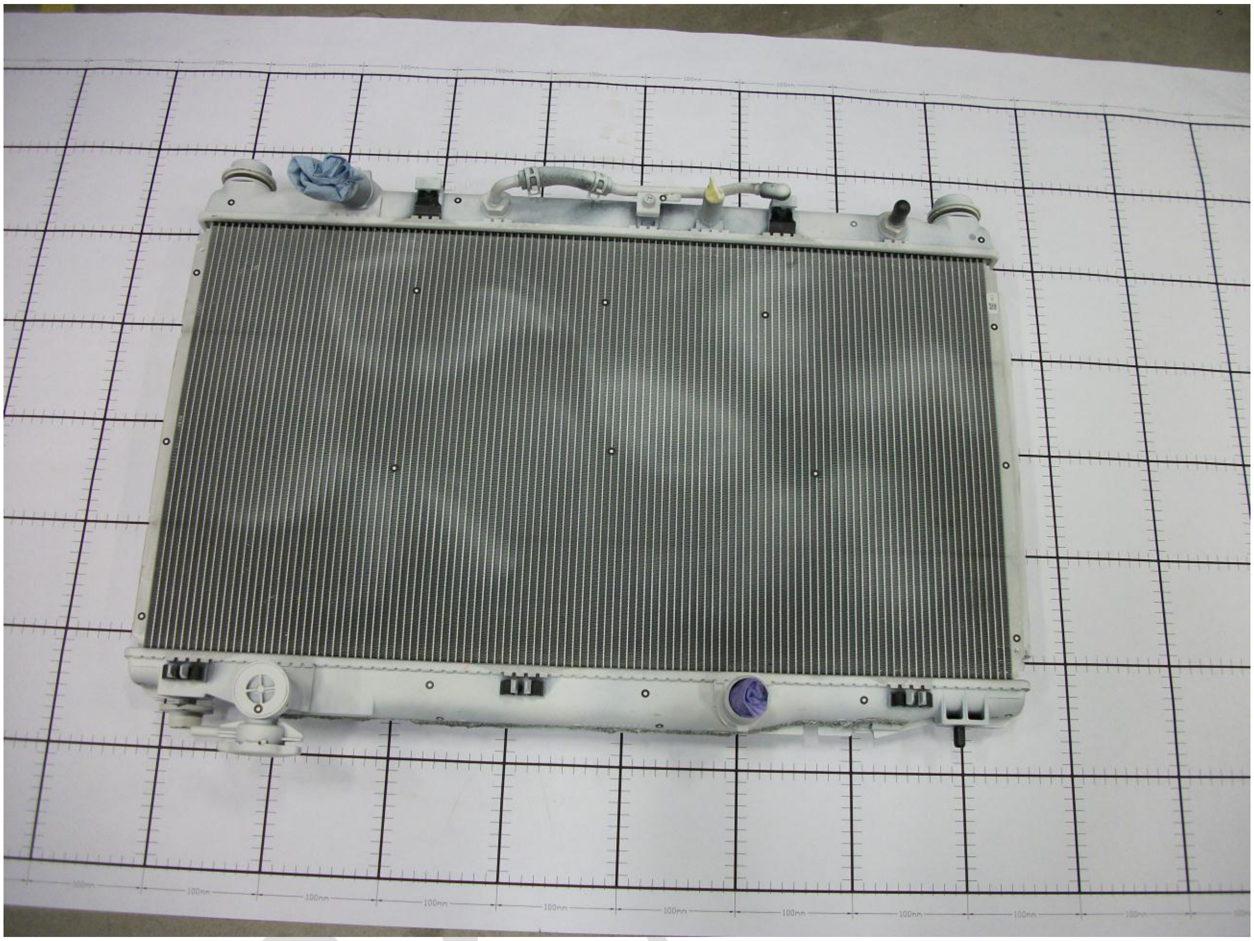


Image F.2-73: Toyota Venza Radiator

(Source: FEV, Inc. photo)

F.2.14.3 Mass-Reduction Industry Trends

Lightweighting trends for cooling system include the use of plastic water pump housings, plastic water pump impellers, and plastic thermostat housings. Coolant transfer tubes are now being manufactured from plastic. Plastic drive pulleys offer an attractive potential for mass savings. Although common for idler pulleys no examples of plastic drive pulleys were identified. Future development of plastic drive pulleys is expected. Transmission heat exchangers assembled in the radiator are now being made from lightweight Aluminum (**Image F.2-74**) instead of copper alloy (**Image F.2-75**) and can save 50% mass.

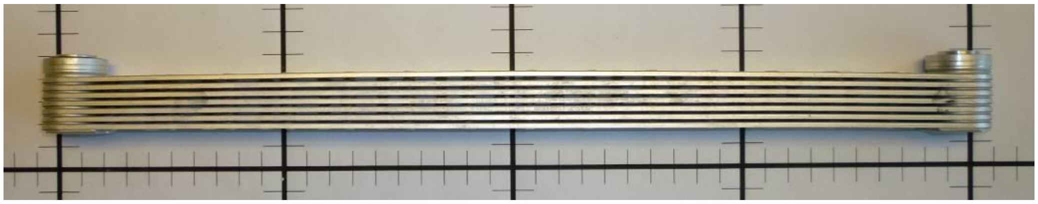


Image F.2-74: Transmission Heat Transfer Element – Aluminum

(Source: FEV, Inc. photo)

Image F.2-75: Transmission Heat Transfer Element – Copper Alloy

(Source: FEV, Inc. photo)

F.2.14.4 Summary of Mass-Reduction Concepts Considered

Lightweighting ideas considered for the cooling system are summarized in **Table F.2-49**.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Radiator	Downsize radiator to match engine size	10% mass reduction	Reduced opportunity for commonizing with other vehicles
Water Pump	Aluminum to Plastic	50% mass reduction	
Radiator Fan Shroud	MuCell	17% mass reduction	Optimum part for MuCell
Transmission Heat Exchanger	Copper to Aluminum	80% mass reduction	Already Aluminum
Water Pump Impeller	Steel to Plastic	80% mass reduction	
Radiator Fan Blade	MuCell	8% mass reduction	
Radiator housings	MuCell	8% mass reduction	
Water Pump Pulley	Steel to Plastic	70% mass reduction	friction loss, friction burn

Table F.2-49: Summary of Mass-Reduction Concepts Considered for Cooling Subsystem

F.2.14.4 Selection of Mass Reduction Ideas

Table F.2-50 summarizes lightweighting ideas selected for the Cooling subsystem.

System	Subsystem	Sub-Subsystem	Description	Mass-Reduction Ideas Selected for Detail Evaluation
01	**14**	**00**	**Cooling Subsystem**	
01	14	01	Water Pumps	Water Pump Housing - Al to Plastic Water Pump Impeller - Steel to Plastic Impeller Housing - Al to Plastic
01	14	02	Thermostat Housings	N/A
01	14	04	Heat Exchangers	Radiator - Downsize for 2.4L Engine Fan Shroud/Fan Blades - MuCell
01	14	05	Pressure Regulators	N/A
01	14	06	Expansion Tanks	N/A
01	14	99	Misc.	N/A

Table F.2-50: Mass-Reduction Ideas Selected for Cooling Subsystem

A lightened Venza means that a smaller engine can match acceleration performance. The engine selected for this study is Toyotas 2.4L. A wet 2.4L radiator was compared to the Venza’s 2.7L radiator for mass savings. After disassembly the 2.4L radiator was found to have a copper alloy transmission heat exchanger. The 2.4L radiator mass was adjusted to assume a lightweight aluminum heat exchanger. Additional savings were applied to the 2.4 Liter by using MuCell to lighten the plastic end caps.

The water pump housing was changed to a two piece design. One section left as aluminum to support the integrated Alternator and tensioner mount, and a second plastic section to serve as the water pump housing. The Audi A3 features a fully plastic water pump assembly. The water pump impeller housing and impeller were changed to plastic. Mini Cooper features a plastic impeller housing (**Image F.2-76**) and plastic impellers on commonplace.

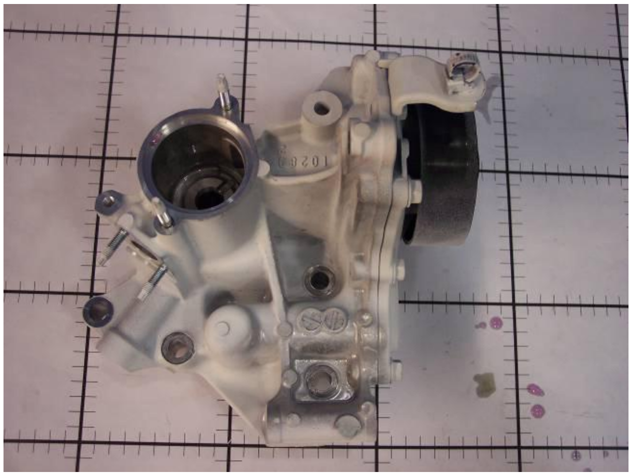


Image F.2-75: [Base Technology]
Water Pump Assembly – Aluminum

(Source: FEV, Inc. photoy)

Image F.2-76: [New Technology]
Water Pump Assembly – Plastic

(Source: FEV, Inc. photo)

Some sections of the fan shroud (**Image F.2-77**) are designed for material flow. Due to the improved flow characteristics of MuCell, these sections can be thinned to their structural requirement making the fan shroud a good candidate for MuCell and a mass savings of 15%. The Radiator fans were also MuCelled, so balancing may be required.

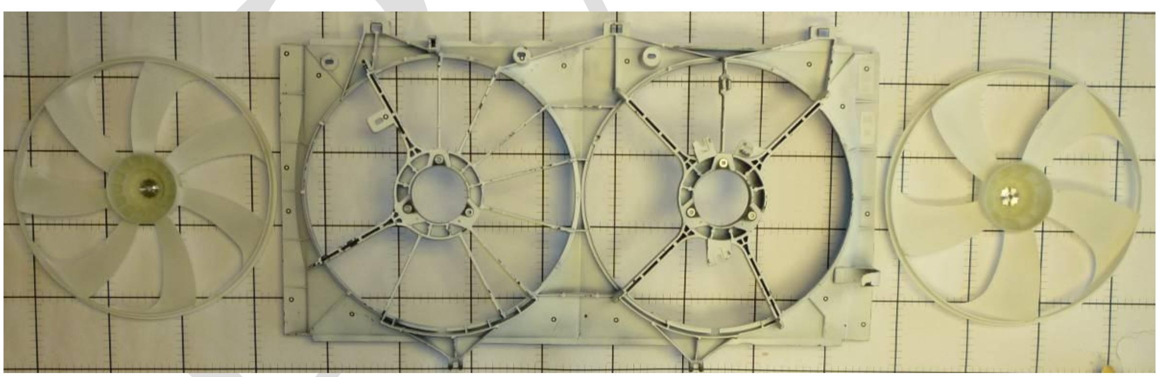


Image F.2-77: Fan Shroud and Fan Blades
Fan Shroud (MuCell – 15% Mass Savings); Fan Blades (MuCell - 7% Mass Savings)

(Source: FEV, Inc. photo)

F.2.14.5 Mass-Reduction & Cost Impact

As seen in **Table F.2-51**, changes made to the Cooling Subsystem saved 2.6kg and $4.62. Changes made to the radiator saved .82kg and $1.10. Changes made to the water pump saved 1.6 kg and $2.84. MuCell applied to the Fan Shroud and Blades saved .170kg and $.68.

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Estimated Mass Reduction "kg" (1)	Estimated Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
01	**14**	**00**	**Cooling Subsystem**						
01	14	01	Water Pumps	A	1.601	$2.84	$1.78	55.75%	0.09%
01	14	02	Thermostat Housings		0.000	$0.00	$0.00	0.00%	0.00%
01	14	04	Heat Exchangers	A	0.990	$1.78	$1.79	10.37%	0.06%
01	14	05	Pressure Regulators		0.000	$0.00	$0.00	0.00%	0.00%
01	14	06	Expansion Tanks		0.000	$0.00	$0.00	0.00%	0.00%
01	14	99	Misc.		0.000	$0.00	$0.00	0.00%	0.00%
				A	**2.591** (Decrease)	**4.620** (Decrease)	**$1.78** (Decrease)	**18.38%**	**0.15%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.2-51: Mass-Reduction and Cost Impact for Cooling Subsystem

(See Appendix for Additional Cost Detail)

F.2.15 Induction Air Charging Subsystem

No Induction Air Charging was identified on the Venza: Toyota's 2.7L AR FE is naturally aspirated.

F.2.16 Exhaust Gas Re-circulation

No EGR system was identified on the Venza.

F.2.17 Breather Subsystem

F.2.17.1 Subsystem Content Overview

Table F.2.52 summarizes the mass breakdown of the Breather Subsystem.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
01	**17**	**00**	**Breather Subsystem**	
01	17	01	Oil/Air Separator	0.853
01	17	02	Valves	0.051
01	17	04	Misc.	0.000
			Total Subsystem Mass =	**0.904**
			Total System Mass =	**172.598**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**0.52%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.05%**

Table F.2-52: Mass Breakdown by Sub-subsystem for Breather Subsystem

F.2.17.2 Toyota Venza Baseline Subsystem Technology

2.7L Venza has a baffle mounted to an aluminum cover and is housed in the engine block (**Image F.2-78**). The PCV valve is integrated into the hose fitting and plumed to the intake. The cover is made from die cast aluminum.

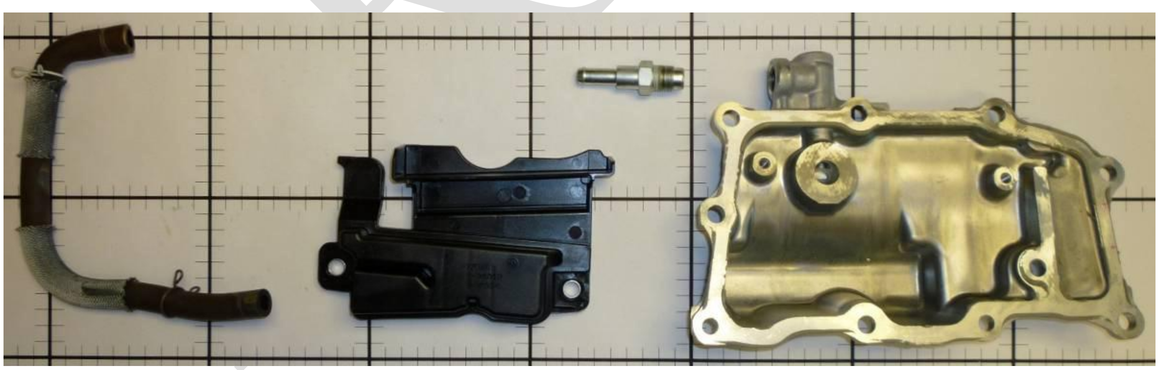


Image F.2-78: Breather Subsystem Components

(Source: FEV, Inc. photo)

F.2.17.3 Mass-Reduction Industry Trends

Positive Crankcase Ventilation system designs vary. In general, metal-to-plastic switching opportunities exist for many systems. Multiple components can be integrated into a single plastic part, thus saving weight and cost.

F.2.17.4 Summary of Mass-Reduction Concepts Considered

As seen in **Table F.2-53**, the ideas generated for the Breather subsystem were a material substitution for the Crank Case Vent Baffle Housing and integrating the baffle into the housing, eliminating the need for fasteners.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Crank Case Vent Baffle Housing	Aluminum to Plastic	50% mass reduction	Reduced cost
Crank Case Vent Baffle Fasteners.	Integrate baffle into housing and eliminate fasteners	100% mass reduction	Reduced cost

Table F.2-53: Summary of Mass-Reduction Concepts Considered for Breather Subsystem

F.2.17.5 Selection of Mass Reduction Ideas

Ideas selected for Breather subsystem (**Table F.2-54**) include a material change for the Crank Case Vent Housing. The die cast housing was changed to injection-molded plastic. The silicon gasket was changed to an inlay rubber seal. The fasteners securing the baffle were eliminated, and the baffle friction welded to the plastic housing.

System	Subsystem	Sub-Subsystem	Description	Mass-Reduction Ideas Selected for Detail Evaluation
01	**17**	**00**	**Breather Subsystem**	
01	17	01	Oil/Air Separator	Crank Case Vent Housing - Al to Plastic Crank Case Vent Baffle Fasteners - Elliminated
01	17	02	Valves	N/A
01	17	04	Misc.	N/A

Table F.2-54: Mass-Reduction Ideas Selected for Cooling Subsystem

F.2.17.6 Mass-Reduction & Cost Impact

As seen in **Table F.2-55**, the metal to plastic change and elimination of fasteners saved mass and cost.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Estimated Mass Reduction "kg" (1)	Estimated Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
01	**17**	**00**	**Breather Subsystem**						
01	17	01	Oil/Air Separator	A	0.219	$4.93	$22.52	25.69%	0.01%
01	17	02	Valves		0.000	$0.00	$0.00	0.00%	0.00%
01	17	05	Misc.		0.000	$0.00	$0.00	0.00%	0.00%
				A	**0.219** (Decrease)	**4.934** (Decrease)	**$22.52** (Decrease)	**24.24%**	**0.01%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.2-55: Mass-Reduction and Cost Impact for Breather Subsystem

(See Appendix for Additional Cost Detail)

F.2.18 Engine Management, Engine Electronic, Elec. Subsystem

F.2.18.1 Subsystem Content Overview

As seen in **Table F.2-56**, Engine Management systems is the largest contributor to the Engine Management, Electronic subsystem and is composed of the ECM and associated brackets. The engine wiring harness is included in *System 18: Electrical Distribution & Electrical Control*.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
01	**60**	**00**	**Engine Management, Engine Electronic, Electrical Subsystem**	
01	60	01	Spark Plugs, Glow Plugs	0.196
01	60	02	Engine Management Systems, Engine Electronic Systems	1.303
01	60	03	Engine Electrical Systems (including Wiring Harnesses, Earth Straps, Ignition Harness, Coils, Sockets)	1.065
01	60	99	Misc.	0.086
			Total Subsystem Mass =	**2.650**
			Total System Mass =	**172.598**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**1.54%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.15%**

Table F.2-56: Mass Breakdown by Sub-subsystem for Cooling Subsystem.

F.2.18.2 Toyota Venza Baseline Subsystem Technology

The Engine Management, Electronic Subsystem includes the ECM, ECM Brackets, sensors, coils, and spark plugs (**Image F.2-79**).

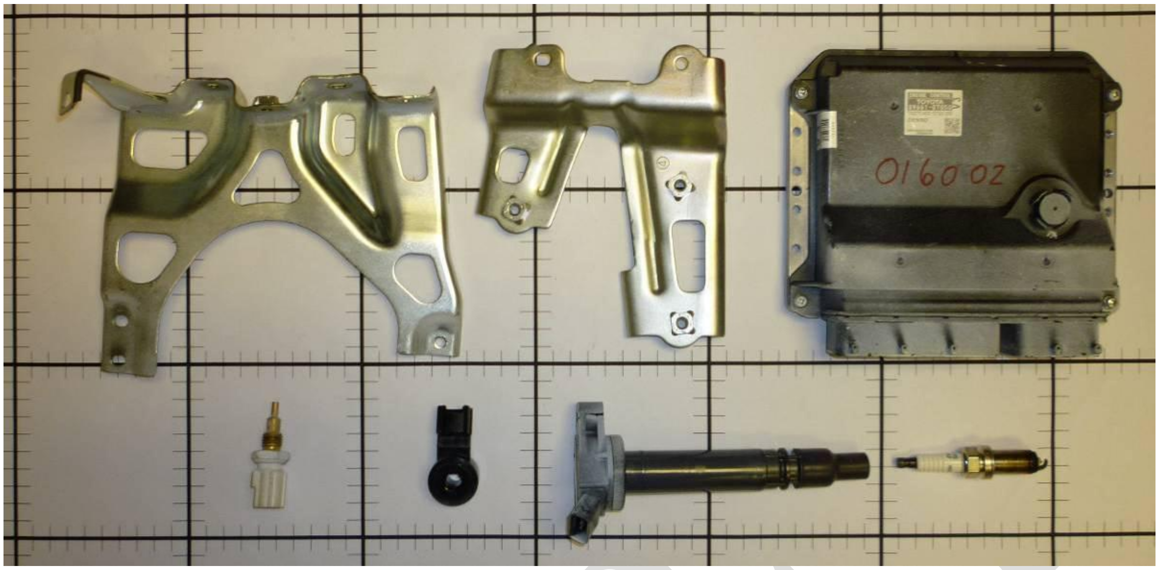


Image F.2-79: Engine Management, Electronic Subsystem Components

(Source: FEV, Inc. photo)

F.2.18.3 Mass-Reduction Industry Trends

No Lightweighting industry trends were identified for Engine Management, Electronic subsystem.

F.2.18.4 Summary of Mass-Reduction Concepts Considered

As shown in **Table F.2-57**, the ECU Bracket Assembly and Spark Coil were considered for mass reduction.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
ECU Bracket Assembly	Steel to Plastic	60% mass reduction	Loss of Rigidness
Spark Coil	Copper Clad Aluminum Wire	10% mass reduction	Larger wire gage for same performance

Table F.2-57: Summary of Mass-Reduction Concepts Considered for Engine Management, Electronic Subsystem

F.2.18.5 Selection of Mass Reduction Ideas

Table F.2-58 summarizes the ideas selected for the Engine Management, Electronic Subsystem. The Venza ECU bracket is a three-piece stamping spot welded and bolted together. This assembly was changed to a single-iece injection molded component.

System	Subsystem	Sub-Subsystem	Description	Mass-Reduction Ideas Selected for Detail Evaluation
01	**60**	**00**	**Engine Management, Engine Electronic, Electrical Subsystem**	
01	60	01	Spark Plugs, Glow Plugs	N/A
01	60	02	Engine Management Systems, Engine Electronic Systems	ECU Bracket Assembly - Two piece stamped steel to single piece Plastic
01	60	03	Engine Electrical Systems (including Wiring Harnesses, Earth Straps, Ignition Harness, Coils, Sockets)	N/A
01	60	99	Misc.	N/A

Table F.2-58: Mass-Reduction Ideas Selected for Engine Management, Electronic Subsystem

F.2.18.6 Mass-Reduction & Cost Impact

As seen in **Table F.2-59**, metal-to-plastic lightweighting applied to the ECU bracket saves both mass and cost.

System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Estimated Mass Reduction "kg" (1)	Estimated Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
				Net Value of Mass Reduction Idea					
01	60	00	**Engine Management, Engine Electronic, Electrical Subsystem**						
01	60	01	Spark Plugs, Glow Plugs		0.000	$0.00	$0.00	0.00%	0.00%
01	60	02	Engine Management Systems, Engine Electronic Systems	A	0.388	$1.00	$2.57	29.78%	0.02%
01	60	05	Engine Electrical Systems (including Wiring Harnesses, Earth Straps, Ignition Harness, Coils, Sockets)		0.000	$0.00	$0.00	0.00%	0.00%
01	60	06	Misc.		0.000	$0.00	$0.00	0.00%	0.00%
				A	**0.388** (Decrease)	**0.998** (Decrease)	**$2.57** (Decrease)	**14.64%**	**0.02%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.2-59: Mass-Reduction and Cost Impact for Breather Subsystem

(See Appendix for Additional Cost Detail)

F.2.19 Accessory Subsystems (Start Motor, Generator, etc.)

F.2.19.1 Subsystem Content Overview

Table F.2-60 summarizes the mass breakdown for the 2.7L engine accessories. The top mass contributors include the AC compressor and the Alternator.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
01	**70**	**00**	**Accessory Subsystems (Start Motor, Generator, etc.)**	
01	70	01	Starter Motors	2.909
01	70	02	Alternators	6.028
01	70	03	Power Steering Pumps	0.000
01	70	04	Vacuum Pumps	0.000
01	70	05	Air Conditioning Compressors	7.225
01	70	06	Hydraulic Pumps	0.000
01	70	07	Ventilator	0.000
01	70	10	Other Accessories	0.000
01	70	99	Misc.	0.400
			Total Subsystem Mass =	**16.562**
			Total System Mass =	**172.598**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**9.60%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.97%**

Table F.2-60: Mass Breakdown by Sub-subsystem for Accessory Subsystem

F.2.19.2 Toyota Venza Baseline Subsystem Technology

The Venza Accessory Subsystem consists of the alternator, starter, AC compressor, and AC Bracket (**Image F.2-80**). The Venza utilizes an electric power steering pump.

Image F.2-80: Accessory Subsystem Components

(Source: FEV, Inc. photo)

F.2.19.3 Mass-Reduction Industry Trends

Lightweight technology for Accessories focuses on compact efficient designs. The Venza starter, weighing only 2.9 kg, represents a standard compact design.

F.2.19.4 Summary of Mass-Reduction Concepts Considered

Table F.2-61 summarizes concepts considered for accessory lightweighting. Integrated starter alternators used on start-stop micro Hybrids were reviewed as a weight reduction. Systems reviewed included an additional starter motor for cold starts and complex controls. For this reason this idea was not implemented. The alternator case is made from lightweight aluminum and a change to plastic was considered. The poor thermo conductivity of plastic eliminated this from consideration. copper-clad aluminum wire has been applied to alternators due to increase copper cost and was reviewed for lightweighting opportunity. The copper content was quantified and mass save estimated to be 10%. The increased gauge diameter required by aluminum copper-clad wire would drive larger packaging potentially offsetting mass savings. In addition, special welding techniques may be required to address high joint temperatures. For these reasons, copper-clad aluminum wire was not further considered as a weight savings. Standard filament bulbs were not replaced with LED's as initially considered, therefore Alternator downsize was not an option.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Starter/Alternator	Replace these two devices with an Integrated Starter-Alternator. This would require additional control circuitry	30% mass reduction	Additional control hardware, limited torque
Alternator	Make outer case out of plastics or some other light material	5% mass reduction	Make outer case out of plastics
AC compressor bracket	material change from cast iron to cast aluminum	65% mass reduction	NVH concern
AC compressor bracket	Integrate into block or stiffenging crankcase	65% mass reduction	
Alternator	reduced load for LED - reduced size	10% mass reduction	
Alternator	Copper Clad Al windings	5% mass reduction	Larger wire gage for same performance

Table F.2-61: Summary of Mass-Reduction Concepts Considered for Accessory Subsystem

F.2.19.5 Selection of Mass Reduction Ideas

As seen in **Table F.2-62**, the AC compressor mounting bracket was selected for lightweighting.

System	Subsystem	Sub-Subsystem	Description	Mass-Reduction Ideas Selected for Detail Evaluation
01	**70**	**00**	**Accessory Subsystems (Start Motor, Generator, etc.)**	
01	70	01	Starter Motors	N/A
01	70	02	Alternators	N/A
01	70	03	Power Steering Pumps	N/A
01	70	04	Vacuum Pumps	N/A
01	70	05	Air Conditioning Compressors	Mounting Bracket - Cast Iron to Al
01	70	06	Hydraulic Pumps	N/A
01	70	07	Ventilator	N/A
01	70	10	Other Accessories	N/A
01	70	99	Misc.	N/A

Table F.2-62: Mass-Reduction Ideas Selected for Accessory Subsystem

The AC compressor bracket found on Venza was Cast Iron (**Image F.2-81**). While there may be NVH drivers for this material selection, similar applications have been constructed from cast Aluminum (**Image F.2-82**).

Image F.2-81: [Base Technology] AC Comp Bracket

(Source: FEV, Inc. photo)

Image F.2-82: [New Technology] AC Comp Bracket (Nissan 350z)

(Source: slidegood.com)

F.2.19.6 Mass-Reduction & Cost Impact

Table F.2-63 shows there is a cost increase for changing the AC Bracket material to aluminum.

System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
				Net Value of Mass Reduction Idea					
01	**70**	**00**	**Accessory Subsystems (Start Motor, Generator, etc.)**						
01	70	01	Starter Motors		0.000	$0.00	$0.00	0.00%	0.00%
01	70	02	Alternators		0.000	$0.00	$0.00	0.00%	0.00%
01	70	03	Power Steering Pumps		0.000	$0.00	$0.00	0.00%	0.00%
01	70	04	Vacuum Pumps		0.000	$0.00	$0.00	0.00%	0.00%
01	70	05	Air Conditioning Compressors	B	0.709	-$0.23	-$0.33	9.82%	0.04%
01	70	06	Hydraulic Pumps		0.000	$0.00	$0.00	0.00%	0.00%
01	70	07	Ventilator		0.000	$0.00	$0.00	0.00%	0.00%
01	70	10	Other Accessories		0.000	$0.00	$0.00	0.00%	0.00%
01	70	99	Misc.		0.000	$0.00	$0.00	0.00%	0.00%
				B	**0.709** (Decrease)	**-0.231** (Increase)	**-$0.33** (Increase)	**4.28%**	**0.04%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.2-63: Mass-Reduction and Cost Impact for Accessory Subsystem

(See Appendix for Additional Cost Detail)

Works Cited:

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F.3 Transmission System

The Toyoda Venza transmission package (U660e) is a 6-speed automatic with a traditional torque converter. Some weight reduction concepts were employed when it was designed. As shown in **Table F.3-1**, we have targeted some key areas in the unit that hold further reduction opportunities.

System	Subsystem	Sub-Subsystem	Description	System & Subsystem Mass "kg"
02	**00**	**00**	**Transmission System**	
02	01	00	External Components	0.023
02	02	00	Case Subsystem	24.573
02	03	00	Gear Train Subsystem	41.437
02	05	00	Launch Clutch Subsystem	9.745
02	06	00	Oil Pump and Filter Subsystem	6.526
02	07	00	Mechanical Controls Subsystem	6.296
02	08	00	Electrical Controls Subsystem	0.777
02	09	00	Parking Mechanism Subsystem	0.904
02	20	00	Driver Operated External Controls Subsystem	2.482
			Total System Mass =	**92.763**
			Total Vehicle Mass =	**1711**
			System Mass Contribution Relative to Vehicle =	**5.42%**

Table F.3-1: Baseline Subsystem Breakdown for Transmission System

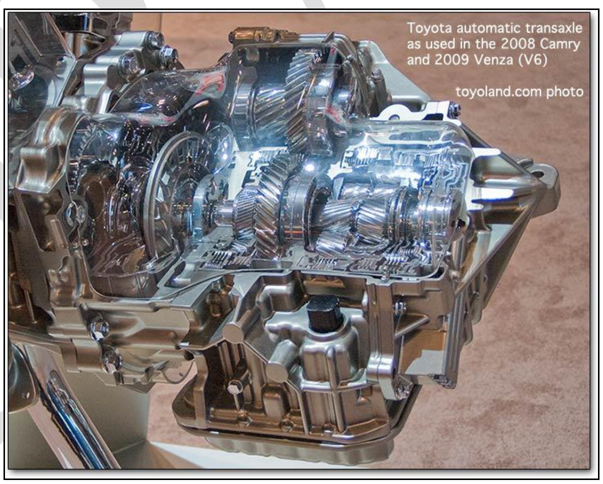

Image F.3-1 : Toyota Automatic Transaxle Transmission

(Source: Toyoland.com)

As shown in **Table F.3-2**, there are material, technological, and process opportunities that have come to the industry that are available in the search for mass reduction in tomorrow's vehicles.

System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
				Net Value of Mass Reduction Idea					
02	00	00	**Transmission System**						
02	01	00	External Components		0.000	$0.00	$0.00	0.00%	0.00%
02	02	00	Case Subsystem	C	7.745	-$11.03	-$1.42	31.52%	0.45%
02	03	00	Gear Train Subsystem	X	3.490	-$119.68	-$34.29	8.42%	0.20%
02	05	00	Launch Clutch Subsystem	A	4.904	$45.16	$9.21	50.32%	0.29%
02	06	00	Oil Pump and Filter Subsystem	A	1.034	$0.90	$0.87	15.84%	0.06%
02	07	00	Mechanical Controls Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
02	08	00	Electrical Controls Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
02	09	00	Parking Mechanism Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
02	20	00	Driver Operated External Controls Subsystem	X	1.726	-$29.49	-$17.08	69.55%	0.10%
				X	**18.900** (Decrease)	**-$114.15** (Increase)	**-$6.04** (Increase)	**20.37%**	**1.10%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.3-2: Mass-Reduction and Cost Impact for Transmission System 2

F.3.1 External Components

F.3.1.1 Subsystem Content Overview

After a systematic investigation there were no opportunities for mass reduction or cost benefits in this subsystem.

F.3.2 Case Subsystem

F.3.2.1 Subsystem Content Overview

As seen in **Table F.3-3,** the most significant contributor to the mass of the Case subsystem is the raw material in the case components themselves. The case subsystem is made up of three sections that enclose the transmission and are currently an aluminum SAE 390 alloy.

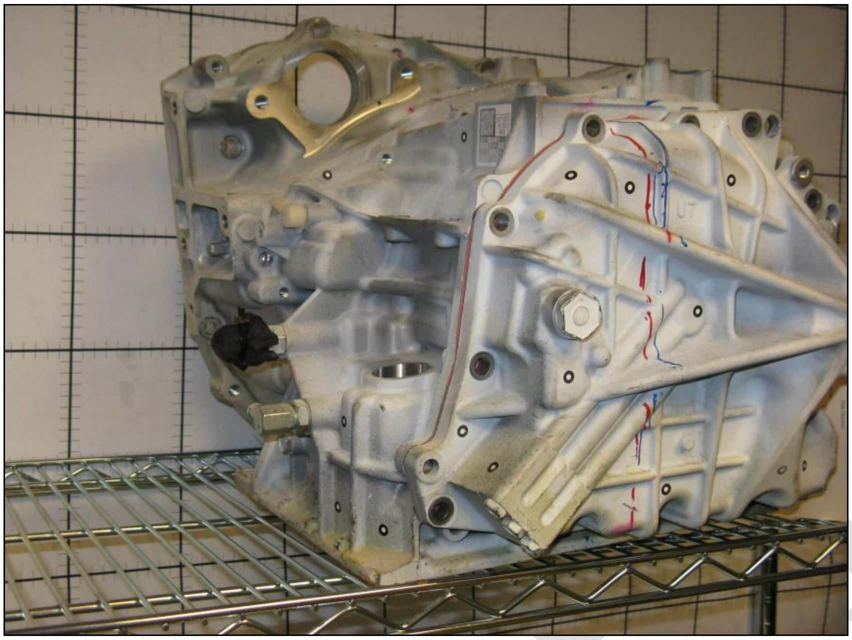

Image F.3-2: Transaxle Housing

(Source: FEV, Inc. photo)

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
02	**02**	**00**	**Case Subsystem**	
02	02	01	Transaxle Case	8.300
02	02	02	Transaxle Housing	11.480
02	02	03	Covers	4.793
			Total Subsystem Mass =	**24.573**
			Total System Mass =	**92.763**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**26.49%**
			Subsystem Mass Contribution Relative to Vehicle =	**1.44%**

Table F.3-3: Mass Breakdown by Sub-subsystem for Cass Subsystem

F.3.2.2 Toyota Venza Baseline Subsystem Technology

Toyota has been using aluminum transmission cases for years and has optimized the thin wall casting technique that they use. The strength and integrity of their cases has never been an issue for them. Its mass weight compares to others in the industry using aluminum in their cases has never been a concern.

F.3.2.3 Mass-Reduction Industry Trends

There are vehicles manufactures in the industry that have adopted alternate materials one being Magnesium alloy to reduce their transmission weight and maintain their case integrity, one of them being (Mercedes-Benz 7G-TRONIC), and at present, General Motors also has approximately 1 million GMT800 full size trucks and sport utility vehicles (SUV) that are produced annually that have two magnesium transfer cases with a (total weight 7 kg) per unit. Since 2002, VW has produced 600 magnesium alloy manual transmission cases daily for the VW Passat and the Audi A4/A6. The magnesium transmission case is a proven mass weight reduction product.

Industry visionaries have also looked at carbon fiber combinations as alternate material for the transmission cases; however, at this time there are no viable products for us to look at as an option.

F.3.2.4 Summary of Mass-Reduction Concepts Considered

Table F.3-4 shows the mass reduction ideas considered for the Case subsystem. Toyoda has always been mass reduction conscious in their designs but tend to lean toward the conservative side of the engineering spectrum in drive train design. That is why carbon fiber and magnesium have not fond their way into drive train components in their vehicles

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Aluminum Case Assemble	Reduce wall thickness	10% weight save	Integrity and strength compromised
Aluminum Case Assemble	Carbon fiber material replacement	50% weight save	Extensive engineering hurdles to overcome
Aluminum Case Assemble	Magnesium material replacement	30% weight save	Low risk moderate cost increase

Table F.3-4: Summary of Mass-Reduction Concepts Initially Considered for Transmission Case Subassembly

F.3.2.5 Selection of Mass Reduction Ideas

The mass reduction ideas selected from this subassembly fell into the "A" group as shown in **Table F.3-5**. Components shown utilizing magnesium alloy will meet the integrity needs of the system and fulfill the mass reduction parameters.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
2	**2**	**00**	**Case Subsystem**	
02	02	01	Transaxle Case	Replace a 390 aluminum casting with Mg AJ62 (Mg-Al-Sr). For 30% weight save
02	02	02	Transaxle Housing	Replace a 390 aluminum casting with Mg AJ62 (Mg-Al-Sr). For 30% weight save
02	02	03	Covers	Replace a 390 aluminum casting with Mg AJ62 (Mg-Al-Sr). For 30% weight save
02	02	99	Misc.	n/a

Table F.3-5 Mass-Reduction Ideas Selected for Detail Case Subsystem

F.3.2.6 Mass-Reduction & Cost Impact Estimates

The greatest mass reduction was gained by the material selection of magnesium alloy as shown in **Table F.3-6**. Doing thin wall analysis on each of the components of the subassembly did not garner an outcome that would have proven to be advantages to the end product. Although there were opportunities to reduce the actual mass of the Case subsystem we have not pursued them at this time. The choice of magnesium has proven to be cost effective and met the mass reduction goals.

			Net Value of Mass Reduction Idea					
Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
02	**00**	**Case Subsystem**						
02	01	Transaxle Case	C	2.947	-$3.38	-$1.15	35.51%	0.17%
02	02	Transaxle Housing	C	3.706	-$6.48	-$1.75	32.28%	0.22%
02	03	Covers	C	1.092	-$1.18	-$1.08	22.78%	0.06%
			C	**7.745** (Decrease)	**-$11.03** (Increase)	**-$1.42** (Increase)	**31.52%**	**0.45%**

"+" = mass decrease, "-" = mass increase
"+" = cost decrease, "-" = cost increase

Table F.3-6 Subsystem Mass Reduction and Cost Impact Estimates for Case Subsystem

F.3.3 Gear Train Subsystem

F.3.3.1 Subsystem Content Overview

As seen in **Table F.3-7**, the gear train offered some opportunities to reduce weight and lower cost for the transmission. We will look outside of the auto industry for ideas to shed weight.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
02	**03**	**00**	**Gear Train Subsystem**	
02	03	01	Planetary Gears	32.407
02	03	02	Carrier Gears	9.030
			Total Subsystem Mass =	**41.437**
			Total System Mass =	**92.763**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**44.67%**
			Subsystem Mass Contribution Relative to Vehicle =	**2.42%**

Table F.3-7: Mass Breakdown by Sub-subsystem for Gear Train Subsystem

F.3.3.2 Toyota Venza Baseline Subsystem Technology

The Gear Train Subsystem in the Toyota U660e transmission is a very compact unit. Care was taken to insure that only minimal space was give between aligning components, with this said lightning exercises done on the gear train did not open many doors for mass reduction. There are other opportunities and we will pursue them

F.3.3.3 Mass-Reduction Industry Trends

In the automotive transmission industry the Gear Train has its opportunities for light weight, cost effective and longer life cycles. The use of aerospace lightened gear designs and raw materials, using new plastic components to reduce weight and cost, reducing the overall mass of the transmission when new and smaller components are used are some of the tactics that we will employ. The actual transmission is getting smaller and gear selection is getting larger in the industry today.

F.3.3.4 Summary of Mass-Reduction Concepts Used

Table F.3-8 shows the mass reduction ideas used for the U660e Gear Train Subsystem. The present Toyoda design of the gear train is compact and demonstrates a conscious engineering choice towards light weight.

Replacing the Industry Standard Needle Bearings with Vespel SP-21 was an easy decision; we looked at other products but deduced that the Dupont product had all the qualities required for a worry free replacement in our application. Vespel has a proven track record of success in other transmissions.

Replacing the Cast Iron Differential Carrier with Aluminum proved to be a significant weight savings' and the cost was not prohibitive after investigation. There are many vehicles in the field that utilize aluminum for this weight save in their differential application.

The Helical Ring Gear inside this transmission to transmit power through the differential to the axels is a traditional 4140 crab and hardened gear. We chose a stronger gear material in Ferrium C61 to help insure that we maintained the gear integrity after going through an aerospace type mass reduction analyses which garnered a 25% weight reduction. At this time the cost and limited availability of the material is a concern but we see this product as a key component in mass weight reduction throughout the drive train in the future. We believe that utilizing C61 throughout the transmission gear train could have garnered another 20% weight save and a reduction in the total size in the transmission package.

Component/ Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Planetary Gear Sub-Subsystem	Replace Thrust Bearings with Vespel SP-21D	75% weight save	Low risk cost benefit
Carrier Gear Sub-Subsystem	Replace cast iron differential carrier with aluminum	50% weight save	Low risk moderate cost increase
Carrier Gear Sub-Subsystem	Change 4140 ring gear raw material with high strength C61 alloy and lighten gear	10% weight save	Low risk moderate cost increase

Table F.3-8: Summary of Mass-Reduction Concepts Initially Considered for the Gear Train Subsystem

F.3.3.5 Selection of Mass Reduction Ideas

The mass reduction ideas selected from this subassembly fell into the "A" group are shown in **Table F.3-9**.

The first component shown utilizes Vespel SP-21D, a DuPont product that is being used by other transmission builders. The second component is the Differential Carrier, which will be casted from a high-strength aluminum alloy.

The third component will be a lightened gear configuration utilizing a high-strength C61 aerospace alloy to insure its integrity in the subassembly.

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System	Subsystem	Sub-Subsystem	Description	Mass-Reduction Ideas Selected for Detail Evaluation
2	3	00	**Gear Train Subsystem**	
02	03	02	All 9 thrust bearing in the gear train	Replace Steel thrust bearings with Dupont (Vispel SP-21D)
02	03	07	Differential carrier housing	Replace ASTM A536, 80-55-06 differential housing with aluminum housing
02	03	07	Differential carrier ring gear	Replace 4140 differential ring gear with high strength reduced mass C61 alloy

Table F.3-9: Mass-Reduction Ideas Selected for Gear Train Subsystem

F.3.3.6 Mass-Reduction & Cost Impact Estimates

The mass reductions in this subsystem were gained by the material selection and gear lightening techniques as shown in **Table F.3-10**. The use of Vespel reduces the cost of the bearings by 60 to 70% with a weight loss per bearing of more than 75%.

Using aluminum instead of cast iron on the differential carrier is a 40% weight saving with a cost that is well within the realm of reason for this large of a weight loss.

Using aerospace gear lighting techniques on all of the gears in an automotive transmission should be the norm.

Image F.3-3: Vespel Thrust Bearing

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
02	**03**	**00**	**Gear Train Subsystem**						
02	03	01	Planetary Gears	A	0.263	$26.05	$98.91	0.81%	0.02%
02	03	02	Carrier Gears	X	3.227	-$145.74	-$45.16	35.74%	0.19%
				X	**3.490** (Decrease)	**-$119.68** (Increase)	**-$34.29** (Increase)	**8.42%**	**0.20%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.3-10: Subsystem Mass Reduction and Cost Impact for Case Subsystem

F.3.4 Internal Clutch Subsystem

F.3.4.1 Subsystem Content Overview

After a systematic investigation there were no opportunities for mass reduction or cost benefits in this subsystem.

F.3.5 Launch Clutch Subsystem

F.3.5.1 Subsystem Content Overview

As seen in **Table F.3-11**, the most significant contributor to the mass of the Launch Clutch subsystem is the Torque converter itself. The case subsystem of the torque converter is a welded construction with SAE 1018 steel as its raw material.

Image F.3-4: Torque Converter Assembly

(Source: FEV, Inc. photo)

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
02	**05**	**00**	**Launch Clutch Subsystem**	
02	05	01	Torque Converter Asm	9.745
			Total Subsystem Mass =	**9.745**
			Total System Mass =	**92.763**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**10.51%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.57%**

Table F.3-11: Mass Breakdown by Sub-subsystem for Launch Clutch Subsystem

F.3.5.2 Toyota Venza Baseline Subsystem Technology

The Launch Clutch system on this vehicle is a direct result of the traditional style of transmission that was selected for it. The present torque converter is an old style auto industry standard that has been around since the 1950. Improvements on this unit will lead to a lighter and better drive system.

F.3.5.3 Mass-Reduction Industry Trends

Although DCTs (Dual Clutch Transmissions) have increased in popularity, they are still more expensive than torque converter style transmissions (depending, of course, on the segment you are looking at). DCTs are coming down in price, especially with the introduction of dry twin-plate designs. They are less complex than a torque converter automatic with planetary gears, much lighter and there will be further price reductions once they are produced in high volume, for instance when some of the new Chinese manufacturing plants come on stream. For a new entrant into the automatic transmission market with no legacy investment in planetary automatics, it is an attractive step. Innovations in advanced engineering always come to the top.

F.3.5.4 Summary of Mass-Reduction Concepts Considered

Table F.3-12 shows the mass reduction ideas considered for the Launch Clutch system. The Toyota gear train design is compact and demonstrates a conscious decision toward light weight. Replacing the industry standard steel torque converter with plastic or aluminum would be a huge improvement. Eliminating the torque converter completely by using a DCT transmission would be the best idea.

Component/ Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Torque Converter	Replace with Plastic Converter using DuPont Zytel® HTN51LG50HSL BK083	75% weight save	application still in R&D
Torque Converter	Replace with DCT transmission	100%	Low risk moderate cost increase
Torque Converter	Replace steel converter with Atlas aluminum component converter	50% weight save	Medium risk moderate cost increase

Table F.3-12: Summary of Mass-Reduction Concepts Initially Considered for the Launch Clutch System

F.3.5.5 Selection of Mass Reduction Ideas

The mass reduction ideas selected from this subassembly fell into the A group are shown in **Table F.3-13**. Regarding the torque converter application, we have proposed using a full Aluminum torque converter assembly in our system. Aluminum torque converters are being used in off-road, racing and heavy industrial equipment and some automotive applications. The casted design of an aluminum turbine, impeller and stator reduce the assemble step process and make for a simpler assembly. There are companies in the industry like Alcast Company Aluminum Foundry that have honed the process of producing the required quality components for the OEMs that produce these converters.

System	Subsystem	Sub-Subsystem	Description	Mass-Reduction Ideas Selected for Detail Evaluation
2	5	00	**Launch Clutch System**	
02	05	01	Torque Converter	Replace Steel Torque converter with Aluminum

Table F.3-13: Mass-Reduction Ideas Selected for Launch Clutch System

F.3.5.6 Preliminary Mass-Reduction & Cost Impact Estimates

The mass reductions in this subsystem were gained by the material selection as shown in **Table F.3-14**. The use of a 5083 Aluminum/Magnesium alloy will give us a 50 to 60% weight loss. This application is in the field today with material and technology in place to produce a good replacement to the traditional steel converter.

Image F.3-5: Aluminum Torque Converter

(Source : alcastcompany.com)

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
02	**05**	**00**	**Launch Clutch Subsystem**						
02	05	01	Torque Converter Asm	A	4.904	$45.16	$9.21	50.32%	0.29%
				A	**4.904** (Decrease)	**$45.16** (Decrease)	**$9.21** (Decrease)	**50.32%**	**0.29%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.3-14: Subsystem Mass Reduction and Cost Impact Estimates for Launch Clutch System

F.3.6 Oil Pump and Filter Subsystem

F.3.6.1 Subsystem Content Overview

As seen in **Table F.3-15**, the most significant contributor to the mass of the Oil Pump and Filter Subsystem is the Oil Pump unit itself. The pump unit is cast iron in our test vehicle.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
02	**06**	**00**	**Oil Pump and Filter Subsystem**	
02	06	01	Oil Pump Asm	4.646
02	06	02	Covers	1.666
02	06	03	Filters	0.214
			Total Subsystem Mass =	**6.526**
			Total System Mass =	**92.763**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**7.04%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.38%**

Table F.3-15: Mass Breakdown by Sub-subsystem for Oil Pump and Filter Subsystem

F.3.6.2 Toyota Venza Baseline Subsystem Technology

The oil Pump is a traditional style cast iron pump that has been around for decades and is a great candidate for new light weight materials that are on the market. There is no benefit in this component staying cast iron.

F.3.6.3 Mass-Reduction Industry Trends

Every day, the auto industry embraces new and innovative technology that comes to them from other sectors of commerce. In the case of the transmission oil pump, the racing industry has led the way in developing light-weight and efficient oil pumps. Aluminum, aluminum-magnesium alloys, and even plastic polymers are available today. This will be a great application match for mass weight reduction at a reasonable cost.

F.3.6.4 Summary of Mass-Reduction Concepts Considered

Table F.3-16 contains the mass reduction ideas considered for the Oil Pump and Filter Subsystem. The use of Aluminum, Magnesium and Plastic are viable materials in this application today.

Component/ Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Transmission Oil Pump	Replace cast iron pump with Aluminum	65% weight save	Low risk moderate cost increase
Transmission Oil Pump	Replace cast iron pump with Magnesium	77% weight save	Low risk medium cost increase
Transmission Oil Pump	Replace cast iron pump with Plastic	84% weight save	High risk low cost

Table F.3-16: Summary of Mass-Reduction Concepts Considered for the Oil Pump and Filter Subsystem,

F.3.6.5 Selection of Mass Reduction Ideas

The mass reduction ideas selected from this subassembly fell into the C group are shown in **Table F.3-17**. TCI Automotive has been producing state of the art aluminum components for the racing world since the late 60's and supplies light weight transmission components to its customers. We can use mass production processes to lower the cost and bring a light weight pump to the industry.

System	Subsystem	Sub-Subsystem	Description	Mass-Reduction Ideas Selected for Detail Evaluation
2	6	00	**Oil Pump and Filter Subasystem**	
02	06	01	Oil Pump Assemble	Replace cast iron with aluminum

Table F.3-17: Preliminary Subsystem Mass Reduction and Cost Impact Estimates for Oil Pump and Filter Subsystem

Image F.3-6: Aluminum Oil Pump Assembly

(Source: Samarins.com)

F.3.6.6 Preliminary Mass-Reduction & Cost Impact Estimates

The mass reductions in this subsystem were gained by the material selection as shown in **Table F.3-18**. The use of an Aluminum AA390 alloy will reduce the weight of the assembly by 65% this application is used by racing component manufacturers to lighten their transmissions and some OEM's with the same intent.

Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea					
			Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
06	00	Oil Pump and Filter Subsystem						
06	01	Oil Pump Asm	C	1.034	$0.90	$0.87	22.26%	0.06%
06	02	Covers	C	0.000	$0.00	$0.00	0.00%	0.00%
06	03	Filters	C	0.000	$0.00	$0.00	0.00%	0.00%
			C	1.034 (Decrease)	$0.90 (Increase)	$0.87 (Increase)	15.84%	0.06%

"+" = mass decrease, "-" = mass increase
"+" = cost decrease, "-" = cost increase

Table F.3-18: Preliminary Subsystem Mass Reduction and Cost Impact Estimates for Launch Clutch System

F.3.7 Mechanical Controls Subsystem

After a systematic investigation it is determined there are no opportunities for mass reduction or cost benefits in this subsystem.

F.3.8 Electrical Controls Subsystem

After a systematic investigation it is determined there are no opportunities for mass reduction or cost benefits in this subsystem.

F.3.9 Parking Mechanism Subsystem

After a systematic investigation it is determined there are no opportunities for mass reduction or cost benefits in this subsystem.

F.3.10 Misc. Subsystem

After a systematic investigation it is determined there are no opportunities for mass reduction or cost benefits in this subsystem.

F.3.11 Electric Motor & Controls Subsystem

After a systematic investigation it is determined there are no opportunities for mass reduction or cost benefits in this subsystem.

F.3.12 Driver Operated External Controls Subsystem

F.3.12.1 Subsystem Content Overview

As seen in **Table F.3-19**, a floor-mounted manual shifter with a steel cable connecting it to the transmission is what is presently in the vehicle, the floor unit itself is plastic and steel. Our proposal will change it to a push button aluminum and plastic control.

Image F.3-7: Shift Module

(Source: FEV, Inc. photo)

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
02	**20**	**00**	**Driver Operated External Controls Subsystem**	
02	20	01	Shift Module Assembly	2.482
			Total Subsystem Mass =	**2.482**
			Total System Mass =	**92.763**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**2.68%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.15%**

Table F.3-19: Mass Breakdown by Sub-subsystem for Driver Operated External Controls Subsystem

F.3.12.2 Toyota Venza Baseline Subsystem Technology

Toyota used their standard floor-mounted shifting system in the Venza. It is made up of a floor console-mounted shift module assembly and a cable assembly that interfaces with the transmission.

F.3.12.3 Mass-Reduction Industry Trends

There are vehicles manufactures in the industry that have adopted the idea of electronic shift controls. One is the Toyota-Tesla Rav4 E, for its light-weight and compact design.

F.3.12.4 Summary of Mass-Reduction Concepts Considered

Table F.3-20 is the compilation of the mass reduction ideas considered for the Driver-operated External Controls subsystem. The presence of more and more electronics is welcomed in today's state-of-the-art vehicles. We will see more electronic innovations in coming models as today's customers expect this in a car.

Component/ Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Shift Module	Replace michanical unit with electronic	70% weight save	New tedhnology low risk higher cost
Shifter Cable	Replaced by a comunication wire	70% weight save	Low risk cost decrease
Shift Cable Bracket	Replaced by a aluminum bracket	30% weight save	Low risk moderate cost increase

Table F.3-20: Summary of Mass-Reduction Concepts Initially Considered for the Driver-Operated External Controls Subsystem,

F.3.12.5 Selection of Mass-Reduction Ideas

The mass-reduction ideas selected from this subassembly fell into the A group and are shown in **Table F.3-21**. Components shown utilizing an electronic control will meet the integrity needs of the system and fulfill the mass-reduction parameters

System	Subsystem	Sub-Subsystem	Description	Mass-Reduction Ideas Selected for Detail Evaluation
2	**20**	**00**	**Driver Operated External Controls Subsystem**	
02	20	01	Shift Module	Replace with Electronic Control

Table F.3-21: Mass-Reduction Ideas Selected for Driver Operated External Controls Subsystem

F.3.12.6 Preliminary Mass-Reduction & Cost Impact Estimates

The mass reductions in this subsystem were gained by replacing Mechanical technology with Electronic as shown in **Table F.3-22**.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
02	**20**	**00**	**Driver Operated External Controls Subsystem**						
02	20	01	Shift Module Assembly	C	1.726	-$29.49	-$17.08	69.55%	0.10%
				C	**1.726** (Decrease)	**-$29.49** (Increase)	**-$17.08** (Increase)	**69.55%**	**0.10%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.3-22: Preliminary Subsystem Mass Reduction and Cost Impact Estimates for Driver Operated External Controls Subsystem

F.3.12.7 Total Mass Reduction and Cost Impact Estimates

Add language in here that summarizes the technologies used in the subsystems and then include the table from the beginning of the document that summarizes the weight and costs.

During the teardown and subsequent evaluation of the Transmission subsystem there were components and materials that were candidates for change.

Materials such as Magnesium, Aluminum, High Strength Steel Alloys and Thermoplastics in our component analysis helped to reduce weight out of our transmission mass. Integrating these materials into the OEM's material used list is the challenge. Only through process development and test will the individual OE's embrace the new materials and components that are available to them in the market place.

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
02	00	00	**Transmission System**						
02	01	00	External Components		0.000	$0.00	$0.00	0.00%	0.00%
02	02	00	Case Subsystem	C	7.745	-$11.03	-$1.42	31.52%	0.45%
02	03	00	Gear Train Subsystem	X	3.490	-$119.68	-$34.29	8.42%	0.20%
02	05	00	Launch Clutch Subsystem	A	4.904	$45.16	$9.21	50.32%	0.29%
02	06	00	Oil Pump and Filter Subsystem	A	1.034	$0.90	$0.87	15.84%	0.06%
02	07	00	Mechanical Controls Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
02	08	00	Electrical Controls Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
02	09	00	Parking Mechanism Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
02	20	00	Driver Operated External Controls Subsystem	X	1.726	-$29.49	-$17.08	69.55%	0.10%
				X	**18.900** (Decrease)	**-$114.15** (Increase)	**-$6.04** (Increase)	**20.37%**	**1.10%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.3-23: Mass-Reduction and Cost Impact for Transmission System 2

F.4A Body Structure Subsystem

F.4A.1 Subsystem Content Overview

The team evaluated the body system of a Toyota Venza using computer-aided engineering (CAE). Noise, vibration, and harshness (NVH) of the vehicle and crash load cases were built based on physical NVH test requirements and regulatory crash and safety requirements respectively. CAE baseline models for each of the NVH and crash-load cases were built and simulated to correlate the CAE results with the test results of a similar vehicle (in this case, the 2009 Toyota Venza with panoramic roof). Upon verifying the model quality based on EDAG CAE guidelines and meeting the correlation targets (<5% difference), the EDAG baseline model was treated as the baseline reference for further development of NVH and crash-iteration models and lightweight optimization processes.

The project scope included the objective of determining lightweight design possibilities of the baseline vehicle. It consisted of optimizing the weight of the baseline model in the areas of body structure, closures, and front bumper. EDAG expertise and standards of lightweight optimization processes were followed throughout the project. The typical lightweight optimization process followed is shown in **Figure F.4A-1**.

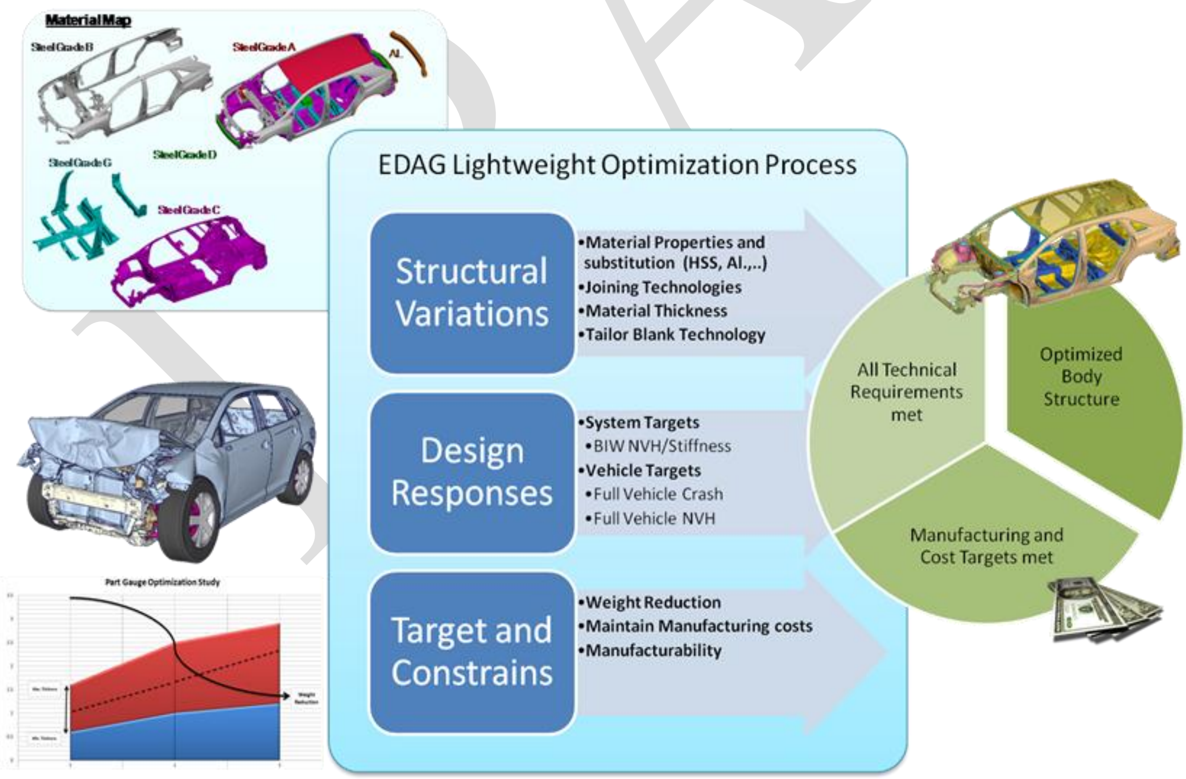


Figure F.4A-1: Lightweight Design Optimization Process

Based on EDAG lightweight optimization process standards and research materials[8]-[17], the following weight reduction strategy was carried out:

- Change material gauges and grades
  - Vary the combinations of part thicknesses and material grades within allowable limits
- Change joining technologies
  - Convert spot-weld connections into laser-weld connections on the body structure
- Apply alternative materials
  - Use aluminum alternatives for panel parts (closures) and bumpers
- Explore alternate manufacturing technologies
  - Use tailor rolled blanks (TRB) instead of tailor welded blanks (TWB)
- Geometry changes
  - Make minimum, if any, design changes needed to meet the performance targets
- Manufacturability constraints
  - Incorporate simultaneously the manufacturability of the parts that are undergoing the changes, in each stage of the optimization process.
- Cost constraints
  - Analyze cost impact due the changes in the optimization process

Even though by redesigning the body parts (geometry change), the potential for weight reduction is increases significantly, since geometry change was not part of the project scope, weight optimization was carried out without undertaking any major design changes.

The final acceptance of the weight reduction options was reviewed to ensure the changes did not impact performance (required to be within 5% of the target). The overall principles followed during the study included:

- Minimize cost impact
- Minimize changes to the components
- Minimize the use of exotic materials
- Minimize the amount of redesign, retooling, or new processing

F.4A.2 Lightweight Design Optimization Process

The lightweight design optimization process involved identifying the components, variables, and constraints to be included in the optimization iteration. A load path analysis (as explained in Appendix B) was conducted on the baseline model to filter out the parts of higher cross-section forces.

The optimization variables and constraints were defined as per EDAG 3G optimization guidelines[2][3]. The variables were gauge (part thickness), grade (material grade), and geometry (part shape). As previously mentioned, geometry change was not included in the optimization; so the entire weight optimization cycle included the following steps:

- Identify components
- Select optimization variables
- Set up optimization model
- Perform computer automated optimization
- Extract optimized design variables (response surface)
- Validate optimized results

F.4A.3 Gauge and Grade Optimization Model

A commercially available computerized optimization tool called HEEDS MDO was used to build the optimization model. The model consisted of 484 design variables, 7 load cases (2 NVH + 5 crash), and 1 cost evaluation. The design variables included 242 gauge variables and 242 grade variables for the identified parts. The load cases selected for optimization were frontal impact with a flat rigid wall barrier, frontal impact with ODB, side impact, roof crush, and rear impact. These load cases were linked in the optimization process in a logical order of structural and crash requirement targets. A typical optimization model built in the HEEDS modeler is shown in **Figure F.4A-2**.

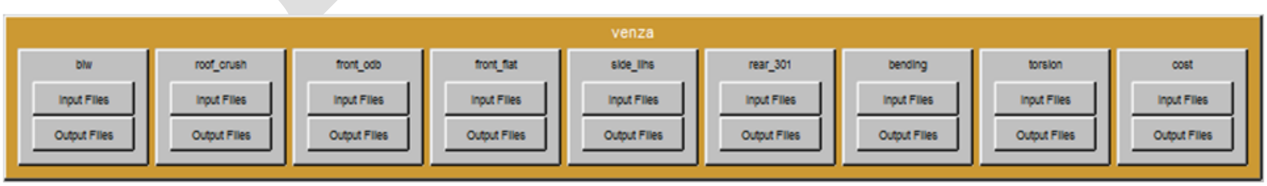


Figure F.4A-2: Toyota Venza Body Weight Optimization Model

The objective, constraints, and responses considered for this optimization model are found in the **Table F.4A-1**.

Objective: Minimize Total Weight			
Parameter	Requirement	Response	Constraints/ Target
Bending Stiffness		Disp. @ Shock tower	< 0.36 mm
Torsion Stiffness		Disp. @ Rocker	< 0.69 mm
Frontal Flat	FMVSS 208	Max. Pulse	35 - 38 G
		Dynamic Crush	< 600 mm
		Max. Dash Intrusion	< 100 mm
Frontal ODB	FMVSS 208	Max. Pulse	35 - 38 G
		Dynamic Crush	< 600 mm
		Max. Dash Intrusion	< 150 mm
Side IIHS	IIHS	Intrusion Gap	> 125 mm
Roof crush	FMVSS 216A	Max. Load	> 47000 N
Rear Impact	FMVSS 301	Zone1 Deformation	< 125 mm
		Zone2 Deformation	> 350 mm
Cost		Total Material Cost	≤ $ 302 (+10%)

Table F.4A-1: Optimization Objective, Response, and Constraints

F.4A.4 Gauge and Grade Optimization Response Surface

The optimizer was set to 500 design iterations with the objective of minimizing the total weight. The optimizer was checked for convergence of the solution in the course of the optimization cycle. After 11 design cycles (24 designs in the first cycle and 20 designs per subsequent cycles), a response surface of 204 designs was found. The response surface obtained for all the load cases was investigated to determine the best optimized design. **Figure F4A-3** shows the response surface output of the optimization cycle.

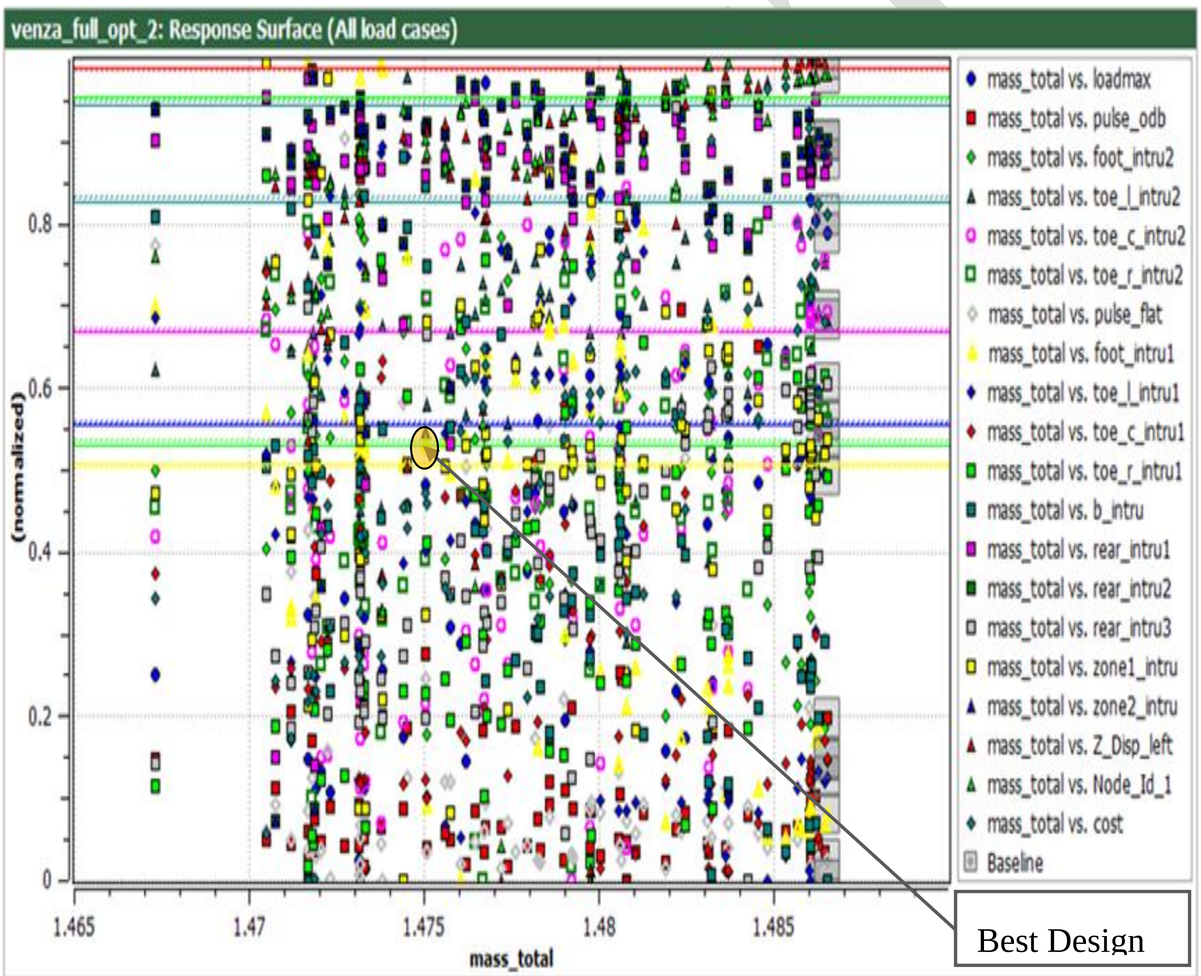


Figure F.4A-3: Response Surface Output from Optimizer

F.4A.5 Gauge and Grade Optimization Results

The optimizer returned the optimized set of design variables and the mass optimized NVH and crash models for bending, torsion, frontal impact, frontal ODB, side impact, roof crush resistance, and rear impact models. The responses output by the optimizer, however, were mathematically predicted. As a result, further CAE simulations were performed using the optimized model to confirm the predicted optimum design met the targets.

F.4A.6 Alternative Joining Technology

In the process of lightweight optimization, an exploration was made into the alternative joining technologies for part assembly. One of the options considered was changing spot welds to laser welds. The potential areas of applying laser welding were identified and the existing spot welds were converted to laser welds. **Figure F.4A-1** represents the areas in green where the spot welds were replaced with laser welds.

Image F.4A-1: Laser Welds Application on Body Structure

F.4A.7 Alternative Materials

Alternative material choices for an automobile's body structure have been one of the recent considerations in building a lightweight vehicle. Aluminum (Al) based materials are proven for their better strength-weight ratio equivalent when compared to steel based materials.[11] They are, therefore, good replacements for the steel grades of bigger panels (Al). Considering the cost and manufacturing constraints, the selected closure and bumper parts were changed to aluminum grade materials.

The thickness was changed by incorporating EDAG expertise and performing further CAE simulations while at the same time also meeting structural and crash performance targets. This option was further supported by the work done by ThyssenKrupp [13] and the Superlight-Car[14] projects. The gauge and material maps of the closure parts are shown in **Images F.4A-2** and **F.4A-3**.

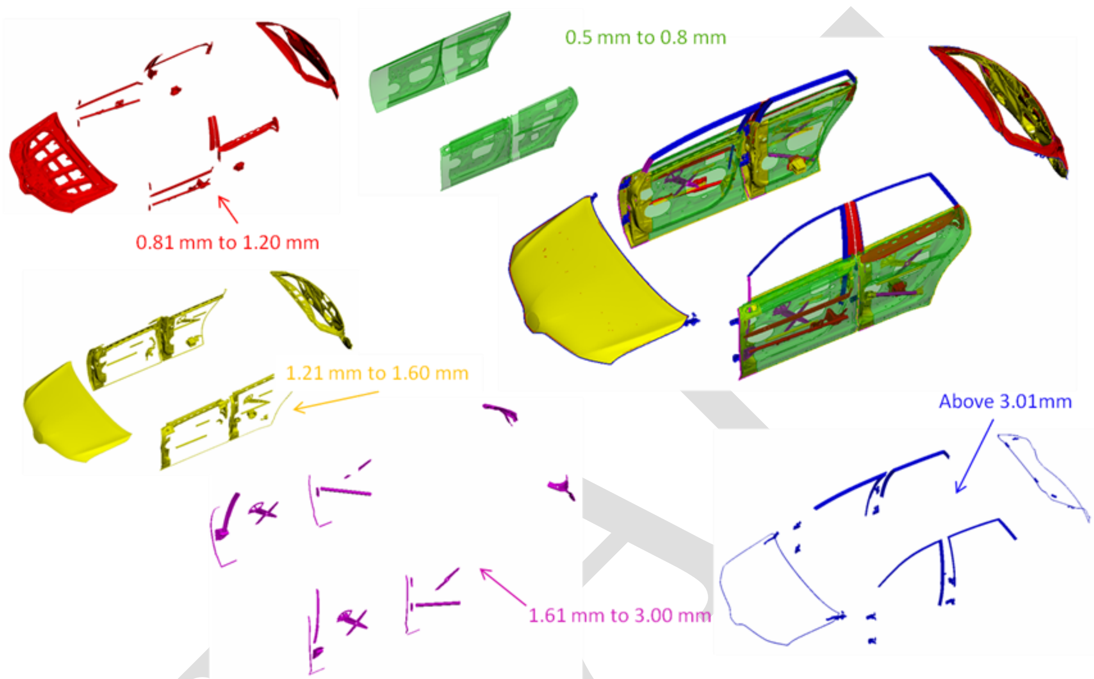


Image F.4A-2: Gauge Map of Optimized Closure parts

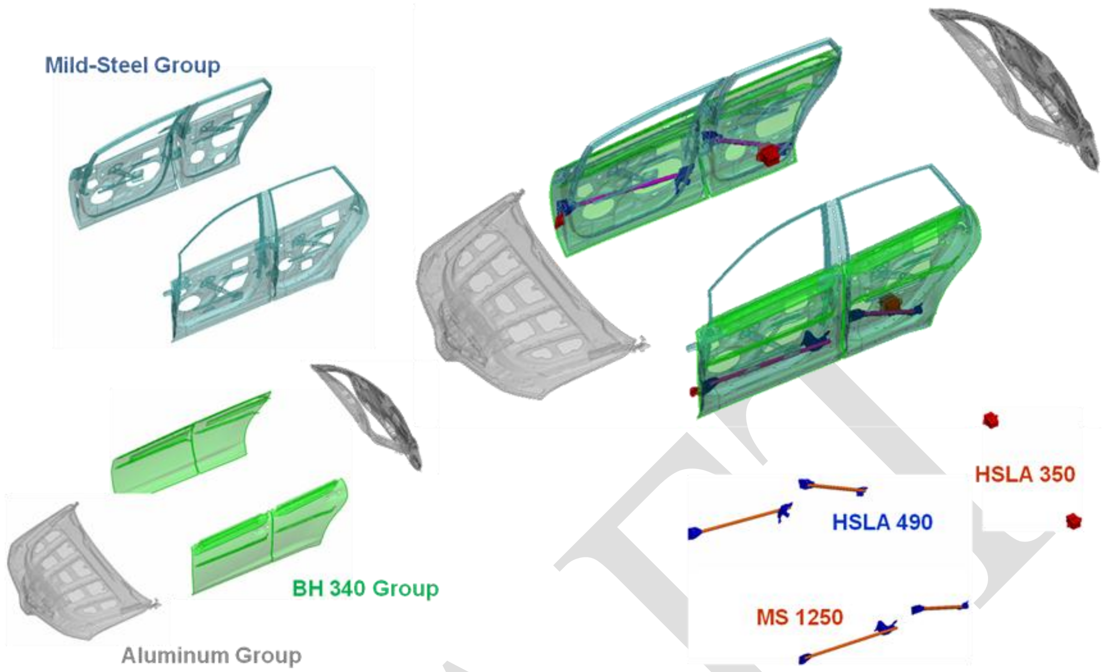


Image F.4A-3: Material Map of Optimized Closure parts

F.4A.8 Alternative Manufacturing Technology

Recent advancements in manufacturing technologies led to the conclusion alternative manufacturing options should also be included in the lightweight design optimization process. One such technology is the manufacturing of hot stamped parts of varied thicknesses using tailor rolled blanks (TRB). In this technology, the blank is prepared by a special rolling process which can produce varied thicknesses along the length of the blank without needing any seam or laser welding or trimming processes. This is considered to achieve better structural strength against weight of the part. For a baseline body structure, the parts of tailored welded blanks (TWB) are good choices. Accordingly, considering the cost impact, potential TWB parts were identified and assessed for the possibility of producing the same parts using TRBs. B-pillar, A-pillar, roof rail, and seat crossmembers are examples of the parts which were assessed using TRB technology. The parts replaced using TRB technology are shown in **Image F.4A-4** and **F.4A-5**.

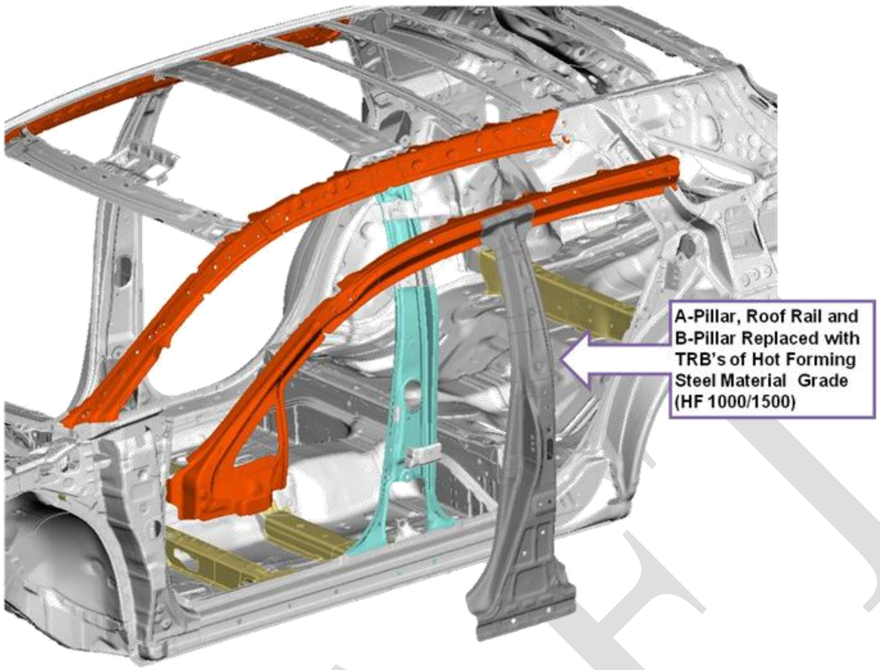


Image F.4A-4: Body Side Parts Replaced with TRB Parts

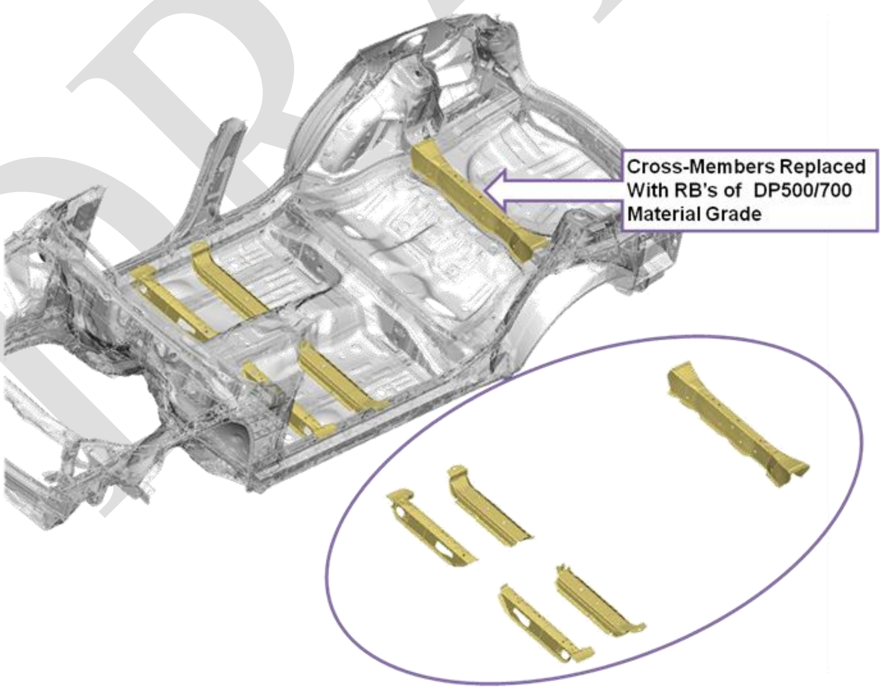


Figure F.4A-5: Crossmembers Replaced with TRB Parts

F.4A.9 Geometry Change

In order to achieve the performance target specifically for the frontal impact load case, the front rail subassembly had to be modified with crush initiators. Vertical slots were introduced on the right side outer front rail. The crush initiators are shown in **Image F.4A-6**.

Image F.4A-6: Design Change on Front Rail Right

Similarly, in order to achieve the performance target for the side impact load case, three bulkhead reinforcements were included in each of the inner rocker of driver and passenger side. The bulkhead reinforcements are shown in **Image F.4A-7**. These design changes improved the frontal crash performance in terms of crash pulse and dash intrusion, and improved side impact performance in terms of an increased intrusion gap.

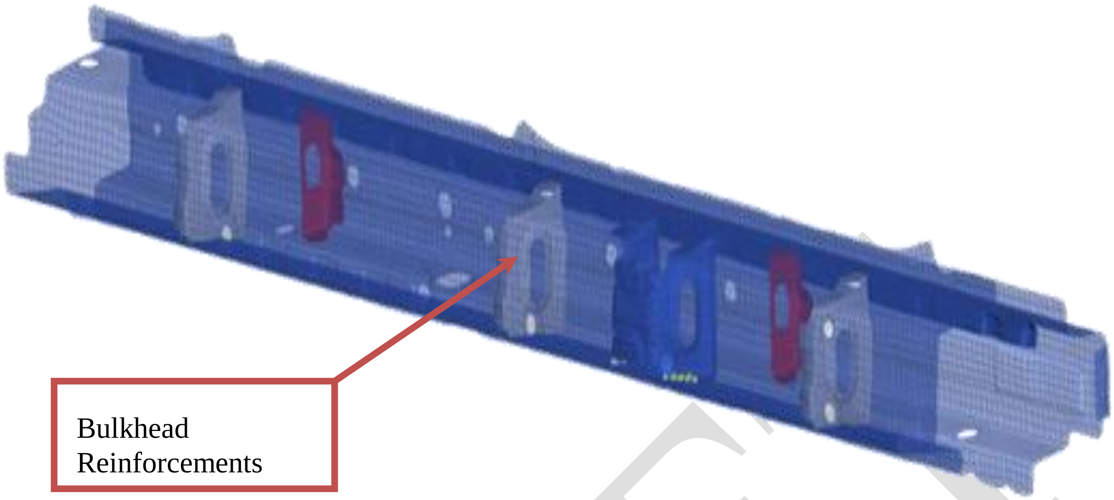


Image F.4A-7: Design Change on Side Inner Rocker (Driver Side)

F.4A.10 Optimized Body Structure

The outcome of the lightweight design optimization included the optimized vehicle assembly and incorporated the following:

- Optimized gauge and material grades for body structure parts
- Laser welded assembly at shock towers, rocker, roof rail, and rear structure subassemblies
- Aluminum material for front bumper, hood, and tailgate parts
- TRBs on B-pillar, A-pillar, roof rail, and seat crossmember parts
- Design change on front rail side members

The optimized gauge and grade map on the Toyota Venza body structure is shown in **Images F.4A-8** and **F.4A-9**.

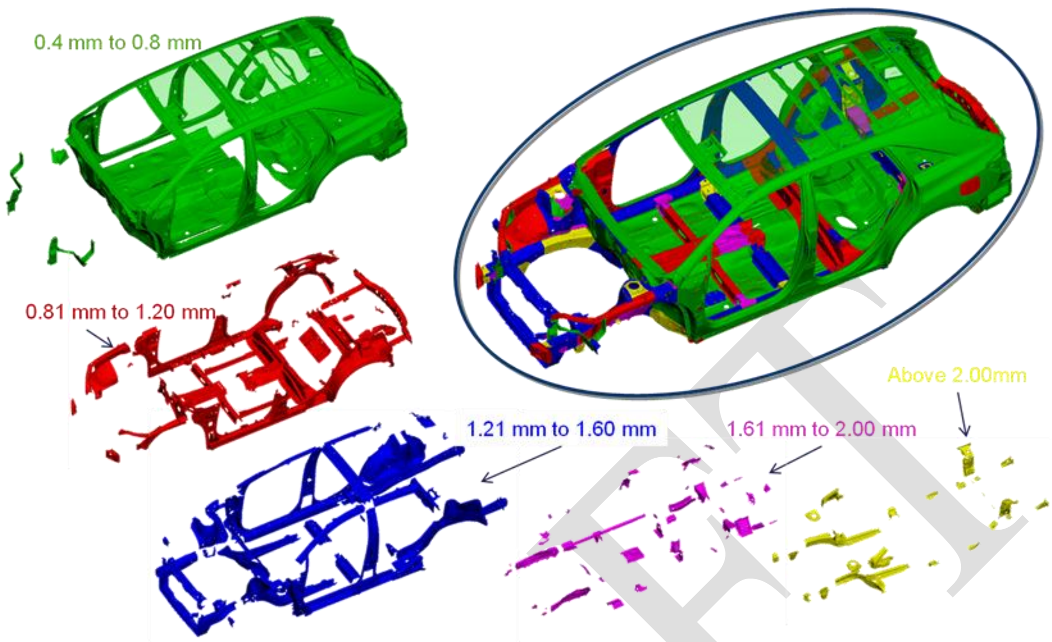


Image F.4A-8: Gauge Map of Optimized Model

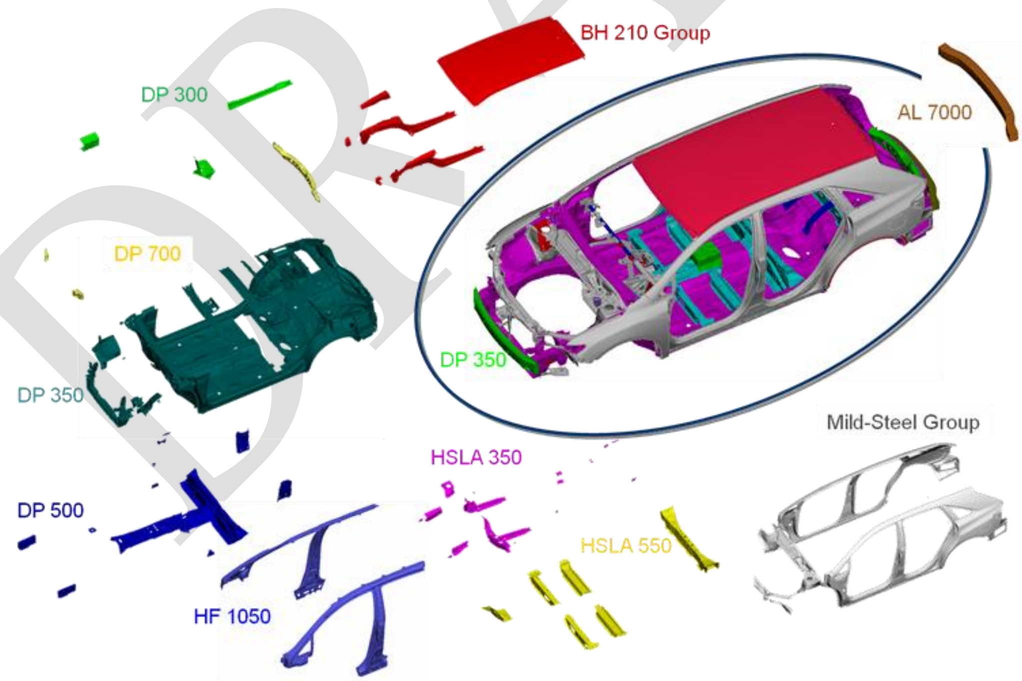


Figure F.4A-9: Material Map of Optimized Model

The major subassembly weights were calculated and tabulated with respect to the baseline weights. **Table F.4A-2** lists the major subassembly weights of the optimized model against the baseline model.

Area		Baseline		Final Optimzied Model		Weight Reduced Percentage
System	Sub-system	System Mass	Sub-Total	System Mass	Sub-Total	
Closures	Door Frt	53.2		53.2		
	Door RR	42.4		42.4		
	Hood	17.8		10.1		
	Tailgate	15.0		7.7		
	Fenders	6.8		4.9		
	Sub-Total		135.3		118.3	13%
BIW	Underbody Asy	40.2		32.0		
	Front Structure	42.0		36.2		
	Roof Asy	31.3		24.1		
	Bodyside Asy	161.9		141.5		
	Ladder Asy	102.6		90.2		
	Sub-Total		378.0		324.0	14%
BIW Extra	Radiater Vertical Support	0.7		0.7		
	Compartment Extra	4.5		3.2		
	Shock Tower Xmbr Plates	3.1		4.4		
	Sub-Total		8.2		8.3	-2%
Bumper	Bumper frt	5.1		4.7		
	Bumper rear	2.4		2.4		
	Sub-Total		7.5		7.1	5%
Edag Target System Total			528.9		457.7	13%

Table F.4A-2: Optimized Weights

The UVW of the optimized model was 1,403 .1 kg, which includes a combined 13% weight reduction from BIW, closures, and bumper parts (**Table F.4A-2**). It also includes a 20% mass reduction of the rest of the non-structural parts. This 20% reduction is an estimated weight reduction from trim and non-structural parts. (See **Appendix D** - by FEV)

The final weight distribution of the optimized full vehicle is tabulated in **Table F.4A-3**, showing the UVW of baseline and optimized models.

Area	Baseline Model	Final Optimzied Model	Weight Reduced Percentage
System	Sub-Total (kg)	Sub-Total (kg)	
FEV Systems - Chassis - Powertrain - Electrical - Body Interior	1181.7	945.4	20%
Edag Target System Total	528.9	457.7	13%
Closures - Door Frt - Door RR - Hood - Tailgate - Fenders	135.3	118.3	13%
BIW - Underbody Asy - Front Structure - Roof Asy - Bodyside Asy - Ladder Asy	378.0	324.0	14%
BIW Extra - Radiater Vertical Support - Compartment Extra - Shock Tower Xmbr Plates	8.2	8.3	-2%
Bumper - Front - Rear	7.5	7.1	5%
UVW	1710.6	1403.1	18%

Table F.4A-3—Final Weight Summary for Optimized Vehicle

From this it can be seen that an overall 18% weight reduction was achieved by weight optimization.

F.4A.11 Optimized Results

The optimization outcome was validated by carrying out further NVH and crash simulations on the optimized model. The optimized NVH and crash models were directly carried over from the optimizer and appropriate load cases were set up. The following sections explain the NVH and crash model results in comparison to the baseline results.

F.4A.11.1 NVH Performance Results

The NVH model (containing only BIW parts and a few bolt-on parts as explained earlier) was once again subjected to static bending, static torsion, and modal frequency simulations by incorporating the optimization outcome. **Table F.4A-4** lists the results of the optimized model for bending stiffness, torsion stiffness, and modal frequency load cases.

Study Description	Overall Torsion Mode (Hz)	Overall Lateral Bending Mode (Hz)	Rear-End Match-Boxing Mode (Hz)	Overall Vertical Bending, Rear-End Breathing Mode (Hz)	Torsion Stiffness (KN.m/rad)	Bending Stiffness (KN/m)	Weight Test Condition (Kg)	Weight BIW (Kg)	Comments
EDAG CAE Model (Full Roof) Baseline Model	54.6	34.3	32.4	41.0	1334.0	18204.5	407.7	378.0	CAE Model of 2010 Full Roof Venza Baseline Vehicle
EDAG CAE Optimized Model	52.2	32.7	33.5	40.6	1333.8	17458.2	356.9	323.9	Optimized CAE Model Vehicle Configuration Same as Baseline
Percentage Change	-4.4	-4.7	3.4	-1.0	0.0	-4.1	-12.5	-14.3	Comparison between Baseline and Optimized Model

Table F.4A-4—NVH Results Summary for Optimized BIW Model

From the table it can be seen the NVH performance of the optimized CAE model is very similar to the baseline model in terms of modal analysis, whereas torsion and bending stiffness meet the <5% comparison error requirement. The optimized model reflects an overall reduction in stiffness due to gauge reduction throughout the BIW structure. This reduction was considered acceptable relative to the amount of weight saving.

The total weight reduction in the optimized BIW is about 14.3% when compared to the BIW weight of the baseline model.

F.4A.11.2 Crash Performance Results

The optimized crash model was validated further for the following five different crash load cases and compared with the results of baseline models respectively.

1) FMVSS 208—35 MPH flat frontal crash (US NCAP),
2) Euro NCAP—35 MPH ODB frontal crash (Euro NCAP/IIHS),
3) FMVSS 214—38.5 MDB side impact,

4) FMVSS 301—50 MPH MDB rear impact,

5) FMVSS 216a—Roof crush resistance (utilizing the more stringent IIHS roof crush resistance requirement).

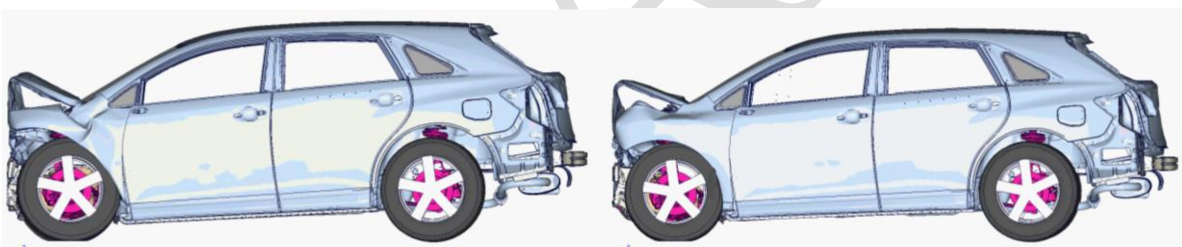
The model set up and test requirements were maintained consistent to that of EDAG baseline models, as explained earlier.

F.4A.11.2.1 FMVSS 208—35 MPH flat frontal crash (US NCAP)

Deformation Mode

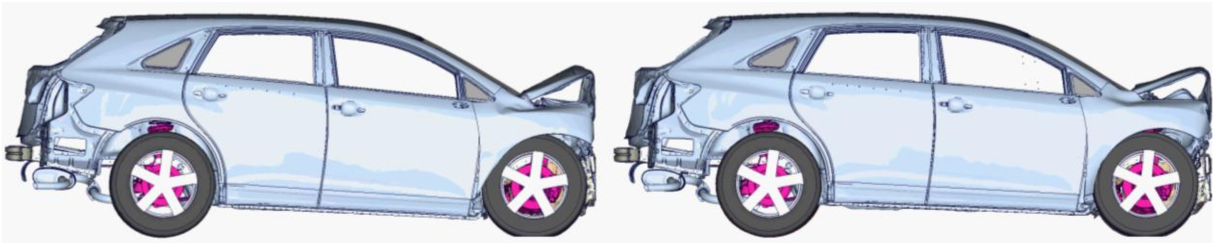
The deformation modes at 100 msec (end of crash event) of the optimized model were compared to that of the baseline model. The deformation modes are presented in **Images F.4A-10** to **F.4A-13**. The left-hand side illustrations show the deformation modes of the baseline model and the right-hand side illustrations show the deformation modes of the optimized model.

Observing the exterior vehicle deformation mode comparisons in different views, the optimized model shows similar characteristics in structural deformation.



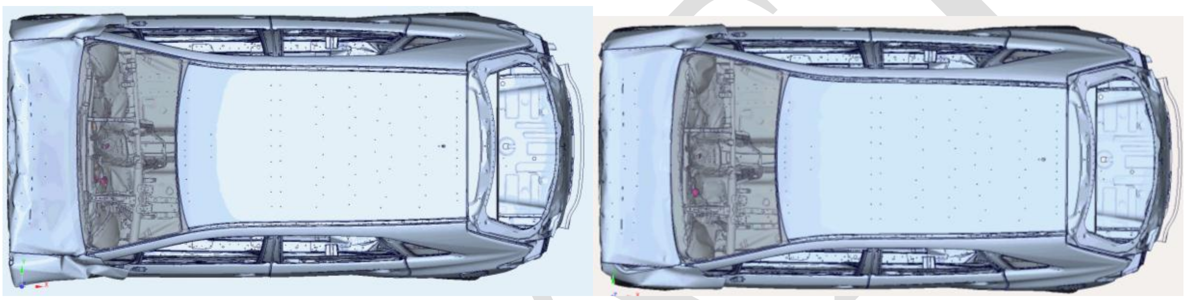
Baseline Optimized

Image F.4A-10: Deformation Mode Left Side View @ 100msec



Baseline Optimized

Image F.4A-11: Deformation Mode Right Side View @ 100msec



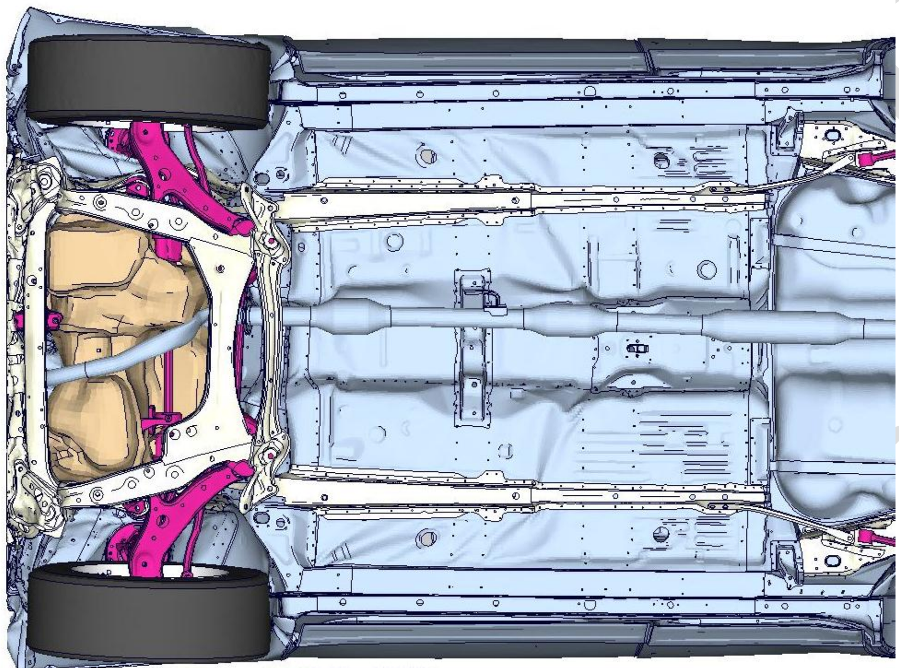
Baseline Optimized

Figure F.4A-12: Deformation Mode Top Side View @ 100msec

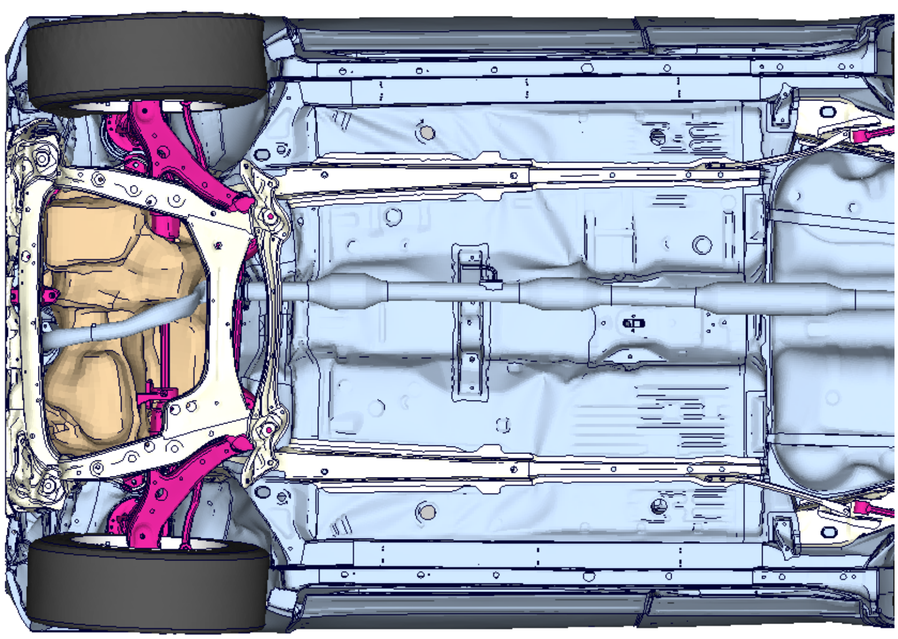
Baseline Optimized

Figure F.4A-13: Deformation Mode Top Side View @ 100msec

The underbody structural deformation modes are compared as shown in **Image F.4A-14**. It is observed the optimized model shows the same level of deformation as that of the baseline target. The engine compartment was well protected from significant deformation in both the optimized and baseline models. From the deformation modes, it is also noted the crush energy is absorbed by the engine compartment, rails, and front cradle. The remaining crush is transferred to understructure members without any major failure on the engine compartment under-ladder structure.



Baseline

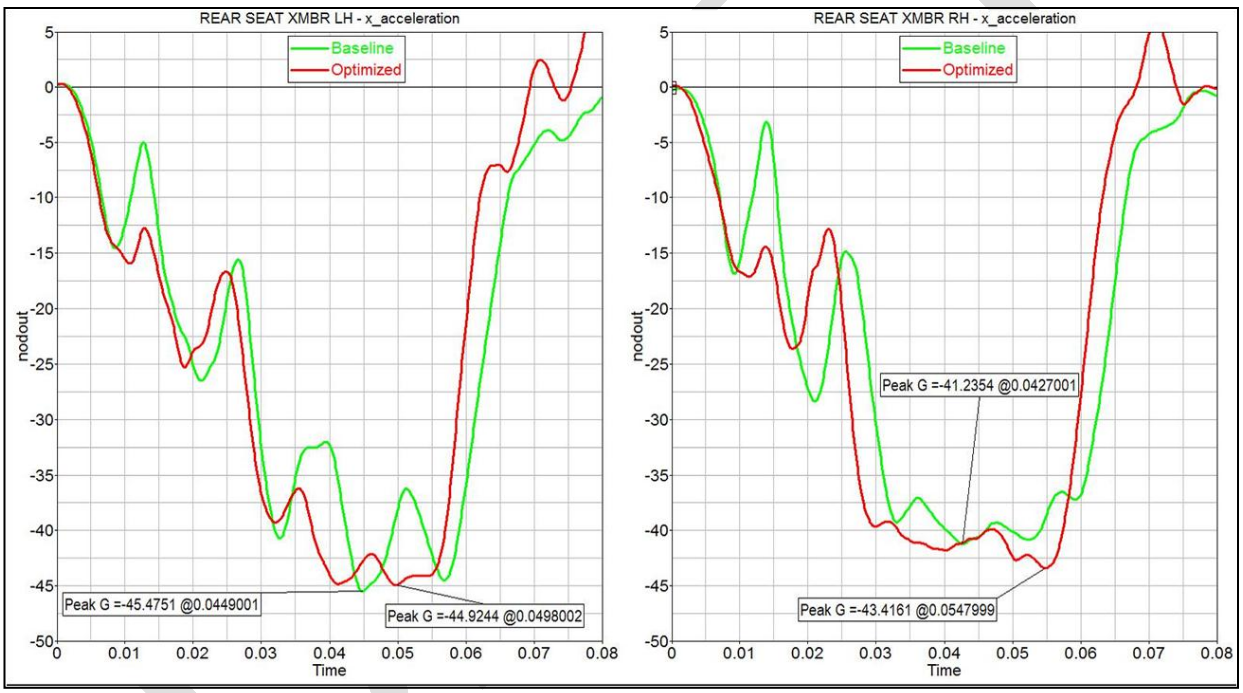


Optimized

Image F.4A-14: Deformation Mode Top Side View @ 100msec

Crash Pulse

The velocity was differentiated to get pulses: 44.9G for the driver side and 43.4G for the passenger side. The baseline model pulses are 45.5G and 41.2G for the driver and passenger sides, respectively. **Figure F.4A-4** shows the pulse comparison between the optimized model and the baseline model. For the final optimized model, the vehicle velocity was measured at the driver and passenger side rear seat cross members, respectively.



Driver side

Passenger side

___ Optimized (Average pulse 44.2G)

___ Baseline (Average pulse 43.4G)

Figure F.4A-4—Vehicle Pulse Comparison Baseline vs. Optimized

The optimized model pulse, then, met the performance target requirement of baseline model within a <5% difference.

Dynamic Crush and Dash Intrusions

The deformation indicator of the vehicle structure dynamic crush is compared as shown in **Figure F.4A-5**. The optimized model shows a shorter dynamic crush (565.0 mm) than that of the baseline model (600.9 mm) at the same level of body pulse. This is an improvement from the baseline model showing better structural performance: It indicates the optimized model retains a good level of vehicle dynamic stiffness even though there is significant mass reduction.

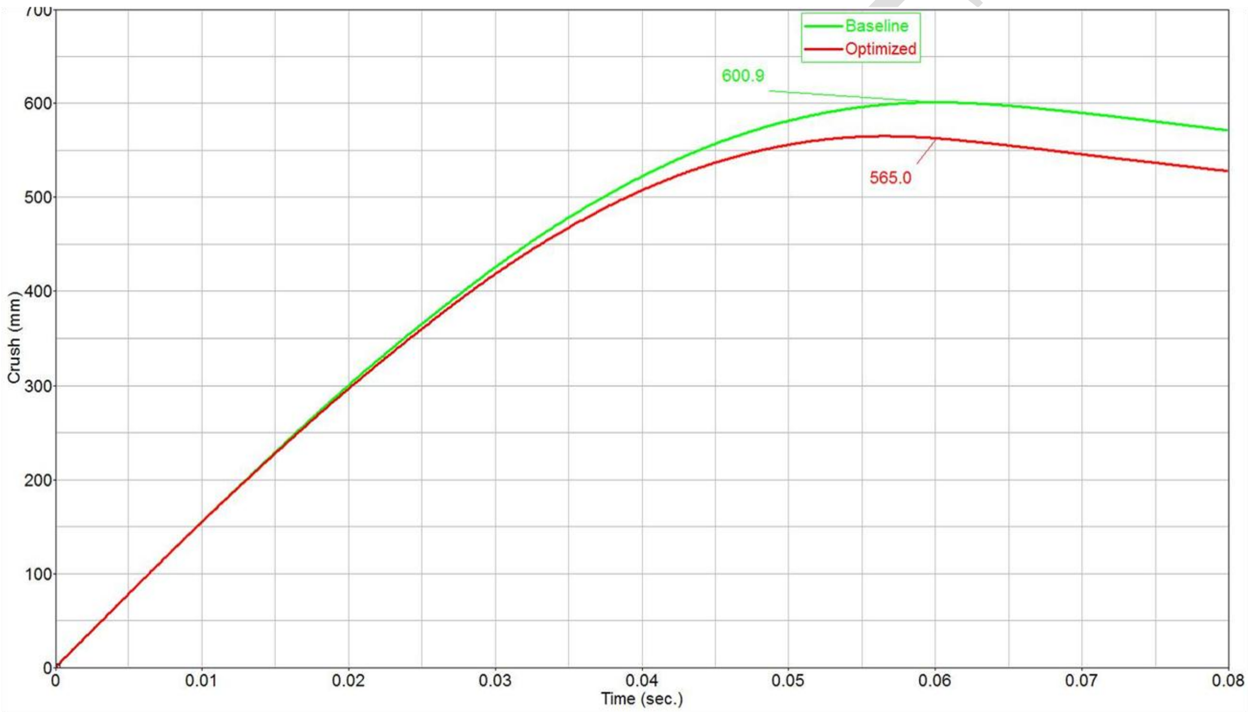


Figure F.4A-5: Dynamic Crush Comparison Baseline vs. Optimized

Another parameter of structural performance comparison is the time-to-zero velocity (TTZV). TTZV is the time measured when the vehicle approaches zero velocity during impact. The TTZV plot is shown in **Figure F.4A-6**.

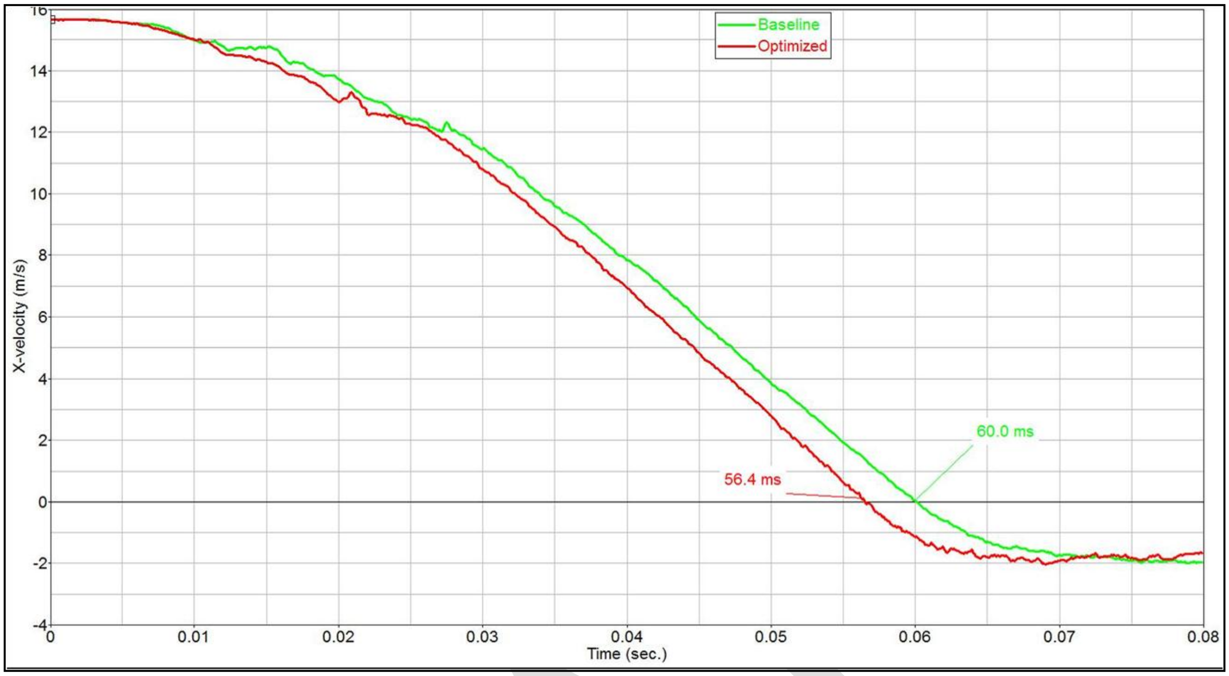


Figure F.4A-6: TTZV Comparison Baseline vs. Optimized

The TTZV of the optimized model (56.4 msec) is less than that of the baseline model (60.0 msec), showing a positive tendency for improved front-end stiffness.

For comparison purposes, the dash intrusions also were measured and are summarized in **Table F.4A-5**.

Vehicle	Driver Footwell (mm)	Driver Toe pan Left (mm)	Driver Toe pan center (mm)	Driver Toe pan Right (mm)
Baseline	58.8	137.1	157.1	102.9
Optimized	19.9	43.1	74.1	82.4

Table F.4A-5—Dash Intrusion Comparison Baseline vs. Optimized

In the case of the optimized model, the dash panel footwell and toe pan intrusions were significantly reduced when compared to that of the baseline model. This also indicates the optimized model met the regulatory requirements (intrusions should be <100mm)[19] and baseline targets, including improvements in the structural performance.

F.4A.11.2.2 Euro NCAP—35 MPH ODB Frontal Crash (Euro NCAP/IIHS)

Deformation Mode

The deformation modes at 100 msec (end of crash event) of the optimized model were compared to that of the baseline model. The deformation modes are presented in **Images F.4A-15** to **F.4A-17**. The left-hand side illustrations show the deformation modes of the baseline model and the right-hand side illustrations show the deformation modes of the optimized model.

Observing the exterior vehicle deformation mode comparisons in different views, the optimized model shows similar characteristics of structural deformation.

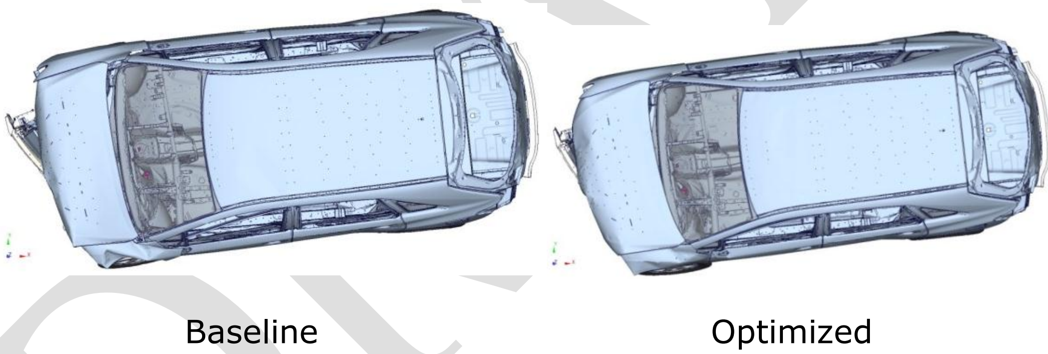
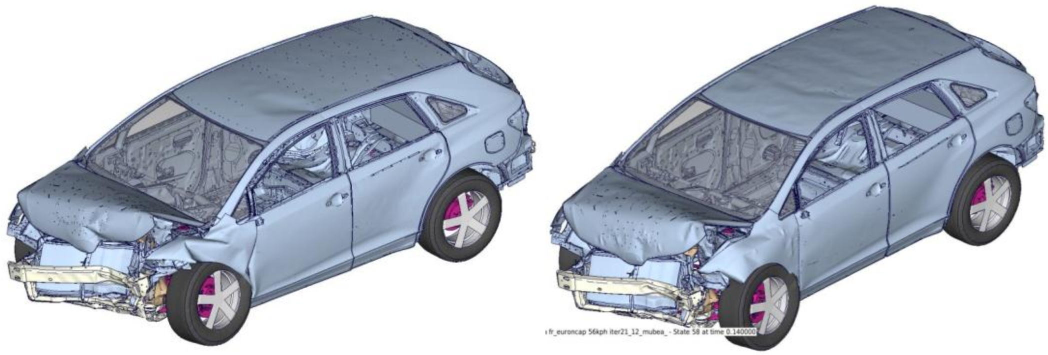
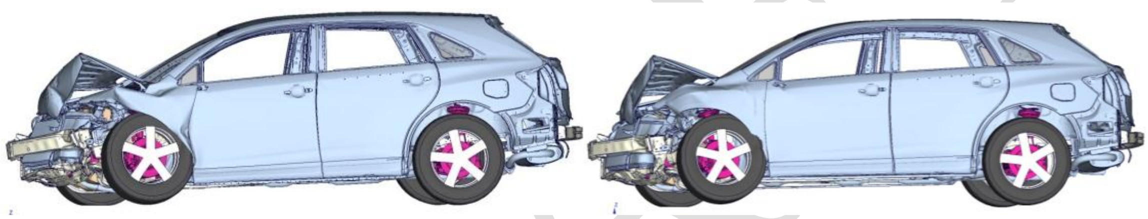


Image F.4A-15: Deformation Mode Top View @ 140msec



Baseline Optimized

Image F.4A-16: Deformation Mode ISO View @ 140msec



Baseline Optimized

Image F.4A-17: Deformation Mode Left Side View @ 140msec

The underbody structural deformation modes are compared as shown **Images F.4A-18** and **F.4A-19** where it can be seen the optimized model shows the same level of deformation as that of the baseline target. The compartment area is well protected from significant deformation in both the optimized and baseline models. From the deformation modes, it is also noted the crush energy is absorbed by the engine compartment, rails, and front cradle. The remaining crush is transferred to understructure members without any major failure on the compartment under-ladder structure.

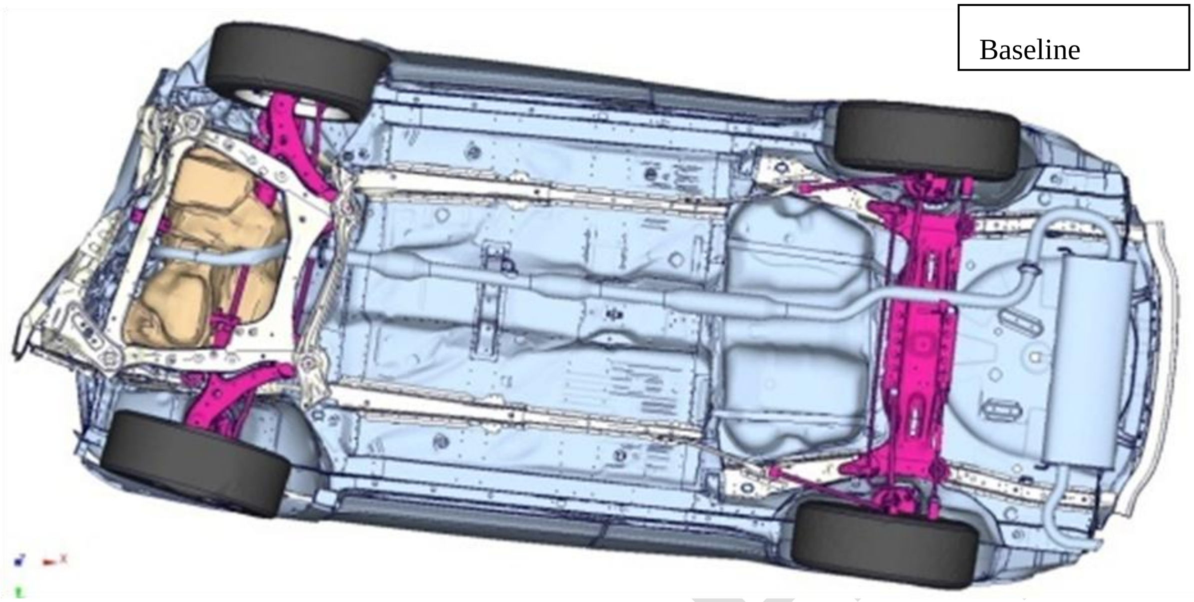


Image F.4A-18: Deformation Mode Bottom View @ 140msec - Baseline

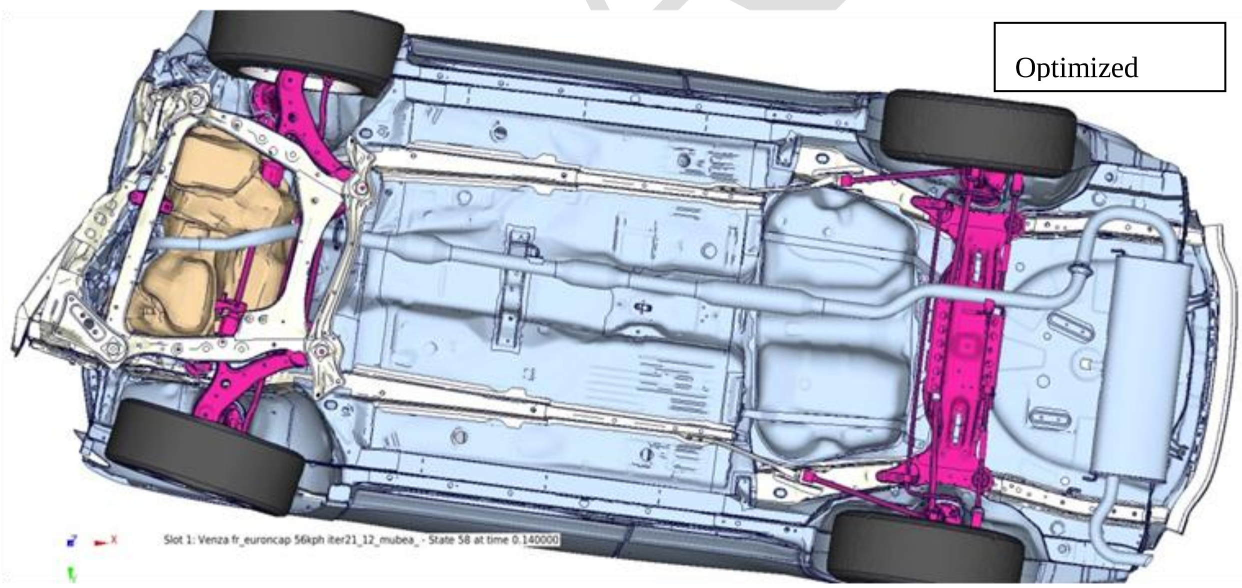
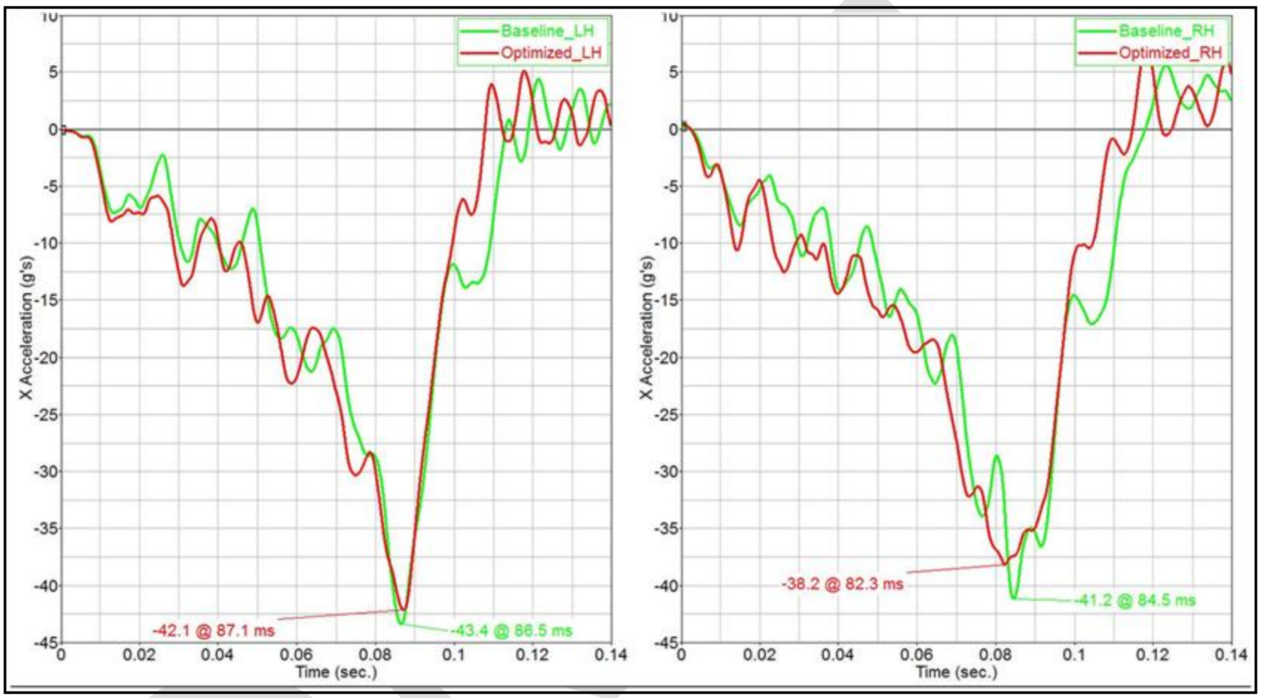


Figure F.4A-19: Deformation Mode Bottom View @ 140msec – Optimized

Crash Pulse

Figure F.4A-7 shows the pulse comparison between the optimized model and the baseline model. For the final optimized model, the vehicle acceleration pulse target was achieved as <42G for driver side and passenger side, measured at driver and passenger side rear-seat crossmembers respectively.



Driver

Passengerer

___ Optimized (Average pulse 40.2G)

Baseline (Average pulse 42.4G)

Figure 1.9.26—Body Pulse Comparison Baseline vs. Optimized

In this case, the optimized model shows a slightly better performance than the baseline model in terms of crash pulse.

F.3.12.7.1 <u>Dynamic Crush</u>

The deformation indicator of the vehicle structure dynamic crash is compared in Figures 1.9.27 and 1.9.28. The total dynamic crush shown in Figure 1.9.27 includes the barrier deformation, also consistent for comparison purposes. Subtracting the barrier deformation from the total crush (shown in Figure 1.9.28), the optimized model shows a shorter dynamic crush (565.0 mm) than that of the baseline model (600.9 mm) at the same level of body pulse. This is an improvement from the baseline model showing better structural performance: It indicates the optimized model retains a good level of vehicle dynamic stiffness even though there is significant mass reduction.

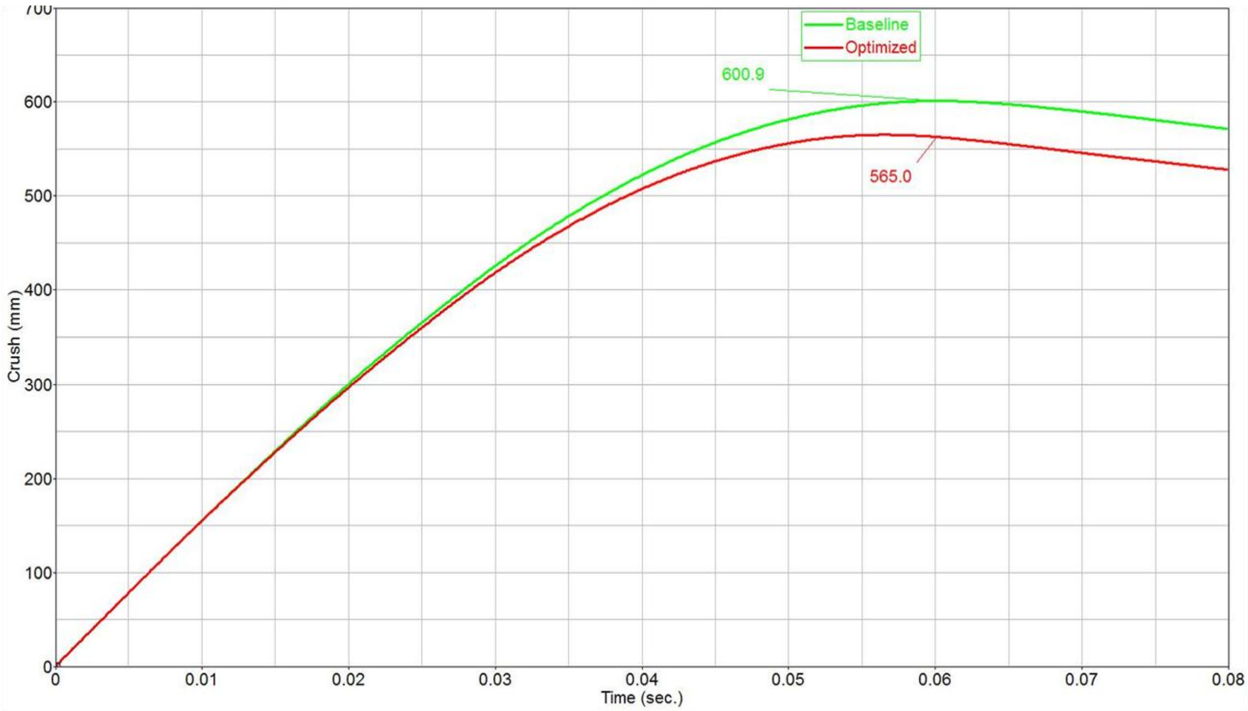


Figure F.4A-7: Dynamic Crush Comparison Baseline vs. Optimized

Another parameter of structural performance comparison is the time-to-zero velocity (TTZV). TTZV is the time measured when the vehicle approaches zero velocity during impact. The TTZV plot is shown in **Figure F.4A-8**.

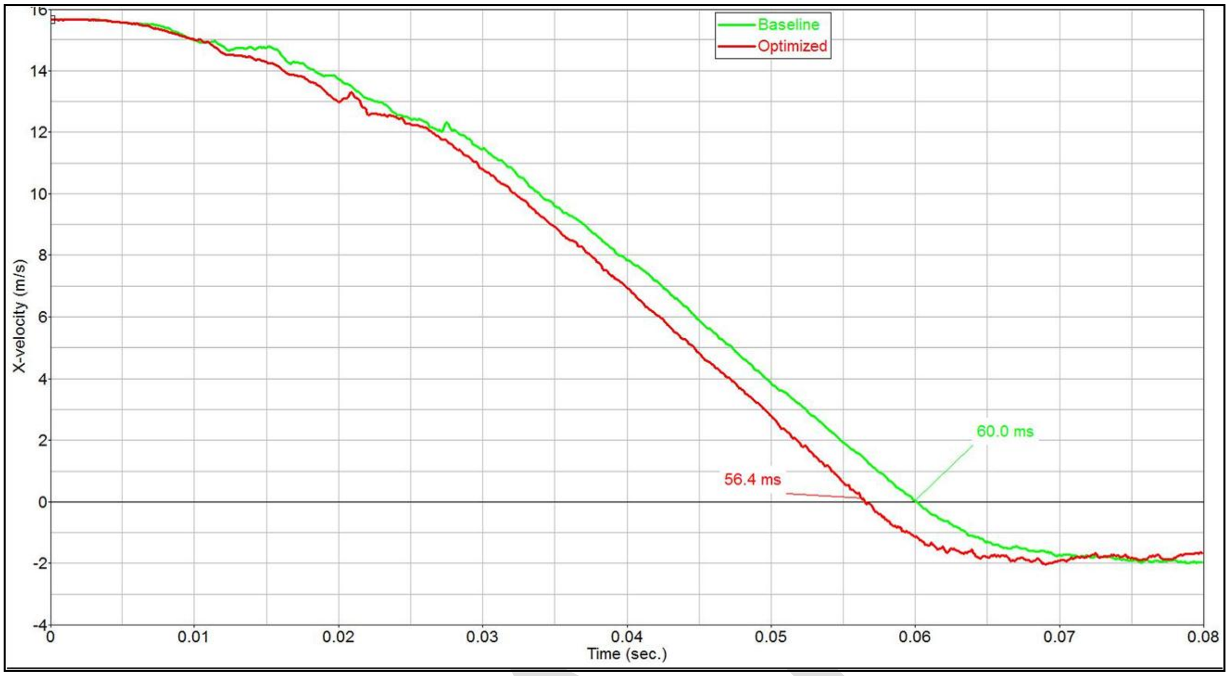


Figure F.4A-8: TTZV Comparison Baseline vs. Optimized

The TTZV of the optimized model (56.4 msec) is less than that of the baseline model (60.0 msec), showing a positive tendency for improved front-end stiffness.

For comparison purposes, the dash intrusions also were measured and are summarized in **Table F.4A-6**.

Vehicle	Driver Footwell (mm)	Driver Toe pan Left (mm)	Driver Toe pan center (mm)	Driver Toe pan Right (mm)
Baseline	58.8	137.1	157.1	102.9
Optimized	19.9	43.1	74.1	82.4

Table F.4A-6: Dash Intrusion Comparison Baseline vs. Optimized

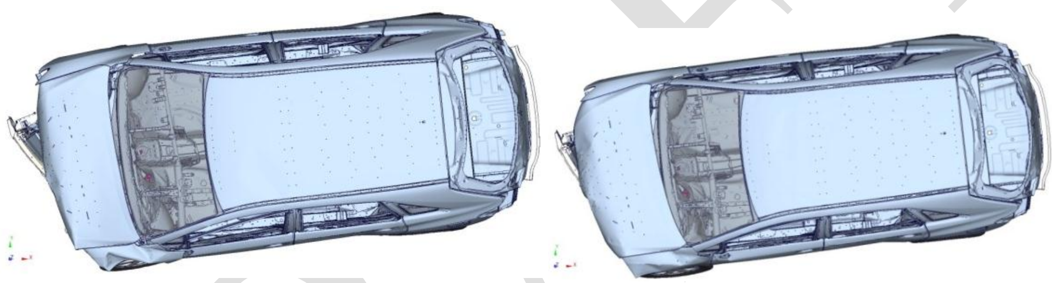
In the case of the optimized model, the dash panel footwell and toe pan intrusions were significantly reduced when compared to that of the baseline model. This also indicates the optimized model met the regulatory requirements (intrusions should be <100mm)[19] and baseline targets, including improvements in the structural performance.

F.4A.11.2.3 Euro NCAP—35 MPH ODB Frontal Crash (Euro NCAP/IIHS)

Deformation Mode

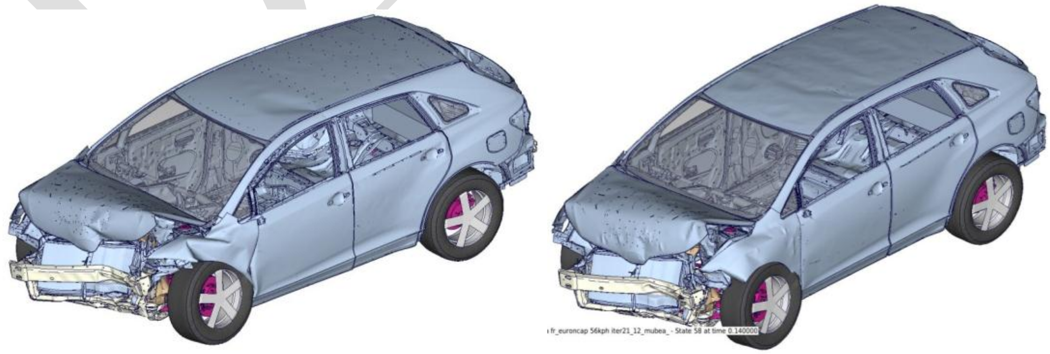
The deformation modes at 100 msec (end of crash event) of the optimized model were compared to that of the baseline model. The deformation modes are presented in **Images F.4A-20** to **F.4A-22**. The left-hand side illustrations show the deformation modes of the baseline model and the right-hand side illustrations show the deformation modes of the optimized model.

Observing the exterior vehicle deformation mode comparisons in different views, the optimized model shows similar characteristics of structural deformation.



Baseline Optimized

Image F.4A-20: Deformation Mode Top View @ 140msec



Baseline Optimized

Image F.4A-21: Deformation Mode ISO View @ 140msec

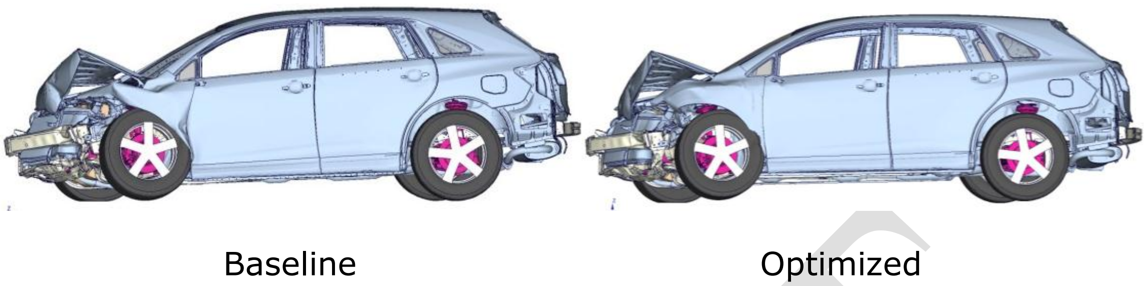


Image F.4A-22: Deformation Mode Left Side View @ 140msec

The underbody structural deformation modes are compared as shown **Figures F.4A-23** and **F.4A-24** where it can be seen the optimized model shows the same level of deformation as that of the baseline target. The compartment area is well protected from significant deformation in both the optimized and baseline models. From the deformation modes, it is also noted the crush energy is absorbed by the engine compartment, rails, and front cradle. The remaining crush is transferred to understructure members without any major failure on the compartment under-ladder structure.

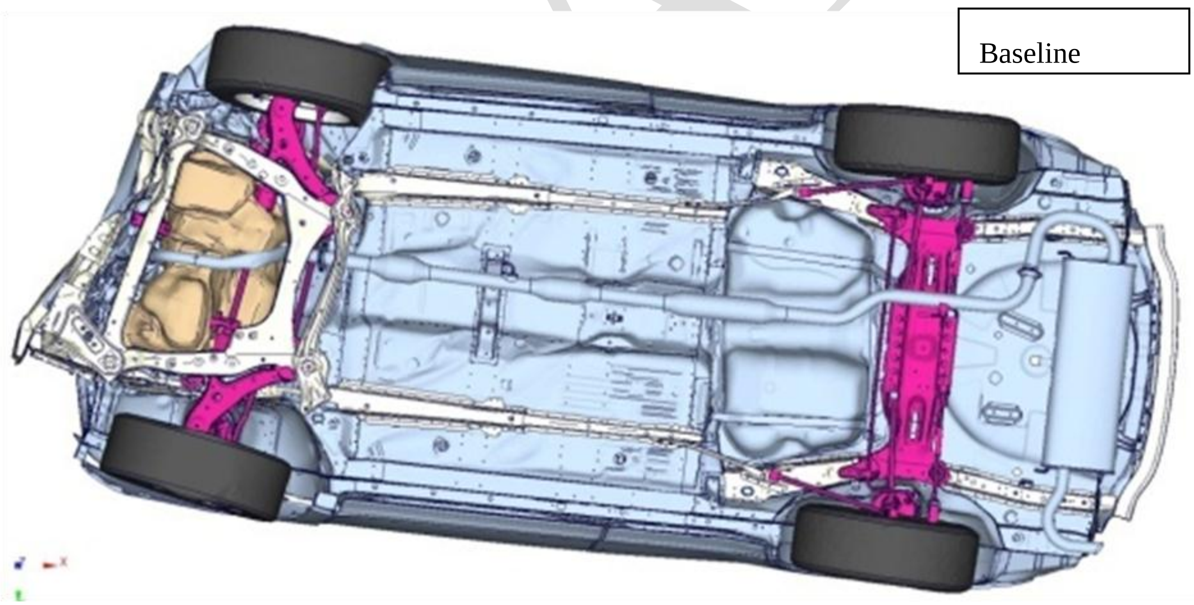


Image F.4A-23: Deformation Mode Bottom View @ 140msec - Baseline

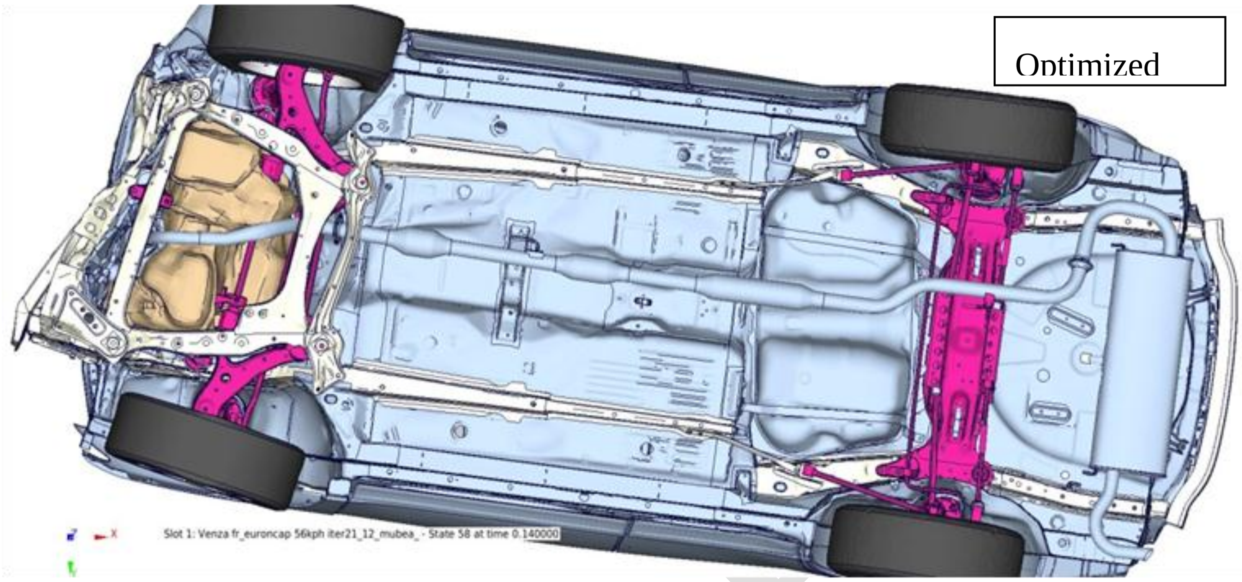


Image F-4A-24: Deformation Mode Bottom View @ 140msec – Optimized

Crash Pulse

Image F.4A-25 shows the pulse comparison between the optimized model and the baseline model. For the final optimized model, the vehicle acceleration pulse target was achieved as <42G for driver side and passenger side, measured at driver and passenger side rear-seat crossmembers respectively.

A summary of Euro NCAP performance measurements is provided in Tables F.4A-6 and F.4A-7.

No.	Frontal crash Measurements	Baseline	Optimized
1	Dynamic Crush (mm)	1071.2	1006.0
2	UVW Weight (kg)	1710.6	1403.1

Table F.4A-7: Dynamic Crush, Baseline vs. Optimized Model for Euro NCAP

Vehicle	Driver Footrest (mm)	Driver Toe pan Left (mm)	Driver Toe pan center (mm)	Driver Toe pan Right (mm)
Baseline	133.7	171.2	169.9	75.9
Optimized	32.3	51.5	59.4	23.8

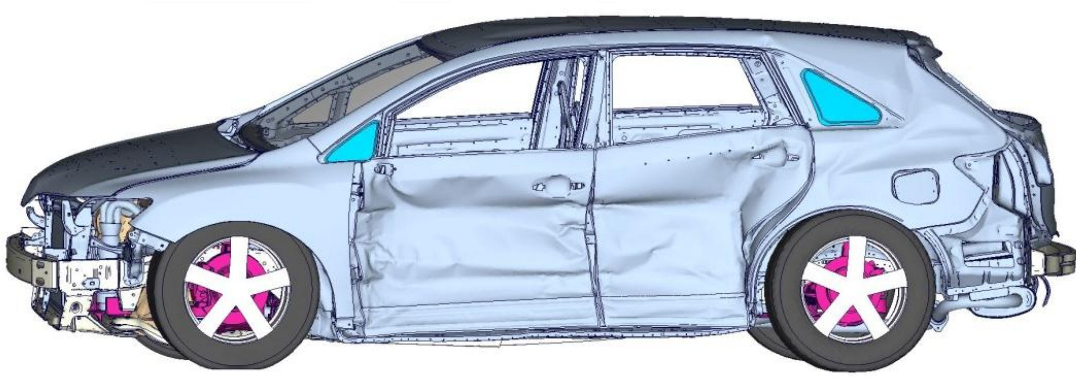
Table F.4A-8: Dash Intrusions, Baseline vs. Optimized Model for Euro NCAP

Based on the analysis, the optimized model meets the frontal offset impact performance requirements.

F.4A.11.2.4 FMVSS 214—38.5 MPH MDB side impact

Deformation Mode

The deformation modes of the side impact optimized model and the baseline model are shown in **Images F.4A-25** to **F.4A-27**. **Image F.4A-25** shows the global deformation of the driver side. It indicates both the baseline and the optimized models have similar deformation.

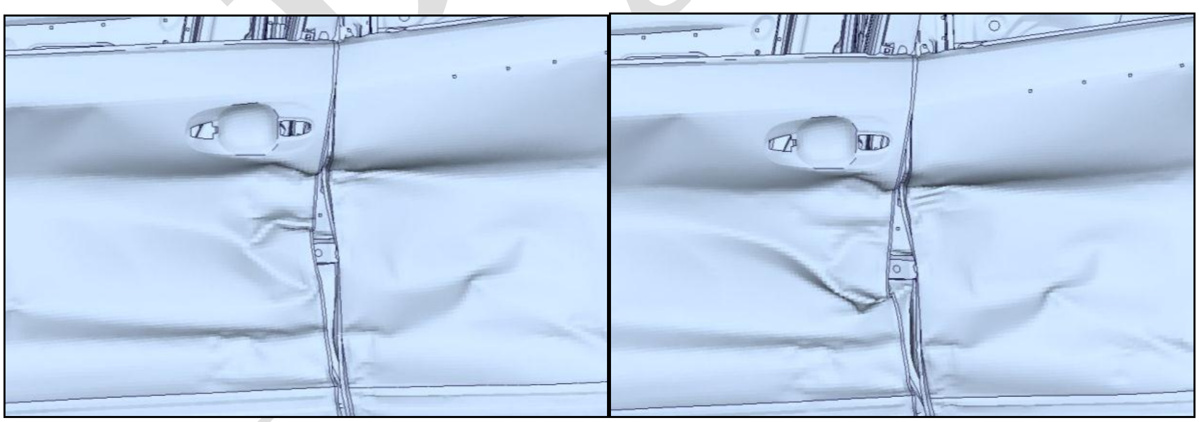


Baseline Model

Optimized Model

Figure F.4A-25: Global Deformation Modes of Baseline and Optimized Models

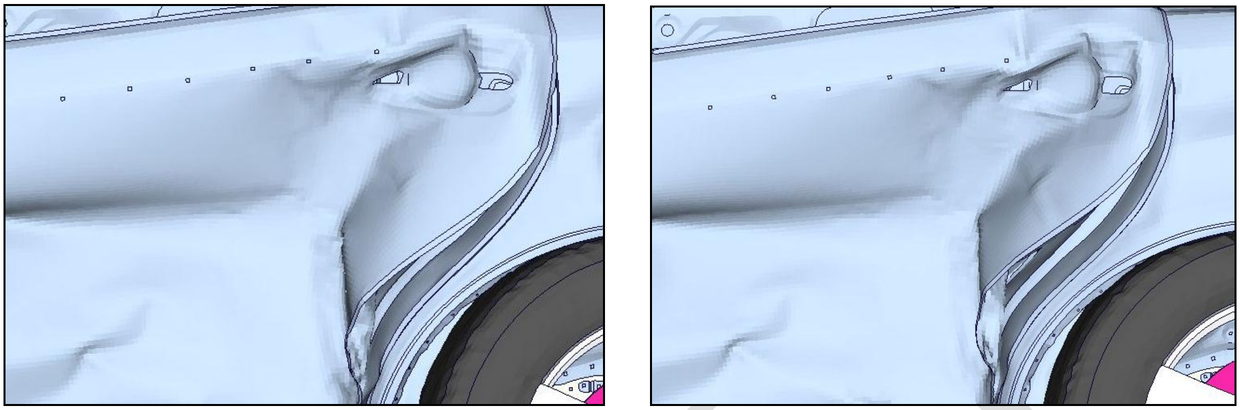
Image F.4A-26 shows front and rear door deformation modes at the impact area of B-pillar. It is observed the optimized model shows similar characteristics of deformation at the impact area.



Baseline Optimized

Image F.4A-26—Deformation Modes of Front and Rear Doors of Baseline and Optimized Models

Similarly, **Image F.4A-27** shows the same characteristics of rear door aperture area deformations for both the baseline and the optimized models.



Baseline Optimized

Image F.4A-27—Rear Door Aperture Deformations of Baseline and Optimized Models

Body Intrusion

The key performance requirement of the side structure intrusion of the optimized model was compared with the baseline model. **Image F.4A-28** shows a relative intrusion of the optimized model at the B-pillar and side rocker sections with respect to the undeformed model. The sectional contour in red indicates the deformed shape and the sectional contour in black indicates the undeformed shape.

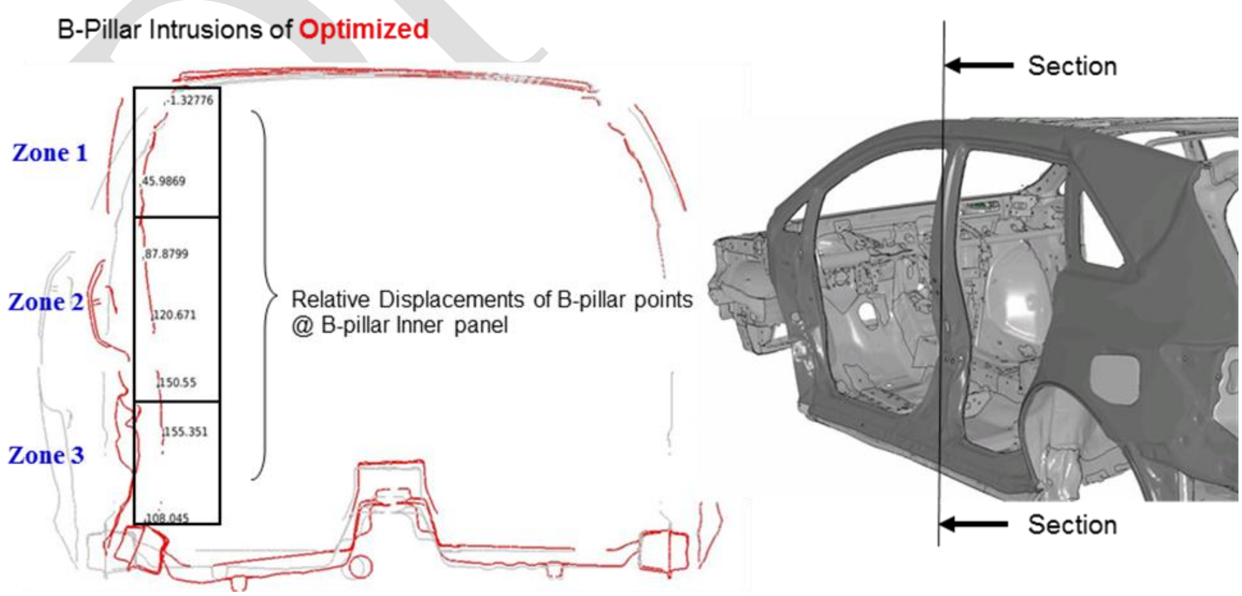


Image F.4A-28—Side Structure Intrusion Plot of Optimized Model @ B-pillar Section

A summary of the relative intrusions of the B-pillar of the optimized model is shown in **Table F.4A-8.**

	Zone 1		Zone 2			Zone 3	
Measured Location	Upper	Lower	Upper	Middle	Lower	Upper	Lower
Intrusion (mm)	-1.3	46.0	87.9	120.7	150.6	155.4	108.0

Table F.4A-8—Optimized model, Relative Intrusions of B-Pillar for FMVSS 214

As explained in section 18.4, the maximum side structure intrusion of 155.4mm is less than the test results. It is also less than the baseline results of 184mm, so the side structure intrusion performance of the optimized model meets the baseline target.

In order to have a better perspective of the comparison, the optimized model result is overlaid on top of the baseline model result. **Image F.4A-29** shows the intrusion contours of both the optimized and the baseline models. The contours in red represents the deformation of the optimized model and the contours in black represents the deformation of the baseline model.

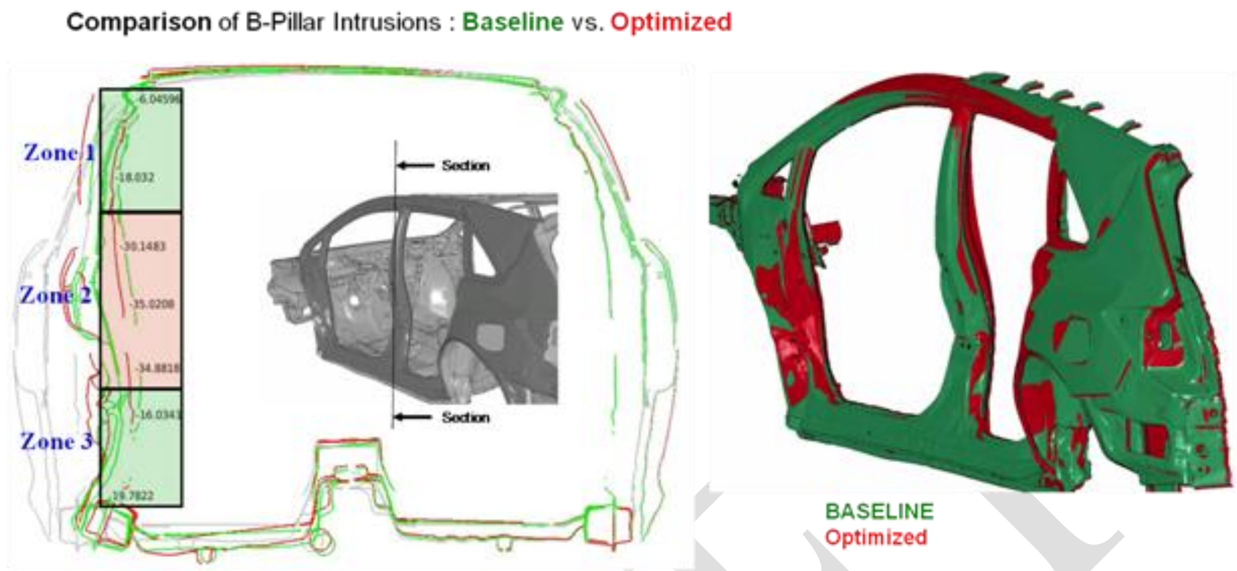


Image F-4A-29: Side Structure Intrusion Plots of Optimized and Baseline Models

A comparison of B-pillar intrusions of the baseline model and the optimized model is shown in **Table F.4A-9**. The negative sign indicates the optimized model shows less deformation than the baseline.

	Zone 1		Zone 2			Zone 3	
Measured Location	Upper	Lower	Upper	Middle	Lower	Upper	Lower
Intrusion (mm)	-6.0	-18.0	-30.0	-35.0	-34.9	-16.0	19.8

Table F-4A-9—Comparison of B-Pillar Intrusions of Baseline and Optimized Models for FMVSS 214

From the comparison in **Table F.4A-9**, it is observed the optimized model deforms less compared to the baseline model; the optimized model leaves a greater gap between the B-pillar and the seat structure. This is a positive indicator of side-impact performance.

F.4A.11.2.5 <u>FMVSS 301—50 MPH MDB Rear Impact</u>

Deformation Mode

The deformation modes of the rear impact simulation of the optimized model are shown in **Images F.4A-30** to **F-4A-32**. Similar to the baseline model, these deformation modes indicate the rear structures protect the fuel tank system well during the crash event. In Figure F.4A-38, the rear door area shows no jamming shut of the door opening.

The skeleton view of the rear inner structure deformation view in **Image F.4A-31** shows the rear underbody was involved resulting in maximizing the crush energy absorption and minimizing the deformation of the rear door and fuel tank mounting areas.

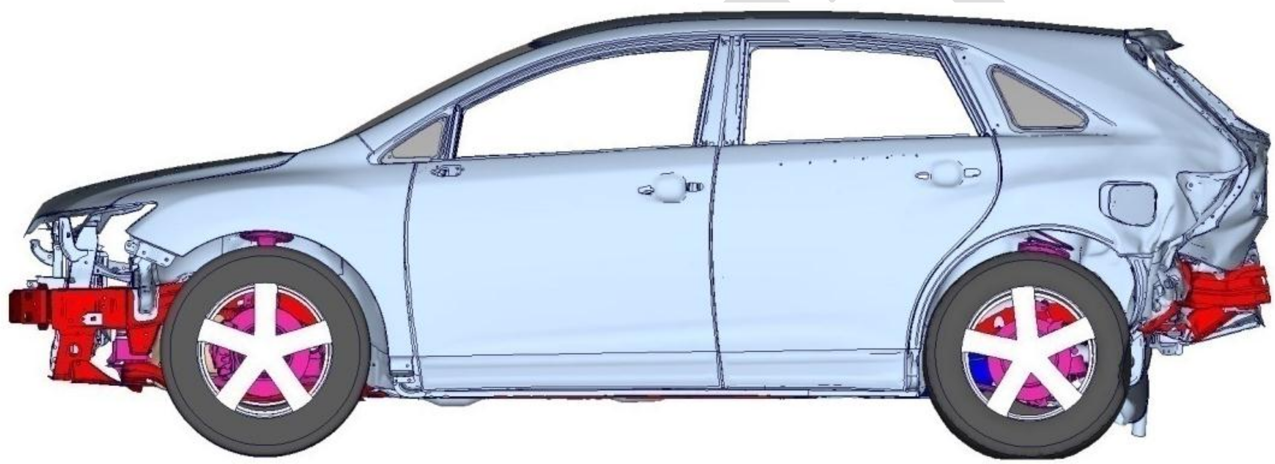


Image F.4A-30: Deformation Mode of Optimized Model, Left Side View

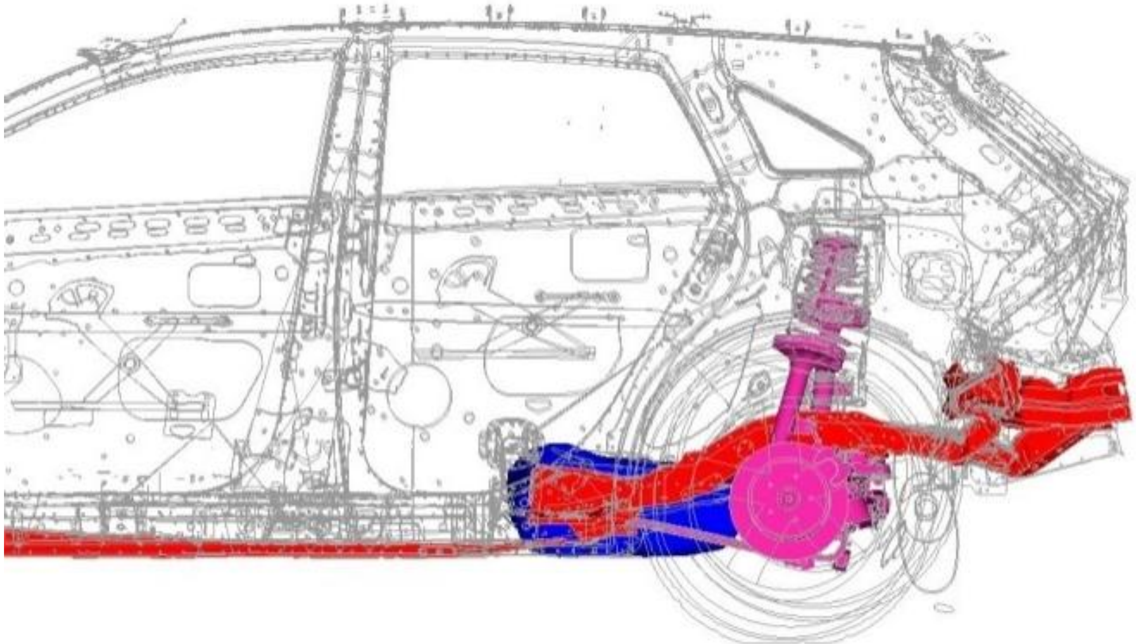


Image F.4A-31: Deformation Mode of Optimized Model Rear Structure Area, Left Side View

The bottom view of the rear underbody structure around the fuel tank area at the end of crash (100 msec) is shown **Images F.4A-32** and **F.4A-33**. This deformation mode shows the rear rail structure and the rear suspension mounting are also intact to protect the fuel tank system.

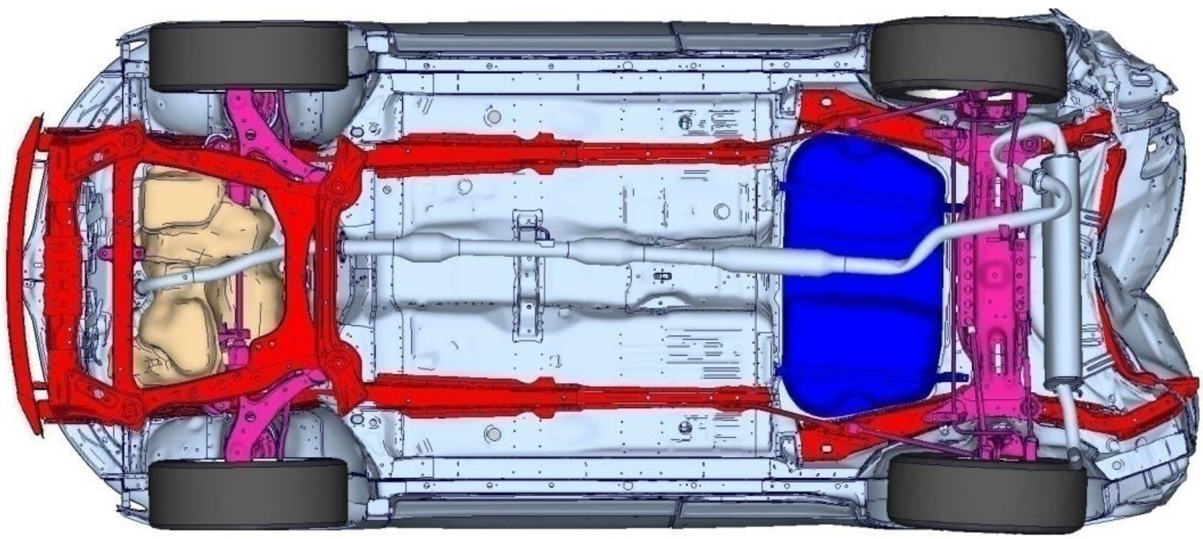


Figure F.4A-32: Deformation Mode of Optimized Model, Bottom View

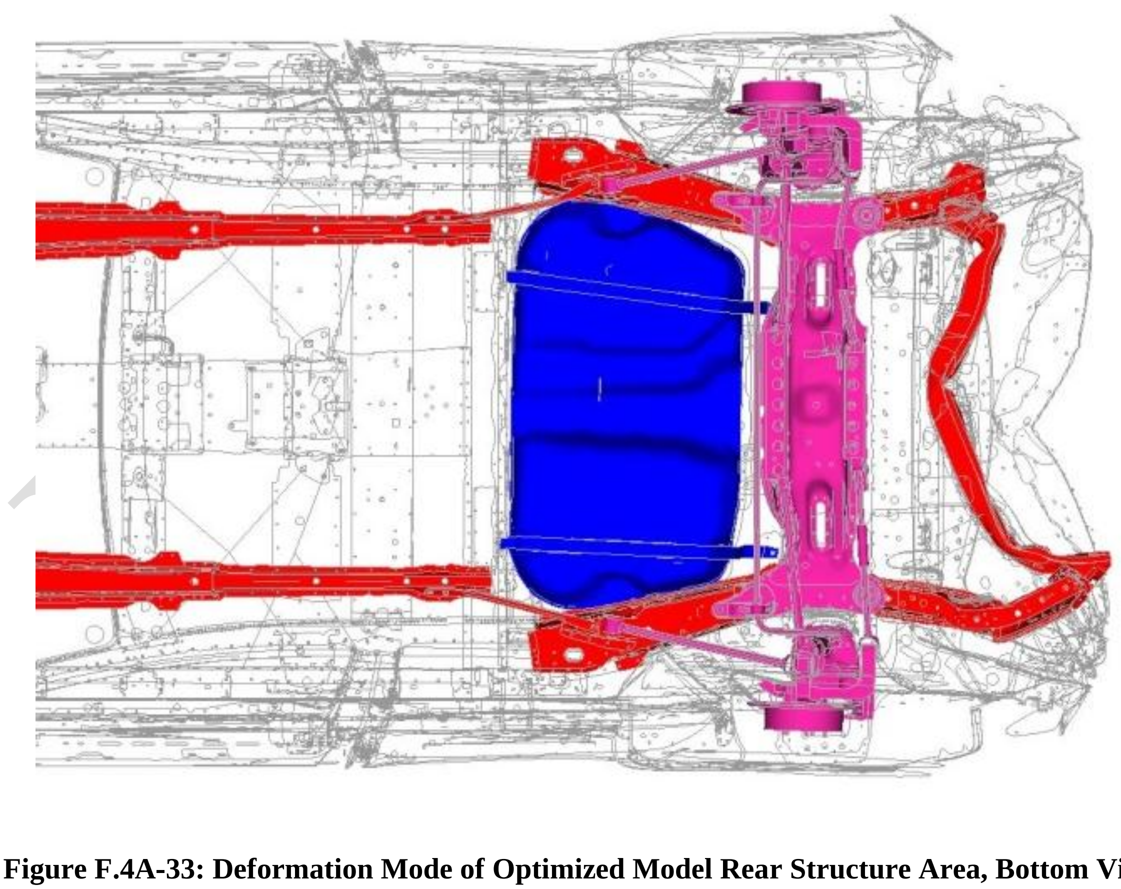


Figure F.4A-33: Deformation Mode of Optimized Model Rear Structure Area, Bottom View

Fuel Tank Integration

The fuel tank integrity of the optimized model is further analyzed by its plastic strain plot and is compared to the baseline model. The fuel tank system strain plot was monitored as one of the necessary parameters in a rear impact scenario. **Figure F.4A-34** shows the comparison of the top and bottom of the fuel tank system's strain plot after the crash.

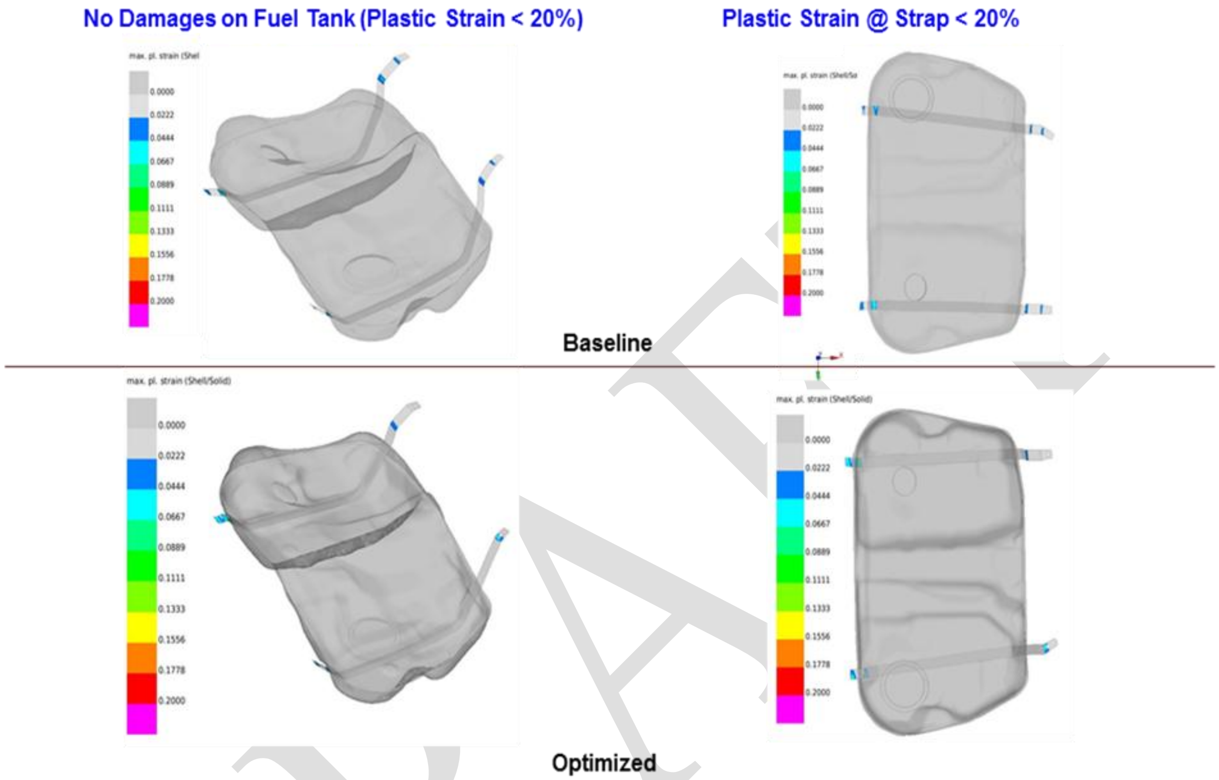


Image F.4A-34: Comparison of Fuel Tank System Integrity

Compared to the baseline model, the optimized model also indicates no significant risk of fuel system damage as the maximum strain amount is less than 20% of the entire fuel tank system's plastic strain. It thus meets the baseline target in terms of fuel tank integrity.

Structural deformation

The rear impact structural performance of the optimized model is further compared with the baseline model in terms of zonal deformation and rear door opening area deformation. **Image F.4A-35** shows different deformation zones of the rear end of the vehicle. The structural deformations measured at these locations are listed and compared to the baseline model in **Table F.4A-10**.

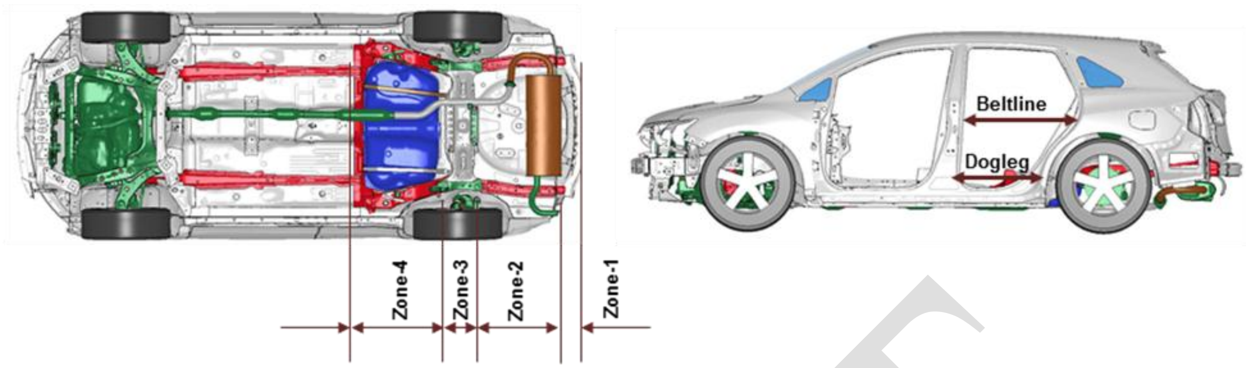


Image F.4A-35: Structural Deformation Measuring Area in Rear Impact

Model	Under Structure Zone Deformation (mm)				Door Opening (mm)	
	Zone-1	Zone-2	Zone-3	Zone-4	Beltline	Dogleg
Baseline	133.9	301.7	0	0	1.8	0
Optimized	108.8	345.7	0	0	1.1	0

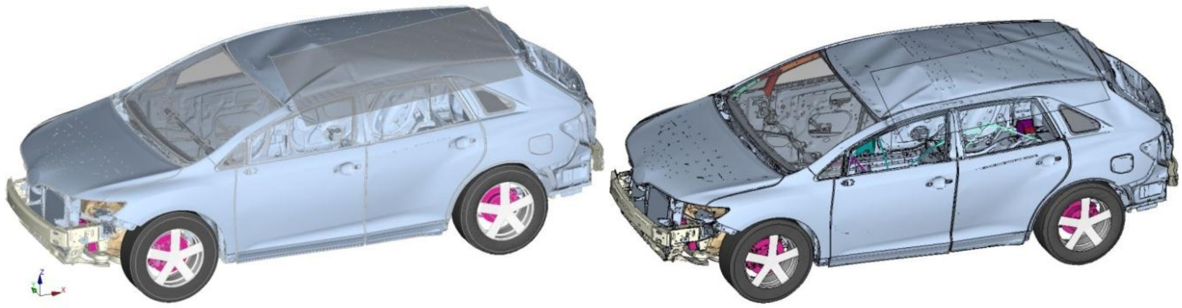
Table F.4A-10: Summary of Structural Deformation Measuring

Based on our acceptance criteria that the rear door must be capable of opening after the impact event and there must be fuel system integrity, the optimized model is judged acceptable. The increase in intrusion value in zone 2 is related to the reduced gauges in the rear structure.

F.4A.11.2.6 FMVSS 216a—Roof Crush Resistance

Deformation Mode

The driver side roof crush deformation mode of the optimized model was compared with the baseline model. The roof crush deformation mode at 140 msec after crush event is shown in **Figure F.4A-36**. It is noted that, similar to the baseline model, most of the deformation is concentrated on the roof rail, the A-pillar, and the B-pillar of the load side. The other neighboring structures remained undeformed. The optimized model structure thus has the same level of roof crush resistance performance as the baseline model.



Baseline Optimized

Figure F.4A-36: Deformation Mode of Roof Crush

Structural Strength

The strength of the roof rail and the B-pillar structure in terms of rear passenger head protection during rollover scenario is determined by the maximum plastic strain plot and platen force vs. displacement. **Image F.4A-37** shows plastic strain distribution of the roof and B-pillar structures of the optimized model. The maximum plastic strain over the roof rail and B-pillar parts are within the 20% limit, the same as the baseline model.

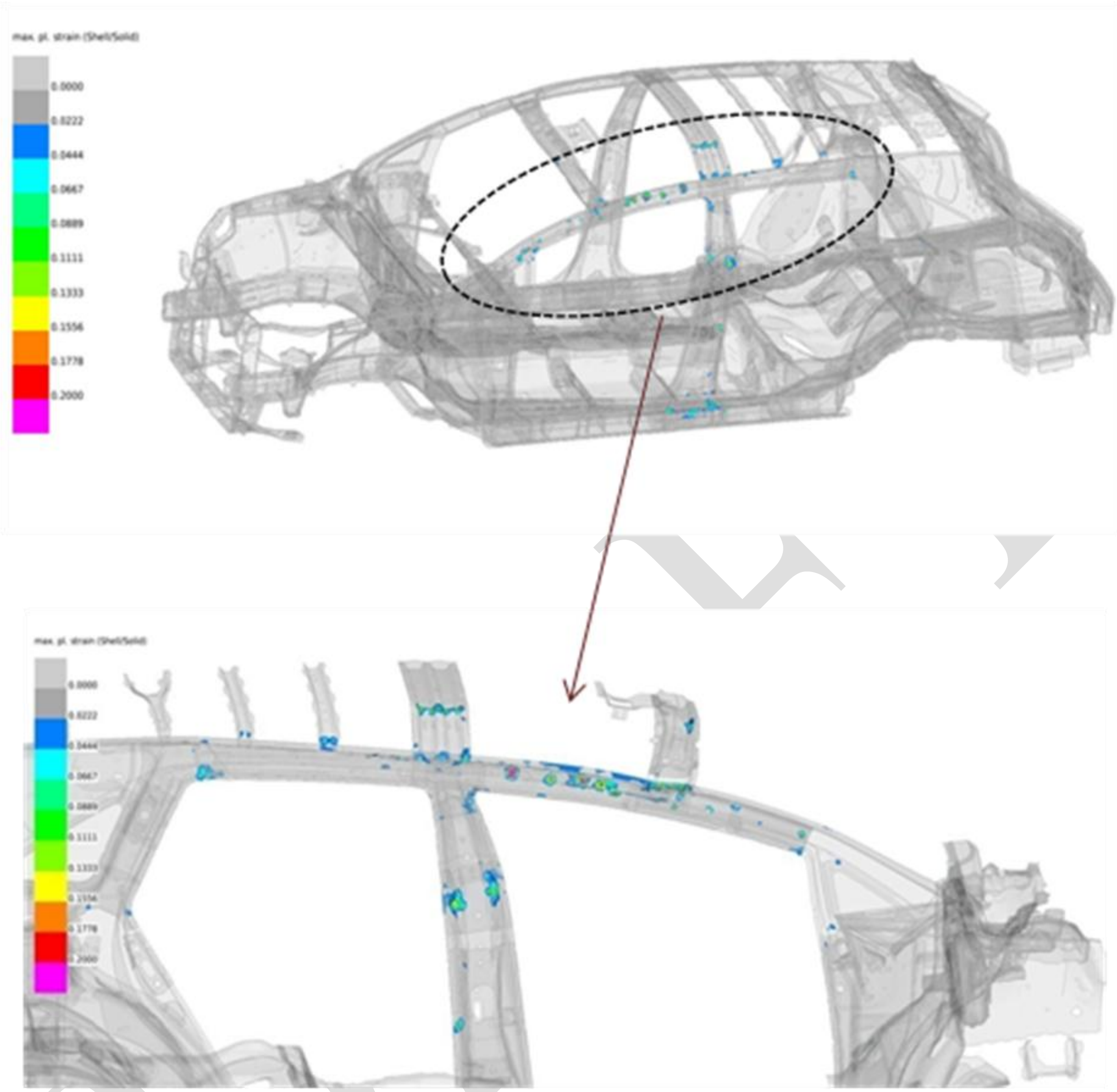


Image F.4A-37: Plastic Strain Contour of Side Upper Structure in Optimized Model

Similar to the baseline model, using four times UVW criteria, the optimized model is evaluated for its roof crush resistance strength. The force vs. displacement curve of the platen is illustrated in **Figure F.4A-9**.

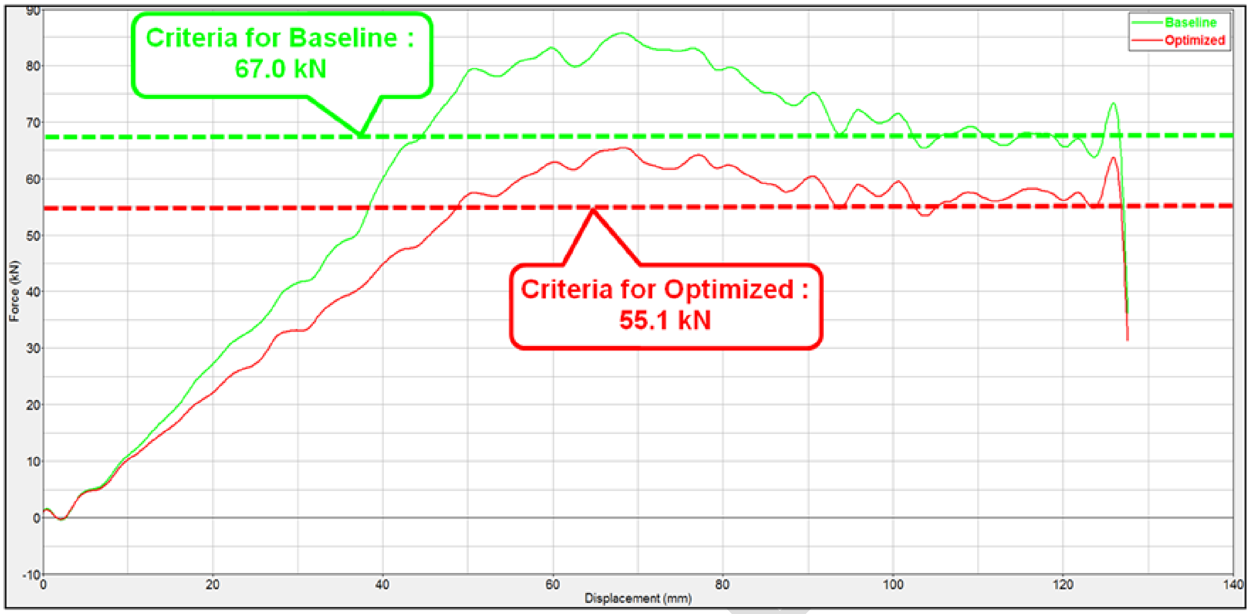


Figure F.4A-9: Roof Crush Load vs. Displacement Plot

As explained in **Section F.4A.10**, the UVW of the optimized roof crush resistance model is 1,403.1 kg. From **Figure F.4A-9**, it is observed the maximum load (65.4 kN) is greater than four times UVW (55.1 kN) within the platen displacement of 127 mm. Therefore, the optimized model also meets both FMVSS 216a and IIHS requirements.

A comparative summary of the optimized model's roof crush performance is found in **Table F.4A-11**.

Model Name	UVW (kg)		BIW, Closures Weight (kg)		Force Criteria (kN)	Max Load (kN)
	UVW	Delta	BIW, Closures	Delta		
Baseline	1710.6	n/a	528.9	n/a	67.0	86
Optimized	1403.1	307.4	457.7	71.2	55.1	65.4

Table.F.4A-11—Summary of Roof Crush Load vs. Displacement Plot

F.4A.11 Cost Impact

The necessary cost constraints were included in the weight optimization cycle to be consistent with each of the strategies applied. The gauge and grades were modified accordingly, while opting for different alternatives such as laser welded assembly and TRB parts. The costs of the changes were obtained based on engineering estimates of the original design cost. The following cost factors were included in the estimation.

- Manufacturing CO2 emissions
- Material price
- Labor cost
- Energy cost
- Equipment cost
- Tooling
- Building
- Maintenance
- Overhead

EDAG standards and best practices were followed in performing the cost estimate with the following general assumptions:

1. Cost of money = 8%
2. Production Volume = 200,000 / year
3. Equipment life = 20 years
4. Product life = 5 years

In addition to these factors, the cost changes in assembly due to the change of laser-welded assembly and introduction of rocker bulkhead reinforcements (Ref. **Section F.4A.9**) also were estimated. The weight and cost impact of the optimized changes is shown in **Table F.4A-12**.

Description	Estimated Mass Reduction "Kg"	Estimated Cost Impact "$"	Average Cost/ Kilogram "$/Kg"
Body Structure Subsystem			
Underbody Asy	8.1	-5.81	-0.72
Front Structure Asy	5.7	-7.03	-1.23
Roof Asy	7.2	4.55	0.63
Bodyside Asy	17.8	-82.41	-4.63
Ladder Asy	11.7	-4.72	-0.40
Bolt on BIP Components	-0.1	-14.75	147.50
Body Closure Subsystem			
Hood Asy	7.7	-39.11	-5.08
Front Door Asy	0.0	0.00	0.00
Rear Door Asy	0.0	0.00	0.00
Rear Hatch Asy	7.2	-29.96	-4.16
Front Fenders	2.0	-21.85	-10.93
Bumpers Subsystem			
Front Bumper Asy	0.4	-10.71	-26.78
Rear Bumper Asy	0.0	0.00	0.00
Totals	67.7	-211.80	-3.13
"+" = mass decrease, "-" = mass increase			
"+" = cost decrease, "-" = cost increase			

Table F.4A-12: Weight and Cost Impact of Optimized Vehicle

The cost impact of assembling the parts due to laser welding is shown in **Table F.4A-13**.

Assembly Cost Going from Spot Welds to Laser Welds		
Assembly Number	Assembly	Assembly cost
1	Front Shock Tower	$0.84
2	Rear Shock Tower	$1.00
3	Body Side Rear	$1.05
4	Front Rail Lower	$0.84
5	Front Rail Upper	$0.68
6	Shotgun	$0.12
7	Roof	-$0.22
8	B-Pillar	$0.85
9	Rear Structure	$0.89
Total		$6.05

Table F.4A-13: Cost Impact of Part Laser Welded Assembly

The cost impact of introducing rocker bulkhead reinforcements is shown in **Table F.4A.14**.

Assembly Cost Adding Rocker Reinforcements		
Assembly Number	Assembly	Assembly cost
10	New Rocker Reinforcements	$13.58
Total		$13.58

Table F.4A.14: Cost Impact of Part Laser Welded Assembly

From the information in the tables, the overall weight savings on the Toyota Venza is about 67.7 kg, with a manufacturing cost increase of $211.80 and an assembly cost increase of $19.63.

F.4A.12 Summary

In summary, the 2010 Toyota Venza was studied for potential weight reduction by utilizing EDAG lightweight design optimization procedures. The performance of the lightweight vehicle was verified by applying CAE principles. The necessary vehicle data was collected from completely disassembling a 2010 Toyota Venza. Weight reduction was optimized while maintaining safety performance regulations and requirements. The weight reduction optimization was carried out in stages based on EDAG lightweight optimization strategies. The result of the weight optimization was a 17.4% weight reduction on a BIW only (**Table F.4A-2**) and a 16.0% weight reduction including closures and bumpers (**Table F.4A-3**), while still meeting the structural performance targets. Additionally, an estimated 20% weight reduction of non-structural parts was included on the full vehicle weight structure. The overall weight reduction of 19% was achieved.

The cost impact of the changes that took place in the lightweight design optimization process was also analyzed. The changes were mostly to body parts, thus the difference was estimated to be an increase of $229.66 in manufacturing costs (**Table F.4A-12**) and a $6.05 increase in assembly costs of the body parts (**Table.F.4A-13**).

F.4A.13 Future Trends and Recommendation

Common practices followed in automotive original equipment manufacturers (OEMs) are within the strategies of component integration, functionality tweaking, innovative/alternative materials use, manufacturing technology advancements, and cost-weight optimization. EDAG's principle of continual research enabled an exploration of alternatives beyond common practices. The lightweight optimization study of the Toyota Venza utilized most of them. There are, however, additional possibilities of weight reduction:

- Exploration of alternative materials for subsystems
- Exploration of alternative technologies for subsystems
- Optimization of the topology of load path subsystems

- Executive-level vehicles (low volume) are currently manufactured using aluminum materials in order to create a super light vehicle, but with the associated higher costs.

Volkswagen Audi is the recent success story, however, of utilizing aluminum alternatives.[8] An attempt was made in the Toyota Venza study to use aluminum as an alternative material for the front bumper, hood, and tailgate parts. This resulted in a savings of 17 kg (13%), with a cost increase of $26.58/kg. In a similar approach, aluminum can be used for door parts. A test of replacing the door materials in the CAE model has shown a weight savings of about 25%.

Magnesium (Mg) based materials are also proven for their better strength-weight ratio equivalent when compared to steel based materials[11]. A similar test of replacing steel materials by magnesium material on the front module of the Toyota Venza revealed approximately 57.26% weight savings with 100% cost increase. The use of magnesium as a viable alternative will be a consideration in future research. Another area where magnesium has the potential to be used is the powertrain housing.[21]

Utilizing a carbon fiber, the proposition of composite materials is one of the emerging ideas in building lightweight vehicles. Currently, the utilization of fiber-composite materials for supporting body parts has been limited to special series, as well as premium and racing models.[22] Assuming a positive cost impact due to an improvement in efficiency, research into using composite materials for auto body parts would be worthwhile.

Another candidate for alternative materials is long-fiber reinforced thermoplastics (LFT). Today, most LFT end products are produced for the automobile industry.[23] These molded parts include body panels, sound shields, front-end assemblies, structural body parts, truck panels and housings, as well as doors, tailgates, and fender (wing) sections. LFT could be tried on these parts of the Toyota Venza.

The use of TRB is yet another example of a recent development in the manufacturing process. It is expected TRB will replace parts manufactured with tailor-welded blanks. Recently, major American and European automotive OEMs have introduced TRB-based parts. They are currently applied on the simple stamped parts of high strength steel. Based on EDAG's experience of TRB trials in other programs, extending the TRB appln to chassis member, frames, crossmembers, etc., is recommended. From the experience of applying TRB in the Toyota Venza study, it is expected significant cost and weight savings will be achieved.

Topology optimization is a computer-simulation based design optimization method used to determine optimized structural load paths in a pre-specified three-dimensional space.

This technique helps to optimize load path parts at the design level. Since any major design change is beyond the scope of this project, design optimization was not undertaken. The potential of weight reduction by design optimization is significant (about 10 – 17% based on EDAG's proven expertise in the Future Steel Vehicle program).[24] This is a clear motivation to attempt topology optimization techniques to achieve further weight reduction in the Toyota Venza.

F.4B Body System Group B

Body System Group B includes the subsystems shown in **Table F.4B-1**. The largest mass contributors are the Seating, Interior Trim, and Instrument Panel/Console subsystems. As seen in **Table F.4B-2**, a substantial amount of mass (41.98 kg) is reduced from Body System Group B. This provides a cost savings of $122.98 and a dollar per kilogram savings of $2.93/kg. The largest contributor of this mass and cost reduction is the Seating subsystem, followed by the Interior Trim and the Instrument Panel subsystems.

System	Subsystem	Sub-Subsystem	Description	System & Subsystem Mass "kg"
03	**00**	**00**	**Body System (Group -B-)**	
03	05	00	Interior Trim and Ornamentation Subsystem	65.202
03	06	00	Sound and Heat Control Subsystem (Body)	4.502
03	07	00	Sealing Subsystem	8.226
03	10	00	Seating Subsystem	92.548
03	12	00	Instrument Panel and Console Subsystem	32.688
03	20	00	Occupant Restraining Device Subsystem	17.438
			Total System Mass =	**220.604**
			Total Vehicle Mass =	**1711**
			System Mass Contribution Relative to Vehicle =	**12.90%**

Table F.4B-1: Baseline Subsystem Breakdown for Body System Group B

System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
				Net Value of Mass Reduction Idea					
03	00	00	**Body System (Group -B-)**						
03	05	00	Interior Trim and Ornamentation Subsystem	A	8.924	$37.72	$4.23	13.69%	0.52%
03	06	00	Sound and Heat Control Subsystem (Body)	A	0.268	$0.38	$1.40	5.95%	0.02%
03	07	00	Sealing Subsystem	A	2.029	$15.70	$7.74	24.67%	0.12%
03	10	00	Seating Subsystem	A	23.392	$84.55	$3.61	25.28%	1.37%
03	12	00	Instrument Panel and Console Subsystem	C	6.330	-$12.49	-$1.97	19.36%	0.37%
03	20	00	Occupant Restraining Device Subsystem	D	1.039	-$2.88	-$2.77	5.96%	0.06%
				A	**41.982** (Decrease)	**$122.98** (Decrease)	**$2.93** (Decrease)	**19.03%**	**2.45%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.4B-2: Mass-Reduction and Cost Impact for Body System Group B

F.4B.1 Interior Trim and Ornamentation Subsystem

F.4B.1.1 Subsystem Content Overview

The Toyota Venza uses a conventional interior trim package as well as upgrade packages. Considerable focus has been paid to the interior regarding the different types of materials used: plastic, rubber, cloth, leather, and steel. As with many of today's vehicle manufacturers, the larger amount of the vehicle sought for weight reductions are those areas which can do so without sacrificing looks, comfort and performance. **Image F.4B-1** shows the inside interior of the Toyota Venza

Image F.4B-1: Toyota Venza Interior

(Source: FEV, Inc. Photo)

F.4B.1.2 Mass-Reduction Industry Trends

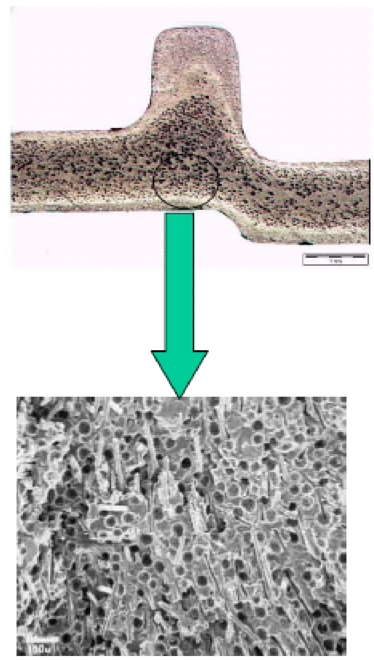
Industry trends for mass reduction in the interior include many different considerations due to the fact that the interior trim is made up of many different components and materials. Among the ways to reduce mass includes reducing the density of the vinyl trim or the thickness of the vinyl trim. Mass density can be reduced by using PolyOne foaming additives or the MuCell® foaming process for the vinyl trim injection molding. Using carbon fiber as a replacement for vinyl trim results in mass reduction, although doing so will add cost to the interior due to carbon fiber's limited availability and raw material cost. Products and techniques using light-weight wood, wood fiber, or foam with a laminated interior surface treatment also involve added processing.

MuCell® by Trexel™ is a microcellular foam injection molding process for thermoplastics materials that injects nitrogen bubbles into the plastic during the injection stage of the molding process. MuCell® by Trexel™ is used in many applications, automotive, medical and the packaging industry. The process is currently used by major OEM's like, Audi, Ford, BMW and VW. The quality advantages of the MuCell Process are complemented by certain direct economic advantages, including the ability to produce 20-33% more parts per hour on a given molded machine, and the ability to mold parts on lower tonnage machines as a result of the viscosity reduction and the elimination of the packing requirement that accompanies the use of supercritical gas.

MuCell® has an added capital cost to a standard injection molding machine, but with this process a smaller machine can be used and a faster cycle time can be realized. MuCell® also provides for a reduction in the amount of plastic used, which offers an overall material savings. MuCell® is not recommended for Class "A" surfaces; however, all non-Class "A" surfaces were quoted with a 10% mass reduction.

Why is Microcellular Foam Different?

- **Microcellular foaming is a technology for**
  - Putting small cells into a thin wall plastic part
- **Primarily using nitrogen as the foaming agent**
  - Sometimes carbon dioxide
- **Direct addition of physical foaming agent provides a high level of expansion pressure**



The MuCell Process

- **Dissolving an SCF into a polymer reduces the material viscosity**
- **Viscosity changes**
  - 10% to 15% for a 30% glass fiber reinforced semi-crystalline engineering resin
  - 15% to 25% for an amorphous resin
- **Reduced injection pressures at equal conditions of temperature and speed**
- **Improved flow lengths**
- **Cell growth provides final packing of the part**
  - Reduces residual stress patterns by eliminating traditional pack and hold phase
  - Results in improved part dimensions
- **Cycle time reduction due to shorter pack/hold and increase mold contact**

Figure F.4B-1: MuCell® by Trexel™ Foaming Process Presentation

(MuCell® presentation information provided by Trexel™)

MuCell® Application

Automotive

Application: Rear Door Carrier

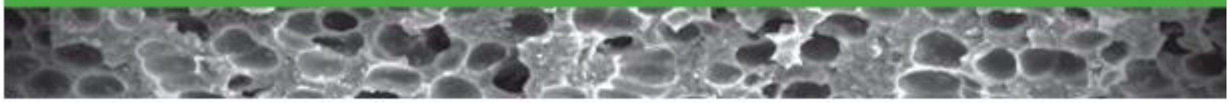
Manufacturer: JCI/Mercedes Benz

Benefits:

- Thinner wall (1.8 mm to 2.0 mm)
- 1:1 wall to rib ratio
- >50% cycle time reduction (MuCell + Tandem-Mold)
- High dimensional stability

MuCell Processes TREXEL INC.

MuCell® Application



Automotive

Application: Climate Control Cover

Manufacturer: Valeo (Ford)

Benefits:

- Reduced injection pressure and lower melt temperatures open the process window for in-mold decorating
- 10% weight/material reduction
- 23% cycle time reduction
- Required clamp tonnage reduction from 250 tons to 75 tons
- Eliminates read-through of the back surface features so there are no sink marks

MuCell® Application

Automotive

Application: Trunk Liner

Manufacturer: VW

Benefits:

- Weight reduction of 10%

TREXEL INC. MuCell Processes

MuCell® Application

Automotive

Application: Interior Door Trim

Manufacturer: VW

Benefits:

- Wall to rib thickness 1:1 allowed for a 50% reduction in nominal wall thickness
- Consolidation of parts by eliminating read through from energy absorbing ribs
- Elimination of separate energy absorbing module
- Weight reduction from foaming and redesign of

TREXEL INC. MuCell Processes

PolyOne has a foaming agent incorporated into pellets which can be added directly into a standard mold machine plastic hopper and mixed with base material plastic pellets to provide the proper ratio of foaming agent to the base material. PolyOne can be used on Class “A” surfaces: all class “A” surfaces using PolyOne were quoted with a 10% mass reduction.

PolyOne Corporation is a global supplier of polymer materials, services, and solutions. PolyOne specializes in performance materials, colors and additives, thermoplastic elastomers, coatings and resins, and inks, among other things. The industries they serve are vast, including building and construction, electrical and electronics, healthcare, industrial, packaging, and transportation.

Of particular interest to this study is PolyOne's OnCap™ Chemical Foaming Agents (CFAs), which is a part of its OnCap™ Additives product line. This line is part of PolyOne's Global Color, Additives & Inks business unit. In typical industry use, these CFAs provide a multitude of benefits to improve polymer processing in a variety of situations. They can also reduce the weight of the plastic part to which they are added. CFAs are formulated products that will decompose in a polymer during processing at a specific temperature and liberate a gas that will form a controlled cellular structure in the solid phase of the polymer.

(Ref. http://www.polyone.com/en-us/docs/Documents/OnCap%20Chemical%20Foaming%20Agents.pdf)

PolyOne's CFAs can effectively reduce the mass of plastic parts both with and without Class "A" surface finishes. For this study, however, the most significant advantage of CFAs is the former. Therefore, PolyOne's CFAs were applied to numerous Class "A" surface-finished plastic parts in this study. PolyOne Corporation provided generic feedback and advice regarding the amount of weight reduction feasible for plastic parts. These CFA application guidelines included considerations for a respective part's material, geometry, and application. In general, a 10% weight reduction was applied to parts for which a CFA was used. Higher mass reduction may be possible for many components, but would require a detailed analysis on the component and its use in order to safely apply such savings. Instead, a conservative estimate was applied based on PolyOne's expertise where parts' properties would not be adversely affected. For parts with a non-Class "A" surface finish, a weight reduction in the 20-30% range is possible.

The use of CFAs for light-weighting must be addressed on a part-by-part basis. Several variables must be taken into account for each component to understand the impact mass reduction will have on the final part's processing and performance. A feasibility breakdown provided by PolyOne is presented here, indicating guidelines and stipulations for the most common plastics used in the Toyota Venza:

20% Talc-filled Polypropylene (PP-GF20)

- Talc can influence the success of the CFA. Based on the grade and particle size talc can improve cell size or potentially increase the rate of splay. The grain can help reduce the visual defects.
- Class "A" surface finish can be difficult to maintain. This will depend upon the geometry of and the gate location on the part.

- Potential weight reduction would be more in the 5-10% range at 1-3% LDR.
- Above 10% will begin to reduce the physical properties and affect the Class "A" surface finish.
- Due to polypropylene's shrinkage rate, the CFA will fill the cavity: weight loss is reduced due to the complete fill of the cavity.
- It does aid in sink mark removal at lower 0.5-1% CFA loadings.
- PolyOne™ CFA CC10117068WE or CC10122763WE would be suggested for polypropylene.
- Surface texture can potentially hide the effects of a CFA so various grain options should be explored.

Polycarbonate / Acrylonitrile Butadiene Styrene (PC/ABS)

- This resin could achieve a 10-15% weight reduction. Careful selection of the proper CFA is required since the alloyed blends can have different ratios. Testing with the high heat CC10153776WE and CC10117068WE would be recommended.
- Class "A" surface finish can be difficult to maintain above 10%. This will depend upon the geometry of and the gate location on the part.
- Surface texture can potentially hide the effects of a CFA so various grain options should be explored.

Polyamide 66 (PA66)

- Processing with the high heat CFA CC10153776WE would be recommended.
- Class "A" surface finish can be difficult to maintain. This will depend upon the geometry of and the gate location on the part.
- Potential weight reduction would be more in the 5-10% range.
- Above 10% will begin to reduce the physical properties and affect the Class "A" surface finish.

20% Glass-filled Polyamide (PA-GF20)

- Processing with the high heat CFA CC10153776WE would be recommended.
- Glass will reduce the success of the CFA due to potential cell coalescence causing larger voids.
- Class "A" surface finish can be difficult to maintain. This will depend upon the geometry of and the gate location on the part.
- Potential weight reduction would be more in the 5-10% range.
- Above 10% will begin to reduce the physical properties and affect the Class "A" surface finish.

15% Glass-filled / 25% Mineral-filled Polyamide 6 (15G/25M PA6)

- Processing with the high heat CFA CC10153776WE would be recommended.
- Glass will reduce the success of the CFA due to potential cell coalescence causing larger voids.
- Class "A" surface finish can be difficult to maintain. This will depend upon the geometry of and the gate location on the part.
- Potential weight reduction would be more in the 5-10% range.
- Above 10% will begin to reduce the physical properties and affect the Class "A" surface finish.

High-Density Polyethylene / Polypropylene (HDPE/PP)

- This resin could achieve a 10-15% weight reduction. CC10117068WE and CC10122763WE are potential CFAs depending upon part geometry.

- Class A surface finish can be difficult to maintain above 10%. This will depend upon the geometry of and the gate location on the part.
- Surface texture can potentially hide the effects of a CFA so various grain options should be explored.
- Above 10% will begin to reduce the physical properties and affect the Class "A" surface finish.

PolyOne's Chemical Foaming Agents are currently used in production in industrial housings and structural foam applications, but not in the automotive industry. Its CFAs, however, are currently undergoing testing by automotive OEMs and can be feasibly implemented by the 2017 model year.

Please refer to PolyOne's Technical Data Sheets in Appendix XX.XX for more information.

F.4B.1.3 Summary of Mass-Reduction Concepts Considered

Some ideas that were considered for weight reduction on the interior trim are shown in **Table F.4B-3**.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Interior trim with class "A" surface	Carbon fiber	10 to 20% Mass Reduction	High cost of raw material, high cost of processing
Interior trim with class "A" surface	Laminated surface to wood underlayment	10 to 20% Mass Reduction	Added processing, Wood underlayment availability
Interior trim with class "A" surface	Laminated surface to wood fiber underlayment	10 to 20% Mass Reduction	Added processing, Wood fiber underlayment availability
Interior trim with class "A" surface	Laminated surface to foam underlayment	15 to 25% Mass Reduction	high processing cost
Interior trim with class "A" surface	PolyOne® foaming process	10% Mass Reduction	No added capital equip. needed, Faster cycle time per part
Interior trim with non-class "A" surface	MuCell® gas foaming process	10% Mass Reduction	Added capital equip., faster cycle time
Carpet floor mats	Reduce total weight	20 to 30% Mass Reduction	Less material, may have durability issues, may require testing
Retractable cargo cover	Replace heavy pull cover with pull screen	50 to 65% Mass Reduction	Diff. product for same function, may have customer preference issues

Table F.4B-3: Summary of Mass-Reduction Concepts Initially Considered for the Interior Trim and Ornamentation Subsystem

F.4B.1.4 Selection of Mass Reduction Ideas

The mass reduction ideas selected for the Interior Trim and Ornamentation subsystem were those to use the PolyOne foaming process for Class “A”-surfaced injection-molded parts and the MuCell® foaming process for injection molded parts without a Class “A” surface. All PolyOne and MuCell® deductions are conservative at a 10% mass reduction per part. With proper engineering of the parts, however, up to 30% weight reduction may be achieved.

The rear luggage pull screen was replaced with a lightweight cargo net. This could be considered an inferior replacement of the original part, however, if weight reduction is an OEM priority, replacing the cargo screen can be done without dramatically affecting functionality and looks. In order to reduce the density (thickness) of the floor mats from 22oz carpet to 14 oz carpet, proper OEM testing will have to be done (**Table F.4B-4**).

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
03	**05**	**00**	**Interior Trim and Ornamentation Subsystem**	
03	05	01	Main Floor Trim	PolyOne® Class "A" Surfaces
				MuCell® Non-Class "A" Surfaces
03	05	03	Headliner Assembly	PolyOne® Class "A" Surfaces
				MuCell® Non-Class "A" Surfaces
03	05	04	Sun Visors	PolyOne® Class "A" Surfaces
				MuCell® Non-Class "A" Surfaces
03	05	05	Front RH & LH Door Trim Panel	PolyOne® Class "A" Surfaces
				MuCell® Non-Class "A" Surfaces
03	05	06	Rear RH & LH Door Trim Panel	PolyOne® Class "A" Surfaces
				MuCell® Non-Class "A" Surfaces
03	05	07	Pillar Trim Lower	PolyOne® Class "A" Surfaces
				MuCell® Non-Class "A" Surfaces
03	05	08	Load Compartment Side Trim	PolyOne® Class "A" Surfaces
				MuCell® Non-Class "A" Surfaces
03	05	09	Rear Closure Interior Trim Panel	PolyOne® Class "A" Surfaces
				MuCell® Non-Class "A" Surfaces
03	05	10	Cargo Retention	Replace heavy pull cover with pull screen
03	05	11	Floor Mats - OEM	Reduce total weight
03	05	12	Load Compartment Floor Trim	PolyOne® Class "A" Surfaces
				MuCell® Non-Class "A" Surfaces
03	05	13	Pillar Trim Upper	PolyOne® Class "A" Surfaces
				MuCell® Non-Class "A" Surfaces
03	05	14	Load Compartment Transverse Trim	PolyOne® Class "A" Surfaces
				MuCell® Non-Class "A" Surfaces

Table F.4B-4: Mass-Reduction Ideas Selected for the Interior Trim and Ornamentation Subsystem

F.4B.1.5 Mass-Reduction & Cost Impact Estimates

Table F.4B-5 shows the 8.924kg weight and $37.72 cost reductions per sub-subsystem. In this Interior Trim and Ornamentation subsystem, Polyone® used on all of the subsystems Class "A" surface interior trim is 4.18kg of the total weight savings and $7.21 cost savings. MuCell® used on all non-Class "A" surface trim provides 1.31kg of the total weight savings and $2.96 of the cost savings. The 10% plastic mass reduction in the parts is replaced with a chemical foaming agent (CFA) or Nitrogen gas, which adds to a faster cycle time and a lower press tonnage for the weight and cost reductions. The lighter cargo cover provides 2.62kg of the total weight savings and $25.50 of the cost savings. Reducing the floor mat carpet fiber weight from 22oz to 14oz is .81kg for the total weight saved and $2.05 of the total cost.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
03	**05**	**00**	**Interior Trim and Ornamentation Subsystem**						
03	05	01	Main Floor Trim	A	0.075	$0.26	$3.44	1.27%	0.00%
03	05	02	NVH Pads		0.000	$0.00	$0.00	0.00%	0.00%
03	05	03	Headliner Assembly	A	0.010	$0.17	$17.30	0.18%	0.00%
03	05	04	Sun Visors	A	0.067	$0.19	$2.88	6.60%	0.00%
03	05	05	Front RH & LH Door Trim Panel	A	0.726	$1.31	$1.80	10.71%	0.04%
03	05	06	Rear RH & LH Door Trim Panel	A	0.689	$1.41	$2.05	10.30%	0.04%
03	05	07	Pillar Trim Lower	A	0.289	$0.54	$1.87	19.90%	0.02%
03	05	08	Load Compartment Side Trim	A	3.842	$27.15	$7.07	34.68%	0.22%
03	05	09	Rear Closure Interior Trim Panel	A	0.027	$0.12	$4.33	9.93%	0.00%
03	05	10	Cargo Retention	A	0.161	$0.64	$4.01	9.99%	0.01%
03	05	11	Floor Mats - OEM	A	0.809	$2.05	$2.53	11.95%	0.05%
03	05	12	Load Compartment Floor Trim	A	1.077	$2.05	$1.90	20.00%	0.06%
03	05	13	Pillar Trim Upper	A	0.275	$0.58	$2.13	15.65%	0.02%
03	05	14	Load Compartment Transverse Trim	A	0.858	$1.13	$1.31	16.77%	0.05%
03	05	15	Carpet Support	A	0.021	$0.11	$5.15	5.33%	0.00%
				A	**8.924** (Decrease)	**$37.72** (Decrease)	**$4.23** (Decrease)	**13.69%**	**0.52%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.4B-5: Sub-Subsystem Mass-Reduction and Cost Impact for Interior Trim and Ornamentation Subsystem.

F.4B.2 Sound and Heat Control Subsystem (Body)

F.4B.2.1 Subsystem Content Overview

As **Table F.4B-6** shows, the Sound and Heat Control subsystem (Body) includes the Heat Insulation Shields - Engine Bay, Noise Insulation - Engine Bay, and Engine Compartment Trim sub-subsystems.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
03	**06**	**00**	**Sound and Heat Control Subsystem (Body)**	
03	06	01	Heat Insulation Shields - Engine Bay	2.553
03	06	02	Noise Insulation, Engine Bay	0.421
03	06	03	Engine Compartment Trim	1.528
			Total Subsystem Mass =	**4.502**
			Total System Mass =	**220.604**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**2.04%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.26%**

Figure F.4B-6: Mass Breakdown by Sub-subsystem for the Sound and Heat Control Subsystem (Body)

F.4B.2.2 Toyota Venza Baseline Subsystem Technology

Due to the large amounts of heat given off by the engine, heat shields are used to protect components and bodywork from heat damage. Along with protection, effective heat shields can provide a performance benefit by reducing under-hood temperatures, therefore reducing the air intake temperatures. There are two main types of automotive heat shields: rigid and flexible. The rigid heat shields, once made from solid steel, are now often made from aluminum. Some high-end rigid heat shields are made out of aluminum sheet or other composites, with a thermal barrier, to improve the heat insulation. A flexible heat shielding is normally made from thin aluminum foils, sold either flat or in a roll, and is formed at installation. High-performance, flexible heat shields sometimes include extras, such as insulation. **Image F.4B-2** shows the under-hood heat and engine shields of the Toyota Venza.

Image F.4B-2: Toyota Venza Heat and Engine Shields

(Source: FEV Photo)

F.4B.2.3 Mass-Reduction Industry Trends

Mass reduction industry trends on the heat shields show using a high-temperature plastic incorporating the MuCell® foaming process and engineering geared for this process reduce the weight by up to 30%. Noise shields vary from two layers of perforated metal with high-temperature foam in between, to a very dense tar-like substance between the layers of body metal.

F.4B.2.4 Summary of Mass-Reduction Concepts Considered

Table F.4B-7 shows the ideas for mass reductions on the Sound and Heat Control subsystem (Body). Reductions were made on the heat shields/engine compartment trim, but none on the noise shields.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Interior trim with non-class "A" surface	MuCell® gas foaming process	10% Mass Reduction	Added capital equip., faster cycle time, lower cost

Table F.4B-7: Summary of Mass-Reduction Concepts Initially Considered for the Sound and Heat Control Subsystem (Body)

F.4B.2.5 Selection of Mass Reduction Ideas

Table F.4B-8 shows the weight deduction idea used for the Sound and Heat Control Subsystem (Body) is based on the MuCell® foaming process for injection molded parts.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
03	**06**	**00**	**Sound and Heat Control Subsystem (Body)**	
03	06	03	Engine Compartment Trim	MuCell® Non-Class "A" Surfaces

Table F.4B-8: Mass-Reduction Ideas Selected for Sound and Heat Control Subsystem (Body)

F.4B.2.6 Mass-Reduction & Cost Impact Estimates

Table F.4B-9 shows the .268kg weight and the $.38 cost reductions per sub-subsystem. Using MuCell® on the Engine Compartment Trim sub-subsystem is 100% of the weight and cost savings. As stated in the Interior section, the reduction of the 10% plastic mass in the parts is replaced with a chemical foaming agent or Nitrogen gas, adding to a faster cycle time and lower press tonnage for the weight and cost reductions.

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
03	**06**	**00**	**Sound and Heat Control Subsystem (Body)**						
03	06	01	Heat Insulation Shields - Engine Bay		0.000	$0.00	$0.00	0.00%	0.00%
03	06	02	Noise Insulation, Engine Bay		0.000	$0.00	$0.00	0.00%	0.00%
03	06	03	Engine Compartment Trim	A	0.268	$0.38	$1.40	17.54%	0.02%
				A	**0.268** (Decrease)	**$0.38** (Decrease)	**$1.40** (Decrease)	**5.95%**	**0.02%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.4B-9: Sub-Subsystem Mass-Reduction and Cost Impact for Sound and Heat Control Subsystem (Body)

F.4B.3 Sealing Subsystem

F.4B.3.1 Subsystem Content Overview

Table F.4B-10 displays what is included in the Sealing subsystem: Front Side Door Dynamic Weatherstrip, Static Sealing, Rear Side Door Dynamic Weatherstrip, Hood Dynamic Weatherstrip, and Fender Seals sub-subsystems.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
03	**07**	**00**	**Sealing Subsystem**	
03	07	01	Front Side Door Dynamic Weatherstrip	1.709
03	07	02	Static Sealing	4.792
03	07	03	Rear Side Door Dynamic Weatherstrip	1.427
03	07	04	Hood Dynamic Weatherstrip	0.124
03	07	05	Fender Seals	0.175
			Total Subsystem Mass =	**8.226**
			Total System Mass =	**220.604**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**3.73%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.48%**

Table F.4B-10: Mass Breakdown by Sub-subsystem for Sealing Subsystem

F.4B.3.2 Toyota Venza Baseline Subsystem Technology

The Venza has typical sealing/weather-stripping. Automotive sealing/weather-stripping must endure extreme hot and cold temperatures, be resistant to automotive liquids such as oil, gasoline, and particularly windshield washer fluid, and must resist years of full sun exposure. Automotive sealing/weather-stripping is commonly made of EPDM, TPE, TPO polymers. **Image F.4B-3** shows the Toyota Venza's door weather stripping

Image F.4B-3: Toyota Venza Door Weather Stripping

(Source: FEV Photo)

F.4B.3.3 Mass-Reduction Industry Trends

Mass reduction industry trends for sealing/weather-stripping show that TPE-v or TPV thermoplastic polyurethanes, thermoplastic copolyester and thermoplastic polyamides can be used to replace EDPM. These materials are 10 to 25% lighter.

F.4B.3.4 Summary of Mass-Reduction Concepts Considered

Table F.4B-11 contains the ideas considered for mass reductions on the Sealing subsystem.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Front Side Door Dynamic Weatherstrip	Use TPV	25% Mass Reduction	Lower cost for material and processing
Static Sealing	Use TPV	25% Mass Reduction	Lower cost for material and processing
Rear Side Door Dynamic Weatherstrip	Use TPV	25% Mass Reduction	Lower cost for material and processing
Hood Dynamic Weatherstrip	Use TPV	25% Mass Reduction	Lower cost for material and processing
Fender Seals	Use TPV	25% Mass Reduction	Lower cost for material and processing

Table F.4B-11: Summary of Mass-Reduction Concepts Initially Considered for the Sealing Subsystem

F.4B.3.5 Selection of Mass Reduction Ideas

Jyco thermoplastic vulcanizates (TPV) weather-stripping materials and technologies were selected in consideration of weight savings and cost savings with a lighter, greener, cost effective product.

A new, better material: TPV. Jyco was founded by pioneers of seal design and processing technologies that have become industry standards. The Team was a multi year recipient of the GM *Supplier of the Year Award*, as well as top technology awards from other Fortune 50 industry leaders. Jyco was founded on the potential of a relative new material to weathersealing, a plastic-rubber compound known as thermoplastic vulcanizates (TPV). This material promised advantages over traditional thermoset rubbers: processing with the ease and economies of plastic, reducing weight and costs, yet performing as well or better than the EPDM rubber that dominated the weather sealing business. In 2000, TPV seals were being used by several Japanese and European OEMs, but the compound was virtually unknown to the North American automotive industry. From its inception, Jyco structured its manufacturing operations around state-of-the-art TPV processing equipment, By doing so, they avoided the capital burden, transitional pains, and retooling that other sealing suppliers face in adapting EPDM systems to processing TPV.

Greener seals: Unlike EPDM, TPV is recyclable. Production scrap can be directly reprocessed. The manufacturing process itself is free of VOCs and particulate emissions characteristic of EPDM processing.

Nimbleness: As a lean, technology-driven company with few layers at the top end – general managers and department heads report directly to the CEO and COO -- Jyco's nimble structure has always allowed the company to incorporate process improvements, respond to market changes, and develop new products with exceptional speed.

Lead by Jyco, TPV sealing systems quickly gained the interest of North American OEMs. Through innovations such as their own JyFlex™ TPV compound, product design and foam extrusions, Jyco's annual revenues increased an average of 55% per year between 2001 and 2007. Jyco had become a global leader in TPV sealing technology for the automotive, with joint venture operations in China, Europe and Latin America. The global automotive industry recognized Jyco as the only TPV supplier TS/ISO/16949/9000 certified for design, testing and manufacturing, as well as for innovations such as their JyGreen™ technology for recycling rubber automobile tires into high performance TPV sealing system. The Society of Plastics Engineers presented Jyco with their 2004 Environmental Innovation of the Year award. The Canadian Manufacturers & Exporters honored Jyco with the "Canadian Automotive Supplier Innovation" award in 2005. Frost & Sullivan has named JYCO the receipent of the 2009 North American Technology Innovation of the Year Award for Automotive Sealing Technologies.

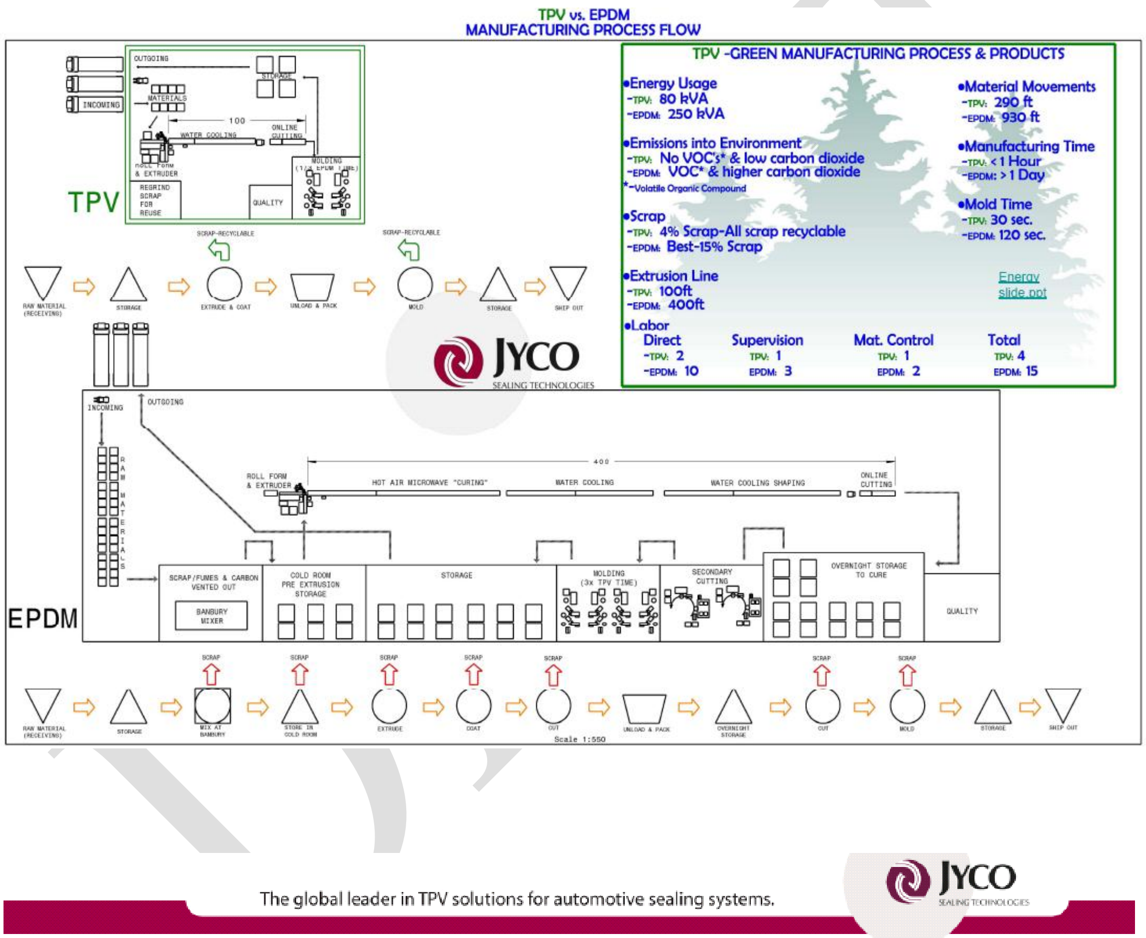


Figure F.4B-2: Jyco Presentation

(All presentation information supplied by Jyco)

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
03	**07**	**00**	**Sealing Subsystem**	
03	05	01	Front Side Door Dynamic Weatherstrip	Use TPV
03	05	02	Static Sealing	Use TPV
03	05	03	Rear Side Door Dynamic Weatherstrip	Use TPV
03	05	04	Hood Dynamic Weatherstrip	Use TPV
03	05	05	Fender Seals	Use TPV

Table F.4B-12: Mass-Reduction Ideas Selected for the Sealing Subsystem

F.4B.3.6 Mass-Reduction & Cost Impact Estimates

Table F.4B-13 shows the 2.029kg weight and the $15.70 cost reductions per sub-subsystem. Using the Jyco TPV material and process provided 100% of the weight and cost savings per the Sealing subsystem.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
03	**07**	**00**	**Sealing Subsystem**						
03	07	01	Front Side Door Dynamic Weatherstrip	A	0.427	$4.21	$9.85	25.00%	0.02%
03	07	02	Static Sealing	A	1.198	$7.17	$5.98	25.00%	0.07%
03	07	03	Rear Side Door Dynamic Weatherstrip	A	0.356	$3.75	$10.53	24.95%	0.02%
03	07	04	Hood Dynamic Weatherstrip	A	0.030	$0.29	$9.44	24.54%	0.00%
03	07	05	Fender Seals	A	0.018	$0.29	$16.36	10.13%	0.00%
				A	**2.029** (Decrease)	**$15.70** (Decrease)	**$7.74** (Decrease)	**24.67%**	**0.12%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.4B-13: Sub-Subsystem Mass-Reduction and Cost Impact for Sealing Subsystem

F.4B.4 Seating Subsystem

F.4B.4.1 Subsystem Content Overview

Table F.4B-14 shows included in the Seating subsystem are the Front Drivers Seat, Front Passengers Seat, Rear 60% Seat, and Rear 40% Seat sub-subsystems.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
03	**10**	**00**	**Seating Subsystem**	
03	10	01	Frt Drivers Seat	26.907
03	10	02	Frt Passenger Seat	22.754
03	10	03	Rear 60% Seat	26.481
03	10	04	Rear 40% Seat	16.406
			Total Subsystem Mass =	**92.548**
			Total System Mass =	**220.604**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**41.95%**
			Subsystem Mass Contribution Relative to Vehicle =	**5.41%**

Table F.4B-14: Mass Breakdown by Sub-subsystem for the Seating Subsystem

F.4B.4.2 Toyota Venza Baseline Subsystem Technology

The Venza front and rear seat frames are a complex array of stamped and welded parts to construct the back and bottom frames for all four seat groups. The foam is then placed on the back and bottom frames over steel springs. The covering is then added over the foam. The covering can be made from number of different materials: cloth, leather, or a blend.

The **Images F.4B-4** through **F.4B-10** show the seat and seat frames for the Toyota Venza.

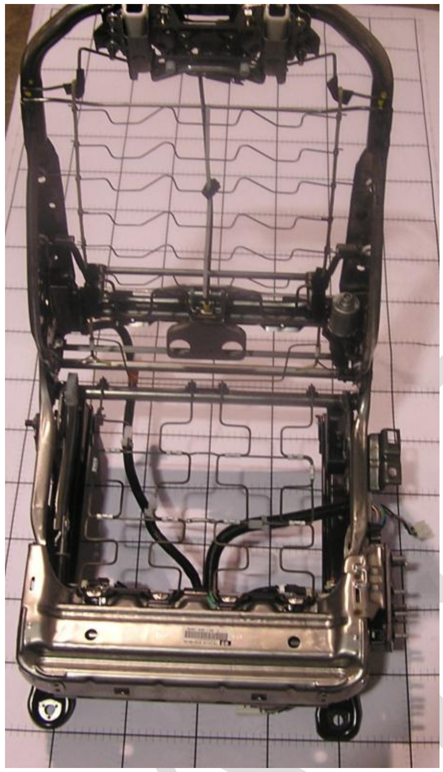


Image F.4B-4: Front Seat Frame

(Source: FEV Photo)

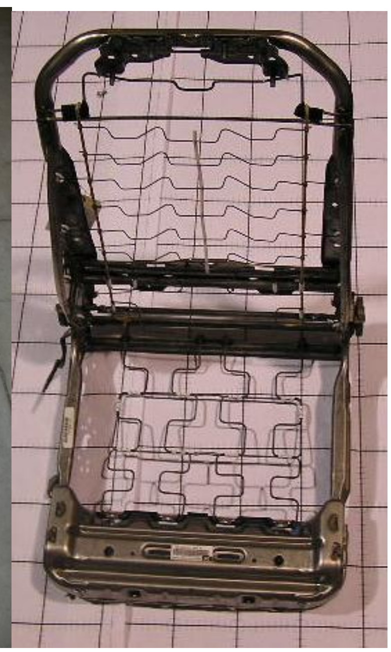


Image F.4B-5: Front Passenger Seat **Image F.4B-6: Front Passenger Seat Frame**

(without tracks and active head rest)

(Source: FEV, Inc. photo)

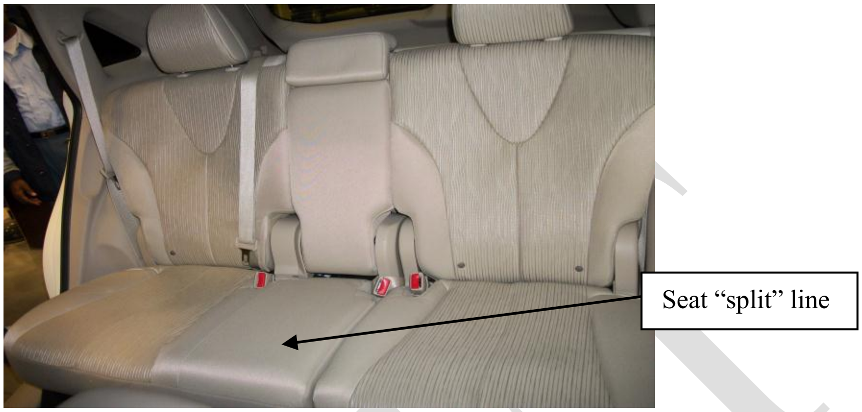


Image F.4B-7: Rear 60% & 40% Seat

(Source: FEV Photo)

The rear seat is split into two parts: the 60% portion is split to include the center arm rest section while the 40% portion composes the remainder of the rear seat.

The 40% rear seat frame (**Image F.4B-8**) shows the two independent bottom frames. When the fold flat seat back is moved down the bottom seat frame moves outward, this is to give the seat back more room to fold flat. Also in **Image F.4B-9** is the bottom frame2 removed from the bottom frame1.

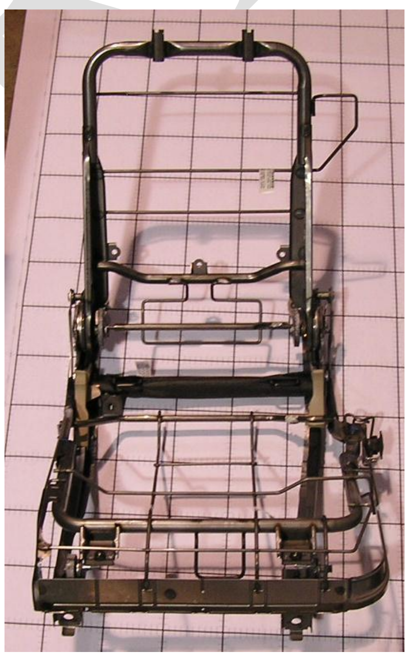


Image F.4B-8: Rear 40% Seat Frame

(Source: FEV Photo)

Image F.4B--9: Bottom pivot frame for the rear 60% seat; both 40% & 60% have these frames

(Source: FEV Photo)

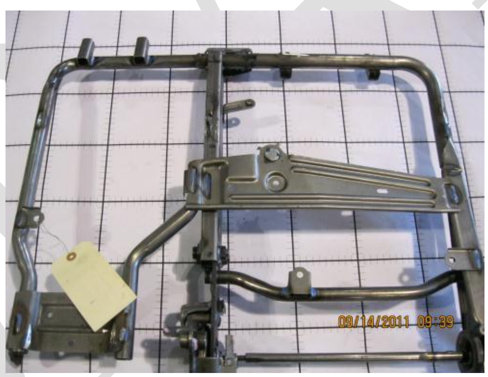


Image F.4B-10: Rear 60% seat back frame

(Source: FEV Photo)

With all of the stampings and weldings in the front and rear seat frames, the weight can be considerable, not counting the tooling and capital cost that goes with them. This is why a Thixomolding® one-piece magnesium bottom or back frame can save a considerable amount of money in piece price. The example used for the calculations was a Thixomolded Lexus seat back

F.4B.4.3 Mass-Reduction Industry Trends

A lot of attention is placed on the automobile seats for the weight that they contribute to the overall vehicle weight, especially the high weight of the frames. In today's market, more and more emphasis is placed on reducing seat weight. Therefore, many different types of seat frame constructions are emerging, such as those of high-strength steel, carbon fiber, plastics, cast magnesium, and aluminum.

F.4B.4.4 Summary of Mass-Reduction Concepts Considered

Reviewing the best option for removing seat frame mass, an in-depth study has to be done looking at current materials and processes. Plastic is less weight and cost, but unproven for durability, safety, and overall performance. Welded stamped and steel tube is proven, and is today's market mainstay. While it is lower in cost, it is not the best option for reducing weight. Welded stamped aluminum provides a good weight savings, but aluminum is expensive in comparison to alternative material selections and manufacturing costs. Cast aluminum offers the weight savings again, but not the best cost savings-to-weight ratio. Carbon fiber offers the best weight savings, but its availability and cost of material and manufacturing put this technology out of reach for the near-term. Cast magnesium offers a proven track record for durability and safety as well as cost savings. A new technology from Thixomat® for injection molding of magnesium stands out as a preferred manufacturing process.

Other ideas for seat weight reductions include using different types of foam for the seats, such as soy or pine wood. After reviewing these types of foam, however, it was determined that they did not provide a substantial weight savings. They also are not readily available for mass production. The costs of these materials are also very high. Their manufacturing process may actually add to greenhouse gas emissions, as well as being non-recyclable. Different types of manufacturing and welding were looked at as well for reducing weight and cost.

When analyzing the various options for seat mass reduction, the same solution was used for the front seat backs and seat bottoms: using the Thixomolded® Magnesium process. This process was also used for the 60/40 rear seat backs. The rear seat bottom solution that provided the best cost to weight improvement came from The Woodbridge Company®. Woodbridge® has developed an EPP foam process and seat design that was selected based on weight reduction and manufacturing cost.

Recliner mechanisms contribute a considerable amount of weight to the overall seat weight total. These were resized using the Lear EVO™ Mini recliner for all seats to reflect the overall reduction in the weight of the seat backs. **Table F.4B-15** shows some of the ideas considered.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Frt Seat Bottom & Back Frames	Composite Seat Frame ((Carbon))	20 to 30% Mass Reduction	Material not readily available and higher cost for material
Frt Seat Bottom & Back Frames	Cast aluminum seat frames	10 to 20% Mass Reduction	Higher material and processing costs
Frt Seat Bottom & Back Frames	Hydro-form seat frame tubes	10 to 20% Mass Reduction	Higher processing and capital costs
Frt Seat Bottom & Back Frames	Plastic	20 to 30% Mass Reduction	Warranty and safety issues
Frt Seat Bottom & Back Frames	Cast Mag	20 to 30% Mass Reduction	High material cost and porosity issues
Frt Seat Bottom & Back Frames	Reduce size of recliner mechanism using Lear EVO™ Mini Recliner	35% Mass Reduction	Higher cost than conventional recliners
Rear 60/40 Back Frames	Stamped AL-6022-T4	10 to 20% Mass Reduction	high costs for tooling, processing and material
Bottom & Back Frames	Laser/Resistance/Friction stir weld instead of mig	2 to 5% Mass Reduction	Not enough weight save for capital and process investment
Bottom & Back Frames	Use Velcro to attach fabric to frame	NA	No advantage
Bottom & Back Frames	Eliminate center cross rod on lower 60% frame	NA	After review this was feasible
Air Bag Sensor	Replace strain gauges with pressure sensitive mat	5 to 10% Mass Reduction	Not app. For weight distribution weight calibration
Foam Cushions	Use pine wood based foam	5 to 10% Mass Reduction	Expensive and not avail.
Foam Cushions	Use soy based foam	5 to 10% Mass Reduction	Expensive and not avail.
Foam Cushions	Use NuBax® foam insert	5 to 10% Mass Reduction	Remove active head rest
Brkts, Armrest RR Seat	Make out of ABS	5 to 10% Mass Reduction	No cost increase
All plastic parts	Use MuCell® for non-class A surface	10% Mass Reduction	No cost increase
All plastic parts	Use Polyone® for class A surface	10% Mass Reduction	No cost increase

Table F.4B-15: Summary of Mass-Reduction Concepts Initially Considered for the Seating Subsystem

F.4B.4.5 Selection of Mass Reduction Ideas

Table F.4B-16 contains the mass-reduction ideas selected for the Seating subsystem

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
03	**10**	**00**	**Seating Subsystem**	
03	**10**	**01**	**Front Drivers Seat**	
03	10	01	Front Drivers Seat ((Seat Back & Seat Bottom))	Thixomold® Mag Seat Back & Bottom
03	10	01	Front Drivers Seat ((Seat Back & Seat Bottom))	Lear EVO™ Mini Recliner
03	10	01	Front Drivers Seat ((Seat Bottom))	ProBax® Structural Foam Insert
03	10	01	Front Drivers Seat	MuCell® Non-Class "A" Surfaces
03	10	01	Front Drivers Seat	PolyOne® Class "A" Surfaces
03	**10**	**02**	**Front Passenger Seat**	
03	10	02	Front Passenger Seat ((Seat Back & Seat Bottom))	Thixomold® Mag Seat Back & Bottom
03	10	02	Front Passenger Seat ((Seat Back & Seat Bottom))	Lear EVO™ Mini Recliner
03	10	02	Front Passenger Seat	MuCell® Non-Class "A" Surfaces
03	10	02	Front Passenger Seat	PolyOne® Class "A" Surfaces
03	**10**	**03**	**Rear 60% Seat**	
03	10	03	Rear 60% Seat ((Seat Back & Seat Bottom))	Lear EVO™ Mini Recliner
03	10	03	Rear 60% Seat ((Seat Back))	Thixomold® Mag Seat Back
03	10	03	Rear 60% Seat ((Seat Bottom))((Weight and cost w60% seat))	Woodbridge® PU/EPP Foam
03	10	03	Rear 60% Seat	MuCell® Non-Class "A" Surfaces
03	10	03	Rear 60% Seat	PolyOne® Class "A" Surfaces
03	**10**	**03**	**Rear 40% Seat**	
03	10	03	Rear 40% Seat ((Seat Back & Seat Bottom))	Lear EVO™ Mini Recliner
03	10	03	Rear 40% Seat ((Seat Back))	Thixomold® Mag Seat Back
03	10	03	Rear 40% Seat ((Seat Bottom))	Woodbridge® PU/EPP Foam
03	10	03	Rear 40% Seat	MuCell® Non-Class "A" Surfaces
03	10	03	Rear 40% Seat	PolyOne® Class "A" Surfaces

Table F.4B-16: Mass-Reduction Ideas Selected for the Seating Subsystem

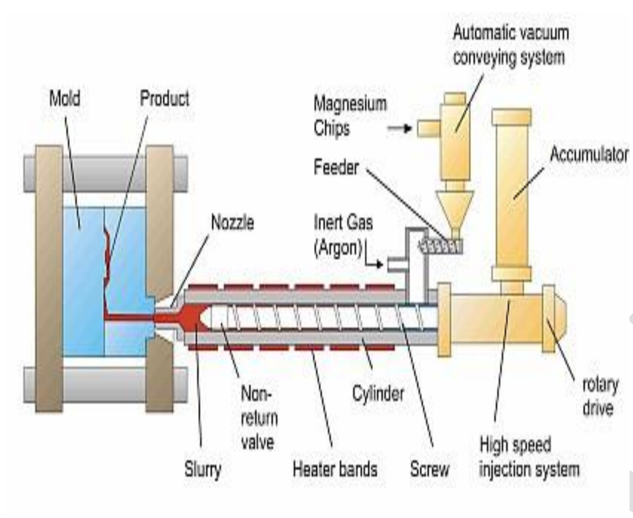
Magnesium was chosen as the best option going forward in the study, many tier one suppliers use magnesium in seat frame applications and using magnesium is a well accepted material for the front seats back and bottom frames. Magnesium was also selected for the back frame of the rear 60/40 seat. Magnesium is 75% lighter than steel and 33% lighter than aluminum. Magnesium is the lightest structural material ($1.8 g/cm^3$). Magnesium is the eighth most abundant element in the Earth's crust. The attributes behind selecting Mg are:

- High impact resistance
- High strength-to-weight ratio
- Can be cast and molded to net shape
- Excellent dimensional stability/repeatability
- Abundant material supply
- 100% recyclable

The Thixomolding® process of injection-molding magnesium provides reductions in cost compared to magnesium die casting, and the weight reduction gained by replacing steel with magnesium make it an attractive option. Following are some facts about the Thixomolding® process.

- Thixomolding® is an environmentally friendly, high-speed, net-shape, semisolid, magnesium injection molding process;
- In a single step, the process transforms room-temperature magnesium chips, heated to a semi-solid slurry inside a barrel and screw, into precision-molded components;
- No sintering or debinding steps are required as in the MIM (metal injection molding) process to complete the densification process;
- Thixomolded® components, after air cooling, are ready for trimming and assembly or secondary operations;
- 50% lower porosity than die cast makes them good candidates for coating or plating without blistering or out gassing;
- Superior mechanical properties and faster cycle rates compared with die casting;
- EMI-RFI shielding;

- High strength-to-weight ratio;
- Dent resistance and good machine ability;
- Heat transfer capability;
- No surface sinks at wall junctions;
- Wide variety of surface finishes available;
- Low draft (zero draft possible, 0.5° to 2° typical);
- Environmentally friendly process with foundry-free environment liquid-free - no molten metal handling;
- Excellent dimensional repeatability, tight tolerances and the ability to mould thin walls;
- Better ductility;
- Longer die life, due to lower temperature of material entering mould, and reduced gate velocities;
- Environmentally friendly production – worker safe and friendly, cooler work area, no global-warming SF6 cover gas, no dross or sludge (unlike Mg foundry operations);
- Net or near net-shape parts with little, if any, machining;
- No heat treatment required;
- Higher metal yield, hence lower costs;
- New part design, consolidating several parts into one molding and integrating multiple functions.



Formerly produced as stamped steel, this prototype Thixomolded magnesium seat back measures 18" x 22 1/2" and is contrasted against a pair of pliers to give an idea of relative size. By switching to Thixomolded magnesium, weight was reduced approximately 35 per cent to 2.2 kilos and partsrequired for the assembly were cut from 13 to 3. The finished part is as moulded, and has a rear load strength of about 4500 Nm.

Manufacturing Method	Relative Component Cost
Thixomolding	100%
Foreign aluminum die caster	145%
Domestic aluminum die caster	172%
Zinc die caster	241%

Figure F.4B-3: Thixomolding® examples

(All presentation material supplied by Thixomolding®)

(Front seat specific) As part of the front seat frames weight reduction, the Lear EVO™ Mini Recliner were selected to replace the current Venza recliner mechanisms. The Lear EVO™ provides 35% weight reduction and uses 50% less packaging space.

Image F.4B-11: Lear EVO® Recliner

(Source: Lear™ website)

Image F.4B-12: Toyota Venza recliner

(Source: FEV Photo)

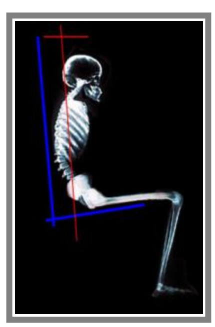
Also included was the ProBax® structural foam insert. This technology used in testing with three global automotive OEMs allows for the removal of the active head rest as well as the lumbar system. No change to the current fir and or function of the seat was made using the ProBax foam insert. The following are other advantages to using the ProBax® system:

- ProBax® requires no changes to the existing seat frame, vehicle homologation, or occupant restraint systems;
- ProBax® seating concept tested and patented in 2001;
- Feasibility confirmed for principal production processes - molded foam, foam in place, cut foam;
- Technology now available in automotive industry, U.K. and U.S. contract seating (healthcare, corporate, educational) and private aircraft;
- First product launch – 2006MY Lotus Elise;

Image F.4B-13: Lotus Elise Seat

(Source: Supplied by EPA)

- Currently in testing with three global Automotive OEMs;
- ProBax® insert supports ischial tuberosities to rotate occupant pelvis forward;
- Support occupant skeletal structure – not musculature;
- Prevent slumped posture (kyphotic spine);
- Promote correct posture (lordotic spine);
- Increase blood flow with less muscle fatigue: See ProBax web site for documentation.

ProBax Foam insert	Without ProBax	With ProBax
		

ProBax® reduces distance from cranium to head restraint by improving posture

Figure F.4B-4: ProBax® System

(All ProBax® presentation material and information provided by ProBax®)

- Removal / reduction of lumbar and active head rest mechanisms

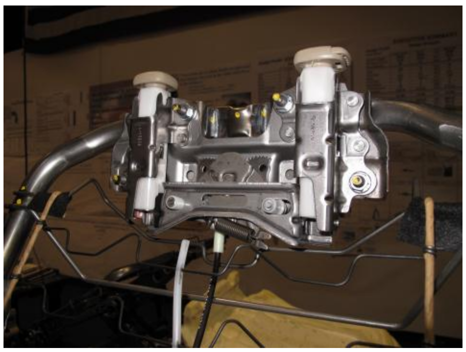


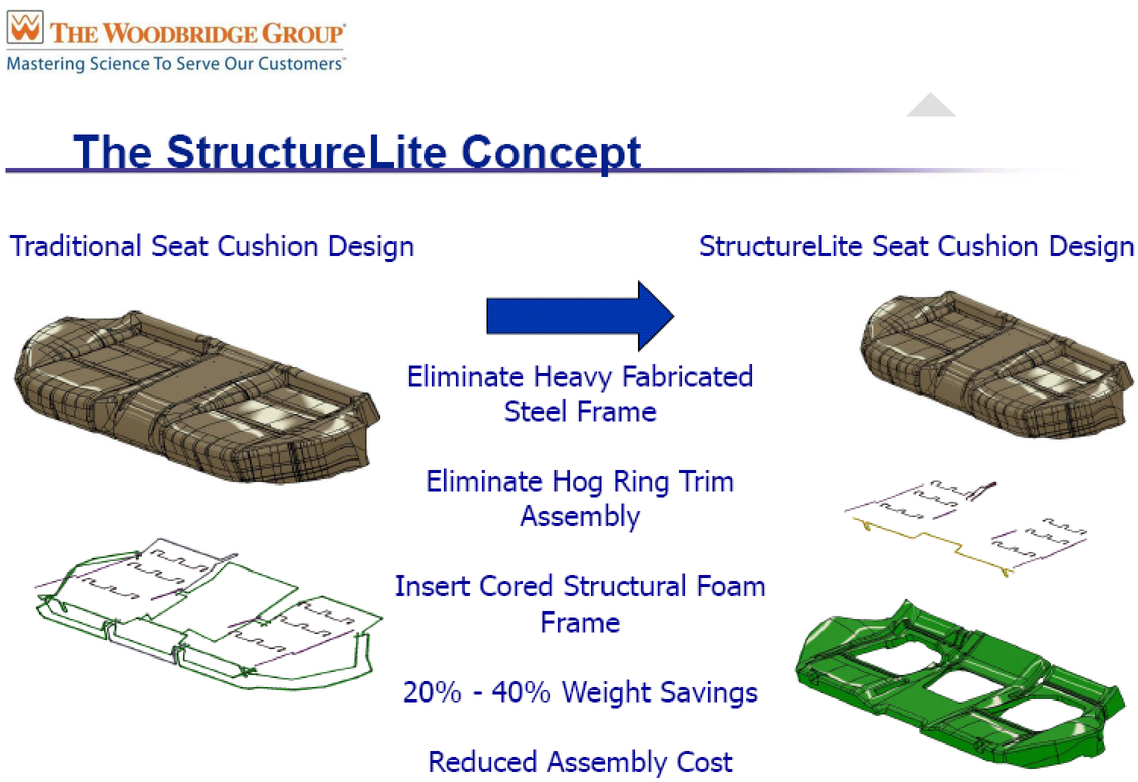
Image F.4B-14:Top of Toyota Venza Active Head Rest

Image F.4B-15: Bottom of Toyota Venza Active Head Rest

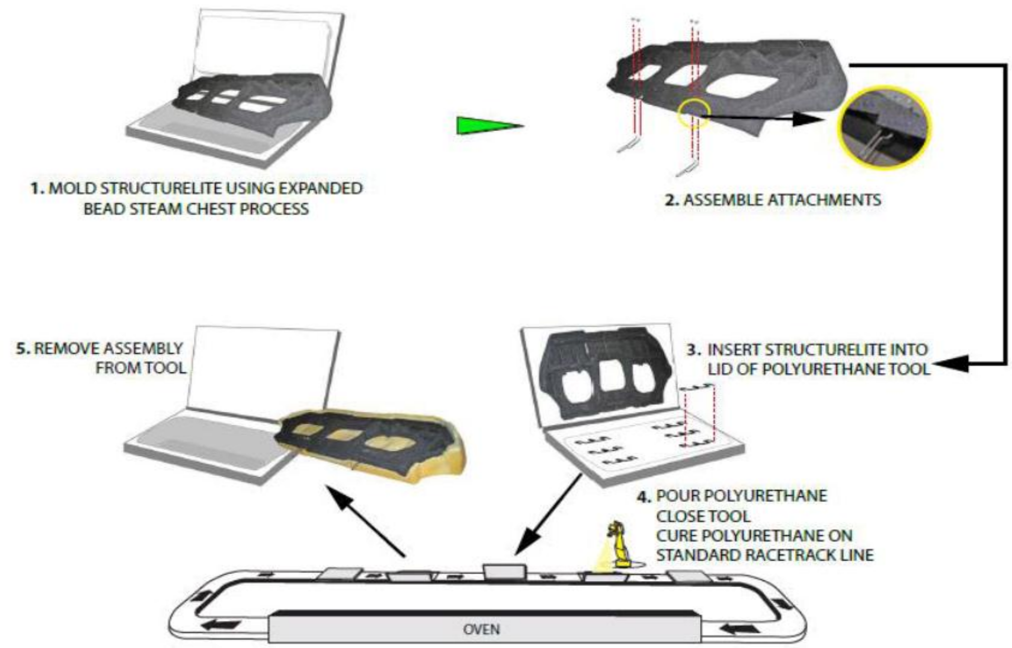
(Source: FEV Photo) *(Source: FEV Photo)*

- Removal of additional components
- Reduction in production time
- Reduction of warranty costs
- Reduction in vehicle weight
- Overall weight reduction from the Lotus Elise seat resulting from introduction of ProBax® technology .8kg
- This equals 15-20$ per vehicle savings over all

(Rear seat specific) Looking at the back seat frame bottom, The Woodbridge Group™ has a PU/EPP foam process that was reviewed for weight and manufacturing. This process removes the welded steel frame and replaces it with a PU/EPP foam structure. The welded steel frame structure that was in the Toyota Venza was a carry over seat from the Toyota Highlander. Even though the carry over of the seat saved Toyota in a unique design and manufacturing costs it was very heavy and not designed for the Toyota Venza application.



Manufacturing Process



Examples

Figure F.4B-5:The Woodbridge Group™ Concept and Process

(All presentation material and information provided by The Woodbridge Group™)

Economics

- Reduced trim assembly labor

- No tooling required for trim assembly
- Eliminate steel welding and fixtures
- BIW savings from integration of anti-sub feature

Market Examples

- Kia TF 30% weight save
- Chevy Impala weight save 4kg
- Porsche Cayenne weight save 10.5kg

Conclusion

- Structural foam concept results in weight savings of 20% - 40%
- System designed to pass FMVSS 207 requirements
- Engineered for comfort
- Overall system cost savings
- Several variants currently in production

F.4B.4.6 Mass-Reduction & Cost Impact Estimates

Table F.4B-17 shows the 22.908kg weight and $83.44 cost reductions per sub-subsystem.

Front Drivers Seat

Back Frame

For the front drivers seat back frame going from welded steel construction to a Thixomolded magnesium injected frame, the weight savings was 1.313kg. The frame, however, needed new upper recliner mounting brackets welded to the new recliners and bolted to the magnesium back frame. This added .749kg back in, for a final welded steel-to-a-Thixomolded injection magnesium back frame total weight savings of .563kg. The cost for going to the Thixomolded magnesium frame and adding in the brackets is an increase of $10.07.

Bottom Frame

The addition of the NuBax foam insert to the bottom frame is a 2.158kg weight savings due to the ability to remove the active head rest assembly and the lumbar system. This also gives a cost decrease of $24.57. Although the NuBax systems data show the possibility and potential of removing the active head rest and lumbar systems, it has not yet been done in production.

The bottom frame going from a welded steel construction to a Thixomolded injection molded magnesium frame is a 2.213kg decrease in weight. Plus, with the new Lear EVO recliners, another .296kg savings can be found.

The bottom recliner brackets, as with the back frame, will have to be added at a .749kg increase, for a total decrease in weight for the bottom seat frame of 1.76kg and a cost increase of $5.30

Front Drivers Seat Trim

The front seat trim also used the PolyOne for Class “A” surfaces (.206kg/$.38 cost and weight savings) and MuCell® for non-Class “A” surfaces (.028kg/$.15 weight and cost savings) for a total front driver seat weight savings of 4.715kg and a cost savings of $9.73.

Front Passenger Seat

Back Frame

For the front passenger seat back frame, going from welded steel construction to a Thixomolded magnesium injected frame, the weight savings was 1.313kg. The frame, however, needed new upper recliner mounting brackets welded to the new recliners and bolted to the magnesium back frame. This added .749kg back in. For a welded steel to a Thixomolded injection magnesium back frame total weight savings of .564kg. The cost for going to the Thixomolded magnesium frame and adding in the brackets is a $10.06 cost increase.

Bottom Frame

The addition of the NuBax foam insert to the bottom frame is a 1.349kg weight savings due to the ability to remove the active head rest assembly. This also is a cost decrease of $16.21. Although the NuBax systems data shows the possibility and potential of removing the active head rest system, it has not yet been done in production.

The bottom frame, going from a welded steel construction to a Thixomolded injection molded magnesium frame, is a 2.006kg decrease in weight. Plus, with the new Lear EVO recliners, another .252kg savings can be found.

The bottom recliner brackets, as with the back frame, will have to be added at a .749kg increase, for a total decrease in weight for the bottom seat frame of 1.509kg – but with a cost increase of $10.19. The cost increase is larger than the front driver seat due to more magnesium used for the bottom frame.

Front passenger seat trim

The front passenger seat trim also used the PolyOne for Class “A” surfaces (.200kg/$.48 weight and cost savings) and MuCell for non-Class “A” surfaces (.018kg/$.062 weight and cost savings) for a total front passenger seat weight savings of 3.638kg and a cost increase of $3.49

Rear 60% Seat

Back Frame

For the rear 60% seat portion back frame, a welded steel construction changed to a Thixomolded magnesium injected frame that will be bolted to the BIW and not to the rear 60% seat base and bottom, a weight savings of 3.622kg can be achieved. The arm rest bracket was also changed from a stamped steel bracket to ABS plastic, with an added 30% volume of plastic for strength. The arm rest bracket is a non-critical load part with a .439kg weight savings.

The overall weight decrease/savings for a welded steel back frame construction to a Thixomolded injection magnesium back frame with an added weight decrease/savings of the arm rest bracket a total weight savings of 4.061kg and a cost savings of $14.94 can be achieved.

Bottom & Base Frame

For the base and bottom frames to be calculated, the rear seat 40% and 60% base and bottoms had to be added together. Using the Woodbridge Group™ PU/EPP foam process (as shown in section 5.3B.4.5) the overall savings are 9.289kg weight and $67.28 cost.

Rear 60% seat trim

The rear 60% seat trim also used the Polyone for Class "A" surfaces (.083kg/$.25 weight and cost savings) and MuCell for non-Class "A" surfaces (.117kg/$.41 weight and cost savings) for a total rear 60% seat and the 40% rear seat base and bottom weight savings of 13.551kg and a cost savings of $82.87

Rear 40% Seat

Back Frame

For the rear seat 40% portion of the back frame, which is a welded steel construction, being changed to a Thixomolded magnesium injected frame that will be bolted to the BIW and not to the rear 40% seat base and bottom, the weight saved was 1.35kg with a $4.94 cost increase.

Rear 40% seat trim

The rear 40% seat trim also used the PolyOne for Class "A" surfaces (.05kg/$.08 weight and cost savings) and MuCell for non-class "A" surfaces (.089kg/$.302 weight and cost savings) for a total rear 40% seat back and trim weight savings of 1.488kg and a cost increase of $4.56.

System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
03	**10**	**00**	**Seating Subsystem**						
03	10	01	Seat Drivers Frt	A	4.715	$9.73	$2.06	17.53%	0.28%
03	10	02	Seat Passenger Frt	D	3.638	-$3.49	-$0.96	15.99%	0.21%
03	10	03	Seat Rear 60%	A	13.551	$82.87	$6.12	51.17%	0.79%
03	10	04	Seat Rear 40% ((Weight & Cost reduction of 40% seat base & bottom w/60% Seat, the weight and cost save calculated here is for the rear 40% seat back & trim only))	D	1.488	-$4.56	-$3.06	9.07%	0.09%
				A	**23.392** (Decrease)	**$84.55** (Decrease)	**$3.61** (Decrease)	**25.28%**	**1.37%**

Net Value of Mass Reduction Idea (columns Idea Level Select through Vehicle Mass Reduction)

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.4B-17: Sub-Subsystem Mass-Reduction and Cost Impact for Seating Subsystem

F.4B.5 Instrument Panel and Console Subsystem

F.4B.5.1 Subsystem Content Overview

As seen in **Table F.4B-19**, the Instrument Panel and Console subsystem has four sub-subsystems containing mass. The primary ones are the Cross-Car Beam (CCB), Instrument Panel Main Molding, and Center Stack sub-subsystems. The CCB includes the beam and all welded brackets. It serves as the primary mounting structure for all Instrument Panel sub-assemblies and modules like the HVAC Main Unit, radio, glove box, center stack, and steering wheel. The Instrument Panel Main Molding includes the instrument panel trim and other plastic covers and structural components that surround the dash. The Center Stack sub-subsystem is made up of the center console and center stack (connects the IP to the center console).

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
03	**12**	**00**	**Instrument Panel and Console Subsystem**	
03	12	01	Cross-Car Beam (IP) (CCB Beam and welded brackets)	10.366
03	12	03	Instrument Panel Main Molding	11.838
03	12	06	Applied Parts - (IP) (Access Panels)	0.008
03	12	18	Center Stack (Center Console)	10.476
			Total Subsystem Mass =	**32.688**
			Total System Mass =	**220.604**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**14.82%**
			Subsystem Mass Contribution Relative to Vehicle =	**1.91%**

Table F.4B-18: Mass Breakdown by Sub-subsystem for the Instrument Panel and Console Subsystem

F.4B.5.2 Toyota Venza Baseline Subsystem Technology

The Toyota Venza has a traditional steel CCB with welded brackets and fixtures as shown in **Image F.4B-16**. The beam has two sections with different diameters. Components are mostly welded together with some use of fasteners.

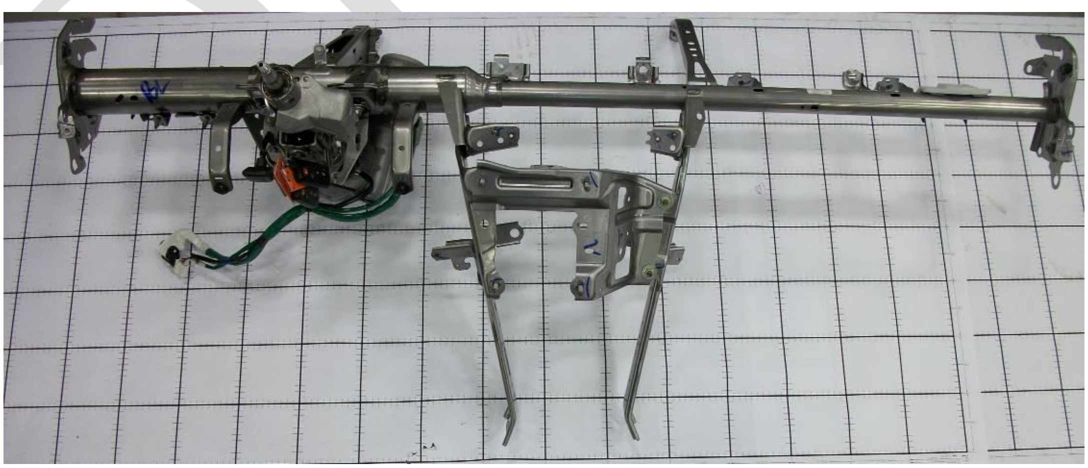


Image F.4B-16: Toyota Venza Cross-Car Beam

(Source: FEV, Inc. Photo)

The Instrument Panel Base Dash, shown in **Image F.4B-17** and **Image F.4B-18**, is a polypropylene and polyethylene talc-filled blend. There is a polyurethane foam (**Image F.4B-19**) under the skin cover. The glove box assembly and all lower dash trim also make up the Instrument Panel Main Molding sub-subsystem. The majority of the glove box and dash trim parts has a Class "A" surface finish and is either talc-filled polypropylene or nylon.

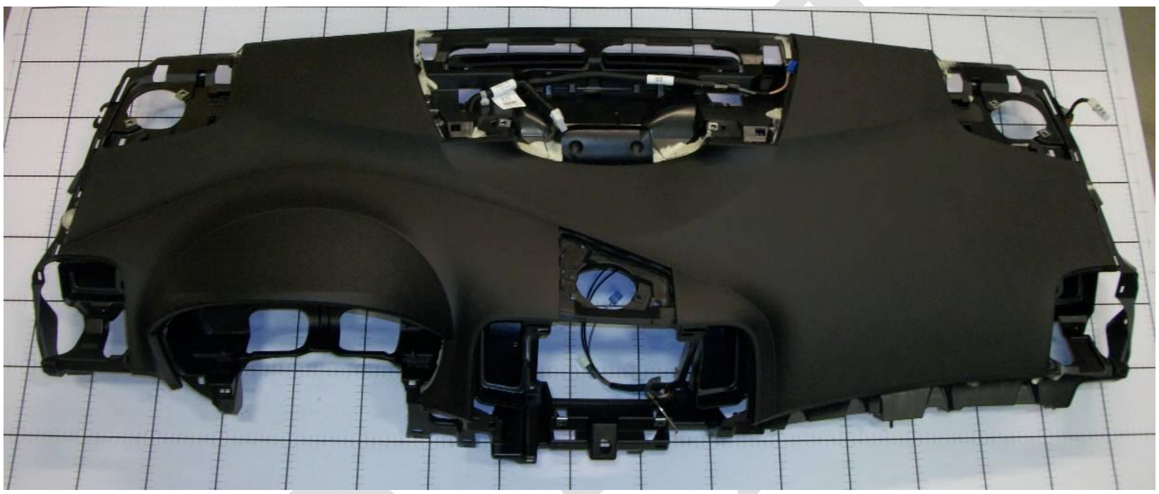


Image F.4B-17: Top of Dash, IP Base with Skin Cover

(Source: FEV, Inc. Photo)

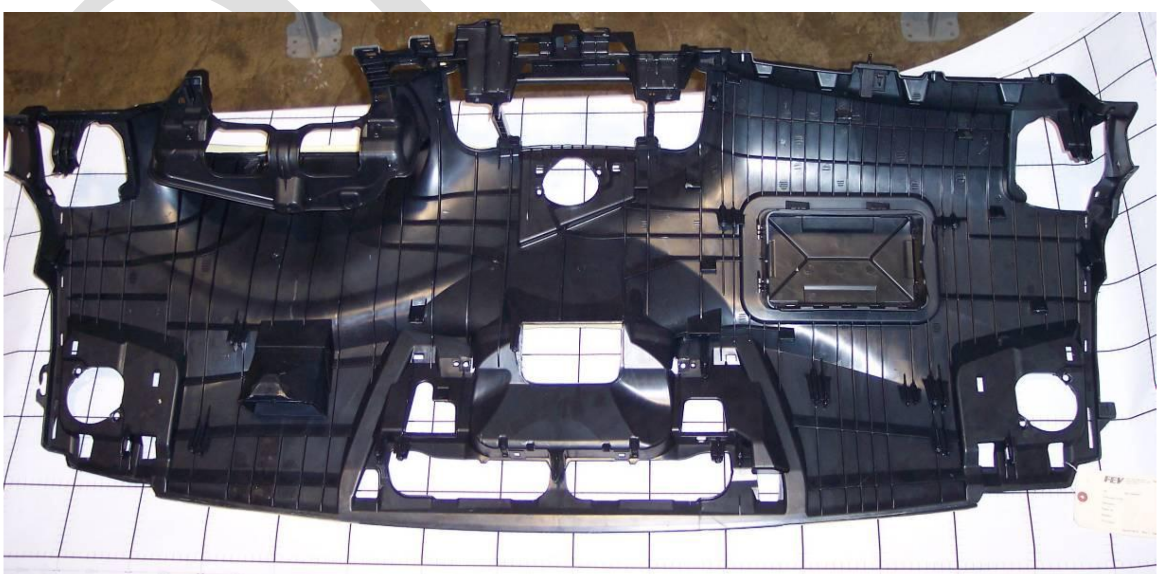


Image F.4B-18: Bottom of Dash, IP Base

(Source: FEV, Inc. Photo)

Image F.4B-19: Dash, IP Base with Skin Cover Removed

(Source: FEV, Inc. Photo)

The Center Stack sub-subsystem of the Instrument Panel includes the entire Center Console and the trim that connects the instrument panel to the console. The Center Stack Trim includes several storage compartments, cup holders, and accessory power outlets. The Center Stack includes some non-Class “A” parts made of ABS, but is mostly composed of Class “A” surface parts made of talc-filled PP or nylon.

F.4B.5.3 Mass-Reduction Industry Trends

The most notable opportunity for light-weighting the Instrument Panel and Console subsystem is with the CCB. There are a variety of light-weighting technologies and ideas being applied to CCBs throughout the industry. Traditionally, CCBs have been rolled steel products, but this is starting to transform. Mubea, Inc. is a company that specializes in Tailor Rolled Products. They use specialty rolling equipment that varies the thickness of a single piece so that thick sections are only applied where structurally necessary (**Figure F.4B-5**). Other sections of the same beam are manufactured to be thinner, thus saving weight compared to a traditional CCB. Utilizing this technology not only saves weight, but the reduced raw material cost will offset the additional processing cost, resulting in a near cost-neutral exchange. Tailor Rolled Beams are currently used on the CCBs of BMW’s 1, 3, 5, and 7 Series vehicles.

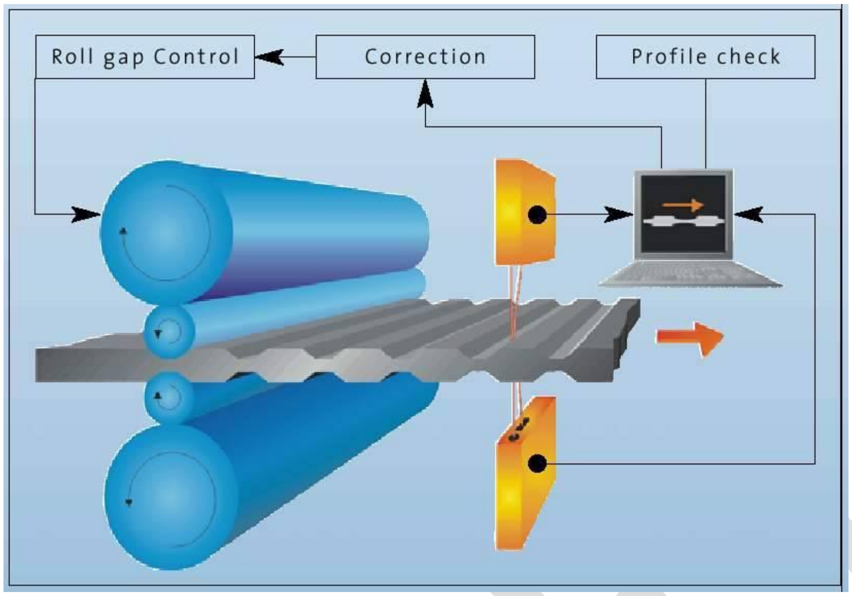
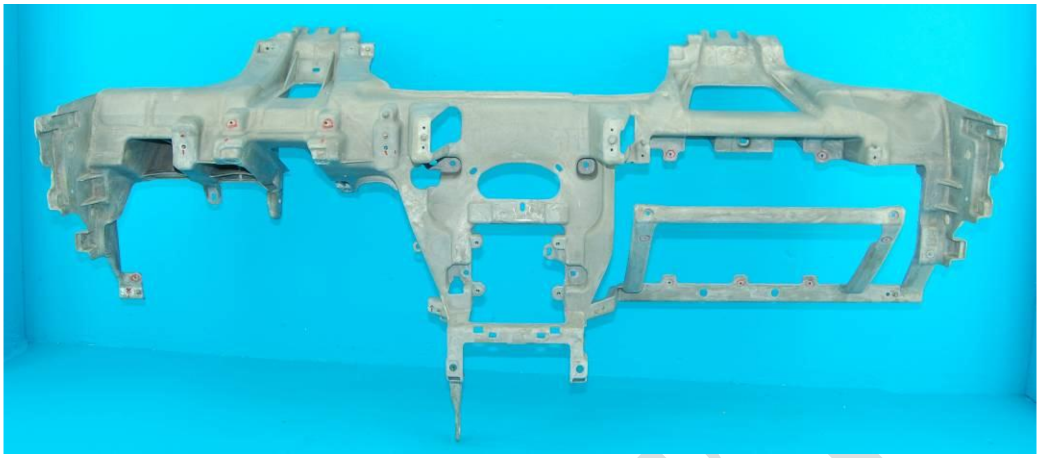


Figure F.4B-6: Illustration of Mubea's Tailor Rolled Blank Process

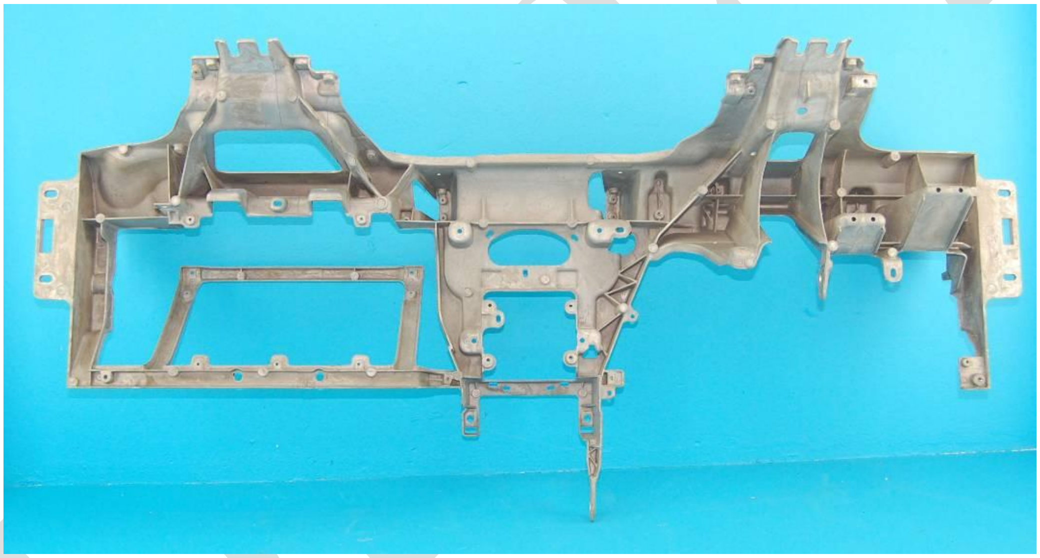
(Source: Mubea http://www.stahl.karosserie-netzwerk.info/59.htm)

Automakers have also begun using alternative materials on cross-car beams. These include the use of both aluminum and magnesium. The McLaren MP4-12C uses aluminum CCBs, and the Jaguar XKR, BMW X5, and BMW X6 all use magnesium. Chrysler has also embraced non-ferrous CCBs, using magnesium in the Dodge Caliber and on numerous Jeep models. The magnesium CCB from the 2010 Dodge Caliber 2.4 R/T is shown in **Image F.4B-20**. This magnesium beam differs significantly in design and manufacturing process than the baseline Venza beam in **Image F.4B-16**. The magnesium beam is a one-piece die casted component while the steel beam is a multi-piece rolled, stamped, and welded assembly.

The Stolfig® Group in Europe conducted a comparison of three CCBs as shown in **Image F.4B-21**. The weight savings associated with aluminum and magnesium beams compared to steel is immediately apparent, but of course this mass reduction is not without a cost penalty.



(a) Front View



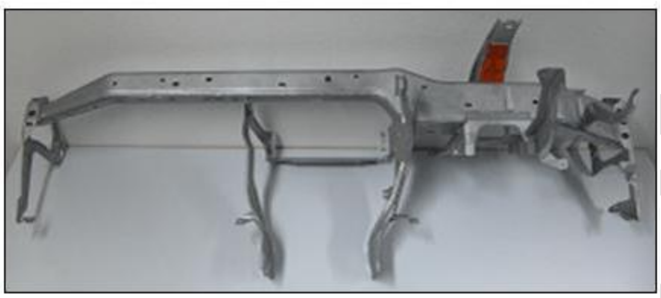
(b) Back View

Image F.4B-20: Dodge Caliber Magnesium Cross-Car Beam

(Source: A2mac1 http://www.a2mac1.com/Autoreverse/reversepart.asp?productid=150&clientid=1&producttype=2)

Material: Steel
Thickness: 1.0 mm
Mass: 8.54 kg

Material: Aluminum
Thickness: 1.5 mm
Mass: 4.41 kg



Material: Magnesium
Thickness: 1.7 mm
Mass: 3.22 kg

Image F.4B-21: CCB Examples Compared by the Stolfig® Group

(Source: Stolfig http://www.stolfig.com/lang/en/services/carbeam.php)

Concerning the plastic components that make up the IP Subsystem, the use of Trexel's MuCell® technology is beginning to be used by Ford to reduce the weight of plastic parts. Also, PolyOne's Chemical Foaming Agents (CFAs) are capable of reducing the mass of plastic components while attempting to maintain a Class "A" surface finish. See Section 5.3B.1.1 of this report for more information on these technologies.

SABIC® is a materials supplier with much of their focus on plastics. They are one of the largest plastics suppliers in the world and provided numerous mass reduction ideas across all systems of the vehicle, one of which is the Instrument Panel subsystem. SABIC's long glass fiber polypropylene (LGF-PP), Stamax®, is a material used on instrument panels to maintain rigidity requirements while also reducing weight. According to SABIC®, a mass reduction of 30% is attainable as the use of LGF-PP allows the wall thickness of the Instrument Panel Dash Base to be reduced to 2 mm (the thickness of the Venza IP is 3 mm). The rigidity is maintained over a wide temperature range. Instrument Panel thicknesses as thin as 1.8 mm are currently in production. LGF-PP has a higher modulus than talc-filled PP, and the use of advanced engineering simulation (Autodesk® Moldflow® software) and FEA allow SABIC® to achieve such mass reduction.

F.4B.5.4 Summary of Mass-Reduction Concepts Considered

Ideas that were considered to reduce the Instrument Panel and Console subsystem mass are compiled in **Table F.4B-20**. For the CCB, aluminum and magnesium material changes were judged along with Mubea's TRB technology. For the plastics parts, Chemical Foaming Agents and MuCell® were options along with SABIC's Stamax® for the Instrument Panel Dash.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Cross-Car Beam	Tailor Rolled Beam	10% mass reduction	Low cost increase, in production on BMW 1, 3, 5, & 7 Series
Cross-Car Beam	Change material to Aluminum	30-50% mass reduction	Moderately high cost, used in low volume production on McLaren MP4-12C
Cross-Car Beam	Change material to Magnesium	40-60% mass reduction	High cost, used in high volume production on Dodge Caliber, Jeep Grand Cherokee, BMW X5 & X6
Plastic Components (non-Class A surface finish)	MuCell®	10% mass reduction	Low cost, MuCell used in high volume production by Ford
Plastic Components (Class A surface finish)	PolyOne Chemical Foaming Agent	10-20% mass reduction	Low cost, CFA for PP currently under test for use in high volume production vehicles
Instrument Panel Plastic Core	SABIC's LGF-PP (Stamax®)	30% mass reduction	Moderately high cost, used on high volume production vehicles

Table F.4B-19: Summary of Mass-Reduction Concepts Initially Considered for the Instrument Panel and Console Subsystem

F.4B.5.5 Selection of Mass Reduction Ideas

The three sub-subsystems that mass reduction ideas were applied to are shown in **Table F.4B-20**. Magnesium was selected to be used for the CCB. While high in material cost, magnesium offers a substantial weight savings and, after evaluation, was favorable to the aluminum CCB and Mubea's TRB process. Magnesium beams are also in current use by multiple OEMs. The multi-piece steel CCB was reduced to a two-component assembly with the magnesium beam. The magnesium beam was manufactured using die casting, which lends itself to component integration. The Tailor Rolled Blank CCB for this particular vehicle did not result in a favorable dollar-per-kilogram ratio. For typical steel CCBs, Mubea's process is competitive; however, for the Toyota Venza, Mubea determined that there were no potential weight savings without a significant cost penalty.

Some general assumptions were initially applied to convert the CCB from steel to magnesium. In particular, the gauge of the material was doubled to account for the reduced strength magnesium exhibits compared to steel. Magnesium's yield strength is in the 200-275 MPa range depending on the alloy used. A common steel used for a CCB is HSLA 420, which exhibits a yield strength of around 420-550 MPa. For the rough assumptions in this analysis, the increase in thickness of the magnesium CCB would increase its moment of inertia, thereby making up for the relatively low strength of magnesium compared to steel. In order to validate this, mathematical modeling would need to be conducted based on the testing requirements for the CCB. Such an engineering analysis was beyond the scope of this study. In light of this, the benchmarking results were cross-referenced. The Dodge Caliber's magnesium beam is 5.6 kg and the BMW X5's is 5.8 kg. In reality, the magnesium CCB will take a much different shape than the baseline steel one as illustrated in the pictures in the previous sections. It was determined that using the mass of existing magnesium CCBs would be a secure approach as opposed to the mass that resulted using the thickness increase assumptions. Therefore, an average of these two numbers was used for the Venza's redesigned CCB resulting in a final mass of 5.7 kg, saving approximately 4 kg versus the baseline steel beam. The magnesium CCB was not considered in the NVH or crash analyses performed.

SABIC's Stamax® LGF-PP was applied to the Dash Instrument Panel Base as it yielded a 30% weight reduction. MuCell® was used on eligible plastic parts that had a non-Class "A" surface finish to reduce the weight by 10%. PolyOne's CFAs were applied to eligible plastic parts that had Class A surface finishes resulting in a 10% mass reduction per part.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
03	**12**	**00**	**Instrument Panel and Console Subsystem**	
03	12	01	Cross-Car Beam (IP) (CCB Beam and welded brackets)	Change CCB from steel to magnesium
03	12	03	Instrument Panel Main Molding	SABIC's Stamax LGF-PP applied to Dash Core. MuCell® and PolyOne CFA on non-Class A and Class A parts, respectively.
03	12	06	Applied Parts - (IP) (Access Panels)	n/a
03	12	18	Center Stack (Center Console)	MuCell® and PolyOne CFA on non-Class A and Class A parts, respectively.

Table F.4B-20: Mass-Reduction Ideas Selected for Detail Analysis of the Instrument Panel and Console Subsystem

F.4B.5.6 Mass-Reduction & Cost Impact Results

Table F.4B-21 shows the weight savings for the ideas applied to the Instrument Panel and Console Subsystem as well as their cost impact. As seen in the first line of this table, the magnesium CCB generates a cost increase of $11.57 and saves approximately 4 kg.

The Instrument Panel Main Molding sub-subsystem includes the Instrument Panel Dash Base, to which the Stamax® LGF-PP was applied, and it accounted for 70% of the 1.627 kg weight saved. The remaining 30% of the mass reduction was reduced by applying PolyOne's CFAs. The Stamax LGF-PP raises the cost of this sub-subsystem by over $3.30, but the cost is decreased to a $2.38 hit when the CFA is applied to the other components in the sub-subsystem.

The Center Stack sub-subsystem resulted in a cost savings because only MuCell® and PolyOne's CFAs were applied. Even though both of these technologies initially add cost, the mass reduction from the parts results in a lower material cost, which typically leads to an overall cost savings. PolyOne's CFAs contribute to 95% of the 0.728 kg weight savings and to 90% of the $1.46 cost savings. The rest is accounted for by MuCell®.

System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
				Net Value of Mass Reduction Idea					
03	**12**	**00**	**Instrument Panel and Console Subsystem**						
03	12	01	Cross-Car Beam (IP)	D	3.975	-$11.57	-$2.91	38.35%	0.23%
03	12	03	Instrument Panel Main Molding	C	1.627	-$2.38	-$1.46	13.74%	0.10%
03	12	06	Applied Parts - (IP) (Access Panels)		0.000	$0.00	$0.00	0.00%	0.00%
03	12	18	Center Stack (Center Console)	A	0.728	$1.46	$2.00	6.95%	0.04%
				C	**6.330** (Decrease)	**-$12.49** (Increase)	**-$1.97** (Increase)	**19.36%**	**0.37%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.4B-21: Mass-Reduction and Cost Impact for the Instrument Panel and Console Subsystem

F.4B.6 Occupant Restraining Device Subsystem

F.4B.6.1 Subsystem Content Overview

The Occupant Restraining Device subsystem includes seat belt assemblies and airbag modules. The sub-subsystem breakdown by name and mass is shown in **Table F.4B-22**. The Seat Belt Assembly Front Row sub-subsystem and Seat Belts – Second Row sub-subsystem weights largely come from the gear and spring mechanisms that retract the seat belt and lock it into position. There are a total of seven airbags in the Toyota Venza: Steering Wheel, Driver's Side Knee, Passenger Side, Front Driver's Seat, Front Passenger's Seat, Driver's Side Air Curtain, and Passenger's Side Air Curtain.

The seat belt restraints did not have any mass reduced and were assumed to remain unchanged going from the baseline to the redesign. An engineering analysis may have to be performed on the seat belt reaction time for the new vehicle due to its overall reduction in mass and different response to a crash, but such an investigation was beyond the scope of this study.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
03	**20**	**00**	**Occupant Restraining Device Subsystem**	
03	20	01	Seat Belt Assembly Front Row	4.250
03	20	03	Passenger Airbag / Cover Unit	2.427
03	20	06	Restraint Electronics (Crash Sensor and Airbag Cables)	0.232
03	20	08	Seat Belts - Second Row	3.353
03	20	10	Front Side Airbag (Side Seat Airbags)	0.862
03	20	13	Deployable Roll Bar Systems (Air Curtains)	3.186
03	20	14	Inflatable Knee Bolster or Active Leg Protection (Driver Knee Airbag)	2.024
03	20	15	Tether Anchorages - Non Integrated	0.006
03	20	18	Steering Wheel Airbag	1.097
			Total Subsystem Mass =	**17.438**
			Total System Mass =	**220.604**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**7.90%**
			Subsystem Mass Contribution Relative to Vehicle =	**1.02%**

Table F.4B-22: Mass Breakdown by Sub-subsystem for the Occupant Restraining Device Subsystem

F.4B.6.2 Toyota Venza Baseline Subsystem Technology

The Toyota Venza represents a conservative approach to the design of the airbag modules. Steel is used for nearly all of the housings and brackets as shown for the Passenger Side Airbag Housing in **Image F.4B-22** and **Image F.4B-23**. The airbag material itself is a standard nylon fabric (used on most airbags in the industry) and dual-stage airbag inflators are used (**Image F.4B-24** and **Image F.4B-25**). As a result of the metal housings used in the baseline Steering Wheel Airbag, numerous fasteners are necessary to assemble components together as pointed out in **Image F.4B-25**. These include screws, rivets, studs, nuts, and springs.

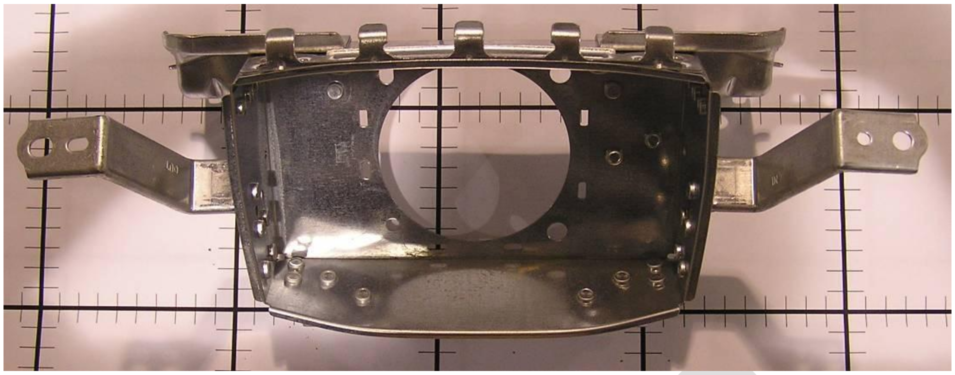


Image F.4B-22: Toyota Venza Passenger Side Airbag Housing (without airbag)

(Source: FEV, Inc. photo)

Image F.4B-23: Toyota Venza Passenger Side Airbag Housing (with airbag)

(Source: FEV, Inc. photo)

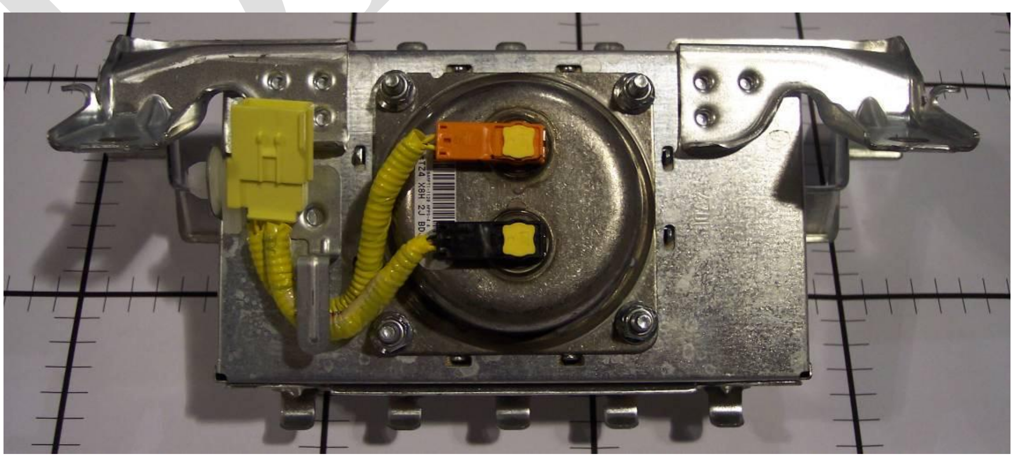


Image F.4B-24: Toyota Venza Passenger Side Airbag Housing (rear view with inflator)

(Source: FEV, Inc. photo)

Despite the numerous fastening commodity components in the Steering Wheel Airbag (**Image F.4B-25**), it is initially a lightweight design. The main housing is die cast from magnesium and is even lighter than many plastic housings.

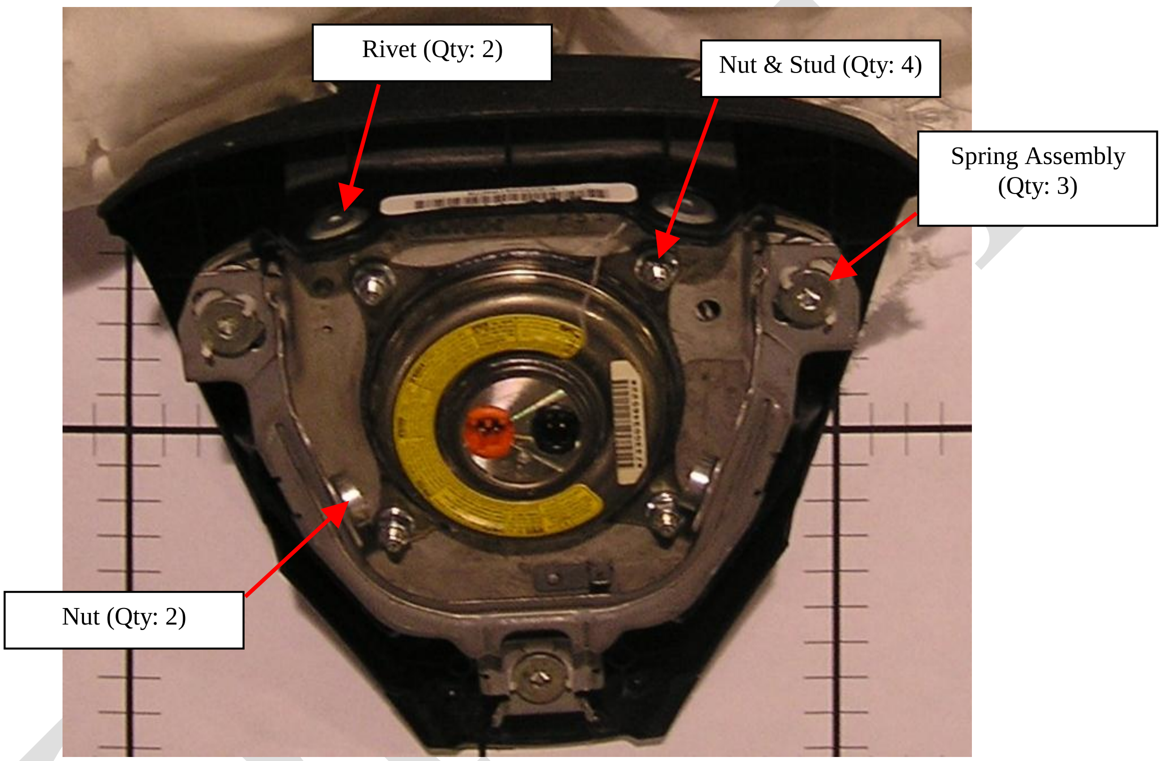


Image F.4B-25: Toyota Venza Steering Wheel Airbag Assembly, showing various fasteners

(Source: FEV, Inc. Photo)

F.4B.6.3 Mass-Reduction Industry Trends

Plastic airbag housings are used on many high volume vehicle applications. DSM Engineering Plastics is a global plastics supplier and specializes in metal to plastic replacements in automotive applications. Their Akulon® products, glass fiber reinforced glass-filled polyamide, have been used on many driver and passenger air bag housings for all of the domestic OEMs over the last 10 years. An example of a steel to plastic airbag housing is shown in **Image F.4B-25**. As seen, the design remains quite similar when changed from a multi-piece steel unit to a single-piece injection-molded housing. This allows for easy integration into an existing product line. **Image F.4B-25**, in fact, displays the baseline Toyota Venza Passenger Side Airbag Housing next to a rendering of a very similar design when converted to plastic. This resemblance reinforces the applicability of a plastic injection molded airbag for the Venza.

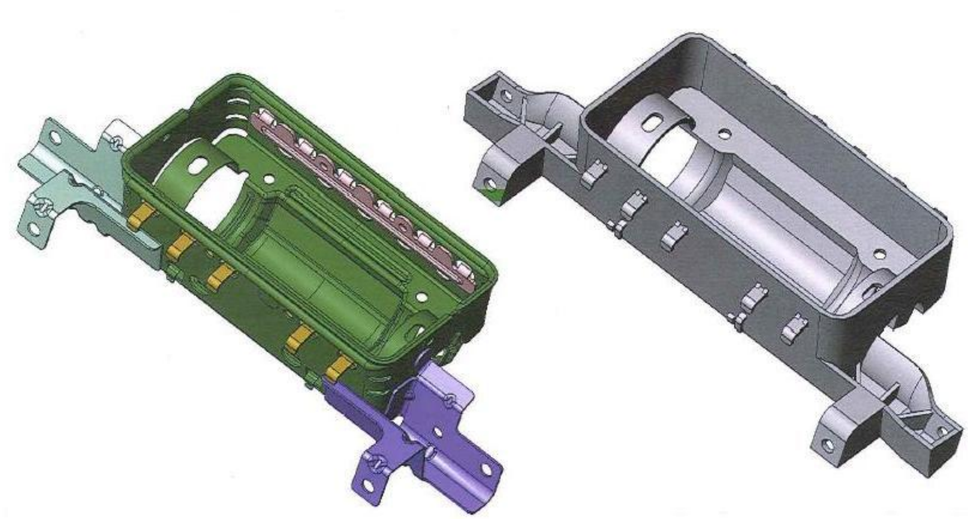


Image F.4B-26: Passenger Side Airbag Housings, Fabricated Steel Assembly (left) and Injection Molded Plastic Component (right)

(Source: Images Courtesy of DSM Engineering Plastics & Takata)

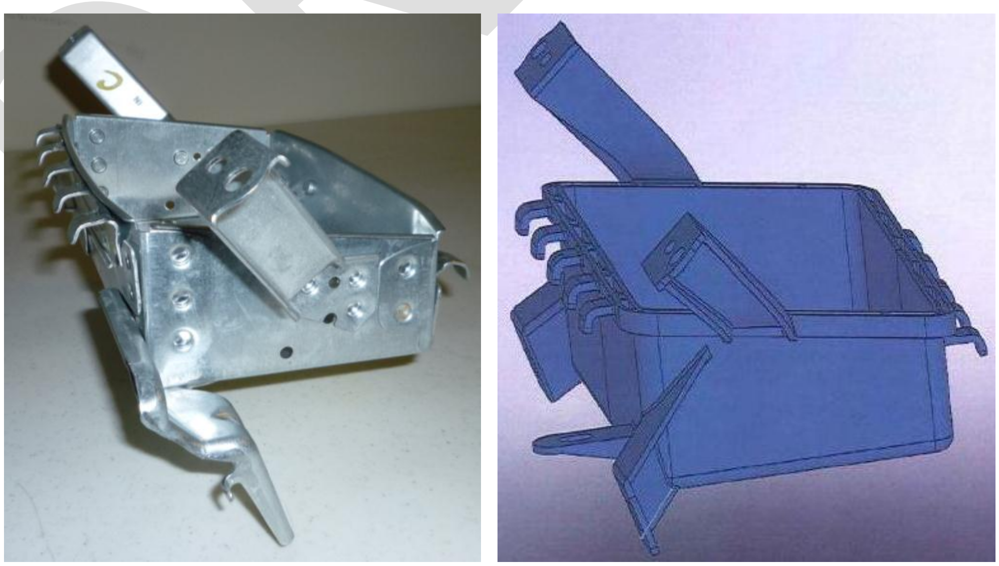


Image F.4B-27: Toyota Venza's Steel Airbag Housing (left) and Plastic Airbag Housing Rendering (right)

(Left Picture Source: FEV, Inc. Photo)
(Right Picture Source: Photo Courtesy of DSM Engineering Plastics)

Takata Corporation, a leading global supplier of automotive safety systems, provided significant mass-reduction ideas for the airbag modules for this study. The most innovative of which was its Vacuum Folding Technology (VFT). VFT is a process that allows the bags to be packed much more tightly than airbags traditionally have been by pulling a vacuum during its packaging. The surrounding components (housings, covers, etc.) can then be made smaller and, therefore, with lighter weight. A size reduction of 30-60% is typically observed accompanied by a mass reduction of around 20-35%. A size comparison of a standard airbag module versus a VFT is illustrated in **Image F.4B-28**.

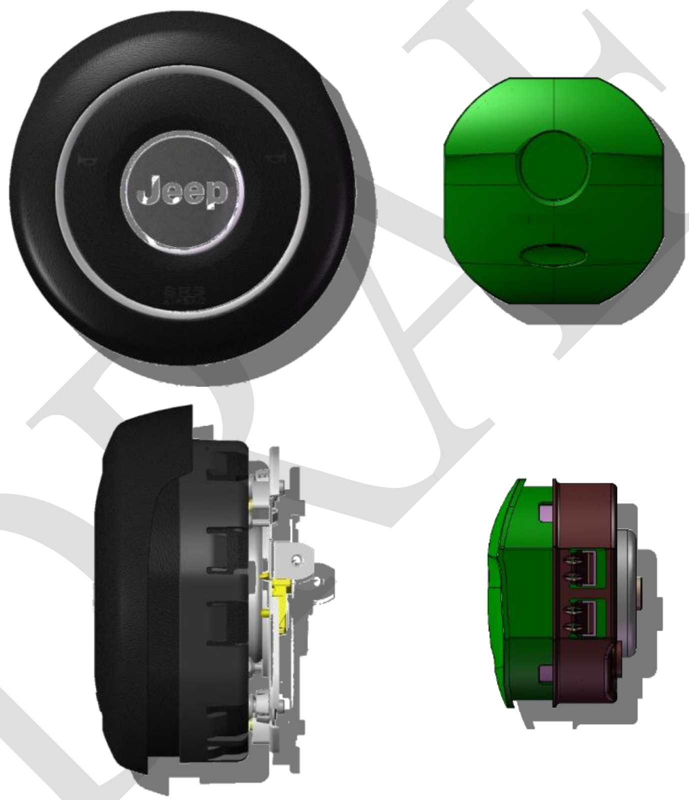


Image F.4B-28: Standard Airbag Module (left) and VFT Module (right)

(Source: Photo Courtesy of Takata)

To keep the airbag tightly packed in a low-pressure state, it is sealed in a multi-layer plastic foil as shown in **Image F.4B-28**. This foil is the only added component in a VFT airbag module and weighs only a few grams.

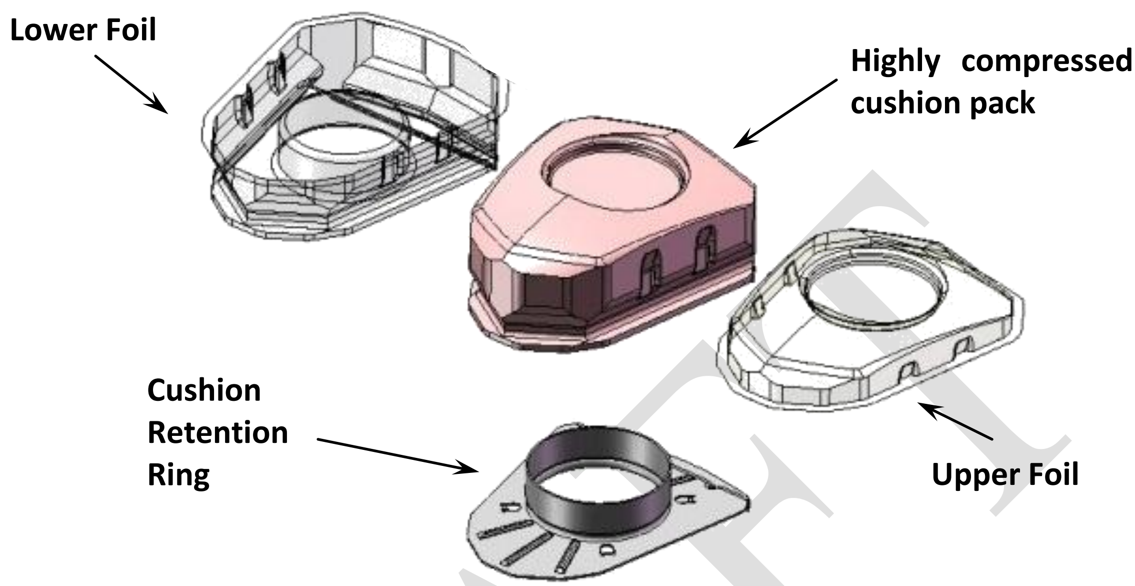


Image F.4B-29: VFT Airbag Foil

(Source: Photo Courtesy of Takata)

The VFT airbag meets all required FMVSS and other safety standards and won a Society of Plastics Engineers award in 2010 and a Pace Award in the Process category for VFT in April of 2011. This VFT technology has already been applied to the Ferrari 458 Italia and McLaren MP4-12C (**Image F.4B-30**), which are both low-volume production vehicles. In 2012, a high-volume vehicle will be released utilizing Takata's VFT airbag.

Image F.4B-30: VFT Airbag used in Ferrari 458 Italia (left) and McLaren MP4-12C (right)

(Source: Photo Courtesy of Takata)

In addition to mass reduction, Takata's VFT airbag module also provides styling benefits allowing the steering wheel designer more freedom as the airbag module decreases in size. Smaller airbag modules may also allow for a possible standardization of hardware as surrounding components can become more common in size due to the now-predictable size of a VFT airbag.

Takata shed light upon single-stage airbag inflators, which will likely replace dual-stage inflators in the near future. Dual-stage inflators were used to vary the force and speed at which the airbag deployed based on the size and orientation of the person in the seat. This will no longer be necessary, however, as the airbags themselves are passively adapting to the passenger allowing the inflators to revert to a smaller and lighter single-stage design as shown in **Image F.4B-31**. The inflators shown are from the same vehicle generation and application for the purposes of a direct and fair comparison. The dual-stage inflator in picture (a) of **Image F.4B-30** weighs 415 grams compared to 340 grams, which is the mass of the single-stage inflator in picture (b). The diameter of each inflator is the same, but the height of the single-stage is 6.8 mm less than the dual-stage.

(a) Dual-stage Inflator (b) Single-stage Inflator

Image F.4B-31: Comparison of Dual and Single-Stage Airbag Inflators

(Source: Photo Courtesy of Takata)

Takata has also been utilizing plastic airbag housings. They have worked with DSM Engineering Plastics to use the 40% glass-filled polyamide (as shown earlier for the passenger airbag housing in **Image F.4B-23** and **Image F.4B-24**) for steering wheel airbag housings also. A high volume production example is shown in **Image F.4B-32**, which is currently being produced for the Chevrolet Cruze. By going to a plastic housing, assembly becomes less complicated. A plastic housing can snap to the mating plastic cover eliminating the need for fastening components thus simplifying design, reducing mass, and reducing cost.

Image F.4B-32: Steering Wheel Airbag Housing for Chevrolet Cruze

(Source: Part Courtesy of Takata, FEV, Inc. Photo)

F.4B.6.4 Summary of Mass-Reduction Concepts Considered

Mass reduction ideas that were considered for the Occupant Restraining Device subsystem are shown in **Table F.4B-23**. Converting the Venza's steel airbag housing assemblies for the passenger side, driver's side knee, and steering wheel were all options as proposed by DSM. Takata's ideas noted in the previous section were also all considered. PolyOne's Chemical Foaming Agent (reference Section 5.3B.1.1 for detailed information) was considered for the Driver's Side Knee Airbag Cover. Lotus Engineering did not apply any light-weighting ideas to the safety systems. Note that the estimated mass reduction percentages in **Table F.4B-23** are relative to the component(s) for that line item, not relative to the entire airbag assembly.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Passenger's Side Airbag Housing	Change from fabricated steel assembly to single piece injection molded DSM Akulon part	50% mass reduction	Potential cost save, used on numerous high volume production applications
Driver's Side Knee Airbag	Change from welded steel assembly to single piece injection molded DSM Akulon part	50% mass reduction	Potential cost save, used on numerous high volume production applications
Driver's Side Knee Airbag Cover	Apply PolyOne CFA to plastic cover	10% mass reduction	Low cost, CFA for PP currently under test for use in high volume production vehicles
Steering Wheel Airbag	Use Takata's Vacuum Folding Technology to reduce size	20 - 35% mass reduction	Moderately high cost, used on low volume production Ferrari 458 Italia and McLaren MP4-12C
Steering Wheel Airbag	Replace dual-stage inflator with single-stage	20% mass reduction	To be used on 2013 model year car according to Takata
Steering Wheel Airbag	Change from magnesium/steel housing to single piece injection molded part	5 - 10% mass reduction	Allows part integration and reduction in fasteners, currently used in Chevrolet Cruze
Steering Wheel Airbag	Replace complex spring mechanism & bracket for horn with singe trace horn system	80% mass reduction	Reduces fasteners and other horn bracket components, easily integrates with plastic housing, in production on multiple Nissan and Toyota models

Table F.4B-23: Summary of Mass-Reduction Concepts Initially Considered for the Occupant Restraining Device Subsystem

F.4B.6.5 Selection of Mass Reduction Ideas

All ideas that were considered for weight savings for this subsystem from **Table F.4B-23** were applied as shown in **Table F.4B-24**. There were no ideas for parts in the sub-subsystems, which contain an "n/a" designation. Each of the ideas that were applied are either being used in high-volume production currently or will be soon.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
03	**20**	**00**	**Occupant Restraining Device Subsystem**	
03	20	01	Seat Belt Assembly Front Row	n/a
03	20	03	Passenger Airbag / Cover Unit	DSM's Akulon® (PA6) replaces steel for housing.
03	20	06	Restraint Electronics (Crash Sensor and Airbag Cables)	n/a
03	20	08	Seat Belts - Second Row	n/a
03	20	10	Front Side Airbag (Side Seat Airbags)	n/a
03	20	13	Deployable Roll Bar Systems (Air Curtains)	n/a
03	20	14	Inflatable Knee Bolster or Active Leg Protection (Driver Knee Airbag)	DSM's Akulon® (PA6) replaces steel for housing. PolyOne's Chemical Foaming Agent applied in plastic cover.
03	20	15	Tether Anchorages - Non Integrated	n/a
03	20	18	Steering Wheel Airbag	Takata's VFT process used to decrease airbag packaging size thereby allowing a size/mass reduction of surrounding components. Use single-stage inflator instead of dual-stage. Convert housing to DSM's Akulon® (PA6). Simplify horn spring assembly.

Table F.4B-24: Mass-Reduction Ideas Selected for Detail Analysis of the Occupant Restraining Device Subsystem

F.4B.6.6 Mass-Reduction & Cost Impact Results

The estimated mass reduction and associated cost impacts are shown in **Table F.4B-25** for the Occupant Restraining Device Subsystem.

The single idea in the Passenger Airbag/Cover Unit sub-subsystem was to replace the multi-piece steel Passenger Side Airbag Housing with a one piece injection molded PA6-GF40 part. This resulted in a 0.483 kg weight save at a $0.72 cost increase as shown in the table.

The Inflatable Knee Bolster sub-subsystem included two mass reduction ideas. The Driver's Side Knee Airbag Housing was converted to plastic and a Chemical Foaming Agent was applied to its already plastic cover. The mass reduction due to the steel to plastic housing conversion accounts for 95% of the 0.377 kg saved and increased the cost by $0.47. Applying the CFA reduced the cost by $0.06 resulting in an overall $0.41 cost hit for this sub-subsystem.

All of the modifications imposed on the Steering Wheel Airbag saved 0.2 kg and caused an overall cost increase of $1.75 for the sub-subsystem as seen in the last line of **Table F.4B-25**. There were four separate ideas applied to the Steering Wheel Airbag. The breakdown on a percentage basis of how much each contributed to the 0.2 kg savings is shown in **Figure F.4B-6**.

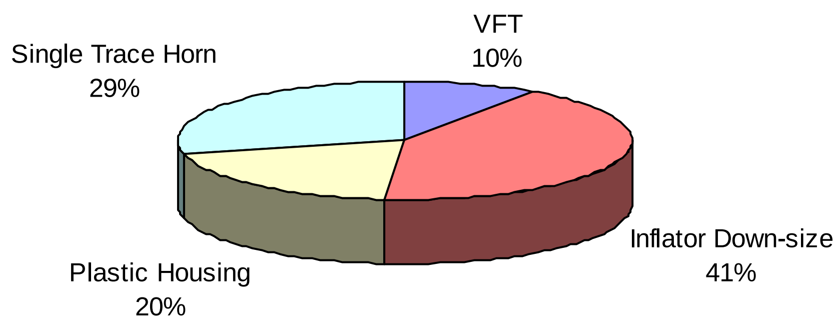


Figure F.4B-6: Breakdown of Steering Wheel Airbag Mass Reductions

It should be noted that the Vacuum Folding Technology applied to the Steering Wheel Airbag can also be applied to other airbag modules throughout the vehicle and will likely be done so on future vehicles although it is not currently in production and was not performed in this study.

System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
				Net Value of Mass Reduction Idea					
03	20	00	**Occupant Restraining Device Subsystem**						
03	20	01	Seat Belt Assembly Front Row		0.000	$0.00	$0.00	0.00%	0.00%
03	20	03	Passenger Airbag / Cover Unit	C	0.483	-$0.72	-$1.49	19.90%	0.03%
03	20	06	Restraint Electronics (Crash Sensor and Airbag Cables)		0.000	$0.00	$0.00	0.00%	0.00%
03	20	08	Seat Belts - Second Row		0.000	$0.00	$0.00	0.00%	0.00%
03	20	10	Front Side Airbag (Side Seat Airbags)		0.000	$0.00	$0.00	0.00%	0.00%
03	20	13	Deployable Roll Bar Systems (Air Curtains)		0.000	$0.00	$0.00	0.00%	0.00%
03	20	14	Inflatable Knee Bolster or Active Leg Protection (Driver Knee Airbag)	C	0.377	-$0.41	-$1.08	18.64%	0.02%
03	20	15	Tether Anchorages - Non Integrated		0.000	$0.00	$0.00	0.00%	0.00%
03	20	18	Steering Wheel Airbag	X	0.200	-$1.75	-$8.76	18.19%	0.01%
				D	**1.060** (Decrease)	**-$2.88** (Increase)	**-$2.71** (Increase)	**6.08%**	**0.06%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.4B-25: Mass-Reduction and Cost Impact for the Occupant Restraining Device Subsystem

F.4C Body Structure Group C

The Body System Group C includes the Exterior Trim and Ornamentation, Rear View Mirror, Front End Module and Rear End Module subsystems. **Table F.4C-1** identifies the Exterior Trim and Ornamentation subsystem as the most significant weight contributor to this system, supplying approximately 50% of the system mass.

System	Subsystem	Sub-Subsystem	Description	System & Subsystem Mass "kg"
03	00	00	**Body System (Group -C-)**	
03	08	01	Exterior Trim and Ornamentation	13.383
03	08	02	Rear View Mirrors	2.760
03	08	04	Front End Modules	5.033
03	08	07	Rear End Modules	5.390
			Total System Mass =	**26.566**
			Total Vehicle Mass =	**1711**
			System Mass Contribution Relative to Vehicle =	**1.55%**

Table F.4C-1: Baseline Subsystem Breakdown for Body System Group C

The main contributor to the mass reduction and cost savings was the Exterior Trim and Ornamentation subsystem, with the front and rear fascias attributing nearly all savings for the Body System Group C.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	System/ Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
03	00	00	**Body System (Group -C-)**						
03	08	01	Exterior Trim and Ornamentation	A	1.147	$2.31	$2.01	4.32%	0.07%
03	08	02	Rear View Mirrors	A	0.218	$0.73	$3.35	0.82%	0.01%
03	08	04	Front End Modules	A	0.514	$2.24	$4.36	1.93%	0.03%
03	08	07	Rear End Modules	A	0.514	$2.32	$4.51	1.93%	0.03%
				A	**2.393** (Decrease)	**$7.60** (Decrease)	**$3.18** (Decrease)	**9.01%**	**0.14%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.4C-2: Mass Reductions and Cost Impact for System Group C

F.4C.1 Exterior Trim and Ornamentation Subsystem

F.4C.1.1 Subsystem Content Overview

Table F.4C-3 identifies the most significant contributor to the mass of the Exterior Trim and Ornamentation subsystem as the lower exterior trim finishers. The rocker trim and all lower door finishers, upper exterior and roof finishers, rear closure finisher, emblems, rear spoiler, cowl vent grill assembly, and subsystem attachments make up the rest of the weight.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
03	**08**	**00**	**Exterior Trim and Ornamentation**	
03	08	01	Radiator Grill	1.460
03	08	02	Lower Exterior Finishers	4.350
03	08	04	Upper Exterior and Roof Finishers	0.870
03	08	07	Rear Closure Finisher	1.334
03	08	12	Emblems	0.096
03	08	14	Rear Spoiler	1.843
03	08	15	Cowl Vent Grill Assembly	2.720
03	08	99	Exterior Trim Attachments	0.710
			Total Subsystem Mass =	**13.383**
			Total System Mass =	**26.57**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**50.38%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.78%**

Table F.4C-3: Mass Breakdown by Sub-subsystem for Exterior Trim and Ornamentation Subsystem

F.4C.1.2 Toyota Venza Baseline Subsystem Technology

The Toyota Venza's Exterior Trim and Ornamentation is typical for the industry. There is a chrome-plated plastic grill with emblem, a rear hatch finishing panel with license plate lighting provisions, and emblems. Also, there is a spoiler, door finishing panels, roof ditch moldings, and cowl vent screen. The materials and the thickness used are common: the differences lay in the size and the intent of their utilization.

Image F.4C-1: Exterior Trim – Lower Exterior Finisher

(Source: FEV, Inc. photo)

Image F.4C-2: Exterior Trim - Cowl Vent Grill Assembly

(Source: FEV, Inc. photo)

Image F.4C-3: Exterior Trim – Rear Spoiler

(Source: FEV, Inc. photo)

Image F.4C-4: Exterior Trim – Radiator Grill

(Source: FEV, Inc. photo)

F.4C.1.3 Mass-Reduction Industry Trends

Down-gauging material thickness is the most common method used to reduce the weight of the exterior trim. Designing in reinforcements while varying material thickness for the whole component or the thickness of a specific section, can provide a significant mass reduction.

Another common industry method for mass reduction is to change materials and processes for selected components. The most promising emerging technology for hard trim is gas assist injection molding. The PolyOne and the MuCell® processes were reviewed.

The PolyOne process can use (parts redesigned for PolyOne process can provide additional mass reductions) existing tooling with varying modifications for each unique solution. Unique gases and materials are used to aerate plastic as it is injected into the tool cavity. This aeration or “foaming” process reduces mass by replacing solid material with air. This process has the potential to reduce mass by up to 30% when applied to larger Class A surface parts or non-Class A surface components.

The MuCell® process, a licensed technology, utilizes unique tooling to aerate plastic as the plastic is injected into the tool cavity. The MuCell® foaming process also allows for faster fill times in tooling cavities due to the reduced material viscosity. The current MuCell® process cannot create a Class A surface components. This process has the potential to reduce mass by up to 30% when applied to non-Class A surface components or grained panels. The Trexel Mucell® foaming process reduces the material thickness necessary to meet mold fill requirements and allows a higher ratio of rib thickness to material thickness without creating sink marks in the show surface.

F.4C.1.4 Summary of Mass-Reduction Concepts Considered

Table F.4C-4 compiles the mass reduction ideas considered for the Exterior Trim and Ornamentation subsystem.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Radiator Grill	Gas Assist Injection Molding (MuCell®, PolyOne)	10% - 20% Mass Savings	Low or no Cost Impact with Mass reduction
Radiator Grill	Mold in Color	0 - 10% Mass Savings	Low Cost, Little Mass Savings Potential
Radiator Grill	Material Change	0 - 10% Mass Savings	Low Cost, Durability Issues
Lower Exterior Finishers	Gas Assist Injection Molding (MuCell®, PolyOne)	10% - 20% Mass Savings	Low or no Cost Impact with Mass reduction
Lower Exterior Finishers	Mold in Color	0 - 10% Mass Savings	Low Cost, Little Mass Savings Potential
Lower Exterior Finishers	Material Change	0 - 10% Mass Savings	Low Cost, Durability Issues
Upper Exterior Finishers	Gas Assist Injection Molding (MuCell®, PolyOne)	10% - 20% Mass Savings	Low or no Cost Impact with Mass reduction
Upper Exterior Finishers	Mold in Color	0 - 10% Mass Savings	Low Cost, Little Mass Savings Potential
Upper Exterior Finishers	Material Change	0 - 10% Mass Savings	Low Cost, Durability Issues
Rear Closure Finishers	Gas Assist Injection Molding (MuCell®, PolyOne)	10% - 20% Mass Savings	Low or no Cost Impact with Mass reduction
Rear Closure Finishers	Mold in Color	0 - 10% Mass Savings	Low Cost, Little Mass Savings Potential
Rear Closure Finishers	Material Change	0 - 10% Mass Savings	Low Cost, Durability Issues
Emblems	Decals	20% Mass Savings	Low Cost, Aesthetically Unappealing, Durabilty Issues
Emblems	Mold in Feature then Paint or Apply Decal	0 - 10% Mass Savings	Low Cost, Aesthetically Unappealing
Rear Spoiler	Gas Assist Injection Molding (MuCell®, PolyOne)	10% - 20% Mass Savings	Low or no Cost Impact with Mass reduction
Rear Spoiler	Mold in Color	0 - 10% Mass Savings	Low Cost, Little Mass Savings Potential
Rear Spoiler	Material Change	0 - 10% Mass Savings	Low Cost, Durability Issues
Cowl Vent Screen	Gas Assist Injection Molding (MuCell®, PolyOne)	10% - 20% Mass Savings	Low or No Cost Impact with Mass reduction
Cowl Vent Screen	Material Change	0 - 10% Mass Savings	Low Cost, Durability Issues

Table F.4C-4: Summary of Mass-Reduction Concepts Initially Considered for the Exterior Trim and Ornamentation Subsystem

F.4C.1.5 Selection of Mass Reduction Ideas

The mass reduction ideas selected that fell into the "A_e" group are shown in **Table F.4C-5**.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
03	**08**	**00**	**Exterior Trim and Ornamentation**	
03	08	01	Radiator Grill	PolyOne Process - Injection Molding
03	08	02	Lower Exterior Finishers	PolyOne Process - Injection Molding
03	08	04	Upper Exterior and Roof Finishers	PolyOne Process - Injection Molding
03	08	07	Rear Closure Finishers	PolyOne Process - Injection Molding
03	08	14	Rear Spoiler	PolyOne Process - Injection Molding
03	08	15	Cowl Vent Screen	PolyOne Process - Injection Molding

Table F.4C-5: Summary of mass-reduction concepts selected for the Exterior Trim and Ornamentation Subsystem

F.4C.1.6 Mass-Reduction & Cost Impact Estimates

The PolyOne process was utilized on the Exterior Trim and Ornamentation sub-subsystems listed in Table F.4C-6. This resulted in a mass savings of 1.147 kg and a cost savings of $2.31.The changes to emblems were not implemented since there were wear and durability issues with the decal life and performance.

System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Sub-Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
				Net Value of Mass Reduction Idea					
03	08	00	**Exterior Trim and Ornamentation**						
03	08	01	Radiator Grill	A	0.155	$0.23	$1.48	1.16%	0.01%
03	08	02	Lower Exterior Finishers	A	0.463	$0.83	$1.79	3.46%	0.03%
03	08	04	Upper Exterior and Roof Finishers	A	0.090	$0.31	$3.44	0.67%	0.01%
03	08	07	Rear Closure Finisher	A	0.145	$0.23	$1.59	1.09%	0.01%
03	08	14	Rear Spoiler	A	0.190	$0.42	$2.21	1.42%	0.01%
03	08	15	Cowl Vent Grill Assembly	A	0.104	$0.29	$2.79	0.78%	0.01%
				A	**1.147** (Decrease)	**$2.31** (Decrease)	**$2.01** (Decrease)	**8.58%**	**0.07%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.4C-6: Summary of Mass-Reduction and Cost Impacts for the Exterior Trim and Ornamentation Subsystem

F.4C.2 Rear View Mirrors Subsystem

F.4C.2.1 Subsystem Content Overview

Table F.4C-7 shows that the most significant contributor to the mass of the Rear View Mirror subsystem is the outside rear view mirrors. This includes both front driver and passenger side outside rear view mirrors. The inside rear view mirror and the trim cover make up the balance of the mass.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
03	**09**	**00**	**Rear View Mirror Subsystem**	
03	09	01	Inside Rear View Mirrors	0.530
03	09	02	Outside Rear View Mirrors	2.218
03	09	99	Trim Cover - Inside Rear View Mirror Wiring	0.012
			Total Subsystem Mass =	**2.760**
			Total System Mass =	**26.566**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**10.39%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.16%**

Table F.4C-7: Mass Breakdown by Sub-subsystem for Rear View Mirrors Subsystem

Image F.4C-5: Outside Rear View Mirrors

(Source: FEV, Inc. photo)

F.4C.2.2 Toyota Venza Baseline Subsystem Technology

The Toyota Venza's rear view mirrors utilize materials and the thicknesses used by most automobile manufacturers and their suppliers.

F.4C.2.3 Mass-Reduction Industry Trends

Down-gauging the material thickness is the most common method used to reduce mass. Designing in reinforcements while varying thickness for the whole component or the thickness of a specific section, can provide a significant mass reduction.

Another common industry method is to change materials and manufacturing processes. These component processes are altered based on materials technology and process production for interior/exterior hardware. The most promising emerging technology for hard trim is gas assist injection molding.

The PolyOne and the MuCell® processes were reviewed: These processes are outlined in Exterior Trim & Ornamentation, **Section F.4B.1.2**.

F.4C.2.4 Summary of Mass-Reduction Concepts Considered

Table F.4C-8 compiles the mass reduction ideas considered for the Rear View Mirrors subsystem.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Inside Rear View Mirror	Gas Assist Injection Molding (MuCell®, PolyOne)	10% - 20% Mass Savings	Low or no Cost Impact with Mass Reduction
Outside Rear View Mirror - Left	Gas Assist Injection Molding (MuCell®, PolyOne)	10% - 20% Mass Savings	Low or no Cost Impact with Mass Reduction
Outside Rear View Mirror - Right	Gas Assist Injection Molding (MuCell®, PolyOne)	10% - 20% Mass Savings	Low or no Cost Impact with Mass Reduction
Trim Cover - Inside Rear View Mirror	Gas Assist Injection Molding (MuCell®, PolyOne)	10% - 20% Mass Savings	Low or no Cost Impact with Mass Reduction

Table F.4C-8: Summary of Mass-Reduction Concepts Initially Considered for the Rear View Mirrors Subsystem

F.4C.2.5 Summary of Mass-Reduction Concepts Selected

The mass reduction ideas selected that fell into the “A_e” group are shown in **Table F.4C-9**.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
03	**09**	**00**	**Rear View Mirrors Subsystem**	
03	09	02	Outside Rear View Mirror - Left	Gas Assist Injection Molding
03	09	02	Outside Rear View Mirror - Right	Gas Assist Injection Molding

Table F.4C-9: Summary of mass-reduction concepts selected for the Rear View Mirrors Subsystem

F.4C.2.6 Summary of Mass-Reduction Concepts and Cost Impacts

The PolyOne gas assist system was utilized for all components in **Table F.4C-10**. This resulted in a mass savings of .218 kg and a cost savings of $0.73.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Sub-Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
03	**09**	**00**	**Rear View Mirrors**						
03	09	01	Outside Rear View Mirror - Left	A	0.109	$0.37	$3.35	3.95%	0.01%
03	09	02	Outside Rear View Mirror - Right	A	0.109	$0.37	$3.35	3.95%	0.01%
				A	**0.218** (Decrease)	**$0.73** (Decrease)	**$3.35** (Decrease)	**7.90%**	**0.01%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.4C-10: Summary of mass-reduction & cost impact concepts for the Rear View Mirror Subsystem

F.4C.3 Front End Module Subsystem

F.4C.3.1 Subsystem Content Overview

Table F.4C-11 shows that the most significant contributor to the mass of the Front End Module subsystem is the front bumper fascia (**Image F.4C-6**). The front lower grill, fog lamp housings, front energy absorber, attachment brackets, and attachments make up the balance of the mass for this subsystem. The front bumper analysis was done along with the Body in White and resides in Body System -A-.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
03	**23**	**00**	**Front End Module Subsystem**	
03	23	02	Module - Front Bumper & Fascia	5.033
			Total Subsystem Mass =	**5.033**
			Total System Mass =	**26.57**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**18.95%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.29%**

Table F.4C-11: Mass Breakdown by Sub-subsystem for the Front End Module Subsystem.

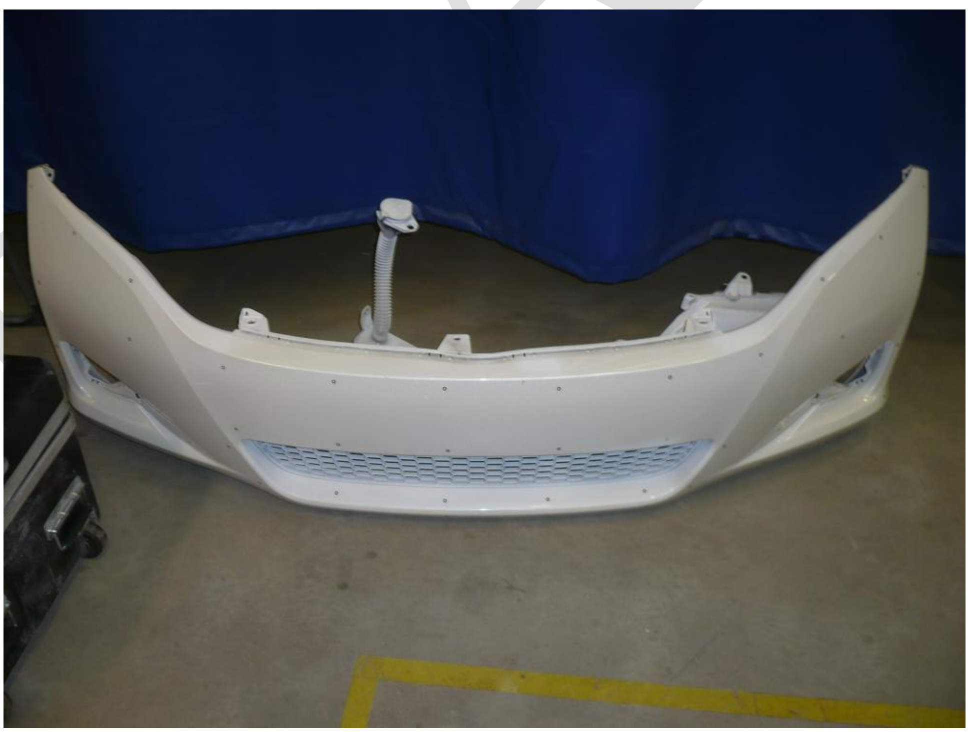


Image F.4C-6: Front Fascia

(Source: FEV, Inc. photo)

F.4C.3.2 Toyota Venza Baseline Subsystem Technology

The materials and thickness used are in common use by many automobile manufacturers and their suppliers.

F.4C.3.3 Mass-Reduction Industry Trends

Down-gauging the material thickness is the most common method used to reduce mass. Designing in reinforcements while varying material thickness for the whole component or the thickness of a specific section, can provide a significant mass reduction.

Another common industry method is to change materials and manufacturing processes. These component processes are altered based on materials technology and process production for interior hardware. The most promising emerging technology for hard trim is gas assist injection molding.

The PolyOne and the MuCell® processes were reviewed: These processes are outlined in Exterior Trim & Ornamentation 1.1.2.

F.4C.3.4 Summary of Mass-Reduction Concepts Considered

Table F.4C-12 compiles the mass reduction ideas considered for the Front End Module subsystem.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Front Fascia	Gas Assist Injection Molding (MuCell®, PolyOne)	10% - 20% Mass Savings	Low or no Cost Impact with Mass reduction
Front Fascia Attachment Brackets	Gas Assist Injection Molding (MuCell®, PolyOne)	10% - 20% Mass Savings	Low or no Cost Impact with Mass reduction

Table F.4C-12: Summary of mass-reduction concepts initially considered for the Front End Module Subsystem

F.4C.3.5 Summary of Mass-Reduction Concepts Selected

The mass reduction ideas selected that fell into the “A_e” group are shown in **Table F.4C-13**.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
03	**23**	**00**	**Front Module Subsystem**	
03	23	02	Module - Front Bumper and Fascia	PolyOne Process - Injection Molding

Table F.4C-13: Summary of Mass-Reduction Concepts Selected for the Front End Module Subsystem

F.4C.3.6 Mass-Reduction & Cost Impact

The PolyOne gas assist system was utilized for all components in **Table F.4C-14**. This produced a mass savings of .514 kg and a cost savings of $2.24 primarily from the front fascia.

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea					
				Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Sub-Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
03	**23**	**00**	**Front End Module**						
03	23	02	Module - Front Bumper and Fascia	A	0.491	$2.23	$4.54	9.76%	0.03%
				A	**0.491** (Decrease)	**$2.23** (Decrease)	**$4.54** (Decrease)	**9.76%**	**0.03%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.4C-14: Summary of Mass-Reduction & Cost Impact for the Front End Module Subsystem

F.4C.4 Rear End Module Subsystem

F.4C.4.1 Subsystem Content Overview

Table F.4C-15 illustrates that the most significant contributor to the mass of the Rear End Module subsystem is the rear fascia. The rear reflectors, rear energy absorber, attachment brackets, and attachments make up the balance of the mass for this subsystem.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
03	**24**	**00**	**Rear End Module Subsystem**	
03	24	02	Module - Rear Bumper and Fascia	5.293
03	24	99	Rear Bumper Fascia - Attachments	0.097
			Total Subsystem Mass =	**5.390**
			Total System Mass =	**26.57**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**20.29%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.32%**

Table F.4C-15: Mass Breakdown by Sub-subsystem for the Rear End Module Subsystem

Image F.4C-7: Rear Fascia

(Source: FEV, Inc. photo)

F.4C.4.2 Toyota Venza Baseline Subsystem Technology

The materials and thickness used are in common use by many automobile manufacturers and their suppliers.

F.4C.4.3 Mass-Reduction Industry Trends

Down-gauging the material thickness is the most common method used to reduce mass. Designing in reinforcements while varying material thickness for the whole component or the thickness of a specific section, can provide a significant mass reduction.

Another common industry method is to change materials and manufacturing processes. These component processes are altered based on materials technology and process production for interior hardware. The most promising emerging technology for hard trim is gas assist injection molding.

The PolyOne and the MuCell® processes were reviewed: These processes are outlined in Exterior Trim & Ornamentation, **Section 5.3B.1.2**.

F.4C.4.4 Summary of Mass-Reduction Concepts Considered

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Rear Fascia	Gas Assist Injection Molding (MuCell®, PolyOne)	10% - 20% Mass Savings	Low or no Cost Impact with Mass reduction
Rear Fascia Attachment Brackets	Gas Assist Injection Molding (MuCell®, PolyOne)	10% - 20% Mass Savings	Low or no Cost Impact with Mass reduction

Table F.4C-16: Summary of mass-reduction concepts initially considered for the Rear End Module Subsystem

F.4C.4.5 Summary of Mass-Reduction Concepts Selected

The mass reduction ideas selected that fell into the "A_e" group are shown in **Image F.4C-17**.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
03	**24**	**00**	**Rear Module Subsystem**	
03	24	02	Module - Rear Bumper and Fascia	PolyOne Process - Injection Molding

Table F.4C-17: Summary of mass-reduction concepts selected for the Rear End Module Subsystem

F.4C.4.6 Mass-Reduction & Cost Impact

The PolyOne gas assist system was utilized for all components in **Table F.4C-18**. The end result is a mass savings of .514 kg and a cost savings of $2.32. Most of the savings is attributable to the rear fascia.

System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Sub-Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
				Net Value of Mass Reduction Idea					
03	24	00	**Rear End Module Subsystem**						
03	24	02	Module - Rear Bumper and Fascia	A	0.514	$2.32	$4.51	9.54%	0.03%
				A	**0.514** (Decrease)	**$2.32** (Decrease)	**$4.51** (Decrease)	**9.54%**	**0.03%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.4C-18: Summary of Mass-Reduction & Cost Impact Concepts Estimates for the Rear End Module Subsystem

Appendix Information

System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Sub-Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
				Net Value of Mass Reduction Idea					
03	08	00	**Exterior Trim and Ornamentation**						
03	08	01	Radiator Grill	A	0.155	$0.23	$1.48	1.16%	0.01%
03	08	02	Lower Exterior Finishers	A	0.463	$0.84	$1.81	3.46%	0.03%
03	08	04	Upper Exterior and Roof Finishers	A	0.090	$0.32	$3.56	0.67%	0.01%
03	08	07	Rear Closure Finisher	A	0.145	$0.24	$1.66	1.08%	0.01%
03	08	12	Emblems		0.000	$0.00			
03	08	14	Rear Spoiler	A	0.190	$0.42	$2.21	1.42%	0.01%
03	08	15	Cowl Vent Grill Assembly	A	0.104	$0.28	$2.69	0.78%	0.01%
03	08	99	Exterior Trim Attachments		0.000	$0.00			
				A	**1.147**	**$2.31**	**$2.01**	**8.58%**	**0.07%**
					(Decrease)	(Decrease)	(Decrease)		

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

The PolyOne gas assist system was utilized for all components in **Table X**. The end result is a mass savings of 1.147 kg and a cost savings of $2.33 for the Exterior Trim and

Ornamentation Subsystem.. Most of the savings is attributable to the lower exterior finishers.

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Sub-Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
03	**09**	**00**	**Rear View Mirror Subsystem**						
03	09	01	Inside Rear View Mirrors						
03	09	02	Outside Rear View Mirrors	A	0.218	$0.73	$3.35	7.90%	0.01%
03	09	99	Trim Cover - Inside Rear View Mirror Wiring						
				A	**0.218** (Decrease)	**$0.73** (Decrease)	**$3.35** (Decrease)	**7.90%**	**0.01%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

The PolyOne gas assist system was utilized for all components in **Table X**. The end result is a mass savings of .218 kg and a cost savings of $0.73. The savings is attributable to the Outside rear view mirrors.

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Sub-Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
03	**23**	**00**	**Front End Module**						
03	23	02	Brackets - Fender to Front Fascia Housing	A	0.010	$0.02	$2.00	0.20%	0.00%
03	23	02	Front Bumper Fascia Assembly	A	0.440	$2.04	$4.64	8.74%	0.03%
03	23	02	Front Bumper Fascia Assembly - Lower Grill	A	0.041	$0.17	$4.15	0.81%	0.00%
				A	**0.491** (Decrease)	**$2.23** (Decrease)	**$4.54** (Decrease)	**9.76%**	**0.03%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

The PolyOne gas assist system was utilized for all components in **Table X**. The end result is a mass savings of .491 kg and a cost savings of $2.23. The bulk of the savings is attributable to the front fascia assembly.

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Sub-Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
03	**24**	**00**	**Rear End Module**						
03	24	02	Brackets - Side	A	0.010	$0.02	$2.00	0.19%	0.00%
03	24	02	Brackets - Upper Side	A	0.004	$0.02	$5.00	0.07%	0.00%
03	24	02	Rear Bumper Fascia Assembly	A	0.486	$2.22	$4.57	9.02%	0.03%
03	24	02	Rear Bumper Fascia - Punch OutTrim Pad	A	0.014	$0.07	$5.00	0.26%	0.00%
				A	**0.514** (Decrease)	**$2.32** (Decrease)	**$4.51** (Decrease)	**9.54%**	**0.03%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

The PolyOne gas assist system was utilized for all components in **Table X**. The end result is a mass savings of .514 kg and a cost savings of $2.33. The bulk of the savings is attributable to the rear fascia assembly.

F.4D Body System Group D

Group D of the Body system includes the Glazing; Handles, Locks , Latches; Rear Hatch Lift Assembly; and Wipers & Washers subsystems, as shown in **Table F.4D-1**. The most significant contributor to this system's mass is the Glazing subsystem, which accounts for approximately 75% of the system mass. The Liftgate Modules, Wiper and Cowl Modules, and Door Modules subsystems are not applicable. The Toyota Venza was broken down such that these modules are integrated into other subsystems. For example, the Windshield Wipers are part of the Wipers and Washers subsystem as opposed to the Wiper and Cowl Modules subsystem.

System	Subsystem	Sub-Subsystem	Description	System & Subsystem Mass "kg"
03	**00**	**00**	**Body System (Group -D-) Glazing and Body Mechatronics Modules**	
03	11	00	Glass (Glazing), Frame, and Mechanism Subsystem	48.010
03	14	00	Handles, Locks, Latches, and Mechanism Subsystem	4.934
03	15	00	Rear Hatch Lift Assembly Subsystem	4.556
03	16	00	Wipers and Washers Subsystem	5.960
03	25	00	Liftgate Modules	0.000
03	28	00	Wiper and Cowl Modules	0.000
03	33	00	Door Modules	0.000
			Total System Mass =	**63.460**
			Total Vehicle Mass =	**1711**
			System Mass Contribution Relative to Vehicle =	**3.71%**

Table F.4D-1: Baseline Subsystem Breakdown for the Body System Group D

As shown in **Table F.4D-2**, the mass reduction ideas applied to the Glazing subsystem resulted in the greatest weight reduction for Body System Group D. The Glazing Subsystem was the largest mass contributor and therefore had more opportunity to reduce weight. The overall weight savings for Body System Group D is 6.153 kg with a cost of $15.25. Approximately 10% of the Body System Group D mass was reduced.

System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
				Net Value of Mass Reduction Idea					
03	00	00	**Body System (Group -D-) Glazing & Body Mechatronics**						
03	11	00	Glass (Glazing), Frame, and Mechanism Subsystem	D	6.062	-$15.67	-$2.59	12.63%	0.35%
03	14	00	Handles, Locks, Latches, and Mechanism Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
03	15	00	Rear Hatch Lift Assembly Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
03	16	00	Wipers and Washers Subsystem	A	0.091	$0.42	$4.62	1.53%	0.01%
03	25	00	Liftgate Modules		0.000	$0.00	$0.00	0.00%	0.00%
03	28	00	Wiper and Cowl Modules		0.000	$0.00	$0.00	0.00%	0.00%
03	33	00	Door Modules		0.000	$0.00	$0.00	0.00%	0.00%
				C	**6.153** (Decrease)	**-15.250** (Increase)	**-$2.48** (Increase)	**9.70%**	**0.36%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.4D-2: Mass-Reduction and Cost Impact for the Body System Group -D-

F.4D.1 Glass (Glazing), Frame, and Mechanism Subsystem

F.4D.1.1 Subsystem Content Overview

As shown in **Table F.4D-3**, the most significant contributor to the Glazing, Frame, & Mechanism subsystem mass is the glass. This includes the Windshield, four Side Windows, Backlight (rear hatch glass), and Front and Rear Fixed Quarter Windows. The Window Regulators, Switch Packs, and Glass Runs and Belts make up the remainder of the mass for this subsystem.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
03	**11**	**00**	**Glass (Glazing), Frame, and Mechanism Subsystem**	
03	11	01	Windshield and Front Quarter Window (Fixed)	15.730
03	11	03	First Row Door Window Lift Assy (Window Regulators)	3.132
03	11	05	Back and Rear Quarter Windows (Fixed)	2.134
03	11	11	Second Row Door, Qtr & Rear Closure Window Lift Assy (Window Regulators)	3.131
03	11	12	Back Window Assy (Backlight, Rear Hatch Glass)	7.036
03	11	13	Front Side Door Glass	8.850
03	11	14	Rear Side Door Glass	6.590
03	11	16	Switch Pack - Front Door (Window Up/Down Controls)	0.373
03	11	17	Switch Pack - Rear Door (Window Up/Down Controls)	0.244
03	11	19	Front Side Doors Glass Runs & Belts	0.464
03	11	20	Rear Side Doors Glass Runs & Belts	0.327
			Total Subsystem Mass =	**48.010**
			Total System Mass =	**63.460**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**75.65%**
			Subsystem Mass Contribution Relative to Vehicle =	**2.81%**

Table F.4D-3: Mass Breakdown by Sub-subsystem for the Glass (Glazing), Frame, and Mechanism Subsystem

F.4D.1.2 Toyota Venza Baseline Subsystem Technology

The 2010 Toyota Venza's glass is representative of today's typical industry standards. This includes a laminated glass front windshield, tempered side windows, and a tempered rear window. The windshield is approximately 5 mm thick, the front side windows a nominal 4.85 mm thick, and the rear side windows and the backlight are nominally 3.85 mm. The fixed quarter windows are tempered glass as well and are a nominal 4.85 mm thick in the front and 3.85 mm in the rear. Each window regulator (**Image F.4D-1**) contains a motor/gearbox assembly and a galvanized steel stamped linkage assembly that bolts to two clips (**Image F.4D-2**) attached to the window.

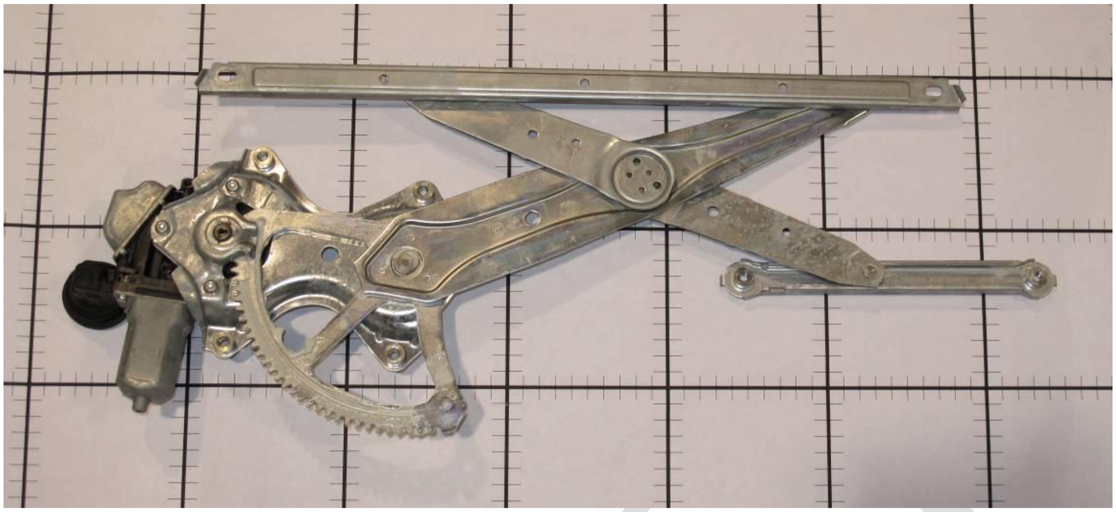


Image F.4D-1: Toyota Venza Window Regulator.

(Source: FEV, Inc. photo)

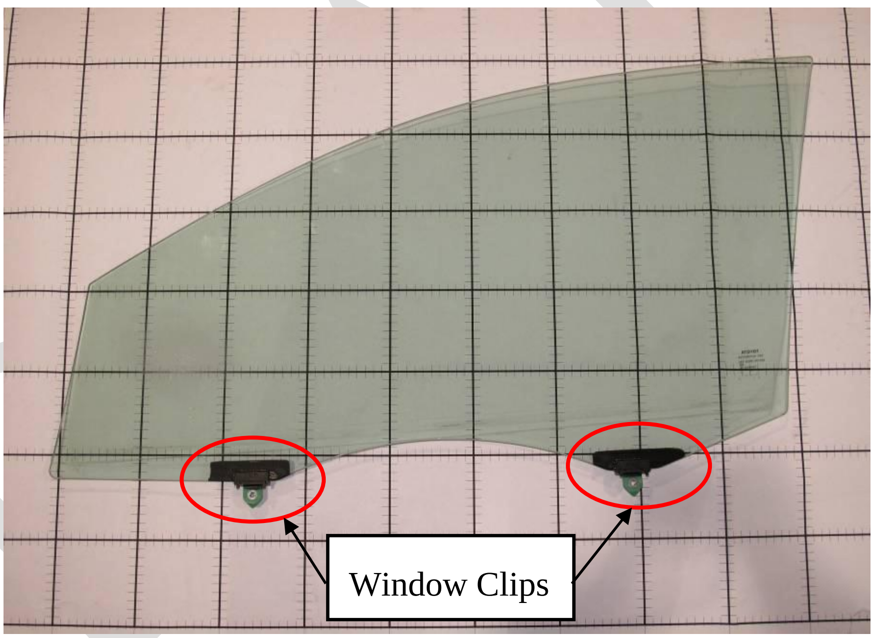


Image F.4D-2: Window Clips on Front Side Door Window of Toyota Venza.

(Source: FEV, Inc. photo)

Laminated glass, as used on the windshield, is a type of safety glass that holds together when shattered. Front windshields use laminated glass exclusively because in the event the glass breaks it is held in place by an interlayer, typically of polyvinyl butyral (PVB), between two layers of glass (**Image F.4D-3**). Laminated glass is typically used when there is a possibility of human impact or where the glass could fall if shattered. The PVB interlayer also gives the glazing a much higher sound insulation rating, due to the damping effect, and blocks 99% of incoming UV radiation.

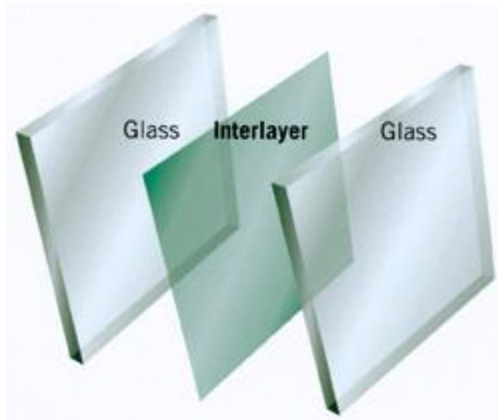


Image F.4D-3: Exploded View of Laminated Glass Cross-Section.

(Source: Thermal Windows, Inc. http://www.thermalwindows.com/ThermalSafe.htm)

The side windows and backlight also follow industry convention, which is the use of tempered glass. The brittle nature of tempered glass causes it to shatter into small oval-shaped pebbles when broken. This eliminates the danger of sharp edges. Due to this property along with its strength, tempered glass is often referred to as safety glass. It is also less expensive than laminated glass. Tempered glass, however, does not have the favorable acoustic properties that laminated glass exhibits.

F.4D.1.3 Mass-Reduction Industry Trends

The industry is beginning to use laminated glass, similar to what is used for the windshield, for the side windows. Guidelines for this were provided by NSG Group-Pilkington, a leading international supplier of glass both within and outside of the automotive industry. Pilkington pioneered float manufacturing, the process by which most glass in the world is manufactured today. It also stands out as a leader in the automotive, building, and specialty glass glazing industry. For side laminated windows, Pilkington provided data indicating that the inner and outer glass layers can be reduced in thickness to 1.6 mm since the plastic interlayer provides additional strength. Applying laminated glass to the four side windows can provide considerable weight savings and favorable acoustic properties, but with a significant cost impact. Nonetheless, it is a proven technology that is currently being used in many high-production vehicles including the Jaguar XJ, Mercedes R-class. It is also used in the front doors of the Chevrolet Malibu, Chevrolet Equinox, and Ford Taurus, to name a few.

Pilkington also suggests down-gauging the tempered glass thickness as another method to reduce the vehicle glass overall weight. The standard side window tempered glass thickness in Europe is 3.15 mm and in Japan it is 2.6 mm. Vehicles sold in the United States typically have slightly higher window thicknesses for NVH purposes, so reducing the window thickness does pose a trade-off: there will be increased sound transmittance through the windows (mostly apparent in the front of the vehicle). Currently in the U.S., however, the Honda Accord, Chevrolet Cobalt, and Toyota Tacoma all have 3.15 mm-thick side windows. There is a slight cost increase when the windows are down-gauged as a result of more expensive processing.

One of the most notable trends to lower glazing weight is to transition away from glass and use polycarbonate (PC) for windows. This is an expensive option, but it can yield substantial weight savings. PC is a thermoplastic, which can be molded and/or thermoformed into a variety of shapes and still act as a clear, transparent window. Aside from weight savings, it also has attractive aesthetic and styling properties as many more shapes can be achieved than with glass. Moreover, the use of PC for windows has favorable thermal insulation characteristics and excellent impact resistance.

In order for PC windows to be useful on a vehicle, two types of coatings need to be applied: Weather and plasma. Exatec®, LLC, a subsidiary of SABIC, is the leading supplier of these coatings. The weather coating helps resist the elements and damage caused by UV radiation. The revolutionary plasma coating developed by Exatec® also increases abrasion resistance. The plasma coating is the most recent development, capable of meeting and exceeding the ECE R43, FMVSS 205, JIS R 3212, and ANSI 26.1 standards. Even with these two coatings, however, polycarbonate is still only applicable for non-moving window applications (not including the windshield). Therefore, front and rear fixed quarter windows and the backlight are all potential candidates for PC. The Smart Fortwo, Chevrolet Corvette, and the Porsche 911 GT3 RS 4.0 are all examples of production vehicles that use polycarbonate glazing.

Exatec® highlighted that the real benefit of polycarbonate is realized when taking advantage of the integration opportunities. When a PC window is injection-molded, the surrounding plastic components can be integrated with it in a two-shot mold, reducing what were numerous components into one piece. The most prominent opportunity for this is with the backlight. The hatchback European version of the Honda Civic integrates the backlight and spoiler into one large injection molded piece as shown in **Image F.4D-4**. This can be a styling, aerodynamic, and potential cost reduction advantage as well as a weight-savings opportunity.

Image F.4D-4: European Honda Civic Backlight/Spoiler Integration through Use of Polycarbonate

(Source: Wheel-O-Sphere http://www.wheelosphere.org/2012-honda-civic-spied-in-europe/european-honda-civic-hatchback-rear-view/)

F.4D.1.4 Summary of Mass-Reduction Concepts Considered

Table F.4D-4 shows the mass-reduction ideas considered for the Glazing subsystem. The industry trends provided by Pilkington regarding the use of laminated glass for side windows and to reduce the gauge of the tempered side windows were each considered. Pilkington also suggests reducing just the inner glass layer of the laminated windshield as a method to lighten the weight of the windshield, also included in **Table F.4D-4**. Replacing the quarter windows and rear backlight with polycarbonate were also considered. Additional ideas are also applied that are not necessarily motivated by current industry trends. For example, the window regulator linkages are galvanized steel. The idea to go to aluminum was judged and analyzed.

The Lotus Engineering study did not apply mass reduction ideas to the Glazing system. Polycarbonate was mentioned as a possible substitute that the industry is taking into account, but this was not included in their final mass reduction results.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Backlight	Reduce thickness from 3.85 mm to 3.15 mm	17% mass reduction	Low cost increase, in production on Dodge Durango
Backlight	Replace with polycarbonate glazing	45% mass reduction	High cost increase, in production on European Honda Civic
Backlight	Replace tempered glass with laminated glass	25% mass reduction	High cost increase
Windshield	Reduce inner glass layer thickness to 1.6 mm	10% mass reduction	Low cost increase, increased sound transmittance to passengers
Front/Rear Fixed Quarter Windows	Reduce thickness from 4.85 (front) and 3.85 (rear) to 3.15 mm	10% mass reduction	Low cost
Front/Rear Fixed Quarter Windows	Replace with polycarbonate glazing	30% mass reduction	High cost increase, in production on Smart For Two
Front/Rear Side Door Windows	Reduce thickness from 4.85 (front) and 3.85 (rear) to 3.15 mm	20-30% mass reduction	Low cost increase, increased sound transmittance to passengers, was in production on Chevrolet Cobalt
Front/Rear Side Door Windows	Replace tempered glass with laminated glass	25-40% mass reduction	High cost increase, in production on Jaguar XJ
Window Regulator Linkage Assembly	Make out of aluminum instead of steel	60% mass reduction	Moderate cost increase
Window Regulator Linkage Assembly	Make out of plastic/steel combination	40% mass reduction	Low cost increase, in production on Chevrolet HHR

Table F.4D-4: Summary of Mass-Reduction Concepts Initially Considered for the Glass (Glazing), Frame, and Mechanism Subsystem.

F.4D.1.5 Selection of Mass Reduction Ideas

The mass reduction ideas selected are shown in **Table F.4D-5**. Reducing the thickness of the tempered Rear Side Windows, Backlight, and the two Rear Quarter Windows to 3.15 mm was chosen. Reducing window gauge was the most favorable option from a cost-per-mass perspective, compared to using laminated or polycarbonate windows. The 3.15 mm thickness is used on production cars sold in the United States. The thickness of the Front Side Windows and the Front Quarter Fixed windows, however, was not reduced. It was determined that the unfavorable NVH effects would be classified as decontenting. If this option were chosen, then an additional 3 kg would have been saved. NVH conditions are more severe at the front of the car since wind makes contact here and it is also closest to the powertrain. Noises caused by these things are much less apparent in the rear of the vehicle, especially on a larger car like the Toyota Venza. It is common for OEMs to design the front windows to be thicker than the rear for these reasons.Polycarbonate and laminated windows are worthy options, but deemed as too pricey for the constraints of this study. If an in-depth engineering analysis were performed on a backlight/rear hatch lift assembly polycarbonate integration, then the cost may be reduced. Such an analysis, however, was beyond the scope of this study.

The inner glass layer of the laminated windshield was reduced in thickness to 1.6 mm. It was determined that this would not result in adverse acoustic effects since the PVB interlayer of the laminated glass is an outstanding sound insulator. The Window Regulators were constructed of aluminum instead of steel. The new aluminum linkages were assumed to increase in gauge to support the same bending stresses as on the baseline steel pieces. The thickness of the aluminum linkage was multiplied by 1.55, which was estimated to increase the section modulus of the beam to make up for aluminum's lower yield strength (compared to steel).

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
03	**11**	**00**	**Glass (Glazing), Frame, and Mechanism Subsystem**	
03	11	01	Windshield and Front Quarter Window (Fixed)	Reduce windshield inner layer thickness from 2.1 to 1.6mm
03	11	03	First Row Door Window Lift Assy (Window Regulators)	Fabicate window regulator linkages out of aluminum instead of steel
03	11	05	Back and Rear Quarter Windows (Fixed)	Reduce quarter window thickness from 3.85 to 3.15mm
03	11	11	Second Row Door, Qtr & Rear Closure Window Lift Assy (Window Regulators)	Fabicate window regulator linkages out of aluminum instead of steel
03	11	12	Back Window Assy (Backlight, Rear Hatch Glass)	Reduce backlight thickness from 3.85 to 3.15mm
03	11	13	Front Side Door Glass	n/a
03	11	14	Rear Side Door Glass	Reduce glass thickness from 3.85 to 3.15mm
03	11	16	Switch Pack - Front Door (Window Up/Down Controls)	n/a
03	11	17	Switch Pack - Rear Door (Window Up/Down Controls)	n/a
03	11	19	Front Side Doors Glass Runs & Belts	n/a
03	11	20	Rear Side Doors Glass Runs & Belts	n/a

Table F.4D-5: Mass-Reduction Ideas Selected for Detail Analysis of the Glass (Glazing), Frame, and Mechanism System.

F.4D.1.6 Mass-Reduction & Cost Impact Results

The mass reduction and cost impact results for the Glazing subsystem can be seen in **Table F.4D-6**. The greatest weight savings came as a result of down-gauging the thickness of the glass on the Venza in various sub-subsystems. Decreasing the thickness of the inner glass layer of the laminated windshield saved 1.559 kg at a cost of $1.68. The

Rear Side Windows, Rear Quarter Fixed Windows, and the Backlight collectively saved 2.624 kg by being reduced to a 3.15 mm thickness and cost an additional $9.25 to do so. Reducing the thickness of the glass saved some on material cost (since less material is used); however, it increased the processing cost. When thinner glass is produced, the float manufacturing line has a lower output per unit time. Therefore, the cost of the equipment is not being paid off as fast. Additionally, when tempering thinner glass additional cooling equipment is needed to complete the tempering process in time, which the supplier may not already have and would increase the cost of the glass.

Using aluminum in place of steel for the Window Regulator Linkages for all four regulators resulted in a total weight savings of 1.878 kg at a cost of $4.74. The Window Regulator Linkages were more expensive due to material cost.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
03	00	00	**Glass (Glazing), Frame, and Mechanism Subsystem**						
03	11	01	Windshield and Front Quarter Window (Fixed)	C	1.559	-$1.68	-$1.08	9.91%	0.09%
03	11	03	First Row Door Window Lift Assy (Window Regulators)	C	0.939	-$2.37	-$2.52	29.98%	0.05%
03	11	05	Back and Rear Quarter Windows (Fixed)	D	0.230	-$0.81	-$3.53	10.80%	0.01%
03	11	11	Second Row Door, Qtr & Rear Closure Window Lift Assy (Window Regulators)	C	0.939	-$2.37	-$2.52	29.99%	0.05%
03	11	12	Back Window Assy (Backlight, Rear Hatch Glass)	D	1.218	-$4.29	-$3.52	17.31%	0.07%
03	11	13	Front Side Door Glass		0.000	$0.00	$0.00	0.00%	0.00%
03	11	14	Rear Side Door Glass	D	1.176	-$4.15	-$3.53	17.85%	0.07%
03	11	16	Switch Pack - Front Door (Window Up/Down Controls)		0.000	$0.00	$0.00	0.00%	0.00%
03	11	17	Switch Pack - Rear Door (Window Up/Down Controls)		0.000	$0.00	$0.00	0.00%	0.00%
03	11	19	Front Side Doors Glass Runs & Belts		0.000	$0.00	$0.00	0.00%	0.00%
03	11	20	Rear Side Doors Glass Runs & Belts		0.000	$0.00	$0.00	0.00%	0.00%
				D	**6.062** (Decrease)	**-15.670** (Increase)	**-$2.59** (Increase)	**12.63%**	**0.35%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.4D-6: Mass-Reduction and Cost Impact for the Glass (Glazing), Frame, and Mechanism Subsystem

F.4D.2 Handles, Locks, Latches & Mechanisms Subsystem.

F.4D.2.1 Subsystem Content Overview

Table F.4D-7 illustrates that the Latches are the most significant contributor to the mass of the Handles, Locks, Latches, Frame, & Mechanisms subsystem. This includes the front doors, rear doors, and the rear hatch. The handle assemblies and the prop rod provide the remainder of the subsystem weight.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
03	**14**	**00**	**Handles, Locks, Latches and Mechanisms Subsystem**	
03	14	04	Latch Assembly - Front Side Doors	1.180
03	14	04	Latch Assembly - Rear Side Doors	1.038
03	14	05	Latch Assembly - Rear Hatch	1.056
03	14	13	Handle Pull, Carrier and Closeout - Front Side Doors	0.666
03	14	13	Handle Pull, Carrier and Closeout - Rear Side Doors	0.579
03	14	19	Prop Rod - Hood	0.346
03	14	99	Subsystem Attachments	0.069
			Total Subsystem Mass =	**4.934**
			Total System Mass =	**63.46**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**7.77%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.29%**

Table F.4D-7: Mass Breakdown by Sub-subsystem for Handles, Locks, Latches and Mechanisms Subsystem.

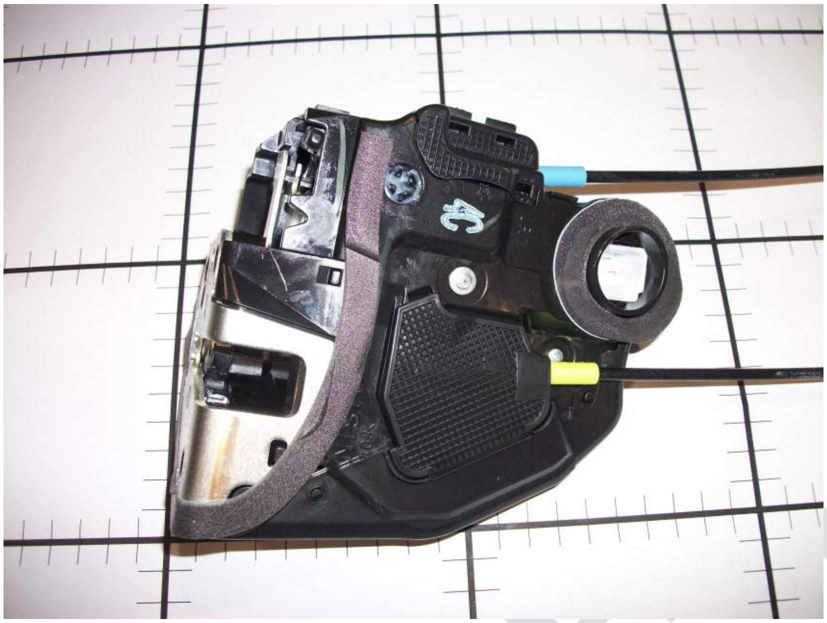


Image F.4D-5: Door Latch Mechanism

(Source: FEV, Inc. photo)

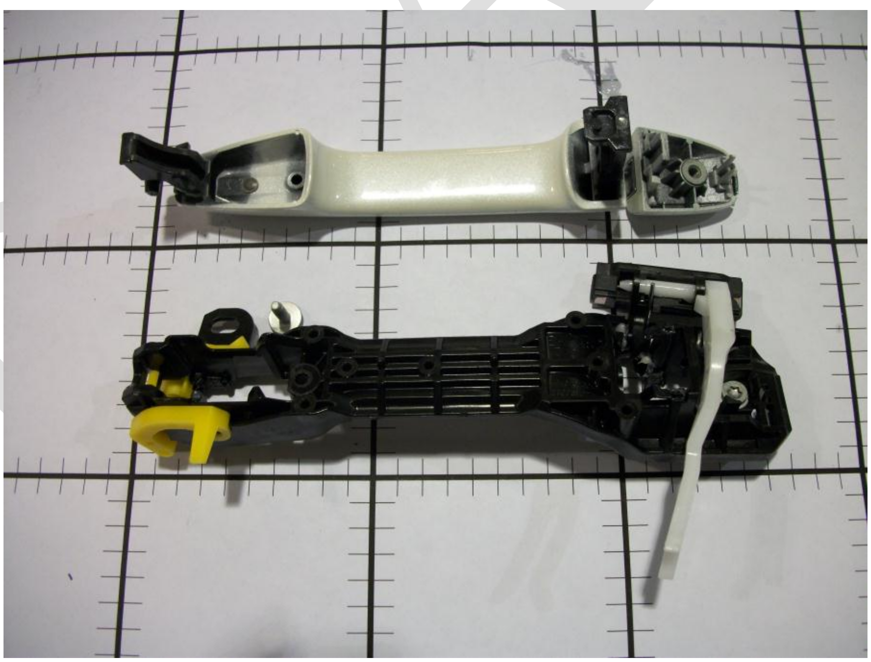


Image F.4D-6: Outer Door Handle and Carrier

(Source: FEV, Inc. photo)

F.4D.2.2 Toyota Venza Baseline Subsystem Technology

The Toyota Venza utilizes the Smart key entry system. This allows the driver to keep the key fob in their pocket when unlocking, locking and starting the vehicle. The key is identified via one of several antennas in the car's bodywork and a radio pulse generator in the key housing. The vehicle is automatically unlocked when the door handle, rear hatch release, or an exterior button is pressed. This system also disengages the immobilizer and activates the engine without inserting a mechanical key, provided the driver has the electronic key inside the car. This is done by pressing a starter button on the Instrument panel.

The Venza has a mechanical back up system, in the form of spare key blades supplied with the vehicle and stored in the electronic keys. The result is an approach to the use and activation of the Handles, Locks, Latches and Mechanisms which is more electrical in nature than traditional subsystems using mechanical keys or Remote Keyless Entry (RKE).

F.4D.2.3 Mass-Reduction Industry Trends

Smart Keys were introduced by Mercedes-Benz in 1998. It was a plastic key to be used in place of the traditional metal key. Electronics that control locking systems and the ignition~~s~~ made it possible to replace the traditional key with a computerized “Key.” This system is considered a step up from remote keyless entry. The Smart Key adopts the remote control buttons from keyless entry into the Smart Key fob. Some vehicles automatically adjust settings based on the smart key used to unlock the car: user preferences such as seat positions, steering wheel position, exterior mirror settings, climate control temperature settings, and stereo presets are popular adjustments, and some models such as the Ford Escape even have settings which can prevent the vehicle from exceeding a maximum speed when a certain key is used to start it.

Manufacturers’ Keyless Authorization Systems Names:

- Acura: **Keyless Access System**
- Audi: **Advanced Key**
- BMW: **Comfort Access**
- Cadillac: **Adaptive Remote Start & Keyless Access**
- Ford: **Intelligent Access with push-button start** or **Ford MyKey**

- General Motors: **Passive Entry Passive Start**
- Hyundai: **Proximity Key**
- Infiniti: **Infiniti Intelligent Key with Push Button Ignition**
- Jaguar Cars: **Smart Key System**
- Jeep **Sentry Key Immobiliser System** "SKIS"
- KIA: **Keyless Entry**
- Lexus: **SmartAccess System**
- Lincoln: **Intelligent Access System**
- Mazda: **Advanced Keyless Entry & Start System**
- Mercedes-Benz: **Keyless Go** integrated into SmartKeys
- Mini: **Comfort Access**
- Mitsubishi Motors: **FastKey**
- Nissan: **Intelligent Key**
- Porsche: **Porsche Entry & Drive System**
- Renault: **Hands Free Keycard**
- Ssang Yong: **Smart Key System**
- Subaru: **Keyless Smart Entry With Push-Button Start**
- Suzuki: **SmartPass Keyless entry & starting system**
- Toyota: **Smart Key System**
- Volkswagen: **Keyless Entry & Keyless Start or KESSY**
- Volvo: **Personal Car Communicator "PCC" and Keyless Drive or Keyless Drive**

(Table Source: Wikipedia)

F.4D.2.4 Summary of Mass-Reduction Concepts Considered

Table F.4D-8 compiles the mass reduction ideas considered for the Handles, Locks, Latches, Frame, & Mechanisms Subsystem. Emphasis was placed on materials and processing to create mass reduction ideas.

The Venza production closure latches, hinges and related mounting hardware were retained; the Venza hardware mass was used for these components. Ancillary sub-system masses, which include handles, latches and locks were not changed because these are typically core components shared corporate wide.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Hood Stand (Prop Rod)	Replace Hood Stand with Gas Springs	20% Mass Savings	Higher Cost, Mass Savings vs Hood Stand Questionable
Hood Stand (Prop Rod)	Replace Hood Stand - Hood Front with Hood Stand - Hood Side	10% Mass Savings	Low Cost, Location on Side a Marketing and Service Issue
Door Handles	Manufacture from Plastic	10% Mass Savings	Low Cost, Ancillary and Esthetic Degrade, Wear and Warranty Issues
Door Handles	Manufacture with Carbon Fiber	15% Mass Savings	High Cost, After Market, Wear and Warranty issues
Door Lock Housings	Manufacture Comonents from Structural Plastic	60% Mass Savings	Low Cost, Wear and Safety Issues

Table F.4D-8: Summary of mass-reduction concepts initially considered for the Handles, Locks, Latches & Mechanisms Subsystem

F.4D.2.5 Selection of Mass Reduction Ideas

The mass reduction ideas selected that fell into the "A_e" group are shown in **Table F.4D-9.**

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
03	14	00	**Handles, Locks, Latches and Mechanisms Subsystem**	None Selected

Table F.4D-9: Mass-Reduction Ideas Selected for Handles, Locks, Latches & Mechanisms Subsystem Analysis

F.4D.2.6 Mass-Reduction & Cost Impact

There was potential shown for mass reduction within this subsystem. Each idea had its own inherent risk or concern. This approach to component changes in the Handles, Locks & Latching subsystem resulted in the decision to **not** recommend any mass reduction initiatives at this time. Most mass savings and cost impacts were modest yet posed risks to durability, aesthetics, and safety.

F.4D.3 Rear Hatch Lift Assembly Subsystem

F.4D.3.1 Subsystem Content Overview

As seen in **Table F.4D-10**, the most significant contributor to the mass of the Rear Hatch Lift Assembly subsystem is the rear hatch lift mechanism. The trim, switches, sensor, switch, and attachments provide the rest of the subsystem weight.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
03	**15**	**00**	**Rear Hatch Lift Mechanism Subsystem**	
03	15	01	Rear Hatch Lift Mechanism	3.272
03	15	02	Rear Hatch Switches	0.029
03	15	03	Rear Hatch Sensor	0.088
03	15	06	Rear Hatch Trim	0.849
03	15	99	Misc.	0.316
			Total Subsystem Mass =	**4.554**
			Total System Mass =	**63.46**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**7.18%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.27%**

Table F.4D-10: Mass Breakdown by Sub-subsystem for Rear Hatch Lift Assembly Subsystem.

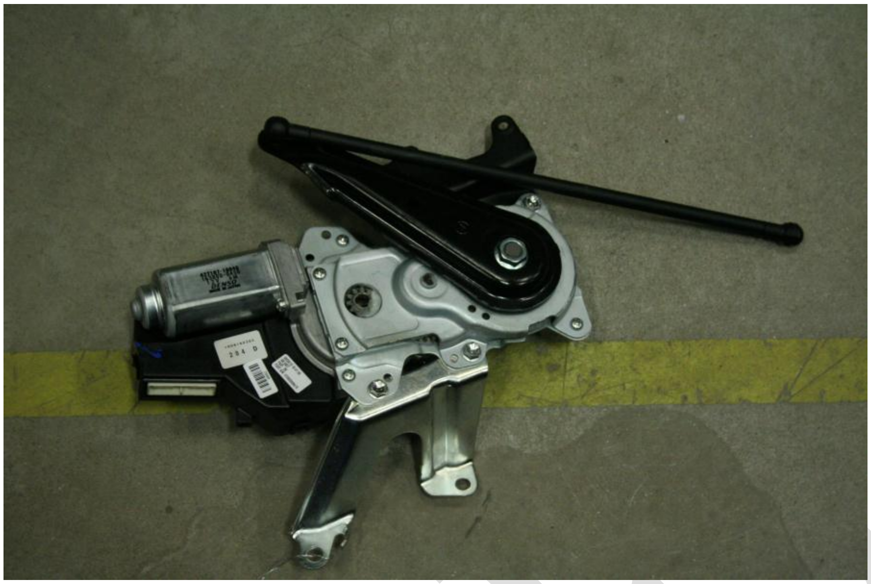


Image F.4D-7: Rear Hatch Lift Mechanism

(Source: FEV, Inc. photograph)

F.4D.3.2 Toyota Venza Baseline Subsystem Technology

The Toyota Venza utilizes the Smart key entry system. It allows the driver to keep the key fob in their pocket when unlocking, locking and starting the vehicle. The key is identified via one of several antennas in the car's bodywork and a radio pulse generator in the key housing. The vehicle is automatically unlocked when the door handle, hatch release, or an exterior button is pressed.

The Venza has a mechanical back up system, in the form of spare key blades supplied with the vehicle and stored in the electronic keys. The result is an approach to the use and activation of the Handles, Locks, Latches and Mechanisms which is more electrical in nature than traditional subsystems using mechanical keys or Remote Keyless Entry (RKE).

F.4D.3.3 Mass-Reduction Industry Trends

Most Rear lift mechanisms are based on the chain lift concept. Toyota and other upper-end companies now use a more complex, but mass-reduced, gear design to operate the rising and lowering features of the rear hatch door.

F.4D.3.4 Summary of Mass-Reduction Concepts Considered

Table F.4D-11 compiles the mass reduction ideas considered for the Rear Hatch Lift Assembly Subsystem. Emphasis was placed on materials and processing to create mass reduction ideas.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Rear Hatch Lift Mechanism	Use Single Motor and Mechanism to Operate Rear Latch and Lift Functions	50% Mass Savings	Different Functions Drive Components and Motors That are Not Interchangable
Rear Hatch Lift Mechanism	Eliminate Power Features for Automatic Lift and Automatic Latch	10% Mass Savings	Low Cost, Functional Degrade
Rear Hatch Lift Mechanism	Hatch Mass Reduction Drives Downsizing of Lift Mechanism	10% Mass Savings	Low Cost, Could Affect Functionality
Rear Hatch Lift Mechanism	Manufacture Components from Structural Plastic	15% Mass Savings	Low Cost, Wear and Load Bearing Issues

Table F.4D-11: Summary of mass-reduction concepts initially considered for the Rear Hatch Lift Assembly Subsystem

F.4D.3.5 Selection of Mass Reduction Ideas

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
03	15	00	Rear Hatch Lift Mechanism	None Selected

Table F.4D-12: Mass-Reduction Ideas Selected for Rear Hatch Lift Assembly Subsystem Analysis

F.4D.3.6 Mass-Reduction & Cost Impact

There was potential shown for mass reduction within this subsystem. Each idea had its own inherent risk or concern. This approach to component changes in the rear lift mechanism resulted in the decision to **not** recommend any mass reduction initiatives at this time. Most mass savings and cost impacts were modest yet proposed risks to both durability and safety.

F.4D.4 Wipers and Washers Subsystem

F.4D.4.1 Subsystem Content Overview

Table F.4D-13 identifies the most significant contributor to the mass of the Wipers and Washers subsystem as the Front Wiper Assembly (includes linkage, bracket, arms and blades). The Rear Wiper Assembly (includes bracket, arm and blade), the Container Assembly – Solvent Bottle, sensors, hoses, nozzles, and attachments provide the rest of the subsystem weight.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
03	**16**	**00**	**Wipers and Washers Subsystem**	
03	16	01	Wiper Motor Assembly - Front	4.000
03	16	08	Wiper Motor Assembly - Rear	1.028
03	16	99	Misc.	0.930
			Total Subsystem Mass =	**5.958**
			Total System Mass =	**63.46**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**9.39%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.35%**

Table F.4D-13: Mass Breakdown by Sub-subsystem for Wipers and Washers Subsystem.

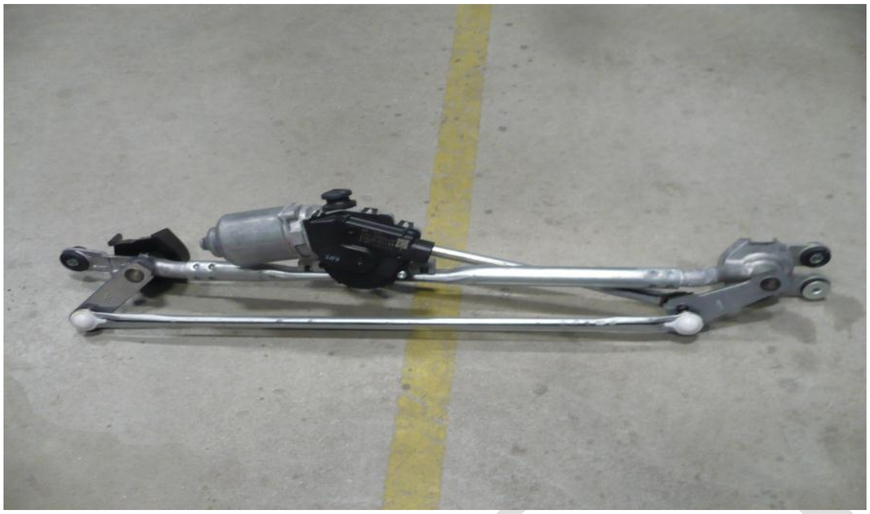


Image F.4D-8: Front Wiper Assembly

(Source: FEV, Inc. photo)

Image F.4D-9: Rear Wiper Assembly

(Source: FEV, Inc. photo)

Image F.4D-10 Solvent Bottle

(Source: FEV, Inc. photo)

F.4D.4.2 Toyota Venza Baseline Subsystem Technology

The wipers combine two mechanical systems to perform their task: an electric motor and worm gear reduction provides power to the wipers. A linkage converts the rotational output of the motor into the back-and-forth motion of the wipers. The worm gear reduction can multiply the torque of the motor by 40 times, while slowing the output speed of the electric motor by 40 times as well. The output of the gear reduction operates the linkage that moves the wipers back and forth. A lever arm is attached to the output shaft of the gear reduction; the lever arm rotates as the wiper motor turns. The lever is connected to a rod and the rotational motion of the lever moves the rod back and forth. The longer rod is connected to a shorter rod that actuates the wiper blade on the driver's side. Another linkage transmits the force from the driver-side to the passenger-side wiper blade.

F.4D.4.3 Mass-Reduction Industry Trends

Some of the different wiper blade schemes used by various Automotive Manufacturers:

Pivot Points **–** Many vehicles have similar wiper designs: Two blades which move together to clean the windshield. One of the blades pivots from a point close to the driver's side of the car, and the other blade pivots from near the middle of the windshield. This is the "Tandem System." This design clears most of the windshield that is in the driver's field of view.

There are other designs used on some automobiles. Mercedes uses a single wiper arm that extends and retracts as it sweeps across the window – Single Arm (Controlled). This design also provides good coverage, but is more complicated than the standard dual-wiper systems. Some systems use wiper blades mounted on opposite sides of the windshield and move in opposing directions. Other vehicles have a single wiper mounted in the middle.

Blades **–** The beam (flat) blade wiper blade is the main trend in wiper blade design. The market drivers are product quality and durability. The contact pressure over the wiper blade element is no longer distributed by the claws of the wiper bracket, but by a spring specifically designed to optimize wiper blade contact with the windshield.

Beam (Flat) Blade

Conventional Blade

Drive Units **–** Another trend is the fact that many wiper systems are being controlled by electronic drive units which determine the arc of wipe and speed. There are few wiper systems that solely move the wiper blades back and forth without electronic speed control, except on some entry level vehicles.

Direct drive systems for windshield wipers are currently in production by Bosch and Valeo for a number of recently launched carlines. The two drives of a dual motor wiper system do not require an additional mechanical linkage and are therefore smaller than traditional wiper systems. The mass of each unit is approximately half a liter. The new Bosch direct drive system needs up to 75 percent less space and is over a kilogram lighter than standard drive and linkage systems. Each wiper has its own compact drive motor and is mounted directly on the drive shaft, which makes the new system easier to integrate into vehicles. Since the direct drives require no linkage, there is more room for other components in the engine compartment. An electronic control unit takes the place of the mechanical linkage. The control unit synchronizes the two drives by monitoring the position of the two wiper arms. Each drive unit consists of a mechatronic drive that can run either backwards or forwards. Specifications for the sweep angle and rest position are programmable. This allows the wiper system~~s~~ to be designed symmetrically for right and left hand drive since the blade alignment is controlled by the software.

F.4D.4.4 Summary of Mass-Reduction Concepts Considered

Table F.4D-14 compiles the mass-reduction ideas considered for the Wiper & Washers subsystem.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Front Washer and Wiper Assembly	Use More Plastic Parts or Castings	10% - 20% Mass Savings	Wear and Durability Issues
Front Washer and Wiper Assembly	Use Lighter Materials to Mount the Motor to the Assembly	10% - 20% Mass Savings	Durability Issues
Front Washer and Wiper Assembly	Use Bayonet Wiper Module Installation	10% - 20% Mass Savings	Blade Attachment Process - No Significant Mass Savings
Front Washer and Wiper Assembly	Use Direct Drive Motor Scheme. Ref. Ford Focus	20% Mass Savings	Electronic Control of Arm Positon and Sweep, More Compact in Size than Mass and Lends Itself to Platform Sharing
Front Wiper Arms	Use Injection Molded Arms	10% - 20% Mass Savings	NVH, Wear and Durability Issues
Front Wiper Arms	Use Carbon Fiber Arms	10% - 20% Mass Savings	High Cost, NVH, Wear and Durability Issues
Front Wiper Arms	Use Aluminum Arms	10% - 20% Mass Savings	High Cost, NVH, Wear and Durability Issues, Billet Aluminum Arms used on Vintage Hot Rods
Front Wiper Arms	Use Overmolded Plastic Arms	10% - 20% Mass Savings	Eliminate Paint and Corrosion Protection
Front Wiper Arms	Use Fiberglass Arms	10% - 20% Mass Savings	NVH, Wear and Durability Issues
Front Wiper Arms	Place Holes in Arms	0 - 10% Mass Savings	NVH, Wear and Durability Issues
Rear Wiper Assembly	Use Lighter Materials to Mount the Motor to the Assembly	10% - 20% Mass Savings	Durability Issues
Rear Wiper Assembly	Mount Rear Wiper Motor to Glass - Eliminate Mounting Brackets	10% - 20% Mass Savings	Brackets Replaced by Reinforcements or Built into Assembly
Solvent Body	Gas Assist Injection Molding (MuCell®, PolyOne)	10% - 20% Mass Savings	Low or no Cost Impact with Mass reduction

Table F.4D-14: Summary of mass-reduction concepts initially considered for the Wipers & Washers Subsystem

F.4D.4.5 Selection of Mass Reduction Ideas

The mass-reduction ideas selected for detailed analysis are shown in **Table F.4D-15.**

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
03	**16**	**00**	**Wipers and Washers Subsystem**	
03	16	99	Container Assembly - Solvent Bottle	PolyOne Process - Injection Mold

Table F.4D-15: Summary of mass-reduction concepts selected for the Wipers & Washers Subsystem

F.4D.4.6 Mass-Reduction & Cost Impact

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Sub-Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
03	**16**	**00**	**Wipers and Washers Subsystem**						
03	16	99	Container Assembly Solvent Bottle	A	0.091	$0.42	$4.62	1.53%	0.01%
				A	**0.091** (Decrease)	**$0.42** (Decrease)	**$4.62** (Decrease)	**1.53%**	**0.01%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.4D-16: Summary of Mass-Reduction & Cost Impact for the Wipers & Washers Subsystem

Tables 5.3D-17 and **5.3D-18** illustrate that there are very limited opportunities for mass reduction in the Toyota Venza Front & Rear Wiper systems**.** The Venza Front Wiper Assembly is very close in mass to the Ford Focus Direct Drive Wiper system; the Venza

Rear Wiper system is close in mass to the Ford Fiesta Rear Wiper Assembly. There was potential shown for mass reduction within this subsystem.

System	Subsystem	Sub-Subsystem	Description	Venza: Tandum Drive, Standard Blades with Traditional "Hook " Style Attachment,	Fiesta: Tandum Drive, Beam Blades with "Bayonet" Style Attachment	Focus: Direct Drive, Beam Blades with "Bayonet" Style Attachment
03	16	01	**Wipers and Washers - Front**			
			Front Wiper Assembly (Includes Linkage and Brackets)	2.623	5.003	2.589
			Front Hoses and Nozzles	0.061	0.064	0.064
			Front Arms & Blades	1.316	1.224	1.224
			Mass (kg) Front Wipers and Washers	**4.000**	**6.291**	**3.877**

Table F.4D-17: Summary of Mass Benchmarking for the Front Wipers & Washers Subsystem

System	Subsystem	Sub-Subsystem	Description	Venza: Tandum Drive, Standard Blades with Traditional "Hook " Style Attachment,	Fiesta: Tandum Drive, Beam Blades with "Bayonet" Style Attachment	Focus: Direct Drive, Beam Blades with "Bayonet" Style Attachment
03	16	08	**Wipers and Washers - Rear**			
			Rear Wiper Assembly (Includes Brackets)	0.715	0.841	N/A
			Rear Hose and Nozzle	0.121	0.073	N/A
			Rear Arm & Blade	0.192	0.192	N/A
			Mass (kg) Front Wipers and Washers	**1.028**	**1.106**	**0.000**

Table F.4D-18: Summary of Mass Benchmarking for the Rear Wipers & Washers Subsystem

Component changes in the Wipers and Washers subsystem are **not** recommended at this time. These systems were left intact except for the application of the PolyOne process for the solvent bottle.

F.4E Body System Group A

F.4E.1 Subsystem Content Overview

Table F.4E-1 shows that the most significant nonmetallic contributor to the Body Structure subsystem mass is the Rear Wheelhouse Arch Liners (**Image F.4E-1**).

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
03	**01**	**00**	**Body Structure Subsystem**	
03	01	07	Rear Wheelhouse Arch Liners	1.460
			Total Subsystem Mass =	**1.460**
			Total System Mass =	**517.860**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**0.28%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.09%**

Table F.4E-1: Mass Breakdown by Sub-subsystem for the Body Structure Subsystem

Image F.4E-1: Rear Wheelhouse Arch Liner
(Source: FEV, Inc. photo)

F.4E.1.1 Toyota Venza Baseline Subsystem Technology

The materials and thickness used are in common use by many automobile manufacturers and their suppliers. They finish off the wheel wells as well as protect the wheelhouse from noise and damage caused by rocks, debris, tires and conditions caused by inclement weather.

F.4E.1.2 Mass-Reduction Industry Trends

Down-gauging the material thickness is the most common method used to reduce mass. Designing in reinforcements while varying material thickness for the entire component or the thickness of a specific section can provide a significant mass reduction.

Another common industry method is to change materials and manufacturing processes. These component processes are altered based on materials technology and process production for interior hardware.

Fiber lined wheelhouse arch liners are being utilized to further reduce NVH that emanates from the wheelhouse areas. They are useful in achieving cab acoustics targets while meeting durability standards.

Spray on products are also being tested as a viable alternative to traditional wheelhouse arches, but as of yet do not provide enough protection or noise reduction to warrant consideration in this study.

The most promising emerging technology for hard trim is gas assist injection molding. The PolyOne and the MuCell® processes were reviewed: These processes are outlined in Exterior Trim & Ornamentation.

F.4E.1.3 Summary of Mass-Reduction Concepts Considered

Table F.4E-2 compiles the mass reduction ideas considered for the Body Structure subsystem. Emphasis was placed on materials and processing to create mass reduction ideas.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Rear Wheelhouse Arch Liners	Gas Assist Injection Molding	10% - 20% Mass Savings	Low or no Cost Impact with Mass Reduction

Table F.4E-2: Summary of Mass-Reduction Concepts Initially Considered for the Nonmetallic Components of the Body Structure Subsystem

F.4E.1.3 Summary of Mass-Reduction Concepts Selected

The mass reduction idea selected that fell into the "A" group is shown in **Table F.4E-3**.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
03	**01**	**00**	**Body Structure Subsystem**	
03	01	07	Rear Wheelhouse Arch Liners	PolyOne Process - Injection Molding

Table F.4E-3: Summary of mass-reduction concepts selected for the nonmetallic Components of the Body Structures Subsystem

F.4E.1.5 Mass-Reduction & Cost Impact

The PolyOne gas assist system was utilized for all components, as shown in **Table F.4E-4**. The mass was reduced .043 kg and cost decreased $0.21.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Sub-Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
03	**01**	**00**	**Body Structure Subsystem**						
03	01	07	Rear Wheelouse Arch Liners	A	0.043	$0.21	$4.88	0.01%	0.00%
				A	**0.043** (Decrease)	**$0.21** (Decrease)	**$4.88** (Decrease)	**0.01%**	**0.00%**

Table F.4E-4: Summary of mass-reduction & cost impacts for the nonmetallic components of the Body Structure Subsystem

F.4E.2 Front End Subsystem

F.4E.2.1 Subsystem Content Overview

Table F.4E-5 demonstrates that the most significant nonmetallic contributors to the Front End subsystem mass are the Rock Shields and the Front Wheelhouse Arch Liners (**Image F.4E-2**).

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
03	**02**	**00**	**Front End Subsystem**	
03	02	04	Front Wheelhouse Arch Liners	1.598
03	02	10	Under Engine Closures or rock shields	2.145
			Total Subsystem Mass =	**3.743**
			Total System Mass =	**517.860**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**0.72%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.22%**

Table F.4E-5: Mass Breakdown by Sub-subsystem for the Front End Module Subsystem.

Image F.4E-2: Front Wheelhouse Arch Liner

(Source: FEV, Inc. photo)

F.4E.2.2 Toyota Venza Baseline Subsystem Technology

The materials and thickness used are in common use by many automobile manufacturers and their suppliers. They finish off the wheel wells as well as protect the wheelhouse from noise and damage caused by rocks, debris, tires and conditions caused by inclement weather.

F.4E.2.3 Mass-Reduction Industry Trends

Down-gauging the material thickness is the most common method used to reduce mass. Designing in reinforcements while varying material thickness for the entire component or the thickness of a specific section can provide a significant mass reduction.

Another common industry method is to change materials and manufacturing processes. These component processes are altered based on materials technology and process production for interior hardware.

Fiber lined wheelhouse arch liners are being utilized to further reduce NVH that emanates from the wheelhouse areas. They are useful in achieving cab acoustics targets while meeting durability standards.

Spray on products are also being tested as a viable alternative to traditional wheelhouse arches, but as of yet do not provide enough protection or noise reduction to warrant consideration in this study.

The most promising emerging technology for hard trim is gas assist injection molding. The PolyOne and the MuCell® processes were reviewed: These processes are outlined in Exterior Trim & Ornamentation.

F.4E.2.4 Summary of Mass-Reduction Concepts Considered

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Front Wheelhouse Arch Liners	Gas Assist Injection Molding (MuCell®, PolyOne)	10% - 20% Mass Savings	Low or no Cost Impact with Mass reduction
Rock Shields	Gas Assist Injection Molding (MuCell®, PolyOne)	10% - 20% Mass Savings	Low or no Cost Impact with Mass reduction

Table F.4E-6: Summary of Mass-Reduction Concepts Initially Considered for the Nonmetallic Components of the Front End Subsystem

F.4E.2.5 Summary of Mass-Reduction Concepts Selected

The mass reduction ideas selected that fell into the A_e group are shown in **Table F.4E-7**.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
03	**02**	**00**	**Front End Subsystem**	
03	02	04	Front Wheelhouse Arch Liners	PolyOne Process - Injection Molding
03	02	10	Under Engine Closures or Rock Shields	PolyOne Process - Injection Molding

Figure 5.4E-7: Summary of Mass-Reduction Concepts Selected for the Nonmetallic Components of the Front End Subsystem

F.4E.2.6 Mass-Reduction & Cost Impact

The PolyOne gas assist system was utilized for all components in **Table F.4A-8**. The resulting mass reduction is 0.172 kg and a $0.55 cost decrease.

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Sub-Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
03	**02**	**00**	**Body Structure Subsystem**						
03	02	04	Front Wheelhouse Arch Liners	A	0.069	$0.30	$4.35	0.08%	0.00%
03	02	10	Under Engine Closures or Rock shields	A	0.103	$0.25	$2.43	0.12%	0.01%
				A	**0.172** (Decrease)	**$0.55** (Decrease)	**$3.20** (Decrease)	**0.20%**	**0.01%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.4E-8: Summary of Mass-Reduction and Cost Impacts for the Nonmetallic Components of the Front End Subsystem

F.5 Suspension System

The Suspension system is composed of seven subsystems: Front Suspension, Rear Suspension, Shock Absorber, Wheels and Tires, Suspension Load Leveling Control, Rear Suspension Modules and Front Suspension Modules subsystems, as shown in **Table F.5-1**. Comparing the seven subsystems, the greatest mass is located in the Wheels and Tires subsystem with approximately 53.6%.

System	Subsystem	Sub-Subsystem	Description	System & Subsystem Mass "kg"
04	**00**	**00**	**Suspension System**	24.416
04	01	00	Front Suspension Subsystem	33.194
04	02	00	Rear Suspension Subsystem	23.749
04	03	00	Shock Absorber Subsystem	42.945
04	04	00	Wheels And Tires Subsystem	141.815
04	05	00	Suspension Load Leveling Control Subsystem	0.000
04	06	00	Rear Suspension Modules	0.000
04	07	00	Front Suspension Modules	0.000
			Total System Mass =	**266.120**
			Total Vehicle Mass =	**1711**
			System Mass Contribution Relative to Vehicle =	**15.56%**

Table F.5-0-1: Baseline Subsystem Breakdown for the Suspension System

The Final Calculated Results Summary for the entire Toyota Venza Suspension system is shown in **Table F.5-2**. This combination of proposed solutions was selected for this cost group due to the significant weight savings calculated to be obtained (approximately 69.445kg) while also allowing for lower overall costs (approximately $ 135.93).

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
04	**00**	**00**	**Suspension System**						
04	01	00	Front Suspension Subsystem		14.182	-$5.74	-$0.40	55.40%	0.83%
04	02	00	Rear Suspension Subsystem		8.320	$4.91	$0.59	41.53%	0.49%
04	03	00	Shock Absorber Subsystem		14.111	$57.99	$4.11	35.88%	0.82%
04	04	00	Wheels And Tires Subsystem		32.833	$78.77	$2.40	25.69%	1.92%
04	05	00	Suspension Load Leveling Control Subsystem		0.000	0.000	$0.00	0.00%	0.00%
04	06	00	Rear Suspension Modules		0.000	0.000	$0.00	0.00%	0.00%
04	07	00	Front Suspension Modules		0.000	0.000	$0.00	0.00%	0.00%
					69.445 (Decrease)	**$135.93** (Decrease)	**$0.51** (Decrease)	**26.47%**	**4.06%**

(1) **"+" = mass decrease, "-" = mass increase**
(2) **"+" = cost decrease, "-" = cost increase**

Table F.5-2: Mass-Reduction and Cost Impact for the Suspension System

F.5.1 Front Suspension Subsystem

F.5.1.1 Subsystem Content Overview

Image F.5-1 shows the major suspension components in the Front Suspension subsystem and their location and position relevant to one another as located on the vehicle front end.

Image F.5-1: Front Suspension Subsystem Relative Location Diagram

(Source: Lotus – 2010 March EPA Report)

As shown in **Image F.5-2**, the Front Suspension subsystem major components consists of the Front Control Arms, Front Knuckle Assemblies, Front Stabilizer Bar, Bushings & Mounts and the miscellaneous attaching components.

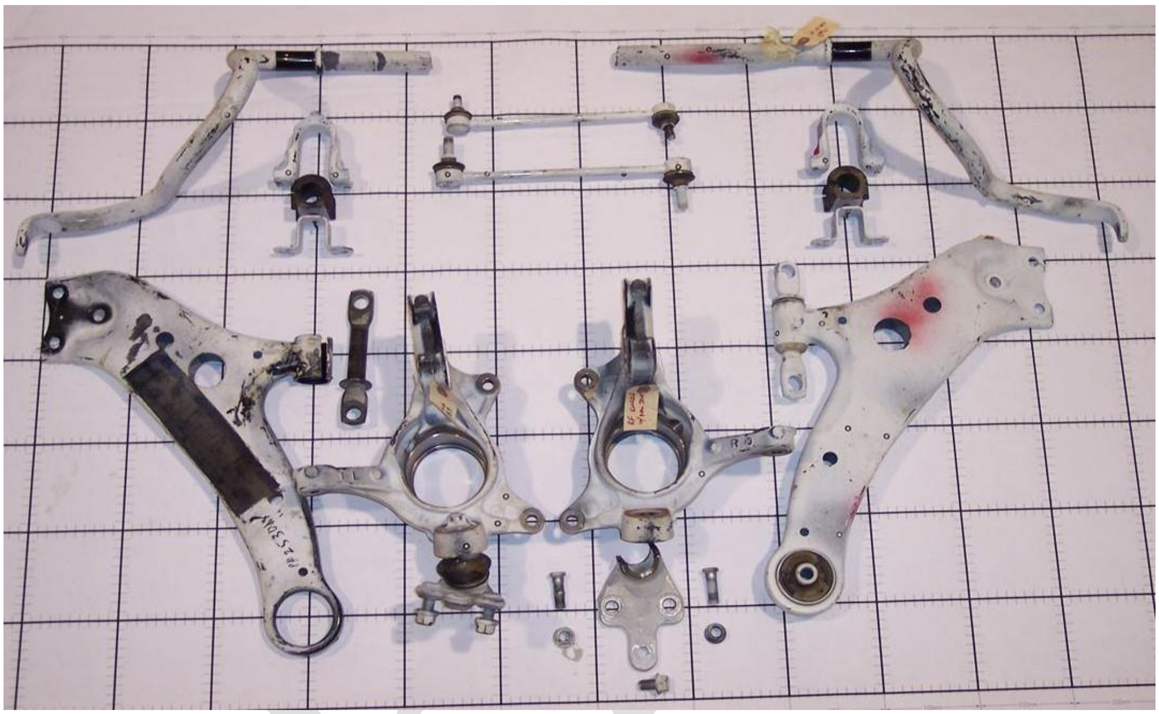


Image F.5-2: Front Suspension Subsystem Current Major Components

(Source: FEV Inc photo)

As seen in **Table F.5-3**, there are three sub-subsystems that make up the Front Suspension subsystem: the Front Suspension Links/Arms Upper and Lower, Front Suspension Knuckle Assembly, and the Front Stabilizer (Anti-Roll) Bar Assembly. The most significant mass contributor within this subsystem was found to be within the Front Suspension Knuckle Assembly (approx 37.6%), followed closely by the Front Suspension Links/Arms Upper and Lower (approx 35.0%), and then the Front Stabilizer (Anti-Roll) Bar Assembly (approx 27.4%).

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
04	**01**	**00**	**Front Suspension Subsystem**	**--**
04	01	02	Front Suspension Links/Arms Upper and Lower	11.614
04	01	04	Front Suspension Knuckle Assembly	12.494
04	01	05	Front Stabilizer (Anti-Roll) Bar Asm	9.086
			Total Subsystem Mass =	**33.194**
			Total System Mass =	**266.120**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**12.47%**
			System Mass Contribution Relative to Vehicle =	**1.94%**

Table F.5-3: Mass Breakdown by Sub-subsystem for the Front Suspension Subsystem

F.5.1.2 Toyota Venza Baseline Subsystem Technology

The Toyota Venza's Front Suspension subsystem (**Image F.5-3**) follows typical industry standards for design and performance. This includes a focus on strength and durability with least material cost. Steel is the material of choice with most components. Welding and assembly of multiple components is automated and requires careful setup, maintenance, and observation to assure quality. Toyota also focuses on providing similar, if not identical, components across all platform variants to take advantage of economies of scale for minimizing production costs. This approach, however, is not optimal for design efficiency based on applications and does not allow for maximum weight-versus-performance efficiency.

The Front Suspension subsystem contains a variety of sub-assemblies and components with a variety of noteworthy characteristics. The Ball Joint Sub-Assembly (**Image F.5-5**) has a cast steel base plate socket while the spindle is forged steel. Both are machined and assembled with other various assembled components. The Ball Joint Sub-Assembly Fasteners (**Image F.5-6**) are typical cold headed steel fabrications. The Control Arm Assembly (**Image F.5-4**) is made up of many components assembled to the control arm. The Control Arm Sub-Assembly (**Image F.5-7**) is composed of several components, including the Control Arm (**Image F.5-8**), which is made from various stamped steel pieces welded together at several locations. The Control Arm Mounting Shaft (**Image F.5-9**) is a single-piece steel design. The Steering Knuckle (**Image F.5-10**) is cast iron and precision machined. The Stabilizer Bar system (**Image F.5-11**) contains the Stabilizer

Bar, Bar Mounts, Mount Bushings, and Link Assemblies. The Stabilizer Bar (**Image F.5-12**) is a solid steel bar bent into shape and pinched flanges with punched holes for mounting points. The Stabilizer Bar Mounts (**Image F.5-13**) are of standard construction with stamped steel brackets. The Stabilizer Bar Mount Bushings (**Image F.5-14**) are molded rubber isolators. The Stabilizer Link Assemblies (**Image F.5-15**) are standard steel design. The steel components include the link rod, link cup diameters, cup bottom plates and ball studs.

Image F.5-3: Front Suspension Subsystem Current Assembly Example

(Source http://www.vehicledynamicsinternational.com)

F.5.1.3 Mass-Reduction Industry Trends

Automakers are deploying a wide variety of low mass materials in new vehicle models regarding all subsystems including suspensions. Implementations have been documented showing reduced component mass for the same functionality using alternative materials such as high-strength steel, aluminum, magnesium, plastics and polymer composites. Design approaches for the active components of suspensions are primarily focused on higher strength steels with lower part volume and high strength aluminum. Also, some notable ventures are into limited applications of magnesium, long fiber polymer composites, and in rare cases, carbon fiber and titanium. The progress has been slow over the years because of the typically higher resultant costs relative to steel. However, recent studies have shown cost comparisons near parity with well designed parts using alternate materials, primarily high strength steel.

Another significant consideration should be the secondary mass-reduction effects - weight reductions for all other vehicle subsystems. Less total vehicle mass reduces the suspension loading and provides opportunities to further reduce suspension mass.

In the last decade, basalt fiber has emerged as a contender in the fiber reinforcement of composites. Proponents of this technology claim their products offer performance similar to S-2 glass fibers at a price point between S-2 glass and E-glass, and may offer manufacturers a less-expensive alternative to carbon fiber for products in which the latter represents over-engineering and much higher cost.

Another technology that bears watching is bulk compound molding using polymer material that is filled with long carbon fiber.

Applications of basalt fiber and bulk molded carbon fiber will be delayed into the indefinite future because of limited production capacity. However, the continental United States has very large deposits of basalt, including the upper peninsula of Michigan. Basalt fiber research, production and most marketing efforts are based in countries once aligned with the Soviet bloc. Companies currently involved in production and marketing include Kamenny Vek (Dubna, Russia), Technobasalt (Kyiv, Ukraine), Hengdian Group Shanghai Russia & Gold Basalt Fibre Co. (Shanghai, China), and OJSC Research Institute Glassplastics and Fiber (Bucha, Ukraine). Basaltex, a division of Masureel Holding (Wevelgem, Belgium), Sudaglass Fiber Technology Inc. (Houston, Texas), and Allied Composite Technologies LLC (Rochester Hills, Michigan).

F.5.1.3.1 Front Control Arm Assembly

The baseline OEM Toyota Venza Front Control Arm Assembly (**Image F.5-4**) is a multi-piece assembly, with the major components made from steel and assembled together. The total mass of this assembly is 5.81kg. This assembly consists of the following components: Ball Joint Assembly, Ball Joint Fasteners and a Control Arm Sub-Assembly. The arm sub-assembly is made up of a Control Arm Sub-Assembly, Rubber Isolator (with a steel ID insert) and the Lower Bushing & Shaft.

Image F.5-4: Front Control Arm Current Assembly Example

(Source: http://www.piranamotorsports.com/servlet/the-990/Toyota-Sienna-2004-2005/Detail)

F.5.1.3.1.1 Front Ball Joint Sub-Assembly

The baseline OEM Toyota Venza Ball Joint Assembly (**Image F.5-5**) is a multi-piece design assembly. The base plate socket is cast steel while the spindle is forged steel. Both are machined and assembled with various components for the socket boot, retaining ring, castle nut, zerk fitting, grease, etc. The overall assembly has a mass of 0.896kg. No other viable high volume manufactured alternate designs were found to substitute. Due to performance requirements for loading and strength, no cost effective material substitutions were identified for replacement. Therefore it was determined that a sizing and normalization activity would need to be performed based on GVW to see if any opportunities exist.

Image F.5-5: Front Ball Joint Sub-Assembly

*(Source:*h*ttp://www.1aauto.com/1A/BallJoint/Toyota)*

F.5.1.3.1.2 *Front Ball Joint Fasteners*

The OEM Toyota Venza Ball Joint design utilizes bolt fasteners, **Image F.5-6**, in a standard attachment configuration to the Control Arm Sub-Assembly. In the design utilized there are two pressed in flanged bolts secured with hex nuts. While these items are of minimal weight contributors there are other designs that use mechanical rivets to attach the ball joint. This fastener design has less assembly process time and less costly components but results in a less serviceable front suspension assembly. Each OEM chooses their own design based on these trade-offs and historical warranty data. The fasteners are common steel and have a combined mass of 0.190kg.

Image F.5-6: Front Ball Joint Sub-Assembly Fastener Example

*(Source:*h*ttp://www.1aauto.com/1A/BallJoint/Toyota)*

F.5.1.3.1.3 *Front Control Arm Sub-Assembly*

The baseline OEM Toyota Venza Front Control Arm Sub-Assembly (**Image F.5-7**) is a multi-piece assembly, with major components made from stamped steel and welded together. It has a total mass of 3.821kg. The rest of the sub-assembly is two hard-rubber isolators (one with a steel ID insert) and the Control Arm Mounting Shaft with bushing.

Image F.5-7: Front Control Arm Current Sub-Assembly Example

(Source: http://www.autopartsexpress.com/Parts/TOYOTA_Control_Arm.html)

F.5.1.3.1.3.1 Front Control Arm

The baseline OEM Toyota Venza Front Control Arm Sub-Assembly (**Image F.5-8**) is a multi-piece assembly. The various pieces are made from stamped steel and welded together at several locations. It has a mass of 3.106kg. Traditionally control arms have been made from either welded steel assemblies or from being cast out of iron. This allows for adequate strength and component life without using more expensive processes or materials. Now with advances in materials and processing methods, other choices are available that have become more cost effective and are being utilized in aftermarket and high performance applications as well as OEM vehicle markets. Among some of these alternate mediums are Al, Ti, Steel, Mg and MMC. Forming methods now include sand casting, semi-permanent metal molding, die casting, machining from billet, and welded fabrications.

Image F.5-8: Front Control Arm Current Component Example

(Source: http://www.autopartsexpress.com/Parts/TOYOTA_Control_Arm.html)

While these alternatives now are designed with the strength and performance required, they do add a significant cost-versus-mass increase. However, the weight savings achieved is quite substantial and assists with reducing vehicle requirements for suspension loads, handling, ride quality, engine hp requirements, etc. Other advanced development includes using bulk molding compound using long randomly oriented carbon fiber continues to be of interest due to the ability to easily mold it into complex shapes.

F.5.1.3.1.3.2 Front Control Arm Mounting Shaft

The baseline OEM Toyota Venza Front Control Arm Mounting Shaft is a single-piece steel design with a mass of 0.390kg. Mounting shafts (**Image F.5-9**) have normally been made from various grades of cast iron for adequate strength and function. Now, with advances in materials and processing methods, other choices are available and being utilized in aftermarket and high performance applications as well as OEM vehicle markets. Among some of these alternate mediums are Al, Ti, Steel and Mg. Forming and fabrication methods include casting, forging and billet machining.

Image F.5-9: Front Control Arm Mounting Shaft Current Component Example

(Source: http://autoparts2k.com/moog-control-arm-bushings-lower-k200037)/

F.5.1.3.2 Front Steering Knuckle

The baseline OEM Toyota Venza Front Steering Knuckle (**Image F.5-10**) is a single piece cast iron knuckle of a standard design configuration with a mass of 5.865kg. Knuckles are historically made from cast iron for strength and function. Over the last several years, advances in alternative materials and processing methods have made new choices available. Rather than cast iron only, Al alloys are now a common choice and are used in high-volume applications by many OEMs. This allows not only similar functional performance, but substantial weight savings along with minimal, if any, cost increase.

Image F.5-10: Front Steering Knuckle Current Component

(Source: Lotus – 2010 March EPA Report)

F.5.1.3.3 Front Stabilizer Bar System

The baseline OEM Toyota Venza Front Stabilizer Bar system (**Image F.5-11**) is standard design and construction composed of solid steel forged bar, molded rubber mount bushings, steel stamped brackets, and miscellaneous fasteners. Together, this system has an overall mass of approximately 9.086kg. The stabilizer bar system has recently undergone some changes relative to design, materials, and processing. Steel bars are now made with a hollow design as well as with alternative materials. Mounting Bushings are being made with various plastics in order to increase rigidity and life. Brackets and mountings are now being made from new casted, forged and molded processes as well as with new materials such as Al, Ti, Mg, and fiber-reinforced plastics.

Image F.5-11: Stabilizer Bar System Current Component Example

(Source: http://www.hotchkis.net/6472_gm_abody_extreme_sway_bar_set.html)

Another trend in suspension stabilization technology is integrating more and more electronics. Electronic dampers allow a wide range between maximum and minimum damping levels and adjust instantly to ensure ride comfort and firm vehicle control. By integrating mechanical and electronic functions within the shock absorber system, automakers can improve handling and potentially reduce costs as technologies mature.

BMW has redesigned a standard suspension piece to resolve some past suspension problems. While roll bars—or sway bars—help control vehicle pitch, they are also a detriment to ride quality because they transmit vibrations from one side of the vehicle to the other.

To remedy this problem, BMW has developed Active Roll Stabilization (**Image F.5-12**) for its 7-series vehicles. On these vehicles, roll bars have evolved into two-piece hydro mechanical parts. Now, when one side of the vehicle noses sharply into a turn or drops down to meet the road, a hydraulic motor located between the bars turns the roll bar on the other side of the vehicle in a counter rotation motion, thereby keeping the entire vehicle flat.

Since the roll bar is separated into two pieces, vibrations from one side are no longer transmitted to the other. That allows the two sides of the vehicle to be truly independent. The result is a vehicle with improved handling and no trade off in ride comfort while also allowing a potential reduction in vehicle front end mass.

Image F.5-12: BMW Active Roll Stabilization System

(Source : http://www.search-autoparts.com/searchautoparts/article/articleDetail.jsp?id=68222)

F.5.1.3.3.1 Front Stabilizer Bar

The baseline OEM Toyota Venza Front Stabilizer Bar (**Image F.5-13**) is standard construction with a solid steel bar bent into shape and pinched flanges with punched holes for mounting points. This bar has a mass of 7.099kg. The stabilizer bar has begun being redesigned in recent years. Design, materials and processing changes now allow hollow designs as well as using alternative materials such as Al, Ti, HSS and fiber reinforced composites. While these materials can effect performance and handling under various conditions, significant mass savings can also be achieved.

Image F.5-13: Stabilizer Bar Current Component

(Source: Lotus – 2010 March EPA Report)

F.5.1.3.3.2 *Front Stabilizer Bar Mountings*

The baseline OEM Toyota Venza Front Stabilizer Bar Mountings (**Image F.5-14**) are of standard construction. There are two stamped steel brackets, one bracket nesting inside the other when assembled. They have a mass of 0.62kg. These brackets have had some changes in design, materials and processing recently. Various configurations include alternate materials for Al, Mg, HSS and plastics. Among the process variations for manufacturing are casting, molding, and forging.

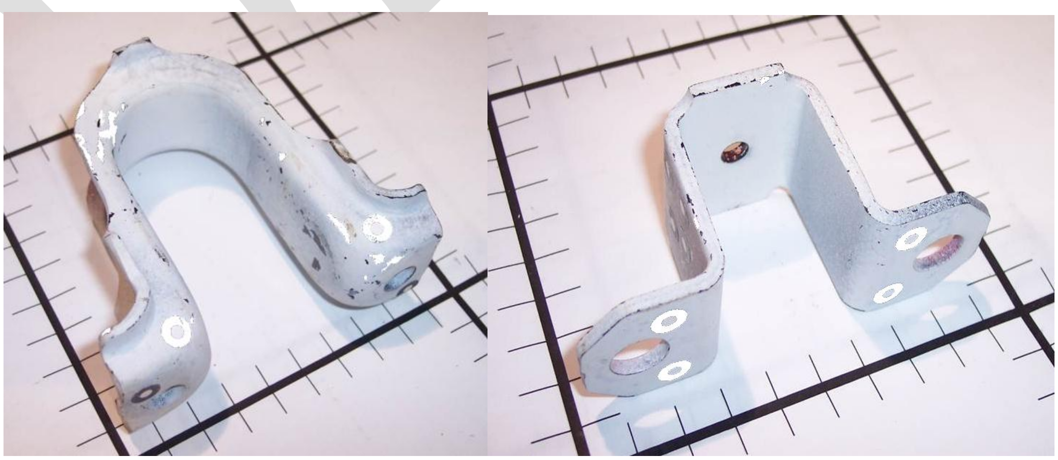


Image F.5-14: Stabilizer Bar Mounting Current Components

(Source: FEV Inc Photos)

F.5.1.3.3.3 Front Stabilizer Bar Mount Bushings

The baseline OEM Toyota Venza Front Stabilizer Bar Mount Bushings (**Image F.5-15**) are of standard design made of molded rubber. They have a mass of 0.091kg. Mounting bushings have had some changes in design, materials, or processing recently. Most changes are material differences and it is now common that nylons and urethanes are used by many OEMs and nearly all after-market manufacturers. While there is only a minimal accomplishment in mass savings, there is a cost savings and functional performance enhancement that is realized.

Image F.5-15: Stabilizer Bar Mount Bushing Current Components

(Source:http://www.wundercarparts.com/item.wws?sku=K90546&itempk=777630&mfr=MOOG&weight=3)

F.5.1.3.3.4 Front Stabilizer Link Sub-Assembly

The baseline OEM Toyota Venza Front Stabilizer Link Sub-Assembly is standard steel construction and has a mass of 0.400kg. This link assembly (**Image F.5-16**) has had little change in design, materials, or processing in recent years. Most are of steel construction components – link rod, link cup diameters, cup bottom plates, and ball studs. The other components include the rubber boots, retaining rings, fastening nuts, and grease. Little has been done to change the basic design of these units, but some manufacturers are beginning to use alternative materials.

Image F.5-16: Front Stabilizer Link Current Sub-Assembly

(Source:http://www.autopartswarehouse.com/details/QQToyotaQQVenzaQQMoogQQSway_Bar_LinkQQ2010QQMOK90344.html)

F.5.1.4 Summary of Mass-Reduction Concepts Considered

Brainstorming activities generated the ideas shown in **Table F.5-4** for the Front Suspension subsystem and their various components. The majority of these mass reduction ideas offer alternatives to traditional steel parts and assemblies. They include part modifications, material substitutions, processing and fabrication differences, and the use of alternative parts currently in production and used on other vehicles and applications. Our team approach to idea selection used judgment from extensive experience and research to prepare a list of the most promising ideas.

Component/ Assembly	Mass Reduction Idea	Estimated Impact	Risk & Trade-offs and/or Benefits
Front Suspension Subsystem			
Ball Joint Fasteners	Rivet ball joints & eliminate fasteners	10-20% wt save	Low Cost. In production - automotive.
Control Arm Mounts	Control Arm Mounts - Use through bolt & nut design and eliminate heavy anchor rods	10% wt save	Not feasible - no room for design chg.
Control Arm Mounting Shaft	Al forging	60-70% wt save	Higher Cost. Auto production C5 Corvette.
Control Arms	Pulltrude control arms	20-30% wt save	Not analyzed due to low ranking score
	Al (cast) control arms	30-40% wt save	Higher Cost. Auto production C5 Corvette.
	Make Bottom arms out of Titanium (sheet)	40-50% wt save	High Cost. Low production - auto racing.
	Replace from 2005 VW Passat (mass:8.66-7.54 & cost:0.98)	10-20% wt save	Low Cost. In production - VW Passat.
	Al (sheet) weld fab control arms	60-70% wt save	Higher Cost. Auto production BMW & GM.
	SS stamped & welded fab control arms	20-30% wt save	Higher Cost.
	Mg cast control arms	30-40% wt save	High Cost. Low production - auto.
	HSS stamped control arms	10-20% wt save	Higher Cost. Auto production.
	Combination. Replace from Passat & chg to Al Welded Fabrication.	70-80% wt save	Higher Cost. Auto production - VW.
Frt Stabilizer Link Asms	Make Frt Stabilzer Link Asm RH & LH out of Forged Al	60-70% wt save	Higher Cost. Low volume production - racing.
	Make Frt Stabilzer Link Asm RH & LH out of Titanium	40-50% wt save	High Cost. Low volume production - off-road.
	Replace from 2005 VW Passat (mass:0.86-0.69 & cost:0.96)	20-30% wt save	Low Cost. In production - VW Passat.
Knuckles	Replace from 2005 VW Passat (is Al) (mass:5.95-3.50 & cost:1.65)	30-40% wt save	High Cost. In production - VW Passat.
	Normalized Cast Aluminum	30-40% wt save	Higher Cost. Auto production - VW & GM.

Table F.5-4 continued on next page

Stabilizer Bar	Make stabilizer bars hollow	30-40% wt save	Higher Cost. Auto production BMW & GM.
	Make stabilizer bars out of Aluminum (solid)	40-50% wt save	High Cost. Low production.
	Make stabilizer bars out of Titanium (hollow)	60-70% wt save	High Cost. Low production - auto racing
	Glass/Epoxy Filament winding (solid)	70-80% wt save	Higher Cost. Auto production BMW & Audi
	Carbon/Epoxy Filament winding (solid)	60-70% wt save	High Cost. Low production - auto racing
	Replace from 2005 VW Passat (hollow) (mass:6.09-3.09 & cost:0.82)	40-50% wt save	Low Cost. In production - VW & BMW.
	Make stabilizer bars out of Aluminum (hollow or tubular)	50-60% wt save	Mod Cost. Development for low production.
	Combination. Replace from Passat & chg to Al (hollow).	60-70% wt save	Moderate Cost.
Stabilizer Bar Mounts	Make stabilizer bar mountings out of cast aluminum	30-40% wt save	High Cost. Low production - auto
	Make stabilizer bar mountings out of sheet stamped aluminum	30-40% wt save	High Cost. Low production - auto racing
	Make stabilizer bar mountings out of cast magnesium	40-50% wt save	High Cost. Low production - auto racing
	Overmold stabilizer bar mountings	5-10% wt save	In production - VW & BMW.
	Use hook & bolt design on stabilizer mounting bracket to eliminate (1) fastener	5-10% wt save	In production - GM.
	Combination. Cast Al & Overmolded.	40-50% wt save	Higher Cost. Low production European Auto.
Stabilizer Bar Mount Bushings	Make stabilizer bushings out of nylon	5-10% wt save	High Cost. Low production - auto racing
Strut Modules & Wheel Carriers	Lt wt suspension composite strut module with integrated wheel carrier	40-50% wt save	High Cost. Development
Front Suspension System	Optimize for downsized (non-hybrid) powertrain, smaller wheels-See Future Steel Vehicle: 25-33% reduction	20-30% wt save	Idea to all encompassing for scope of project - done instead with specific components

Table F.5-4 continued on next page

Balljoints	Replace from 2005 VW Passat (mass:1.97-1.32 & cost:0.93)	40-50% wt save	Low Cost. In production - VW Passat.
Dust Covers	Replace from 2005 VW Passat (mass:0.00-0.75 & cost:x)	Lotus idea - wt increase.	Not implemented due to wt increase. In production - VW Passat.
Mass Damper	Replace from 2005 VW Passat (mass:1.30-0.00 & cost:x)	100% wt save	In production - VW Passat.

Table F.5-4: Summary of Mass-Reduction Concepts Initially Considered for the Front Suspension Subsystem

F.5.1.5 Selection of Mass Reduction Ideas

Table F.5-5 shows a subset of the ideas generated from the brainstorming activities. These ideas were selected for detailed evaluation of both the mass savings achieved and the manufacturing cost. Several ideas suggest alternative materials as well as part substitutions from other vehicle designs, such as those currently being used on the VW Passat (as determined in the March 2010 Lotus Report).

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
04	**01**	**00**	**Front Suspension Subsystem**	
04	01	00	Ball Joint Fasteners	Rivet ball joints & eliminate fasteners
04	01	00	Control Arm Mounting Shaft	Al forging
04	01	00	Control Arms	Combination. Replace from Passat & chg to Al Welded Fabrication.
04	01	00	Frt Stabilizer Link Asms	Make Frt Stabilzer Link Asm RH & LH out of Forged Al
04	01	00	Knuckles	Normalized Cast Aluminum
04	01	00	Stabilizer Bar	Combination. Replace from Passat & chg to Al (hollow).
04	01	00	Stabilizer Bar Mounts	Make stabilizer bar mountings out of cast magnesium
04	01	00	Stabilizer Bar Mount Bushings	Make stabilizer bushings out of nylon
04	01	00	Strut Modules & Wheel Carriers	Lt wt suspension composite strut module with integrated wheel carrier
04	01	00	Balljoints	Replace from 2005 VW Passat (mass:1.97-1.32 & cost:0.93)

Table F.5-5: Mass-Reduction Ideas Selected for the Detailed Front Suspension Subsystem Analysis

The new mass-reduced front suspension system configuration (**Image F.5-17**) is still that of typical vehicle designs utilized by nearly all OEMs. The mass reductions achieved were done so by improving and replacing individual sub-assemblies and components. The overall design and function remains the same, thus eliminating drastic revisions that will cause significant vehicle interface redesigns.

Image F.5-17: Front Suspension Rotor Mass Reduced System Example

(Source http://www.vehicledynamicsinternational.com)

F.5.1.5.1 Front Control Arm Assembly

The solutions chosen for implementation on the final Front Control Arm Assembly (**Image F.5-18**) are a combination of multiple ideas across several different sub-assemblies and components. The total mass of this new sub-assembly is 4.33 kg. These ideas included modifications to design, material utilized, and processing methods required to the following sub-assemblies and components: Ball Joint Assembly, Ball Joint Fasteners, and a Control Arm Sub-Assembly. The Arm Sub-Assembly is made up of a Control Arm, Rubber Isolator (with a steel ID insert), and the Lower Bushing & Shaft.

Image F.5-18: Front Control Arm Mass Reduced Assembly Example

(Source: http://www.amazon.com/Dorman-521-026-Front-Lower-Control/dp/B0049E2L2I)

F.5.1.5.1.1 *Front Ball Joint Sub-Assembly*

The solution used for the Ball Joint Assembly (**Image F.5-19**) is the sub-assembly substitution from the VW Passat application. No other viable high-volume manufactured alternate designs were found for substitution. Due to loading and strength performance requirements, no cost-effective material substitutions were identified for replacement. Therefore, it was determined that a sizing and normalization activity would be applied based on GVW. The overall sub-assembly has a 0.60kg replacement mass.

Image F.5-19: Front Ball Joint Mass Reduced Sub-Assembly

*(Source:*http*://www.1aauto.com/1A/BallJoint/Toyota)*

F.5.1.5.1.2 Front Ball Joint Fasteners

The answer implemented for Ball Joint Fasteners (**Image F.5-20**) was to eliminate the bolts used in the standard attachment configuration to the Control Arm Sub-Assembly. Rivets replaced these bolts for simpler and easier assembling process time as well as a small weight savings. These new rivets have a new net mass of 0.102kg.

Image F.5-20: Front Ball Joint Sub-Assembly Mass Reduced Fastener Example

(Source: http://www.ecklerscorvette.com/corvette-ball-joint-rivet-set-lower.html)

F.5.1.5.1.3 Front Control Arm Sub-Assembly

The new Front Control Arm Sub-Assembly (**Image F.5-21**) is still a multi-piece assembly; however, now with the major components being made from forged aluminum together. This design utilizing Al for the control arm is now very common in the industry and used by nearly all major OEMs, in particular GM, BMW, Mercedes, Toyota, Honda, and Audi. This component has a total mass of 3.73 kg. The rest of the sub-assembly consists of two hard-rubber isolators (one with a steel ID insert) and the Control Arm Mounting Shaft with bushing.

Image F.5-21: Front Control Arm Mass Reduced Sub-Assembly Example

(Source: http://www.amazon.com/Dorman-521-026-Front-Lower-Control/dp/B0049E2L2I)

F.5.1.5.1.2.1 Front Control Arm

The solution for Front Control Arm Sub-Assembly (**Image F.5-22**) is still a single piece forged aluminum component. Due to the replacement of steel with Al, an additional material volume of 30-40% was made. This design, utilizing Al for the control arm, is now very common in the industry and used by nearly all major OEMs, in particular GM, BMW, Mercedes, Toyota, Honda, and Audi. This cast component has a total mass of 2.74kg.

Traditionally control arms have been made from either welded steel assemblies or from being cast out of iron. This allowed for adequate strength and component life without using more expensive processes or materials. Now with advances in materials and processing methods, other choices are available that have become more cost effective and are often being utilized in aftermarket and by OEMs. Among some of these alternate mediums are Al, Ti, Steel and Mg. Forming methods now include sand casting, semi-permanent metal molding, die casting, machining from billet, and welded fabrications.

Image F.5-22: Front Control Arm Mass Reduced Component Example

(Source: http://www.amazon.com/Dorman-521-026-Front-Lower-Control/dp/B0049E2L2I)

The weight savings achieved is quite substantial and assists with reducing vehicle requirements for suspension loads, handling, ride quality, engine hp requirements, etc. Consideration must still be given to adequate validation testing to fit this solution to particular vehicle requirements.

F.5.1.5.1.2.2 Front Control Arm Mounting Shaft

The change utilized on the Front Control Arm Mounting Shaft (**Image F.5-23**) is to now use forged Al instead of a steel component. Due to the replacement of steel with Al, an additional material volume of 20-30% was made. Mounting shafts have normally been made from various grades of steel for adequate strength. Now, with advances in materials and processing methods, other choices are available and being utilized in aftermarket and high-performance applications as well as in some OEM vehicle markets. Among some of these alternate are Al and Ti. Forming and fabrication methods include forging and billet machining. This new component had a mass of 0.18kg.

Image F.5-23: Front Control Arm Mounting Shaft Mass Reduced Example

(Source: http://www.track-star.net/store/corvette-c6-z06-suspension/pfadt-racing-spherical-bushing-set-2006-2011-c6-z06)

F.5.1.5.2 Front Steering Knuckle

The new Front Steering Knuckle (**Image F.5-24**) is a component substitution from the VW Passat application. In addition to this the material will be changed to Al as well. Due to the replacement of steel with Al, an additional material volume of 20% was made. Al alloys are now a common choice and are used in high volume applications by many OEMs, including GM, BMW, Audi, Honda, Toyota, Ford, and Chrysler. Due to loading and strength performance requirements, proper validation testing would be required dependent on the application. Therefore, it was determined that a sizing and normalization activity would be applied based on GVW. The overall sub-assembly has a replacement mass of 2.71kg.

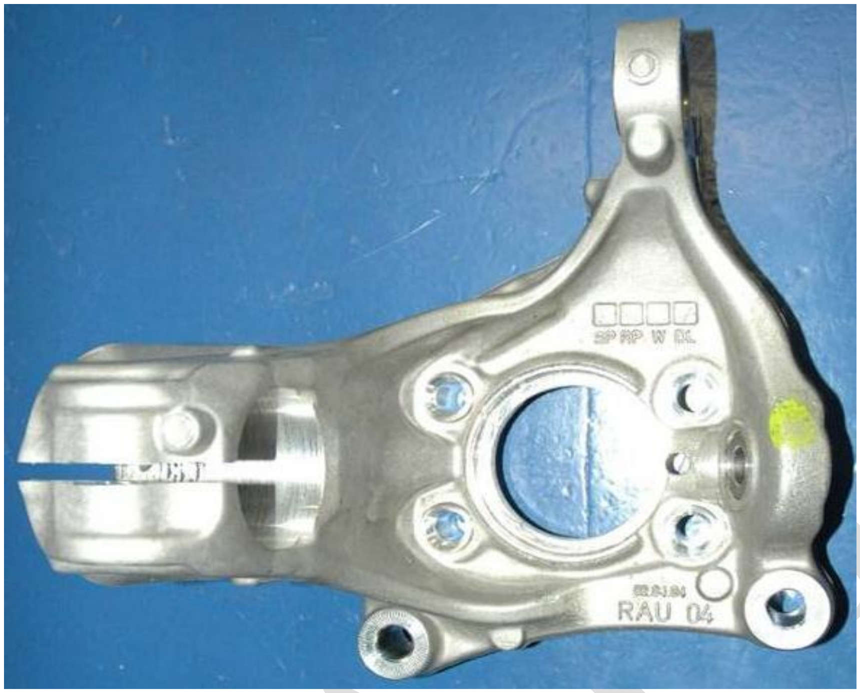


Image F.5-24: Front Steering Knuckle Mass Reduced Component

(Source: Lotus – 2010 March EPA Report)

F.5.1.5.3 Front Stabilizer Bar System

The proposed Front Stabilizer Bar system (**Image F.5-25**) is of standard configuration with a different design and construction. Rather than solid steel forged bar composition with molded rubber mount bushings and steel stamped brackets, it is now a hollow Al bar with cast Mg mounting brackets and nylon bushings. Together, this new system has reduced mass to a total of 3.297kg.

Image F.5-25: Stabilizer Bar System Mass Reduced System Example

(Source: http://www.tundraheadquarters.com/blog/toyota-tundra-trd-parts-accessories)

F.5.1.5.3.1 *Front Stabilizer Bar*

The mass reduced Front Stabilizer Bar (**Image F.5-26**) is now of hollow design with Al material. Additional material volume of 40-45% was added for increasing the bar strength relative to steel as well as increasing the bar diameter by 50% to allow an adequate cross-section relative to being hollow versus solid. Hollow stabilizer bars are becoming common on many European vehicles and beginning to being utilized in North America. This new bar now has a mass of 2.16kg. As with other suspension components, proper validation must be performed based on the vehicle performance requirements.

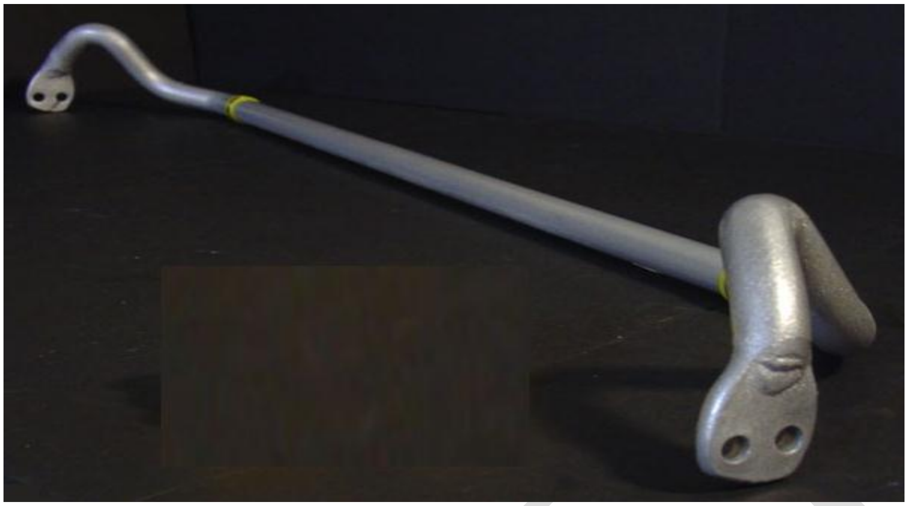


Image F.5-26: Stabilizer Bar Mass Reduced Component Example

(Source: http://www.i-club.com/forums/suspension-brakes-handling-wheels-tires-162)

F.5.1.5.3.2 Front Stabilizer Bar Mountings

The new Front Stabilizer Bar Mountings (**Image F.5-27**) are now mad of die cast Mg brackets. Due to the replacement of steel with Al, an additional material volume of 50-60% was made. They have a mass of 0.335kg. These brackets have progressed with some changes in design, materials, and processing. These designs include alternate materials for Al, Mg, HSS, and fiber plastics. Among the process variations for manufacturing include casting, molding, and forging.

Image F.5-27: Stabilizer Bar Mounting Mass Reduced Component Example

(Source: http://www.tickperformance.com/products/UMI-Heavy-Duty-Billet-Aluminum-Rear-Sway-Bar-Mounts.html)

F.5.1.5.3.3 Front Stabilizer Bar Mount Bushings

The redesigned Front Stabilizer Bar Mount Bushings (**Image F.5-28**) are of standard design but utilize an alternate material of nylon versus rubber. They have a mass of 0.086kg. Many aftermarket as well as OEM manufacturers now utilize this new material choice for many vehicle applications. This is due to improved handling performance, increase component life and even a small amount of mass reduction.

Image F.5-28: Stabilizer Bar Mount Bushing Mass Reduced Component Example

(Source: http://www.suspensionconnection.com/cgi-bin/suscon/18-1116.html)

F.5.1.5.3.4 Front Stabilizer Link Sub-Assembly

The new Front Stabilizer Link Sub-Assemblies (**Image F.5-29**) are now redesigned using cast Al construction for a 0.298kg mass. Due to the replacement of steel with Al, an additional material volume of 60-70% was made. This link assembly eliminates several components and a great deal of assembly and machining for a simplified design. Components combined include: link rod, link cup diameters, and cup bottom plates.

Image F.5-29: Front Stabilizer Link Mass Reduced Sub-Assembly

(Source: http://www.mjmautohaus.com/catalog/VW)

F.5.1.6 Calculated Mass-Reduction & Cost Impact Results

Table F.5-6 shows the results of the mass reduction ideas that were evaluated for the Front Suspension subsystem. These ideas resulted in an overall subsystem mass savings of 14.182kg and a cost increase differential of $5.74.

System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
				Net Value of Mass Reduction Idea					
04	**01**	**00**	**Front Suspension**						
04	01	01	Front Road Spring		0.000	$0.00	$0.00	0.00%	0.00%
04	01	02	Front Suspension Links/Arms Upper & Lower	A	1.934	-$0.65	-$0.34	39.31%	0.11%
04	01	03	Front Suspension Knuckle Assembly	A	6.759	$6.78	$1.00	62.70%	0.40%
04	01	04	Front Stabilizer Bar Assembly	C	5.489	-$11.87	-$2.16	65.93%	0.32%
				A	**14.182** (Decrease)	**-$5.74** (Increase)	**-$0.40** (Increase)	**55.40%**	**0.83%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.5-6: Mass-Reduction and Cost Impact for the Front Suspension Subsystem

F.5.2 Rear Suspension Subsystem

F.5.2.1 Subsystem Content Overview

The **Image F.5-30** pictorial diagram represents the major suspension components in the Rear Suspension subsystem and their relative location and position relevant to one another as located on the vehicle rear end.

Image F.5-30: Rear Suspension Subsystem Relative Location Diagram

(Source: Lotus – 2010 March EPA Report)

As seen in **Image F.5-31**, the Rear Suspension subsystem consists of the major components of the Rear Arms – Upper and Lower, Rod Arms, Rear Carrier Assemblies, Rear Stabilizer Bar, Bushings and Mounts, and the miscellaneous attaching components.

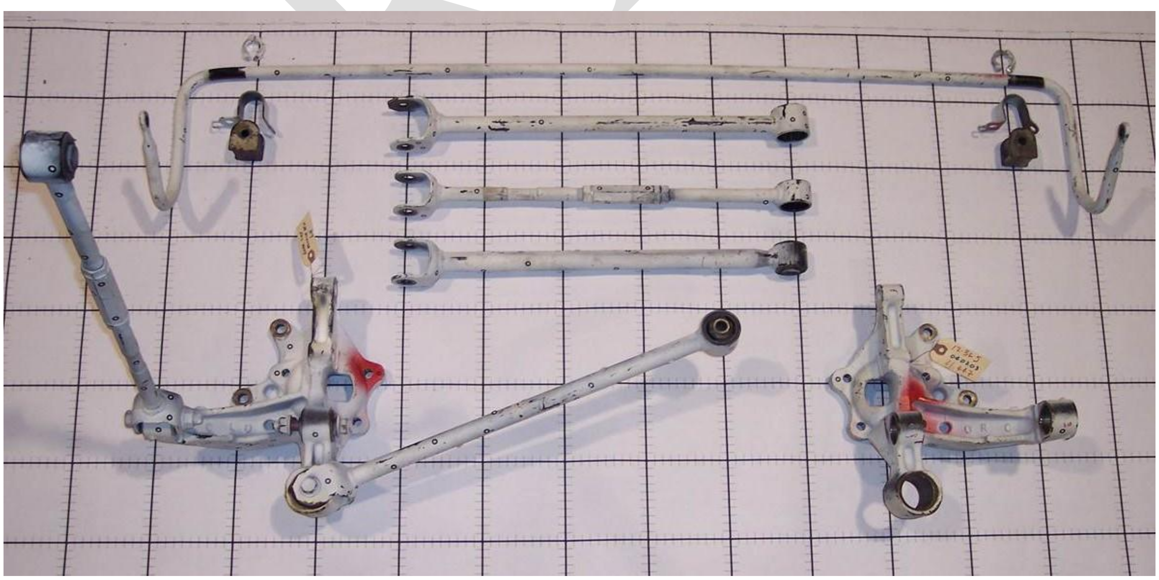


Image F.5-31: Rear Rotor / Drum and Shield Subsystem Current Major Components

(Source: FEV, Inc Photo)

As seen in **Table F.5-7**, the three sub-subsystems that make up the Rear Suspension subsystem are: the Rear Suspension Links/Arms Upper and Lower; Rear Suspension Knuckle Assembly; and Rear Stabilizer (Anti-Roll) Bar Assembly. The most significant contributor to the mass of the Rear Suspension subsystem is the Knuckle Assembly (approx 47.8%), followed closely by Links/Arms Upper and Lower (approx 35.7%) and then the Stabilizer Bar (approx 16.5%).

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
04	**02**	**00**	**Rear Suspension Subsystem**	**--**
04	02	02	Rear Suspension Links/Arms Upper and Lower	8.479
04	02	03	Rear Suspension Knuckle Assembly	11.341
04	02	05	Rear Stabilizer (Anti-Roll) Bar Asm	3.929
			Total Subsystem Mass =	**23.749**
			Total System Mass =	**266.120**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**8.92%**
			System Mass Contribution Relative to Vehicle =	**1.39%**

Table F.5-7: Mass Breakdown by Sub-subsystem for the Rear Suspension Subsystem

F.5.2.2 Toyota Venza Baseline Subsystem Technology

As with the front suspension, the Toyota Venza's rear suspension system follows typical industry standards. See **Section F.4.1.2** for additional information.

The Toyota Venza's Rear Suspension subsystem, **Image F.5-32**, follows typical industry standards for design and performance. This includes a focus on strength and durability with least material cost. Steel is the material of choice with most components, with welding and assembly being done on multiple components. Toyota also focuses on providing similar if not identical components across all platform variants to take advantage of economies of scale in minimizing production costs. This approach, however, is not optimal for design efficiency based on applications and does not allow for maximum weight-versus-performance efficiency.

The Rear Suspension subsystem contains a variety of sub-assemblies and components with a variety of noteworthy characteristics: The Rear Arm #1 Assembly (**Image F.5-33**) is a steel welded fabrication with two assembled rubber isolators, as is the Rear Arm #2 Assembly (**Image F.5-34**). The Rear Rod Assembly (**Image F.5-35**) is made from various steel pieces are welded together and assembled with two rubber isolators. The Bearing Carrier Knuckle (**Image F.5-36**) is cast iron and precision machined. The Stabilizer Bar system (**Image F.5-37**) contains the Stabilizer Bar, Bar Mounts, Mount Bushings and Link Assemblies. The Stabilizer Bar (**Image F.5-38**) is a solid steel bar bent into shape and pinched flanges with punched holes for mounting points. The Stabilizer Bar Mounts (**Image F.5-39**) are standard construction with stamped steel brackets. The Stabilizer Bar Mount Bushings (**Image F.5-40**) are molded rubber isolators. The Stabilizer Link Assemblies (**Image F.5-41**) are standard steel design. The steel components include the link rod, link cup diameters, cup bottom plates, and ball studs.

Image F.5-32: Rear Suspension Subsystem Current Assembly Example

(Source http://www.bestcarsguide.com/what-is-rear-end-suspension)

F.5.2.3 Mass-Reduction Industry Trends

Automakers are deploying a wide variety of low-mass materials in new vehicle models regarding all subsystems, including suspensions. Implementations have been documented showing reduced component mass for the same functionality using alternative materials such as high-strength steel, aluminum, magnesium, plastics, and polymer composites. Design approaches for the active components of suspensions are primarily focused on higher strength steels with lower part volume and high-strength aluminum. Also, some notable ventures are into limited applications of magnesium, long fiber polymer composites, and in rare cases, carbon fiber and titanium. The progress has been slow over the years because of the typically higher resultant costs relative to steel. However, recent studies have shown cost comparisons near parity with well designed parts using alternate materials, primarily high strength steel.

Another significant consideration should be the secondary mass-reduction effects - weight reductions for all other vehicle subsystems. Less total vehicle mass reduces the suspension loading and provides opportunities to further reduce suspension mass.

F.5.2.3.1 Rear Arm Assembly #1

The baseline OEM Toyota Venza Rear Arm Assembly #1 (**Image F.5-33**) is a multi-piece assembly with the major portions being made from steel tubing welded together. The total mass of this assembly is 0.826kg. This assembly also consists of two rubber isolators with metal ID sleeves. No other viable high volume manufactured alternate designs were found to substitute. Due to loading and strength performance requirements, no cost-effective material substitutions were identified. Therefore, it was determined that a sizing and normalization activity would need to be performed based on GVW to see if any opportunities exist.

Image F.5-33: Rear Arm #1 Current Assembly

(Source: http://www.streetperformance.com/auto/2000-toyota-camry-ce/trailing-arm)

F.5.2.3.2 Rear Arm Assembly #2

The baseline OEM Toyota Venza Rear Arm Assembly #2 (**Image F.5-34**) is a multi-piece assembly, with the major portions being made from steel tubing welded together. The overall assembly mass is 1.130kg.

Image F.5-34: Rear Arm #2 Current Assembly Example

(Source: http://www.streetperformance.com/auto/2000-toyota-camry-ce/trailing-arm)

F.5.2.3.3 Rear Rod Assembly

The baseline OEM Toyota Venza Front Control Arm Sub-Assembly (**Image F.5-35**) is a multi-piece assembly with major components made from steel tubing and welded together. It contains an installed threaded insert for adjustability. This unit has a total mass of 1.222kg. The rest of the sub-assembly is two hard-rubber isolators (one with a steel ID insert) and the Control Arm Mounting Shaft with bushing.

Image F.5-35: Rear Rod Current Assembly Example

(Source: http://www.ebay.com/itm/REAR-SUSPENSION-LEFT-LATERAL-LINK-TOYOTA)

F.5.2.3.4 Rear Bearing Carrier Knuckle

The baseline OEM Toyota Venza Rear Bearing Carrier Knuckle (**Image F.5-36**) is a single piece cast iron knuckle of a standard design configuration with a mass of 5.282kg. Knuckles are historically made from cast iron for strength and function. Over the last several years, advances in alternative materials and processing methods have allowed new choices to be available. Rather than cast iron only, Al alloys are now a common choice and are used in high volume applications by many OEMs. This allows not only similar functional performance but substantial weight savings along with minimal, if any, cost increase.

Image F.5-36: Rear Bearing Carrier Knuckle Current Component

(Source: Lotus – 2010 March EPA Report)

F.5.2.3.5 Rear Stabilizer Bar System

The baseline OEM Toyota Venza Rear Stabilizer Bar system (**Image F.5-37**) is standard design and construction composed of solid steel forged bar, molded rubber-mount bushings, steel-stamped brackets, and miscellaneous fasteners. Together, this system has an overall mass of approximately 3.929kg. The stabilizer bar system has undergone some changes relative to design, materials, and processing recently. Steel bars are now being made with a hollow design as well as with alternative materials. Mounting Bushings are now made with various plastics in order to increase rigidity and life. Brackets and mountings are now being made from new casting, forging, and molding processes as well as utilizing new materials such as Al, Ti, Mg and fiber-reinforced plastics.

Image F.5-37: Stabilizer Bar System Current Component Example

(Source: http://www.hotchkis.net/6472_gm_abody_extreme_sway_bar_set.html)

F.5.2.3.5.1 Rear Stabilizer Bar

The baseline OEM Toyota Venza Rear Stabilizer Bar (**Image F.5-38**) is standard construction with solid steel bar bent into shape and pinched flanges with punched holes for mounting points. This bar has a mass of 2.880kg. The stabilizer bar has undergone redesign in recent years: Design, materials, and processing changes now allow for hollow designs as well as using alternative materials such as Al, Ti, HSS, and fiber-reinforced composites. While these materials can effect performance and handling under various conditions, significant mass savings is also achieved.

Image F.5-38: Stabilizer Bar Current Component Example

(Source: http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.2.3.5.2 Rear Stabilizer Bar Mountings

The baseline OEM Toyota Venza Rear Stabilizer Bar Mountings (**Image F.5-39**) are of standard stamped steel construction and have a mass of 0.127kg. These brackets have had some recent changes in design, materials and processing, including alternate configurations with materials such as Al, Mg, HSS, and plastics. Process variations for manufacturing include casting, molding, and forging.

Image F.5-39: Stabilizer Bar Mounting Current Components

(Source: FEV Inc Photo)

F.5.2.3.5.3 *Rear Stabilizer Bar Mount Bushings*

The baseline OEM Toyota Venza Rear Stabilizer Bar Mount Bushings (**Image F.5-40**) are of standard design made of molded rubber. They have a mass of 0.073kg. Mounting bushings have had some changes in design, materials or processing recently. Most changes are material differences and it is now common that nylons and urethanes are used by many OEMs and nearly all after-market manufacturers. While there is only a minimal accomplishment in mass savings, there is a cost savings and functional performance enhancement that is realized.

Image F.5-40: Stabilizer Bar Mount Bushing Current Components

(Source:http://www.wundercarparts.com/item.wws?sku=K90546&itempk=777630&mfr=MOOG&weight=3)

F.5.2.3.5.4 *Rear Stabilizer Link Sub-Assembly*

The baseline OEM Toyota Venza Rear Stabilizer Link Sub-Assembly is standard steel construction and has a mass of 0.2974kg. This link assembly (**Image F.5-41**) has had little change in design, materials or processing in recent years. Most are of steel construction components – link rod, link cup diameters, cup bottom plates, and ball studs. The other components include the rubber boots, retaining rings, fastening nuts, and grease. Little has been done to change the basic design of these units, but some manufacturers are beginning to use alternative materials.

Image F.5-41: Rear Stabilizer Link Current Sub-Assembly

(Source:http://www.autopartswarehouse.com/details/QQToyotaQQVenzaQQMoogQQSway_Bar_LinkQQ2010QQMOK90344.html)

F.5.2.4 Summary of Mass-Reduction Concepts Considered

The brainstorming activities generated the ideas shown in **Table F.5-8** for the Rear Suspension subsystem and its various components. The majority of these mass reduction ideas offer alternatives to steel with material substitutions, part modifications, processing and fabrication differences, and the use of alternative parts currently in production and used on other vehicles and applications.

Component/ Assembly	Mass Reduction Idea	Estimated Impact	Risk & Trade-offs and/or Benefits
Rear Suspension Subsystem			
Rear Arm Asm #1	Make LH Rear Arm Asm out of Forged Aluminum Bars	40-50% wt save	Higher Cost. In Production - Auto.
	Make LH Rear Arm Asm out of Steel Tube	30-40% wt save	In Production - Most Auto Makers
	Make LH Rear Arm Asm out of Titanium (Hollow)	20-30% wt save	Low production - auto racing
	Replace from 2005 Alfa Romeo 147 (mass:3.128-3.119 & cost:0.95)	5-10% wt save	In production - Alfa Romeo.
Rear Arm Asm #2	Make RH Rear Arm Asm out of Forged Aluminum Bars	40-50% wt save	Higher Cost. In Production - Auto.
	Make RH Rear Arm Asm out of Steel Tube	30-40% wt save	In Production - Most Auto Makers
	Make RH Rear Arm Asm out of Titanium (Hollow)	20-30% wt save	Low production - auto racing
	Replace from 2005 Alfa Romeo 147 (mass:3.119-2.856 & cost:0.99)	5-10% wt save	In production - Alfa Romeo.
Rear Rod Asm	Make Rear Rod Asm out of Forged Aluminum Bars	40-50% wt save	Higher Cost. In Production - Auto.
	Make Rear Rod Asm out of Steel Tube	30-40% wt save	In Production - Most Auto Makers
	Make Rear Rod Asm out of Titanium (Hollow)	20-30% wt save	Low production - auto racing
	Replace from 2005 Alfa Romeo 147 (mass:2.366-2.061 & cost:0.99)	5-10% wt save	In production - Alfa Romeo.
Rear Suspension System	Lightweight elastomeric rear suspension system DCX ESX3	20-30% wt save	In production - GM C5 Corvette. Not implemented due to complexity of system validation & scope of work req'd.
Frt Stabilizer Link Asms	Make Frt Stabilzer Link Asm RH & LH out of Forged Al	60-70% wt save	Higher Cost. Low volume production - racing.
	Make Frt Stabilizer Link Asm RH & LH out of Titanium	40-50% wt save	High Cost. Low volume production - off-road.
	Replace from 2005 Alfa Romeo 147 (mass:0.620-0.586 & cost:1.00)	20-30% wt save	Low Cost. In production - Alfa Romeo.
Knuckles	Replace from 2005 Alfa Romeo 147 & Al (mass:11.160-3.820 & cost:1.00)	30-40% wt save	High Cost. In production - Alfa Romeo.
	Normalized Cast Aluminum	30-40% wt save	Higher Cost. Auto production - VW & GM.

Table F.5-8 continued on next page

Stabilizer Bar	Make stabilizer bars hollow	30-40% wt save	Higher Cost. Auto production BMW & GM.
	Make stabilizer bars out of Aluminum (solid)	40-50% wt save	High Cost. Low production.
	Make stabilizer bars out of Titanium (hollow)	60-70% wt save	High Cost. Low production - auto racing
	Replace from 2005 Alfa Romeo 147 (mass:2.866-2.344 & cost:1.00)	40-50% wt save	Low Cost. In production - Alfa Romeo, VW & BMW.
	Make stabilizer bars out of Aluminum (hollow or tubular)	50-60% wt save	Mod Cost. Development for low production.
Stabilizer Bar Mounts	Make stabilizer bar mountings out of cast aluminum	30-40% wt save	High Cost. Low production - auto
	Make stabilizer bar mountings out of sheet stamped aluminum	30-40% wt save	High Cost. Low production - auto racing
	Make stabilizer bar mountings out of cast magnesium	40-50% wt save	High Cost. Low production - auto racing
	Overmold stabilizer bar mountings	5-10% wt save	In production - VW & BMW.
	Use hook & bolt design on stabilizer mounting bracket to eliminate (1) fastener	5-10% wt save	In production - GM.
	Combination. Cast Al & Overmolded.	40-50% wt save	Higher Cost. Low production European Auto.
Stabilizer Bar Mount Bushings	Make stabilizer bushings out of nylon	5-10% wt save	High Cost. Low production - auto racing
Strut Modules & Wheel Carriers	Lt wt suspension composite strut module with integrated wheel carrier	40-50% wt save	High Cost. Development
Rear Suspension System	Replace dual coil spring system w/ traverse leaf spring (and anti-roll bar, mounts & links and two control arms)	30-40% wt save	Not analyzed - out of scope of study due to magnitude of design changes & validation rqd.
Mass Damper	Replace from 2005 Alfa Romeo 147 (mass:1.263-0.000 & cost:x)	100% wt save	In production - Alfa Romeo.

Table F.5-8: Summary of Mass-Reduction Concepts Initially Considered for the Rear Suspension Subsystem

F.5.2.5 Selection of Mass Reduction Ideas

Table F.5-9 shows a subset of the ideas generated from the brainstorming activities. These ideas were selected for detailed evaluation of both the mass savings achieved and the manufacturing cost. Also included are part substitutions from other vehicle designs such as those currently in use in the Alfa Romeo 147 (as determined in the March 2010 Lotus Report).

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
04	**02**	**00**	**Rear Suspension Subsystem**	
04	02	00	Rear Arm Asm #1	Replace from 2005 Alfa Romeo 147 (mass:3.128-3.119 & cost:0.95)
04	02	00	Rear Arm Asm #2	Replace from 2005 Alfa Romeo 147 (mass:3.119-2.856 & cost:0.99)
04	02	00	Rear Rod Asm	Replace from 2005 Alfa Romeo 147 (mass:2.366-2.061 & cost:0.99)
04	02	00	Frt Stabilizer Link Asms	Make Frt Stabilzer Link Asm RH & LH out of Forged Al
04	02	00	Knuckles	Replace from 2005 Alfa Romeo 147 & Al (mass:11.160-3.820 & cost:1.00)
04	02	00	Stabilizer Bar	Make stabilizer bars out of Aluminum (solid)
04	02	00	Stabilizer Bar Mounts	Combination. Cast Al & Overmolded.
04	02	00	Stabilizer Bar Mount Bushings	Make stabilizer bushings out of nylon

Table F.5-9: Mass-Reduction Ideas Selected for the Detailed Rear Suspension Subsystem Analysis

The new mass-reduced Rear Suspension system (**Image F.5-42**) configuration is still that of typical vehicle designs utilized by nearly all OEMs. The mass reductions achieved were done so by improving and replacing individual sub-assemblies and components. The overall design and function remains the same thus eliminating drastic revisions causing significant vehicle interface redesigns.

Image F.5-42: Rear Suspension Rotor Mass Reduced System Example

(Source http://www.wired.com/images_blogs/autopia/2010/09/lamborghini-miura-sv-05.jpg)

F.5.2.5.1 Rear Arm Assembly #1

The solution chosen for implementation on the final Rear Arm #1 Assembly (**Image F.5-43**) was the normalization of size from an Alfa Romeo 147 arm assembly. This allowed for both a mass and cost reduction. The total mass of this replacement assembly is 0.764kg.

Image F.5-43: Rear Arm #1 Mass Reduced Assembly

(Source: http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.2.5.2 Rear Arm Assembly #2

The solution chosen to be implemented on the final Rear Arm #2 Assembly (**Image F.5-44**) was the normalization of size from an Alfa Romeo 147 arm assembly. This allowed for both mass and cost reduction. The total mass of this replacement assembly is 1.574kg.

Image F.5-44: Rear Arm #2 Mass Reduced Assembly

(Source: http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.2.5.3 Rear Rod Assembly

The solution chosen to be implemented on the final Rear Rod Assembly (**Image F.5-44**) was the normalization of size from an Alfa Romeo 147 arm assembly. This allowed for both a mass and cost reduction. The total mass of this replacement assembly is 1.518kg.

Image F.5-45: Rear Rod Mass Reduced Assembly

(Source: http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.2.5.4 Rear Bearing Carrier Knuckle

The new Rear Bearing Carrier Knuckle (**Image F.5-48**) is combination of a component substitution from the Alfa Romeo 147 Knuckle (**Image F.5-46**) application and utilizing an Al knuckle (**Image F.5-47**). Al alloys are now a common choice and are used in high-volume applications by many OEMs, including GM, BMW, Audi, Honda, Toyota, Ford, and Chrysler. The replacement of steel with Al, an additional material volume of 10-20% was made. Due to loading and strength performance requirements, proper validation testing would be required dependent on the application. Therefore, it was determined that a sizing and normalization activity would be applied based on GVW. The overall sub-assembly has a replacement mass of 2.620kg.

Image F.5-46: Rear Carrier Alfa Romeo

(Source: Lotus – 2010 March EPA Report)

Image F.5-47: Rear Bearing Al Carrier

(Source: http://forums.vwvortex.com)

Image F.5-48: Rear Bearing Carrier Knuckle Mass Reduced Component Example

(Source: http://www.factoryfive.com/table/ffrkits/GTM/donorpartslist.html)

F.5.2.5.5 Rear Stabilizer Bar System

The proposed Rear Stabilizer Bar system (**Image F.5-49**) is of standard configuration with a different design and construction. Rather than solid steel forged bar composition with molded rubber mount bushings and steel stamped brackets, it is now a hollow Al bar with cast Mg mounting brackets and nylon bushings. Together, this new system has reduced mass to a total of 2.205kg.

Image F.5-49: Stabilizer Bar System Mass Reduced System Example

(Source: http://www.tundraheadquarters.com/blog/toyota-tundra-trd-parts-accessories)

F.5.2.5.5.1 *Rear Stabilizer Bar*

The mass-reduced Rear Stabilizer Bar (**Image F.5-50**) is now made with an Al material. Additional material volume of 35-45% was added for increasing the bar strength relative to steel. This new bar now has a mass of 1.410kg. As with other suspension components, proper validation must be performed based on vehicle performance requirements.

Image F.5-50: Stabilizer Bar Mass Reduced Component Example

(Source: http://www.i-club.com/forums/suspension-brakes-handling-wheels-tires-162/racecomps-financial-crisis-buy-parts-help-economy-sale-192991/)

F.5.2.5.5.2 *Rear Stabilizer Bar Mountings*

The new Rear Stabilizer Bar Mountings (**Image F.5-51**) are now made of die cast Mg brackets. Due to the replacement of steel with Al, an additional material volume of 150-160% was made. They have a mass of 0.112kg. These brackets have had some progress with changes in design, materials, and processing. These designs include alternate materials for Al, Mg, HSS, and fiber plastics. Among the process variations for manufacturing include casting, molding, and forging.

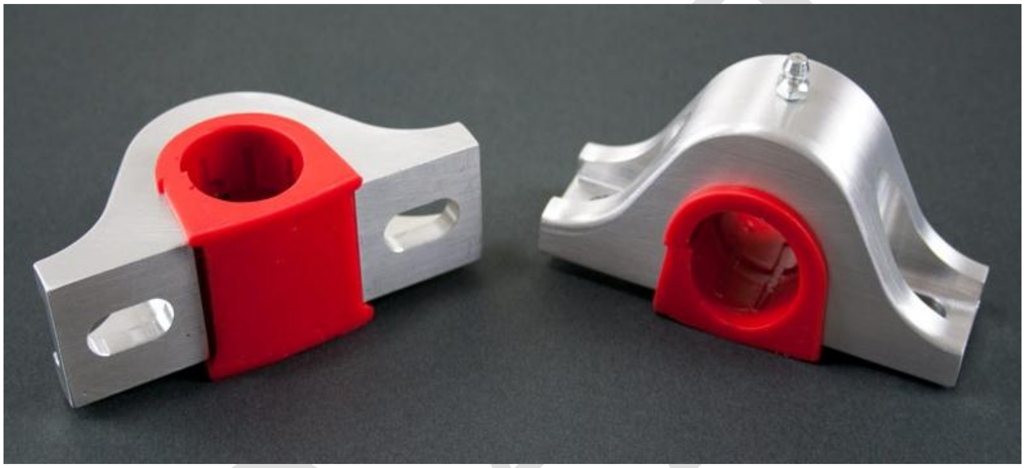


Image F.5-51: Stabilizer Bar Mounting Mass Reduced Component Example

(Source: http://www.tickperformance.com/products/UMI-Heavy-Duty-Billet-Aluminum-Rear-Sway-Bar-Mounts.html)

F.5.2.5.5.3 *Rear Stabilizer Bar Mount Bushings*

The redesigned Rear Stabilizer Bar Mount Bushings (**Image F.5-52**) are of standard design but utilize an alternate material of nylon versus rubber. They have a mass of 0.070kg. Many aftermarket as well as OEM manufacturers now utilize this new material choice for several vehicle applications. This is due to improved handling performance, increase component life, and even a small amount of mass reduction.

Image F.5-52: Stabilizer Bar Mount Bushing Mass Reduced Component Example

(Source: http://www.suspensionconnection.com/cgi-bin/suscon/18-1116.html)

F.5.2.5.5.4 *Rear Stabilizer Link Sub-Assembly*

The new Rear Stabilizer Link Sub-Assemblies (**Image F.5-53**) are now redesigned using cast Al construction for a mass of 0.262kg. Due to the replacement of steel with Al, an additional material volume of 40-50% was made. This link assembly eliminates several components and a great deal of assembly and machining for a simplified design. Components combined include: link rod, link cup diameters, and cup bottom plates.

Image F.5-53: Rear Stabilizer Link Mass Reduced Sub-Assembly

(Source: http://www.mjmautohaus.com/catalog/VW)

F.5.2.6 Calculated Mass-Reduction & Cost Impact Results

Table F.5-10 shows the results of the mass reduction ideas evaluated for the Rear Suspension subsystem, which resulted in a subsystem overall mass savings of 8.32kg and a cost savings differential of $-4.91.

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
04	**02**	**00**	**Rear Suspension**						
04	02	01	Rear Road Spring		0.000	$0.00	$0.00	0.00%	0.00%
04	02	02	Rear Suspension Links/Arms Upper & Lower	A	0.995	$2.31	$2.32	6.03%	0.06%
04	02	03	Rear Suspension Knuckle Assembly	A	5.765	$9.46	$1.64	62.53%	0.34%
04	02	04	Rear Stabilizer Bar Assembly	X	1.560	-$6.86	-$4.39	57.55%	0.09%
04	02	05	Heavy Truck Lifting Mechanism		0.000	$0.00	$0.00	0.00%	0.00%
				A	**8.320** (Decrease)	**$4.91** (Decrease)	**$0.59** (Decrease)	**41.53%**	**0.49%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.5-10: Mass-Reduction and Cost Impact for the Rear Suspension Subsystem

F.5.3 Shock Absorber Subsystem

F.5.3.1 Subsystem Content Overview

Image F.5-54 represents the major strut assembly components in the Shock Absorber subsystem. There are separate assemblies for the front and the rear of the vehicle. Each group has some small differences in design but share the same basic component layouts. These include the Shock tower Sub-assemblies, Upper and Lower Strut Mounts, Coil Springs, Upper and Lower Spring Seats, Upper and Lower Spring Isolators, and associated hardware and fasteners.

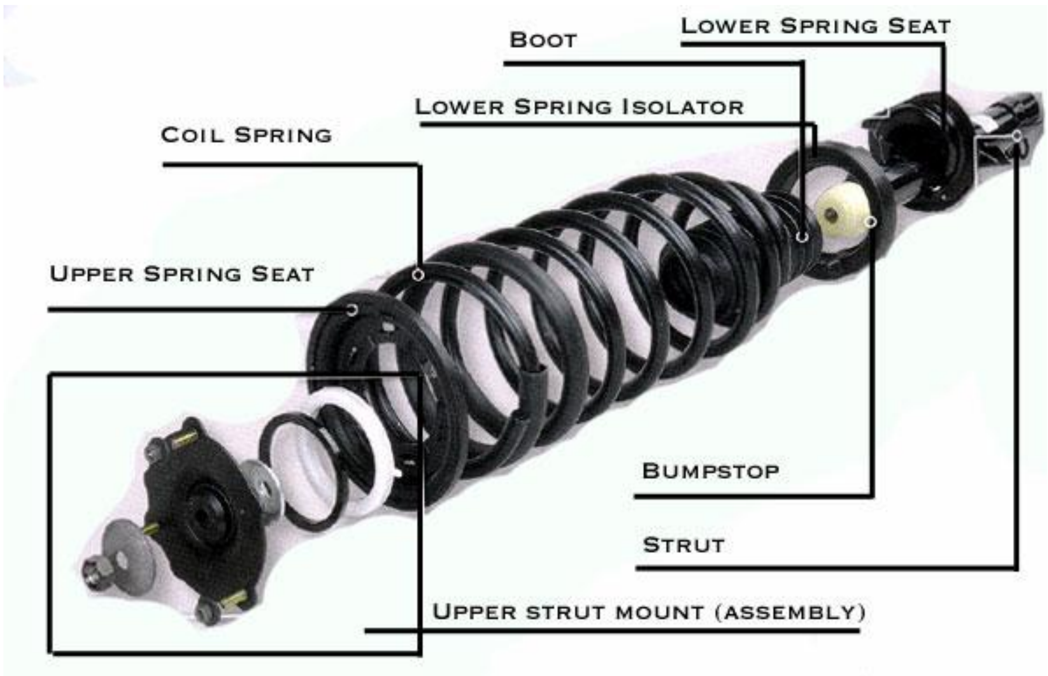


Image F.5-54: Front & Rear Shock Absorber Subsystem, Current Sub-Assembly Components

(Source: Lotus – 2010 March EPA Report)

As seen in **Image F.5-55**, the Rear Strut Damper subsystem consists of the major components of the Rear Shock Tower, Shock Piston Shaft, Shock Lower Mount, Lower Mount Fasteners, Rear Coil Spring, Bump Stop/Jounce Bumper, Upper Strut Mount, Upper and Lower Isolators, and the Shock Tower Boot.

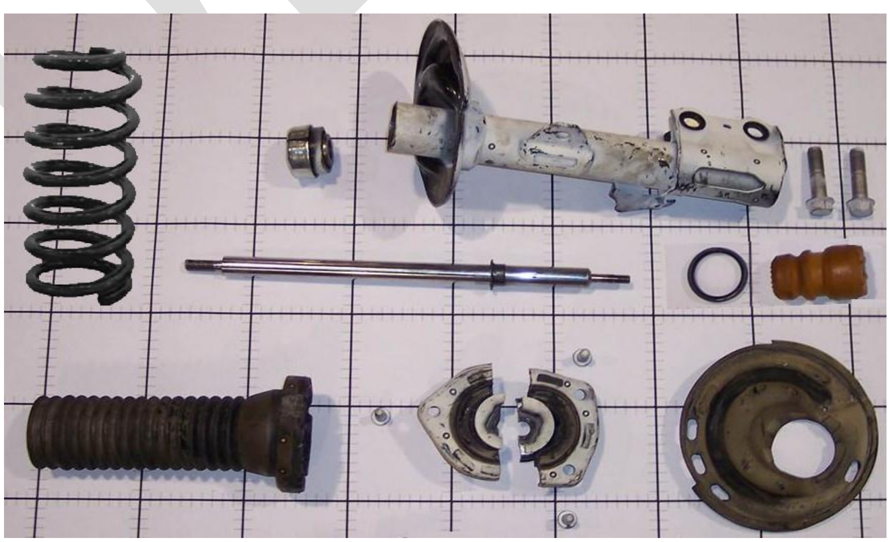


Image F.5-55: Rear Strut / Damper Subsystem Current Major Components

(Source: FEV Inc Photo)

As seen in **Image F.5-56**, the Front Strut Damper subsystem consists of the major components of the Rear Shock Tower, Shock Piston Shaft, Shock Lower Mount, Lower Mount Fasteners, Rear Coil Spring, Bump Stop/Jounce Bumper, Upper Strut Mount, Upper and Lower Isolators, and the Shock Tower Boot.

Image F.5-56: Front Strut / Damper Subsystem Current Major Components

(Source: FEV Inc Photo)

It can be seen in **Table F.5-11** that the Shock Absorber subsystem consists of the Front and the Rear Strut/Damper Assemblies. The most significant contributor to the mass of the Shock Absorber subsystem is the Front Strut/Damper Assembly (approx 51.5%), followed closely by the Rear Strut/Damper Assembly (approx 48.5%).

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
04	**03**	**00**	**Shock Absorber Subsystem**	**--**
04	03	01	Front Strut / Damper Asm	22.121
04	03	02	Rear Strut / Damper Asm	20.824
			Total Subsystem Mass =	**42.945**
			Total System Mass =	**266.120**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**16.14%**
			System Mass Contribution Relative to Vehicle =	**2.51%**

Table F.5-11: Mass Breakdown by Sub-subsystem for the Shock Absorber Subsystem

F.5.3.2 Toyota Venza Baseline Subsystem Technology

The Toyota Venza's Rear Strut/Damper (**Image F.5-57**) and Front Strut/Damper Sub-systems (**Image F.5-58**) represent typical industry standards. This includes a focus on functional performance and durability with least material cost. Toyota also focuses on providing similar, if not identical, components across all platform variants to take advantage of scaling economies and minimize production and purchasing costs.

Image F.5-57: Rear Strut Module Assembly Subsystem Current Configuration Example

(Source:http://www.carbodyparts.net/1998_toyota_camry/shock_absorber_and_strut_assembly_front_passenger_side-rept280504.html)

Image F.5-58: Front Strut Module Assembly Subsystem Current Configuration Example

(Source:http://www.carbodyparts.net/1998_toyota_camry/shock_absorber_and_strut_assembly_front_passenger_side-rept280504.html)

F.5.3.3 Mass-Reduction Industry Trends

Basic trends in shock absorber technology include low mass materials where function is not deteriorated. Also, high strength steel is used for mass reduction of springs, notably in Alfa Romeo and BMW vehicles.

Another trend in shock absorber technology is integrating more and more electronics. Electronic dampers allow a large range between maximum and minimum damping levels and adjust instantly to ensure ride comfort and firm vehicle control. By integrating mechanical and electronic functions within the shock absorber system, automakers can improve handling and potentially reduce costs as technologies mature.

Delphi developed the MagneRide concept (**Image F.5-59**) in which a Magneto-Rheological (MR) fluid passes through an orifice that can be "restricted" by applying an electric field. The MagneRide system produces a mechanically simple but very responsive and controllable damping action without any valves. A synthetic hydraulic oil contains suspended iron particles. When surrounded by a magnetic field, these particles realign, changing the viscosity of the fluid.

These MR shocks and struts feature a tube that rides on a stationary internal piston containing an electromagnet. When current is fed to the magnet, the surrounding MR fluid instantaneously changes viscosity to resist the tube/piston movement in a way that best copes with road conditions. According to Delphi, within a millisecond, the fluid transforms from the consistency of mineral oil to compensate for low dampening forces to a thin jelly consistency for high dampening.

Because the viscosity of the MR fluid can be infinitely varied through changes in the current, Delphi shocks and struts are designed to provide far greater dampening range compared with conventional shocks. This translates into a smoother, more responsive ride. Because the tube is the only moving part, the shock is more trouble-free and should not wear out as quickly as conventional shocks. Among other advantages, Delphi says its new technology reduces suspension weight and overall costs.

Image F.5-59: Delphi MagneRide (MR) Strut System

(Source: http://www.search-autoparts.com/searchautoparts/article/articleDetail.jsp?id=68222)

F.5.3.3.1 Strut / Damper Module Assemblies

The baseline OEM Toyota Venza Rear and Front Strut/Damper Module Assemblies (**Image F.5-57** and **Image F.5-58**, respectively) are multi-piece designs of stamped steel fabrications welded into a sub-assembly along with various molded and sub-assembled components that are then filled with fluid and charged to pressure. The primary sub-assemblies and components that were investigated for implemented changes include: Shock Tower Sub-Assembly (**Image F.5-60**) and the attached components of the interior Strut Piston Shaft (**Image F.5-6**) and the Strut Lower Mount (**Image F.5-62**); the Strut Dust Cover and the Strut Lower Mount Fasteners (**Image F.5-63**); the Bump Stop and the Jounce Bumper components (**Image F.5-64**); the Boot, Tower Cover (**Image F.5-65**), along with the Upper Spring Insulator (**Image F.5-66**)**,** and the Lower Spring Insulator (**Image F.5-67**); the Coil Spring (**Image F.5-68**); the Spring Upper Seat (**Image F.5-69**); and the Strut Top Mount (**Image F.5-70**). These overall strut assemblies have a mass of 14.386kg and 13.150kg for the Rear and Front Struts, respectively.

Many high-performance and luxury vehicle models, such as BMW, Mercedes, Audi, and even some within GM, have began utilizing alternate materials and designs in order to improve mass and expense across many of these components within these assemblies. These individual components are reviewed and shown individually here in greater detail:

F.5.3.3.1.1 Shock Tower Sub-Assemblies

The baseline OEM Toyota Venza Rear and Front Shock Tower Sub-Assemblies (**Image F.5-60**) are multi-piece sub-assemblies of stamped steel and welded fabrications with various brackets and fasteners added. These sub-assemblies have a mass of 3.489kg for the Rear Shocks and 3.364kg for the Front Shocks. Some vehicle models and manufacturers are now utilizing alternate materials (HSS, Al and Ti) and design changes for these components allowing for some mass savings in the assembled units.

Image F.5-60: Rear & Front Shock Tower Current Sub-assembly Example

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.3.3.1.1.1 Strut Piston Shafts

The current OEM Toyota Venza Strut Piston Shafts (**Image F.5-61**), located inside the shock tower sub-assemblies, are single piece designs for steel machined components. These components have a mass of 1.143kg for the Rear Piston Shafts and 1.085kg for the Front Piston Shafts.

Image F.5-61: Rear & Front Strut Piston Shaft Current Component Example

(Source: FEV Inc, Photo)

F.5.3.3.1.1.2 Strut Lower Mounts

The baseline OEM Toyota Venza Rear and Front Strut Lower Mounts (**Image F.5-62**) are multi-piece designs with two stamped steel components, each welded together to the lower shock tower outer diameter. These sub-assemblies have a mass of 1.13kg for the Rear Lower Mounts and 1.05kg for the Front Lower Mounts.

Image F.5-62: Rear & Front Strut Lower Mount Current Component Example

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.3.3.1.2 *Strut Lower Mount Fasteners*

The baseline OEM Toyota Venza Rear and Front Strut Lower Mount Fasteners (**Image F.5-63**) are cold-headed steel components. These parts have a mass of 0.39kg for both the rear and front struts, respectively. Some vehicle models and manufacturers have begun utilizing alternate materials for some of these fasteners depending on vehicle loading requirements during normal operation.

Image F.5-63: Rear & Front Mount Fasteners Current Component Examples

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.3.3.1.3 Strut Bump Stops and Jounce Bumpers

The baseline OEM Toyota Venza Rear and Front Strut Bump Stops and Jounce Bumpers (**Image F.5-64**) are molded plastic components. These components have a combined mass of 0.08kg for the Rear Struts and 0.07kg for the Front Struts. There are no alternate materials found to use to effectively replace these parts. So no significant savings could be specifically identified.

Image F.5-64: Rear & Front Bump Stop / Jounce Bumper Current Component Example

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.3.3.1.4 *Strut Boots, Tower Cover*

The current OEM Toyota Venza Rear and Front Strut Boot Tower Covers (**Image F.5-65**) are single-piece molded plastic components, with a mass of 0.06kg for the Rear Boots and 0.04kg for the Front.

Image F.5-65: Rear & Front Strut Boot, Tower Covers Current Component Example

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.3.3.1.5 *Strut Upper Spring Isolators*

The OEM Toyota Venza Rear and Front Strut Upper Spring Isolators (**Image F.5-66**) are single-piece molded rubber components. These parts have a mass of 0.25kg for the Rear Upper Isolators and 0.17kg for the Front.

Image F.5-66: Rear & Front Strut Upper Spring Isolator Current Component Example

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.3.3.1.6 *Strut Lower Spring Isolators*

The current OEM Toyota Venza Rear and Front Strut Lower Spring Isolators (**Image F.5-67**) are single-piece molded rubber components. These parts have a mass of 0.172kg for the Rear Lower Isolators and 0.082kg for the Front.

Image F.5-67: Rear & Front Strut Lower Spring Isolator Current Component Example

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.3.3.1.7 *Strut Coil Springs*

The baseline OEM Toyota Venza Rear and Front Strut Coil Springs (**Image F.5-68**) are single-piece, steel hot-wound coil springs. These components have a mass of 3.003kg for the Rear Springs and 3.336kg for the Front Springs. Some vehicle models and manufacturers are utilizing alternate materials and making design changes for springs to include HSS and other steel alloy variations. Other materials, including long fiber polymers, have been successfully implemented for leaf spring applications but not for coil configurations in automobiles.

Image F.5-68: Rear & Front Strut Coil Spring Current Component Example

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.3.3.1.8 *Strut Spring Upper Seats*

The baseline OEM Toyota Venza Rear and Front Strut Spring Upper Seats (**Image F.5-69**) are single-piece, stamped steel platforms that are assembled to the strut shock tower. These components have a mass of .655kg for the Rear Upper Seats and 0.532kg for the Front Upper Seats. Some vehicle models and manufacturers have utilized alternate materials for these components, including HSS, Al, Ti, Mg and Plastics.

Image F.5-69: Rear & Front Strut Spring Upper Seat Current Component Example

(Source: March 2010 Lotus Report)

F.5.3.3.1.9 *Strut Top Mount Sub-Assemblies*

The baseline OEM Toyota Venza Front Shock Tower Sub-Assemblies (**Image F.5-70**) are multi-piece assemblies of stamped steel and welded fabrications with various brackets and fasteners added. This sub-assembly has a mass of 1.25kg. Some vehicle models and manufacturers are utilizing alternate materials and design changes for these components that allow for some mass savings once the unit is assembled. The materials include HSS, Al, and Ti as well as some development work in polymers.

Image F.5-70: Front Strut Top Mount Current Sub-Assembly Example

(Source: March 2010 Lotus Report)

F.5.3.4 Summary of Mass-Reduction Concepts Considered

The brainstorming activities generated the ideas shown below in the tables for both of the Rear Strut/Shock Absorber sub-subsystem (**Table F.5-12**) and the Front Strut/Shock Absorber/Damper sub-subsystem (**Table F.5-13**). The majority of these mass-reduction ideas are related to technologies in production on other vehicles and alternatives to steel. This includes part modifications, material substitutions, and use of parts currently in production on other vehicles.

Component/ Assembly	Mass Reduction Idea	Estimated Impact	Risk & Trade-offs and/or Benefits
Shock Absorber Subsystem			
Rear Strut/Damper Assy Sub-Subsystem			
Shock Absorber	Stell - Proprietary technology - Active Continuously varible shock absorber (2.39kg)	10-20% wt save	Not enough inof to evaluate - not analyzed.
	Substituting monotube for twin tube shocks	0-10% wt save	Considered decontenting - not analyzed
	Replace from 2005 Alfa Romeo 147 (mass:10.815-7.716 & cost:1.00)	20-30% wt save	In production - Alfa Romeo.
Shock Tower	AL-356-T6 AL-6022-T4	20-30% wt save	Not enough info to cost analyze
	AM50 (2.8kg)	20-30% wt save	Not enough info to cost analyze
	Carbon Fiber Damper (reduces weight by 50% vs. aluminum)	50% wt save	Not enough info to cost analyze
	Eliminate spring cap and/or isolator (must be carbon fiber damper)	100% wt save	Not enough info to cost analyze
	Replace from 2005 Alfa Romeo 147 (mass:6.138-5.760 & cost:0.99)	10-20% wt save	In production - Alfa Romeo.
Strut Piston Shaft	High strength steel	10-20% wt save	Low volume production
	Bilstein lightweight strut system - Hollow Shaft - Rear	No change	Already Bilstien w/ hollow shafts
Dust Cover Strut	Replace from 2005 Alfa Romeo 147 (mass:0.308-0.052 & cost:0.66)	60-70% wt save	Low Cost. In production - Alfa Romeo.
Strut Mount	Aluminum (sheet) Strut Mounts	40-50% wt save	Low volume production - motorcycles
	Aluminum (cast) Strut Mounts	30-40% wt save	Low volume production - motorcycles
	Titanium (sheet) Strut Mounts	20-30% wt save	Low volume production - auto racing
	HSS Strut Mounts	10-20% wt save	In production - auto.
	Mg Strut Mounts	50-60% wt save	Low volume production - auto racing
Bump Stop	Replace from 2005 Alfa Romeo 147 (mass:0.093-0.026 & cost:0.91)	70-80% wt save	Lower Cost. In production - Alfa Romeo.

Table F.5-12 continued on next page

Jounce Bumper	Replace from 2005 Alfa Romeo 147 (mass:0.083-0.044 & cost:0.98)	40-50% wt save	In production - Alfa Romeo.
Boot, Tower Cover	Replace boot material (NR) with TPO	0-5% wt save	Lower Cost. In production - auto
	Replace from 2005 Alfa Romeo 147 (mass:0.013-0.013 & cost:1.00)	Lotus idea - no change	In production - Alfa Romeo.
Mounting Fasteners	Use a single fastener on strut to knuckle mounting	50% wt save	2 required for orientation & stabilization - not evaluated
	Reduce lower strut mounting bolt & nut size	20-30% wt save	In production GM
	Use 6082T6 Al Alloy Tower Bolts	20-30% wt save	Low volume production - auto
Upper Spring Insulator	Replace from 2005 Alfa Romeo 147 (mass:0.000-0.083 & cost:x)	Lotus idea - wt increase.	In production - Alfa Romeo.
	Make upper seat spring isolator out of plastic	0-5% wt save	In production - Auto
Lower Spring Insulator	Replace from 2005 Alfa Romeo 147 (mass:0.058-0.105 & cost:1.06)	Lotus idea - wt increase.	In production - Alfa Romeo.
	Make lower seat spring isolator out of plastic	0-5% wt save	In production - Auto

Table F.5-12 continued on next page

Component/ Assembly	Mass Reduction Idea	Estimated Impact	Risk & Trade-offs and/or Benefits
Shock Absorber Subsystem			
Front Strut/Damper Assy Sub-Subsystem			
Shock Absorber	Stell - Proprietary technology - Active Continuously varible shock absorber (2.39kg)	10-20% wt save	Not enough inof to evaluate - not analyzed.
	Substituting monotube for twin tube shocks	0-10% wt save	Considered decontenting - not analyzed
	Replace from 2005 VW Passat (mass:11.56-7.81 & cost:1.00)	20-30% wt save	In production - VW Passat.
Shock Tower	AL-356-T6 AL-6022-T4	20-30% wt save	Not enough info to cost analyze
	AM50 (2.8kg)	20-30% wt save	Not enough info to cost analyze
	Carbon Fiber Damper (reduces weight by 50% vs. aluminum)	50% wt save	Not enough info to cost analyze
	Eliminate spring cap and/or isolator (must be carbon fiber damper)	100% wt save	Not enough info to cost analyze
	Replace from 2005 VW Passat (mass:5.88-3.8 & cost:0.95)	10-20% wt save	Lower Cost. In production - VW Passat.
Strut Piston Shaft	High strength steel	10-20% wt save	Low volume production
	Bilstein lightweight strut system - Hollow Shaft	No change	Already Bilstien w/ hollow shafts
Dust Cover	Replace from 2005 VW Passat (mass:0.21-0.07 & cost:0.71)	60-70% wt save	Low Cost. In production - VW Passat.
Dust Cover	Replace from 2005 VW Passat (mass:0.09-0.02 & cost:0.85)	70-80% wt save	Low Cost. In production - VW Passat.
Strut Mount	Aluminum (sheet) Strut Mounts	40-50% wt save	Low volume production - motorcycles
	Aluminum (cast) Strut Mounts	30-40% wt save	Low volume production - motorcycles
	Titanium (sheet) Strut Mounts	20-30% wt save	Low volume production - auto racing
	HSS Strut Mounts	10-20% wt save	In production - auto.
	Mg Strut Mounts	50-60% wt save	Low volume production - auto racing

Table F.5-12 continued on next page

Jounce Bumper	Replace from 2005 VW Passat (mass:.07-.05 & cost:0.99)	20-30% wt save	In production - VW Passat.
Boot, Tower Cover	Replace boot material (NR) with TPO	0-5% wt save	Lower Cost. In production - auto
Strut Top Mount	Replace from 2005 VW Passat - use Al metals (mass:1.23-0.33 & cost:1.47)	70-80% wt save	High Cost. In production - VW Passat.
Mounting Fasteners	Reduce lower strut mounting bolt & nut size	20-30% wt save	In production GM
	Use a single fastener on strut to knuckle mounting	50% wt save	2 required for orientation & stabilization - not evaluated
	Use 6082T6 Al Alloy Tower Bolts	20-30% wt save	Low volume production - auto
Spring Isolator	Make lower seat spring isolator out of plastic	0-5% wt save	In production - Auto
Upper Spring Seat	Replace from 2005 VW Passat - use nylon (mass:0.54-0.12 & cost:0.31)	60-70% wt save	Low Cost. In production - VW Passat.

Table F.5-12: Summary of Mass-Reduction Concepts Initially Considered for the Front Strut / Shock / Damper Sub-Subsystem

F.5.3.5 Selection of Mass Reduction Ideas

The next two tables show the subsets of the ideas generated from the brainstorming activities listed in the previous chart for the Rear Strut/Shock Absorber/Damper sub-subsystem (**Table F.5-13**) and the Front Strut/Shock Absorber/Damper sub-subsystem (**Table F.5-14**).

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
			Shock Absorber Subsystem	
04	**03**	**01**	**Rear Strut/Damper Assy Sub-Subsystem**	
04	03	01	Shock Absorber	Replace from 2005 Alfa Romeo 147 (mass:10.815-7.716 & cost:1.00)
04	03	01	Shock Tower	Replace from 2005 Alfa Romeo 147 (mass:6.138-5.760 & cost:0.99)
04	03	01	Strut Piston Shaft	High strength steel
04	03	01	Dust Cover Strut	Replace from 2005 Alfa Romeo 147 (mass:0.308-0.052 & cost:0.66)
04	03	01	Strut Mount	HSS Strut Mounts
04	03	01	Bump Stop	Replace from 2005 Alfa Romeo 147 (mass:0.093-0.026 & cost:0.91)
04	03	01	Jounce Bumper	Replace from 2005 Alfa Romeo 147 (mass:0.083-0.044 & cost:0.98)
04	03	01	Boot, Tower Cover	Replace boot material (NR) with TPO
04	03	01	Mounting Fasteners	Use 6082T6 Al Alloy Tower Bolts
04	03	01	Upper Spring Insulator	Make upper seat spring isolator out of plastic
04	03	01	Lower Spring Insulator	Make lower seat spring isolator out of plastic

Table F.5-13: Mass-Reduction Ideas Selected for the Detailed Shock Absorber Subsystem (Rear Strut / Damper Assembly Sub-Subsystem) Analysis

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
			Shock Absorber Subsystem	
04	**03**	**02**	**Front Strut/Damper Assy Sub-Subsystem**	
04	03	02	Shock Absorber	Replace from 2005 VW Passat (mass:11.56-7.81 & cost:1.00)
04	03	02	Shock Tower	Replace from 2005 VW Passat (mass:5.88-3.8 & cost:0.95)
04	03	02	Strut Piston Shaft	High strength steel
04	03	02	Dust Cover	Replace from 2005 VW Passat (mass:0.21-0.07 & cost:0.71)
04	03	02	Dust Cover	Replace from 2005 VW Passat (mass:0.09-0.02 & cost:0.85)
04	03	02	Strut Mount	HSS Strut Mounts
04	03	02	Jounce Bumper	Replace from 2005 VW Passat (mass:.07-.05 & cost:0.99)
04	03	02	Boot, Tower Cover	Replace boot material (NR) with TPO
04	03	02	Strut Top Mount	Replace from 2005 VW Passat - use Al metals (mass:1.23-0.33 & cost:1.47)
04	03	02	Mounting Fasteners	Use 6082T6 Al Alloy Tower Bolts
04	03	02	Spring Isolator	Make lower seat spring isolator out of plastic
04	03	02	Upper Spring Seat	Replace from 2005 VW Passat - use nylon (mass:0.54-0.12 & cost:0.31)

Table F.5-14: Mass-Reduction Ideas Selected for the Detailed Shock Absorber Subsystem (Front Strut / Damper Assembly Sub-Subsystem) Analysis

The solution for the mass reduced Rear Strut/Damper (**Image F.5-71**) and Front Strut/Damper (**Image F.5-72**) sub-systems are shown as represented by the configuration utilized in an assembly replacement from the Alfa Romeo 147 and VW Passat, respectively. The changes made at the individual component and sub-assembly levels are each explained in greater detail.

Image F.5-71: Rear Strut Module Assembly Subsystem Mass Reduced Configuration Example

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

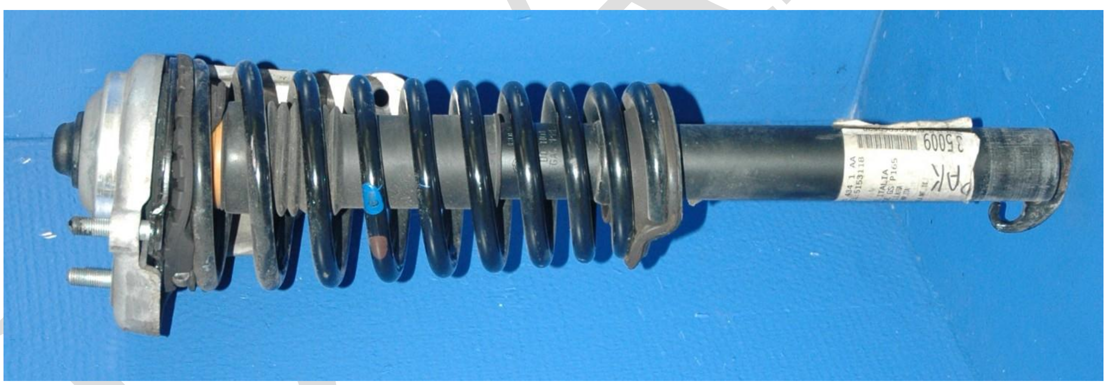


Image F.5-72: Front Strut Module Assembly Subsystem Mass Reduced Configuration Example

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.3.5.1 Strut / Damper Module Assemblies

The solutions chosen to implemented on the Rear and Front Strut/Damper Module Assemblies (**Image F.5-71** and **Image F.5-72**, respectively) range across several different components and sub-assemblies. Although the overall design and function of the strut modules remain the same, small changes were instituted across the entire unit. The effected designs are detailed in the following for each area of redesign and change. The primary sub-assemblies and components that were investigated for implemented changes include: Shock Tower Sub-Assembly (**Image F.5-73**) and the attached components of the interior Strut Piston Shaft (**Image F.5-74**) and the Strut Lower Mount (**Image F.5-75**); the Strut Dust Cover and the Strut Lower Mount Fasteners (**Image F.5-76**); the Bump Stop and the Jounce Bumper components (**Image F.5-77**); the Boot, Tower Cover (**Image F.5-78**) along with the Upper Spring Insulator (**Image F.5-79),** and the Lower Spring Insulator (**Image F.5-80).** The Coil Spring **(Image F.5-81**), the Spring Upper Seat (**Image F.5-82**), and the Strut Top Mount (**Image F.5-83**). These new mass reduced strut assemblies now have a mass of 15.628kg for the Rear Struts and 13.205kg for the Front Struts.

F.5.3.5.1.1 *<u>Shock Tower Sub-Assemblies</u>*

The new redesigned Rear and Front Shock Tower Sub-Assemblies (**Image F.5-73**) are still multi-piece sub-assemblies of stamped steel and welded fabrications with various brackets and fasteners. Although alternate materials (HSS, Al and Ti) are available, they were not selected in the vehicle solution matrix for implementation. Instead, a replacement and size normalization was selected by utilizing the shock tower sub-assembly from the Alfa Romeo 147. These new scaled sub-assemblies now have a net mass of 5.112kg for the Rear Shocks and 3.651kg for the Front Shocks

Image F.5-73: Rear & Front Shock Tower Mass Reduced Sub-assembly Example

(Source: http://www.ioffer.com/c/Auto-Parts-Accessories-35000/1995%20-?view=0)

F.5.3.5.1.1.1 Strut Piston Shafts

The mass reduction change for Strut Piston Shafts (**Image F.5-74**), located inside the shock tower sub-assemblies, is a replacement of the standard low-carbon steel with HSS material. The new, stronger shaft allows for a smaller diameter component (approximately 5%), creating some mass savings. The new shaft has a mass of 1.019kg for the Rear Piston Shafts and 0.727kg for the Front Piston Shafts.

Image F.5-74: Rear & Front Strut Piston Shaft Mass Reduced Component Example

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.3.5.1.1.2 Strut Lower Mounts

The change for the Rear & Front Strut Lower Mounts (**Image F.5-75**) are still multi-piece designs with two stamped steel components, each welded together to the lower shock tower outer diameter. The standard steel has now been upgraded to HSS, allowing for a thinner component (approximately 5%) with equal performance strength. These sub-assemblies now have a new mass of 1.012kg for the Rear Lower Mounts and 0.646kg for the Front Lower Mounts.

Image F.5-75: Rear & Front Strut Lower Mount Mass Reduced Component Example

(Source: http://www.ioffer.com/c/Auto-Parts-Accessories-35000/1995%20-?view=0)

F.5.3.5.1.2 Strut Lower Mount Fasteners

The solution found for the Rear & Front Strut Lower Mount Fasteners (**Image F.5-76**) is to switch material from steel to Al components. Due to the replacement of steel with Al, an additional material volume of 30-40% was made. In order to maintain functional integrity, the bolt diameter size was increased significantly. Nonetheless, this still resulted in a net mass decrease with a mass of 0.170kg for both the rear and front strut fasteners, respectively.

Image F.5-76: Rear & Front Mount Fasteners Mass Reduced Component Examples

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.3.5.1.3 Strut Bump Stops and Jounce Bumpers

The change for the Rear & Front Strut Bump Stops and Jounce Bumpers (**Image F.5-77**) are made by replacing and normalizing the same components from the VW Passat bumpers. These new scaled components have a combined mass of 0.041kg for the Rear Struts and 0.050kg for the Front Struts. There are no alternate materials found to effectively replace these parts other than the component exchange methodology.

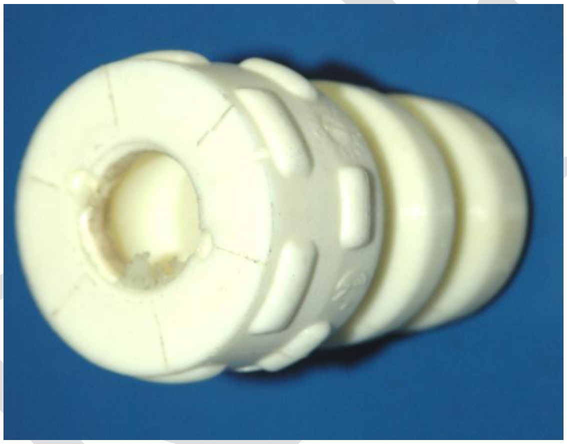


Image F.5-77: Rear & Front Bump Stop / Jounce Bumper Mass Reduced Component Example

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.3.5.1.4 Strut Boots, Tower Cover

The solution for the Rear & Front Strut Boot Tower Covers (**Image F.5-78**) is implemented by replacing the current material with TPO polymer, single-piece molded components. There is no reinforcement implemented with this material change. These parts have a mass of 0.010kg for the Rear Boots and 0.041kg for the Front.

Image F.5-78: Rear & Front Strut Boot, Tower Covers Mass Reduced Component Example

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.3.5.1.5 <u>*Strut Upper Spring Isolators*</u>

The mass change implemented for the Rear & Front Strut Upper Spring Isolators (**Image F.5-79**) is by replacing the single-piece molded rubber component with a polymer material. There is no reinforcement implemented with this material change. These parts have a new reduced mass of 0.042kg for the Rear Upper Isolators and 0.165kg for the Front.

Image F.5-79: Rear & Front Strut Upper Spring Isolator Mass Reduced Component Example

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.3.5.1.6 <u>*Strut Lower Spring Isolators*</u>

The mass change implemented for the Rear & Front Strut Lower Spring Isolators (**Image F.5-80**) is by replacing the single-piece molded rubber component with a polymer material. There is no reinforcement implemented with this material change. These parts have a new reduced mass of 0.123kg for the Rear Lower Isolators and 0.082kg for the Front.

Image F.5-80: Rear & Front Strut Lower Spring Isolator Mass Reduced Component Example

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.3.5.1.7 *Strut Coil Springs*

The selected solution for the Rear & Front Strut Coil Springs (**Image F.5-81**) is to replace and scale the coil spring from the Alfa Romeo 147 (rear) and the VW Passat (front). The springs are still both single piece coil springs, but are now made from HSS and cold-wound to produce a smaller diameter and stronger design. The replacement of steel with HSS allowed a size reduction of approximately 5-10% volume reduction due to increase strength. These new components have a mass of 1.600kg for the Rear Springs and 1.792kg for the Front.

Image F.5-81: Rear & Front Strut Coil Spring Mass Reduced Component Example

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.3.5.1.8 *Strut Spring Upper Seats*

The solution chosen for the Rear & Front Strut Spring Upper Seats (**Image F.5-82**) is to replace the single-piece, stamped steel piece with a molded glass-filled nylon design from the Mazda 5. Due to the replacement of steel with GF Nylon, an additional material volume of 30-40% was made. These vehicle platforms have approximately the same GVW, so it is a direct replacement not requiring scaling. These components have a reduced mass of 0.655kg for the Rear Upper Seats and 0.160kg for the Front Upper Seats.

Image F.5-82: Rear & Front Strut Spring Upper Seat Mass Reduced Component Example

(Source: March 2010 Lotus Report)

F.5.3.5.1.9 *Strut Top Mount Sub-Assemblies*

The selected mass reduction for the Strut Top Mount Sub-Assemblies (**Image F.5-83**) is a multi-piece assembly of stamped steel and welded fabrication. The new replacement is from a VW Passat with size normalization as well as Al material instead of steel. Due to the replacement of steel with Al, an additional material volume of 20-30% was made. These redesigned sub-assemblies have a new mass of 0.655kg for the Rear Struts and 0.411 64kg for the Front Struts.

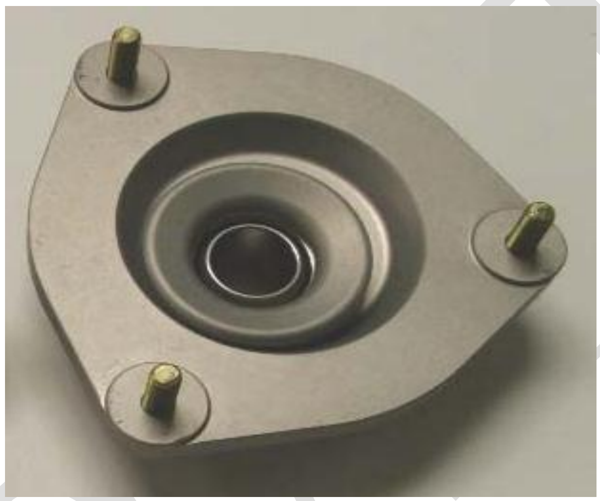


Image F.5-83: Front Strut Top Mount Mass Reduced Sub-Assembly Example

(Source:http://performanceshock.com/index/manufacturers_id/19?zenid=c4c5cb77d94ed8395449208159712883)

F.5.3.6 Calculated Mass-Reduction & Cost Impact Results

Table F.5-15 shows the results of the mass reduction ideas that were evaluated for the Strut/Shock Absorber/Damper Sub-subsystem. This resulted in a subsystem overall mass savings of 14.111 kg and a cost savings differential of $-57.99.

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
04	**03**	**00**	**Shock Absorber Subsystem**						
04	03	01	Front Strut / Damper Assembly	A	9.326	$26.10	$2.80	40.56%	0.55%
04	03	02	Rear Strut / Damper Assembly	A	4.785	$31.89	$6.66	30.91%	0.28%
04	03	03	Active Dampening		0.000	$0.00	$0.00	0.00%	0.00%
				A	**14.111** (Decrease)	**$57.99** (Decrease)	**$4.11** (Decrease)	**35.88%**	**0.82%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.5-15: Mass-Reduction and Cost Impact for the Shock Absorber Subsystem (Rear & Front Strut / Damper Assembly Sub-Subsystem)

F.5.4 Wheels and Tires Subsystem

F.5.4.1 Subsystem Content Overview

Image F.5-84 shows the relative location of the Road Wheel & Tire Sub-Assemblies and the Spare Wheel & Tire Sub-Assembly on the vehicle chassis. The current OEM Toyota Venza Wheel and Tires subsystem have a total mass of 4.658kg.

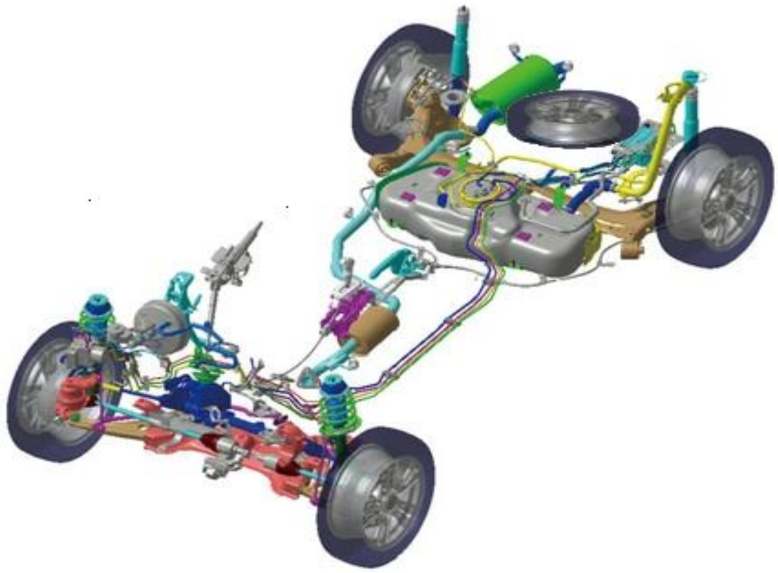


Image F.5-84: Road Wheel & Tire Position Diagram

(Source: http://boronextrication.com/files/2010/11/2011_Honda_CR-Z_Chasis_Layout.jpg)

These pictures represent the major sub-assemblies and components in the Wheels and Tires subsystem. These include the Road Wheel and Tire Assembly (**Image F.5-85**) and the Spare Wheel and Tire Assembly (**Image F.5-88**). The current OEM Toyota Venza Wheels and Tires subsystem have a total mass of 141.815kg.

In **Table F.5-16**, the Wheels and Tires subsystem consists of the Road Wheels and Tire Assembly sub-subsystem and the Spare Wheel and Tire Assembly sub-subsystem. The most significant contributors to the mass of this subsystem are the Road Wheels and Tire Assembly sub-subsystem (approx 86.4%) and the Spare Wheel and Tire Assembly sub-subsystem (approx 13.6%).

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
04	**04**	**00**	**Wheels And Tires Subsystem**	**--**
04	04	01	Road Wheels and Tire Assembly	122.597
04	04	02	Spare Wheel and Tire Assembly	19.218
			Total Subsystem Mass =	**141.815**
			Total System Mass =	**266.120**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**53.29%**
			System Mass Contribution Relative to Vehicle =	**8.29%**

Table F.5-16: Mass Breakdown by Sub-subsystem for the Wheels and Tires Subsystem

F.5.4.2 Toyota Venza Baseline Subsystem Technology

The Toyota Venza's Wheels and Tires subsystem represents typical industry standards. This includes a focus on style, functional performance and durability with least material cost. Toyota also concentrates on providing similar, if not identical, components across all platform variants to take advantage of scaling economies to minimize production and purchasing costs.

F.5.4.3 Mass-Reduction Industry Trends

The March 2010 Lotus report describes several industry examples, including Alcoa aluminum forged wheels, carbon fiber composites, two-piece low-mass wheels, Michelin Tweel, and Active Wheel designs.

New proprietary magnesium alloys are being developed for racing applications, including wheels and lug nuts, with claims of matching the strength of steel with impressive mass reduction.

As mentioned in **Section 5.4.1.3**, basalt fiber is a potential low-cost substitute for carbon fiber when production capabilities can support automotive quantities.

F.5.4.3.1 Road Wheel & Tire Assemblies

The Venza uses four standard Road Wheel & Tire Assemblies (**Image F.5-85**) with radial molded tires mounted on an Al cast rims. The current OEM Venza Road Tire Assembly sub-subsystem has a total mass of 120.99kg.

Image F.5-85: Road Wheel & Tire Current Assembly

(Source: March 2010 Lotus Report)

F.5.4.3.1.1 *Road Wheels*

The Toyota Venza OEM Road Wheels (**Image F.5-86**) are single-piece cast Al design. The size of the OEM wheel used on the Venza is 19" outer diameter x 7.5" width. Although alternate materials (Mg, GF Polymers, and Carbon Fiber) exist and are used by some aftermarket manufacturers, they are uncommon and very ineffective for cost in most applications. The current Venza Road Wheels (4pcs) have a total mass of 61.20kg.

Image F.5-86: Road Wheel Current Component

(Source: March 2010 Lotus Report)

F.5.4.3.1.2 *Road Tires Sub-Assembly*

The Toyota Venza OEM Road Tires (**Image F.5-87**) are multi-layer design of various materials all over-molded NR. The size of the OEM tire used on the Toyota Venza is P225/60R19. Alternate material variations are used for the internal layers as well as the final over-molding compound. However, manufacturers use these variables to help tune a specific tire design to the performance desired for a particular vehicle application. The following image shows a common tire design, features, and its associated naming nomenclature. No significant material developments exist that allow any appreciable weight savings while maintaining a standard design configuration. The current Venza Road Tires (4pcs) have a total mass of 59.52kg.

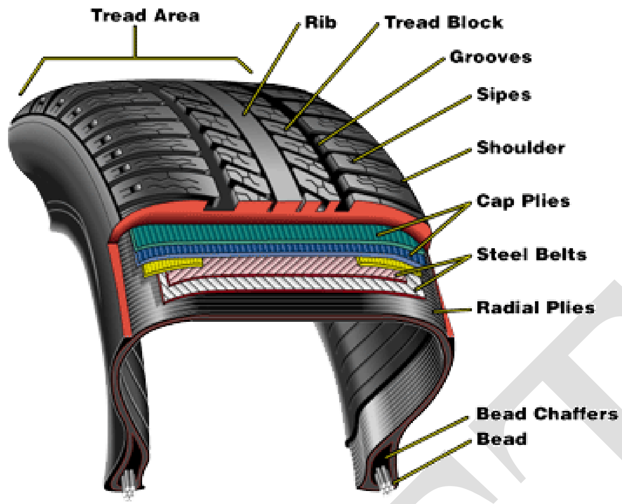


Image F.5-87: Road Wheel Current Component Design Example

(Source: http://www.vbattorneys.com/practice_areas/defective-product-lawyer-product-liability-attorney-houston-texas.cfm)

F.5.4.3.2 Spare Wheel & Tire Assembly

The Spare Wheel & Tire Assembly (**Image F.5-88**) is a typical narrow, short side-walled, molded spare tire mounted on a large diameter, stamped steel wheel assembly. The current OEM Toyota Venza Spare Tire Assembly sub-subsystem has a mass of 19.176kg.

Image F.5-88: Spare Wheel & Tire Current Assembly Example

(Source:http://media.photobucket.com/image/toyota%20spare%20tire/)

F.5.4.3.2.1 *<u>Spare Wheel</u>*

The Toyota Venza OEM Spare Wheel (**Image F.5-89**) is large diameter and narrow, stamped steel fabrications. Although alternate materials (Al, Mg, GF Polymers, and Carbon Fiber) exist, they are not typically used for spare wheels due to lack of mass versus cost reduction. Therefore, they are not used by any manufacturer even though they could easily be used if chosen. The current OEM Toyota Venza Spare Wheel has a mass of 10.731kg.

Image F.5-89: Spare Wheel Current Component Example

(Source:http://media.photobucket.com/image/toyota%20spare%20tire/)

F.5.4.3.2.2 *<u>Spare Tire Sub-Assembly</u>*

The Toyota Venza OEM Spare Tire (**Image F.5-90**) is multiple layers of steel and plastic, over-molded by NR. Alternate material variations are used for the internal and external layers, but manufacturers use these variables to help tune a specific tire design to the desired performance. The current OEM Toyota Venza Spare Tire Sub-Assembly has a mass of 8.435kg.

Image F.5-90: Road Wheel Current Component Example

(Source:http://media.photobucket.com/image/toyota%20spare%20tire/)

F.5.4.3.3 Lug Nuts

The Lug Nuts, or Wheel Fastener Nuts, (**Image F.5-91**) are a typical cold-headed steel configuration with a stamped steel, chrome-plated shell pressed over the nut surface. The current OEM Toyota Venza Lug Nuts (20pcs) have a mass of 1.406kg.

Image F.5-91: Lug Nut Current Components

(Source: FEV Inc. Photo)

F.5.4.4 Summary of Mass-Reduction Concepts Considered

The brainstorming activities for the Wheels and Tires subsystem generated the ideas shown in **Table F.5-17**. The majority of these mass-reduction ideas are related to technologies in production on other vehicles and size alternatives. There are also ideas that cover part design modifications as well as material substitutions.

Component/ Assembly	Mass Reduction Idea	Estimated Impact	Risk & Trade-offs and/or Benefits
Wheels and Tires Subsystem			
All Tires (P225/60R19)	Low rolling resistance tires	5% Susp Sys wt save	Not used due to EPA matrix: save 1.5–4.5% of all gasoline consumption (-5%gvw=+3%mpg)
	Replace from 2008 Toyota Prius (mass:14.880-13.200 & cost:0.98)	5-10% wt save	In production - Toyota.
All Wheels (19 x 7.5)	Ultra-Lt Wt Forged Al Wheels (Cross-spoked)	10-15% wt save	In production - Mercedes Brabaus SLS AMG
	Lt Wt Wheels (hybrid glass & carbon fiber composite w/ steel)	30-40% wt save	Low vol production - military applications
	Replace from 2008 Toyota Prius (mass:15.300-8.600 & cost:0.93)	40-50% wt save	In production - Toyota.
	Upsize wheels from 15 x 6 to 19 x 7.5	10-20% wt save	Not analyzed - already implemented on vehicle
	Upsize wheels from 15 x 6 to 19 x 7.5	10-20% wt save	Not analyzed - already implemented on vehicle
	See 17-in alum (see FEV/EPA Fusion HEV)	20-30% wt save	Not analyzed - Al wheels already implemented
Lug Nuts	Make lug nuts out of magnesium	50-60% wt save	In production - BMW
	Make lug nuts out of aluminum	30-40% wt save	Development
	Use conical lug nuts - Eliminate flange on hub	0-5% wt save	In production - most auto manufacturers
	Combination. Make lug nuts out of magnesium using conical design.	55-65% wt save	Low volume production
Spare Tire Wheel	Add lightening holes in spare tire rim	5-10% wt save	In production - most auto manufacturers
	Make spare tire rim out of aluminum	10-20% wt save	Low production - auto
	Lt Wt Wheels (hybrid glass & carbon fiber composite w/ steel: 41% wt red vs Al wheels)	30-40% wt save	Low vol production - military applications
	Eliminate spare tire and use run-flat tires	100% wt save	In production - GM C5 Corvette
	Make rim out of Al and make like wagon wheel	10-20% wt save	Not analyzed - wagon spoke steel wheels normally from steel for strength
	Downsize - Replace from 2008 Toyota Prius (mass:10.731-9.731 & cost:1.00)	10-20% wt save	In production - Toyota.

Table F.5-17 continued on next page

Spare Tire	Make honeycomb spare tire	20-30% wt save	Not analyzed - non-pneumatic, not legal for road use in US
	Smaller/less rubber	5-10% wt save	Low volume production
	Downsize - Replace from 2008 Toyota Prius (mass:8.435-7.435 & cost:0.98)	10-20% wt save	In production - Toyota.
Spare Tire/Wheel	Eliminate spare tire & wheel	100% wt save	In production - most auto manufacturers
	Eliminate jacking harware by removing spare tire	100% wt save	In production - auto
	Eliminate spare tire hold down	100% wt save	In production - auto
	Combinination. Eliminate spare tire & wheel, jacking hardware and spare hold down	100% wt save	In production - auto
Wheels	Optimize for downsized (non-hybrid) powertrain, smaller wheels-See Future Steel Vehicle	20-30% wt save	Not analyzed - out of scope of study due to magnitude of design changes & validation rqd
Al Air Suspension system	Al 4-corner air system (idea 80) utilizes enhanced bonding & adhesive eliminating all welding	10-20% wt save	Not analyzed - out of scope of study due to magnitude of design changes & validation rqd
All rotational components (tires, wheels, etc)	Weight reduction in "un-sprung" mass has multipilying of being equivalent to 3-5 times effect vs "sprung" mass	30-40% wt save	No answer from EPA as to credit being allowed
All Suspension components	Convert to lt wt Al 4-corner air system w/ lt wt dampers, mounts & air springs	20-30% wt save	Not analyzed - out of scope of study due to magnitude of design changes & validation rqd

Table F.5-17: Summary of Mass-Reduction Concepts Initially Considered for the Tires and Wheels Subsystem

F.5.4.5 Selection of Mass Reduction Ideas

Table F.5-18 shows the mass reduction ideas for the major components of the Wheels and Tires subsystem that were chose for detailed evaluation. Included are five components that are being redesigned and changed in order to achieve mass reductions.

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System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
04	**04**	**01**	**Wheels and Tires Subsystem**	
04	04	01	All Tires (P225/60R19)	Replace from 2008 Toyota Prius (mass:14.880-13.200 & cost:0.98)
04	04	01	All Wheels (19 x 7.5)	Replace from 2008 Toyota Prius (mass:15.300-8.600 & cost:0.93)
04	04	01	Lug Nuts	Combination. Make lug nuts out of magnesium using conical design.
04	04	01	Spare Tire Wheel	Eliminate spare tire and use run-flat tires
04	04	01	Spare Tire	Downsize - Replace from 2008 Toyota Prius (mass:8.435-7.435 & cost:0.98)

Table F.5-18: Mass-Reduction Ideas Selected for the Detailed Wheels and Tires Subsystem Analysis

The mass saving solutions selected for the various components within the Wheel and Tire Subsystem are primarily by component substitution from the Toyota Prius as recommended in the March 2010 Lotus Report. The details of these changes vary greatly and are summarized in greater detail below.

F.5.4.5.1 Road Wheel & Tire Assemblies

The solution selected for the Road Wheel & Tire Assemblies (**Image F.5-92**) is to substitute the current OEM units with those from the Toyota Prius. This would change the effective mass without altering the effective design content or visual aspect in relation to the vehicle appearance. Both vehicles have Al cast rims and similar tire profiles. The new implemented Road Wheel & Tire Assemblies (4 pieces) have a total mass of 92.010kg.

Image F.5-92: Road Wheel & Tire Mass Reduced Assembly

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.4.5.1.1 Road Wheels

The chosen mass reduction for the Road Wheels (**Image F.5-93**) is still using an Al cast wheel design but instead substitute the Toyota Prius Road Wheel in its place. The size of wheel used on the Prius is a 16.5" outer diameter x 7.0" width. This size was normalized up to a 19" OD in order to maintain the styling and appearance of the current Venza vehicle. This new Road Wheel (4 pieces) has a total mass of 38.00kg.

Image F.5-93: Road Wheel Mass Reduced Component

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.4.5.1.2 Road Tire Assembly

The solution selected for the Road Tire Assemblies (**Image F.5-94**) is a substitution of the Toyota Prius tire as a replacement. The size of the tire used on the Prius is P185/65R16. This size was normalized up to a P225/60R19 in order to maintain the appearance and handling function of the current Venza vehicle. The new Road Tire Assemblies (4 pieces) have a net mass of 52.80kg.

Image F.5-94: Road Tire Mass Reduced Assembly

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.4.5.2 Spare Wheel & Tire Assembly

The solution implemented for the Spare Wheel & Tire Assembly (**Image F.5-95**) is substituting a Toyota Prius unit in its place. The design configuration and construction are the same and will not affect function or performance. Both use an over-molded spare tire mounted on a large-diameter, stamped steel wheel assembly. The mass-reduced Prius Spare Tire Assembly has a mass of 17.176kg.

Image F.5-95: Spare Wheel & Tire Mass Reduced Assembly

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.4.5.2.1 *Spare Wheel*

The new redesigned Spare Wheel (**Image F.5-96**) is still a multi-piece sub-assembly of stamped steel and welded fabrications. This wheel is being directly replaced with the Toyota Prius spare wheel. The new mass-reduced Spare Wheel has a mass of 9.731kg.

Image F.5-96: Spare Wheel Mass Reduced Assembly

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.4.5.2.2 *Spare Tire*

The mass-reduced Spare Tire Assembly (**Image F.5-97**) is achieved by replacing the Venza tire with the Prius tire. This results in a new mass of 7.435kg.

Image F.5-97: Road Wheel Mass Reduced Component

(Source:http://a2mac1.com/AutoReverse/reversepart.asp)

F.5.4.5.3 Lug Nuts

The Lug Nuts (**Image F.5-98**) are standard steel configuration, as is true with most OEMs. The new solution implemented for these fasteners is to use Mg material with a conical interface design. Due to the replacement of steel with Mg, an additional material volume of 30-40% was made. This style is commonly used by aftermarket manufacturers due to tremendous weight savings and reduction to unsprung rotational mass. The new Lug Nuts (20pcs) are calculated to have a net mass of 0.494kg.

Image F.5-98: Lug Nut Mass Reduced Component Examples

(Source: http://www.amazon.com/Drop-Engineering-ALG-RD-152-Aluminum-Thread)

F.5.4.6 Calculated Mass-Reduction & Cost Impact Results

Table F.5-19 shows the results of the mass reduction ideas that were evaluated for the Wheels and Tires subsystem. The implemented solutions resulted in a subsystem overall mass savings of 32.833kg and a cost decrease differential of $78.77.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
04	04	00	**Wheels and Tires Subsystem**						
04	04	01	Road Wheels and Tires Assy	A	30.833	$78.51	$2.55	28.08%	1.80%
04	04	02	Spare Wheel and Tire Assembly	A	2.000	$0.26	$0.13	10.41%	0.12%
04	04	04	Tire Pressure Warning & Adjust		0.000	$0.00	$0.00	0.00%	0.00%
				A	**32.833** (Decrease)	**$78.77** (Decrease)	**$2.40** (Decrease)	**25.69%**	**1.92%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.5-19: Mass-Reduction and Cost Impact for the Brake Actuation Subsystem

F.6 Driveline System

As shown in **Table F.6-1**, the Driveline system is made up of six subsystems: Driveshaft, Rear Drive Housed Axle, Front Drive Housed Axle, Front Drive Half Shafts, Rear Drive Half Shafts, and 4WD Driveline Control. The Driveshaft, Rear Drive Half-Shafts, and the 4WD Driveline Control subsystems are not applicable to this study as the Toyota Venza is a front-wheel-drive vehicle. The Rear Drive Housed Axle subsystem is comprised primarily of the Rear Wheel Bearing and Hub Assemblies. The Front Drive Housed Axle subsystem contains the Drive Hubs. The Front Drive Half Shafts subsystems contain the right and left half-shafts along with the carrier bearing.

In comparing the three subsystems, the greatest mass is located in the Front Drive Half-Shafts subsystem.

System	Subsystem	Sub-Subsystem	Description	System & Subsystem Mass "kg"
05	**00**	**00**	**Driveline System**	
05	01	00	Driveshaft Subsystem	0.000
05	02	00	Rear Drive Housed Axle Subsystem	8.631
05	03	00	Front Drive Housed Axle Subsystem	6.354
05	04	00	Front Drive Half-Shafts Subsystem	18.672
05	05	00	Rear Drive Half-Shafts Subsystem	0.000
05	07	00	4WD Driveline Control Subsystem	0.000
			Total System Mass =	**33.657**
			Total Vehicle Mass =	**1711**
			System Mass Contribution Relative to Vehicle =	**1.97%**

Table F.6-1: Baseline Subsystem Breakdown for Driveline System

Table F.6-2 shows the calculated mass-reduction results for the ideas generated related to the Driveline system. A mass savings of 1.503kg was realized with a cost increase of $0.16, resulting in a cost increase of $0.11 per kg.

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
05	00	00	**Driveline System**						
05	01	00	Driveshaft Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
05	02	00	Rear Drive Housed Axle Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
05	03	00	Front Drive Housed Axle Subsystem	A	0.733	$1.54	$2.10	11.54%	0.04%
05	04	00	Front Drive Half-Shafts Subsystem	C	0.770	-$1.70	-$2.21	4.12%	0.04%
05	05	00	Rear Drive Half-Shafts Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
05	07	00	4WD Driveline Control Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
				B	**1.503** (Decrease)	**-$0.16** (Increase)	**-$0.11** (Increase)	**4.47%**	**0.09%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.6-2: Calculated Mass-Reduction and Cost Impact for Driveline System

F.6.1 Front Drive Housed Axle Subsystem

F.6.1.1 Subsystem Content Overview

As seen in **Table F.6-3**, the only contributor to the mass of the Front Drive Housed Axle subsystem is the Front Drive Unit. The Front Drive Unit contains the left- and right-hand drive hub assembly (**Image F.6-1)** and associated hardware.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
05	03	00	**Front Drive Housed Axle Subsystem**	
05	03	04	Front Drive Unit (Drive Hubs)	6.354
			Total Subsystem Mass =	**6.354**
			Total System Mass =	**33.657**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**18.88%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.37%**

Table F.6-3: Mass Breakdown by Sub-subsystem for Front Drive Housed Axle Subsystem

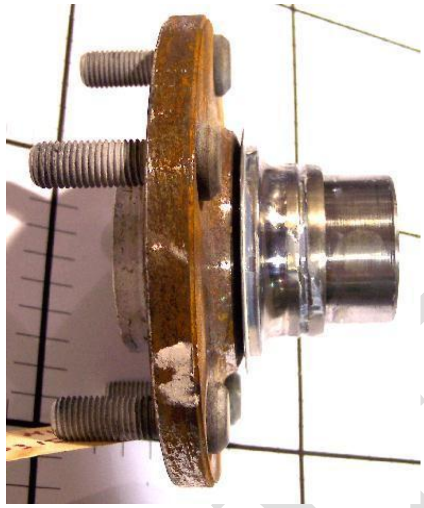


Image F.6-1: Front Drive Hub Assembly

(Source: FEV photo)

F.6.1.2 Toyota Venza Baseline Subsystem Technology

The Toyota Venza Front Drive Housed Axle subsystem follows typical industry standards in that there is nothing new, eye catching, or unique. The Front Drive Hubs (**Image F.6-2**) are forged and machined to OEM specifications.

F.6.2 Mass-Reduction Industry Trends

F.6.2.1 Drive Hubs

Drive hubs (**Image F.6-2**) for cars will continue to require high-strength parts to provide reliable, safe functionality as a driveline part. Steel forgings produce advantageous grain flow for superior strength compared to castings and fully machined billets. Compared to castings, forgings offer high strength/weight ratios and high impact resistance. Heat treatment is usually required to maintain dimensional stability.

Although carbon fiber parts are in use for hubs, they currently appear only in Formula 1 race cars and some of the very low production volume supercars. Applications of carbon fiber hubs in regular production cars will require significant development of low cost production methods and much larger material availability. A technology that bears watching is bulk compound molding using polymer material that is filled with long carbon fiber. The hope is that low-cost, low-mass carbon fiber parts can be made with strength equivalent to steel.

In the last decade, basalt fiber has emerged as a contender in the fiber reinforcement of composites. Proponents of this technology claim their products offer performance similar to S-2 glass fibers at a price between S-2 glass and E-glass, and may offer manufacturers a less expensive alternative to carbon fiber.

Applications of basalt fiber and bulk-molded carbon fiber will be delayed into the indefinite future because of limited production capacity. However, the continental United States has very large deposits of basalt. Michigan, in fact, in its upper peninsula, is among the continental states that contain basalt deposits. Basalt fiber research, production and most marketing efforts are based in countries once aligned with the Soviet bloc. Companies currently involved in basalt production and marketing include Kamenny Vek (Dubna, Russia), Technobasalt (Kyiv, Ukraine), Hengdian Group Shanghai Russia & Gold Basalt Fibre Co. (Shanghai, China), OJSC Research Institute Glassplastics and Fiber (Bucha, Ukraine), Basaltex, a division of Masureel Holding (Wevelgem, Belgium), Sudaglass Fiber Technology Inc. (Houston, Texas), and Allied Composite Technologies LLC (Rochester Hills, Michigan).

Simple part modification can also be applied to the front and rear hubs as seen on the 2011 Toyota Sienna. The Sienna achieved weight reduction by drilling holes between each tire stud, scallops and reduced thickness of the wheel mounting flange. In the absence of lighter material options, scallops were applied to the front hub flange as seen in **Image F.6-3**.

Image F.6-2: Front Drive Hub

(Source: FEV photo)

F.6.3 Summary of Mass-Reduction Concepts Considered

Table F.6-4 shows the mass reduction ideas considered from the brainstorming activity for the Front Axle Hub.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Front Axle Hub	Scallop front axle hubs	20% Weight Save	10% Cost Increase
	Drill ½" Holes in front axle hubs	3% Weight Save	Minimal Cost Increase
	Go to a 4 stud design instead of 5 studs	30% Weight Save	Low Production Application
	Make out of 6AL4V Titanium Alloy	50% Weight Save	800% Cost Increase

Table F.6-4: Summary of mass-reduction concepts initially considered for the Front Drive Housed Axle Subsystem

F.6.4 Selection of Mass Reduction Ideas

Table F.6-5 shows the selected mass reduction ideafor the Front Drive Housed Axle subsystem for detailed evaluation of both mass savings achieved and the cost to manufacture.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
05	**03**	**00**	**Front Drive Housed Axle Subsystem**	
05	03	04	Front Drive Unit	Scallop front axle hubs

Table F.6-5: Mass-Reduction Ideas Selected for Front Drive Housed Axle Subsystem Analysis

F.6.4.1 Front Drive Unit

The solution chosen to be implemented on the Front Drive Unit (**Image F.6-3**) was the idea that reduced the most mass with the lowest possible cost impact. Scalloped hubs (**Image F.6-3**) allow for additional mass savings with no cost impact since the material is removed during the forging process.

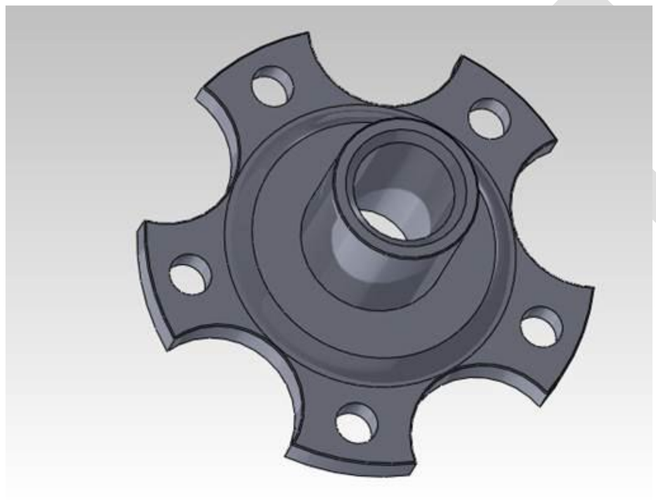


Image F.6-3: Front Axle Hub

(Source: FEV)

F.6.5 Calculated Mass-Reduction & Cost Impact Results

Table F.6-6 shows the evaluated mass reduction results for the Front Drive Housed Axle subsystem, which totaled an overall subsystem mass savings of 0.733kgand a cost savings of $1.54.

The Front Drive Unit sub-subsystem includes the Front Axle Hub, which was changed from a solid flange design to a multi-scallop design and accounts for 100% of the 0.733 kg weight save. The Front Drive Unit sub-subsystem reduces the cost of this sub-subsystem by $1.54.

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
05	03	00	**Front Drive Housed Axle Subsystem**						
05	03	04	Front Drive Unit	A	0.733	$1.54	$2.10	11.54%	0.04%
				A	**0.733** (Decrease)	**$1.54** (Decrease)	**$2.10** (Decrease)	**11.54%**	**0.04%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.6-6: Calculated Subsystem Mass-Reduction and Cost Impact Results for Front Drive Housed Axle Subsystem

F.6.6 Front Drive Half-Shafts Subsystem

F.6.6.1 Subsystem Content Overview

Image F.6-4shows the entire Front Right-hand Drive Half Shaft system and how the individual parts connect to each other. The bearing shown at the left side of the photo is housed inside the Bearing Carrier (**Image F.6-5**).

Image F.6-4: Half Shafts

(Source: FEV photo)

Image F.6-5: Bearing Carrier

(Source: FEV photo)

Table F.6-7 shows the mass breakdown of the Front Drive Half Shafts subsystem. This subsystem contains the Front Half-Shaft sub-subsystem, which includes Half Shafts, Bearing Carrier, Bearing Carrier Bolt, and Mounting Fasteners.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
05	04	00	**Front Drive Half-Shafts Subsystem**	
05	04	01	Front Half Shaft (Half Shafts, Bearing Carrier)	18.672
			Total Subsystem Mass =	**18.672**
			Total System Mass =	**33.657**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**55.48%**
			Subsystem Mass Contribution Relative to Vehicle =	**1.09%**

Table F.6-7: Mass Breakdown by Sub-subsystem for Front Drive Half-Shafts Subsystem

F.6.7 Toyota Venza Baseline Subsystem Technology

The Toyota Venza Front Drive Half-Shafts subsystem follows typical industry standards as it has nothing new, out of the ordinary, or unique. The right-hand half-shafts are steel and have been weight-reduced for the most part. The bearing carrier housing is cast iron. It is machined to accept the carrier bearing and provide a suitable mounting surface. The bearing carrier has a steel M10-1.25 bolt fastened to the side – which adds no value or benefit.

F.6.8 Mass-Reduction Industry Trends

A company called Precision Shaft Technologies has developed a lightweight, one-piece driveshaft for racing featuring forged 7075 aluminum tube yoke bonded into pultruded carbon fiber tubing. Cost will be a deterrent for some time to come regarding application to regular car production.

F.6.8.1 Right-Hand Half Shaft

The Front RH Drive Shaft (**Image F.6-6**) was found to offer further weight reduction opportunity as it is the only solid shaft in the Front RH Driveshaft system. All other shafts in the Driveshaft system have been light weighted by the use of tubing.

Image F.6-6: Front RH Driveshaft

(Source: FEV photo)

F.6.8.2 Bearing Carrier

The Bearing Carrier, Figure 1-14, was found to offer further weight reduction as it is cast iron. There are several examples of bearing carriers being manufactured from cast aluminum.

Image F.6-7: Bearing Carrier

(Source: FEV photo)

F.6.8.3 Bearing Carrier Bolt

The Bearing Carrier Bolt (**Image F.6-8**) was found to provide further weight reduction opportunity as it is not utilized in this Venza model.

Image F.6-8: Bearing Carrier Bolt

(Source: FEV photo)

F.6.9 Summary of Mass-Reduction Concepts Considered

The Front Drive Half-Shafts subsystem summary chart **Table F.6-8** shows several mass reduction ideas that suggest changing components from steel to titanium, magnesium, or aluminum components.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Axle Half-Shaft	Make axle shafts out of carbon fiber pulltrusion	60% Weight Save	Significant cost increase
	Make out of 6AL4V Titanium Alloy (solid)	40% Weight Save	Significant cost increase
	Make out of 6AL4V Titanium Alloy (tubular or hollow)	40% Weight Save	Significant cost increase
	Hollow out non hollow shaft	6% Weight Save	Cost Increase
Bearing Carrier	Make bearing carrier out of cast aluminum instead of cast steel	60% Weight Save	50% Cost Savings
	Make out of Al forged 6061-T6	60% Weight Save	50% Cost Savings
	Go to a 3 hole mounting design instead of 4 holes	20% Weight Save	Cost Save, Unproven Capability
Bearing Carrier Bolt	Replace carrier bearing bolt with plastic plug	70% Weight Save	Cost Save

Table F.6-8: Summary of mass-reduction concepts initially considered for the Front Drive Half-Shafts Subsystem

F.6.10 Selection of Mass Reduction Ideas

Table F.6-9 shows ideas selected for detail evaluation.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
05	04	00	Front Drive Half-Shafts Subsystem	
05	04	01	Front Half shaft	Hollow out non-hollow shaft
05	04	01	Bearing Carrier - Center Axle	Replace bearing carrier bolt with plastic plug
05	04	01	Bearing Carrier - Center Axle	Make out of forged aluminum 6061-T6

Table F.6-9: Mass-Reduction Ideas Selected for Front Drive Half-Shafts Subsystem Analysis

F.6.10.1 RH Half Shaft

The solution selected for implementation on the Front RH Driveshaft (**Image F.6-9**) is hollowing out the driveshaft.

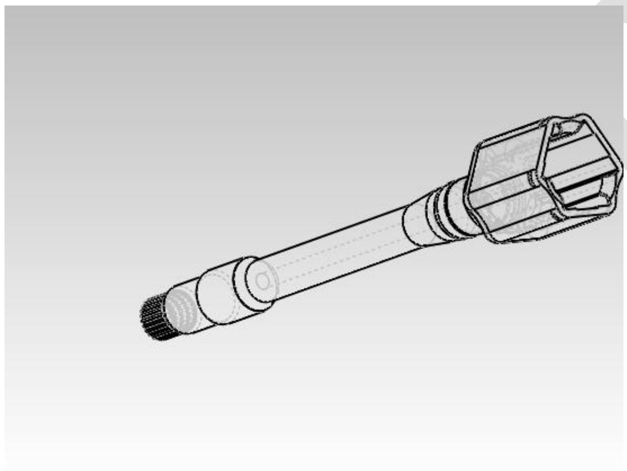


Image F.6-9: Front RH Driveshaft

F.6.10.2 Bearing Carrier

The solution selected for implementation on the Bearing Carrier (**Image F.6-10**) is to cast the housing out of aluminum instead of steel.

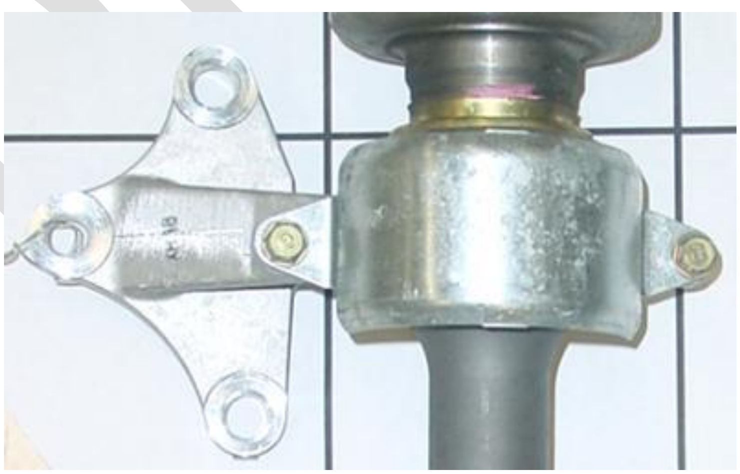


Image F.6-10: Bearing Carrier

(Source: FEV photo)

F.6.10.3 Bearing Carrier Bolt

The solution selected for implementation on the Bearing Carrier Bolt is to replace the bolt with a push-in plastic plug (**Image F.6-11**).

Image F.6-11: Push-in plastic plug

(Source: FEV photo)

F.6.11 Calculated Mass-Reduction & Cost Impact Results

Table F.6-12 shows the results of the mass reduction ideas applied to the Front Drive Half-Shafts subsystem as well as the cost impact which totaled an overall subsystem mass savings of 0.770kg and a cost hit of $1.70

The Front Half Shaft sub-subsystem includes the Front Drive Shaft, which was drilled out and accounts for 33% of the 0.770 kg weight save. The remaining 67% of the mass reduction was reduced by changing the Bearing Carrier from a cast iron design to a cast aluminum design.

System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
				Net Value of Mass Reduction Idea					
05	04	00	**Front Drive Half-Shafts Subsystem**						
05	04	01	Front Half Shaft	C	0.770	-$1.70	-$2.21	4.12%	0.04%
				C	**0.770** (Decrease)	**-$1.70** (Increase)	**-$2.21** (Increase)	**4.12%**	**0.04%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.6-10: Calculated Mass-Reduction and Cost Impact Results for the Front Drive Half-Shafts Subsystem

F.7 Braking System

As shown in **Table F.7-1**, the Brake system is composed of six subsystems: Front Rotor/Drum and Shield; Rear Rotor/Drum and Shield; Parking Brake & Actuation; Brake Actuation; Power Brake; and Brake Controls Subsystems. In comparing the six subsystems, the greatest mass is located in the Front Rotor/Drum and Shield subsystem with approximately 38.45%.

System	Subsystem	Sub-Subsystem	Description	System & Subsystem Mass "kg"
06	**00**	**00**	**Brake System**	
06	03	00	Front Rotor/Drum and Shield Subsystem	32.971
06	04	00	Rear Rotor/Drum and Shield Subsystem	22.470
06	05	00	Parking Brake and Actuation Subsystem	13.405
06	06	00	Brake Actuation Subsystem	5.536
06	07	00	Power Brake Subsystem (for Hydraulic)	2.829
06	09	00	Brake Controls Subsystem	8.527
			Total System Mass =	**85.740**
			Total Vehicle Mass =	**1711**
			System Mass Contribution Relative to Vehicle =	**5.01%**

Table F.7-0-2: Baseline Subsystem Breakdown for the Braking System

The Final Calculated Results Summary for the entire Toyota Venza Brake system is shown in **Table F.7-2**. This combination of proposed solutions were selected for this cost group due to the significant weight savings that were calculated to be obtained (approx 40.089kg) while also allowing for lower overall costs (approximately $116.24).

				Net Value of Mass Reduction Ideas					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
06	**00**	**00**	**Brake System**						
06	03	00	Front Rotor/Drum and Shield Subsystem	A	16.599	-$6.07	-$0.37	50.34%	0.97%
06	04	00	Rear Rotor/Drum and Shield Subsystem	A	9.676	$6.08	$0.63	43.06%	0.57%
06	05	00	Parking Brake and Actuation Subsystem	A	9.635	$82.98	$8.61	71.88%	0.56%
06	06	00	Brake Actuation Subsystem	A	2.984	$31.90	$10.69	53.90%	0.17%
06	07	00	Power Brake Subsystem (for Hydraulic)	A	1.196	$1.35	$1.13	42.25%	0.07%
06	09	00	Brake Controls Subsystem		0.000	0.000	$0.00	0.00%	0.00%
				A	**40.089** (Decrease)	**$116.24** (Decrease)	**$2.90** (Decrease)	**52.29%**	**2.34%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.7-2: Mass-Reduction and Cost Impact for the Braking System

F.7.1 <u>Front Rotor / Drum and Shield Subsystem</u>

F.7.1.1 Subsystem Content Overview

This pictorial diagram, **Image F.7-1**, represents the major brake components in the Front Rotor/Drum and Shield subsystem and their relative location and position relevant to one another as located on the vehicle front corner.

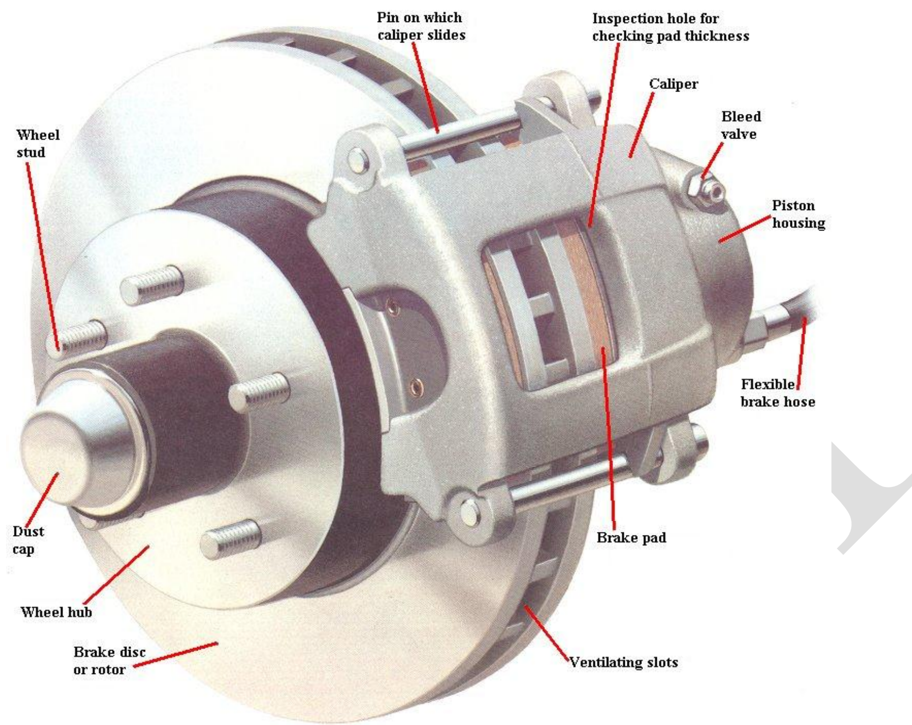


Image F.7-1: Front Rotor / Drum and Shield Subsystem Relative Location Diagram

(Source: http://www.motorera.com/dictionary/di.htm)

As seen in **Image F.7-2**, the Front Rotor/Drum and Shield subsystem consists of the major components of the Front Rotor, the Front Splash Shield, the Front Caliper Assembly, the Front Caliper Mounting and miscellaneous Anchor and Attaching components.

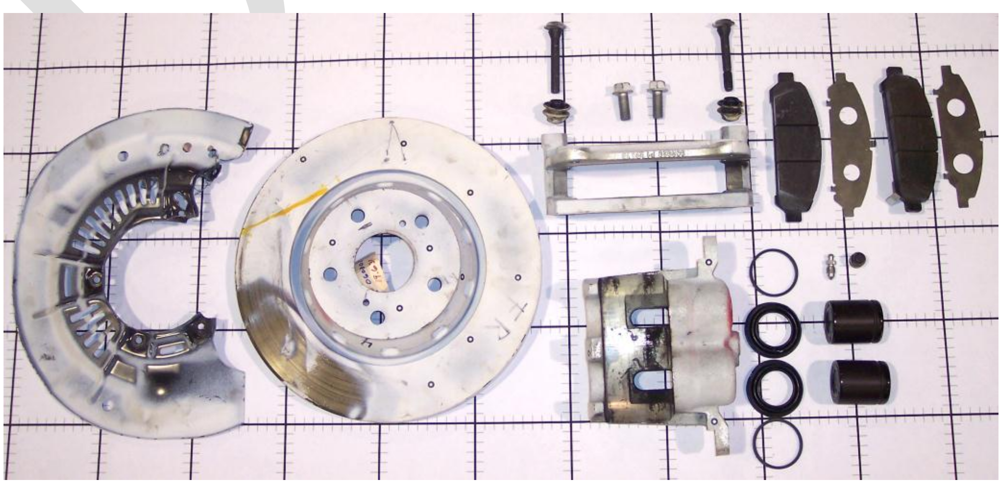


Image F.7-2: Front Rotor / Drum and Shield Subsystem Current Major Components

(Source: FEV Inc photo)

Table F.7-3 indicates the two sub-subsystems that make-up the Front Rotor/Drum and Shield subsystem. These are the Front Rotor and Shield sub-subsystem and the Anchor and Attaching Components sub-subsystem. The most significant contributor to the mass within this subsystem was found to be within the Front Rotor and Shield Sub-subsystem (approx 57.6%).

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
06	**03**	**00**	**Front Rotor/Drum and Shield Subsystem**	**--**
06	03	01	Front Rotor and Shield	18.922
06	03	02	Front Caliper, Anchor and Attaching Components	13.925
			Total Subsystem Mass =	**32.847**
			Total System Mass =	**85.740**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**38.31%**
			System Mass Contribution Relative to Vehicle =	**1.92%**

Table F.7-3: Mass Breakdown by Sub-subsystem for the Front Rotor / Drum and Shield Subsystem

F.7.1.2 Toyota Venza Baseline Subsystem Technology

The Toyota Venza's Front Rotor and Shield subsystem (**Image F.7-3**) follows typical industry standards for design and performance. The Rotors (**Image F.7-4**) are single piece, vented design cast out of grey iron and manufactured to SAE specifications. The Splash Shields (**Image F.7-5**) are typical stamped and vented steel fabrications. The Caliper Assembly (**Image F.7-6**) is composed of several components. These include: The Caliper Housings (**Image F.7-7**) which are high nickel content cast iron with the appropriate machining. The Caliper Mountings, (**Image F.7-8**) are cast iron and machined. The Brake Caliper Assembly houses the Brake Pads and Pistons. The Caliper Pistons (**Image F.7-9**) are molded phenolic glass-filled plastic with standard seal configurations. The Brake Pads (**Image F.7-10**) are of standard construction with steel backing plates and friction pad materials. The current OEM Toyota Venza Front Brake Corner Assembly, example shown below, has a mass of 35.88kg.

Image F.7-3: Front Brake System Current Assembly Example

(Source: http://www.imakenews.com/tituswillford)

F.7.1.3 Mass-Reduction Industry Trends

F.7.1.3.1 Rotors

The baseline OEM Toyota Venza Front Rotor (**Image F.7-4**) is a single piece, vented design cast out of grey iron and has a mass of 8.92kg. Many high performance and luxury vehicle models have began utilizing alternate rotor designs in order to improve both performance and economy. Two-piece rotor assemblies are now found in many Mercedes', BMW's, Audi's, Corvette's, and Porsche's across multiple platforms and models. This two-piece configuration was also mentioned in the March 2010 Lotus Report. Besides OEM's, there are aftermarket suppliers that use this design. Brembo and Wilwood are two such companies that have used this rotor design in various production applications. This two-piece design usually utilizes an Aluminum Center Hub (or Hat) along with a disc braking surface (typically cast iron or steel).

Image F.7-4: Front Rotor Current Component

(Source: Lotus – 2010 March EPA Report)

The Rotor Center (Hat) can be made from several material choices including Aluminum (Al), Titanium (Ti), Magnesium (Mg), Grey Iron or Steel (Fe) and manufactured from cast forms or billet machined from solid.

The Rotor disc surfaces are also able to be made from various materials and processing methods. These include Aluminum Metal Matrix Composites (Al/MMC), MMC, Ti and Fe. Even Carbon / Ceramic matrices have been used to produce rotors of less mass. Processing includes casting vented or solid disc plates and the machining cross-drilled plates, slotted plates and scalloped disc diameter (both ID and OD) profiles.

Some race cars and airplanes use brakes with carbon fiber discs and carbon fiber pads to reduce weight. For these systems, wear rates tend to be high, and braking may be poor or “grabby” until the brake is heated to the proper operating temperature. Again, this technology adds substantial costs if considered for regular high volume automotive production capacities.

F.7.1.3.2 Splash Shields

The baseline OEM Toyota Venza Front Splash Shield is a multi-piece welded, vented design, stamped of common steel and has a mass of 0.435kg. A majority of splash shields (or dust shields) (**Image F.7-5**) are made from stamped, light gage steel. Some are vented or slotted for reduced material usage and increased weight savings. Alternative materials are now beginning to be examined for use to further reduce weight contribution. These include Al, high strength steels and even various reinforced plastics.

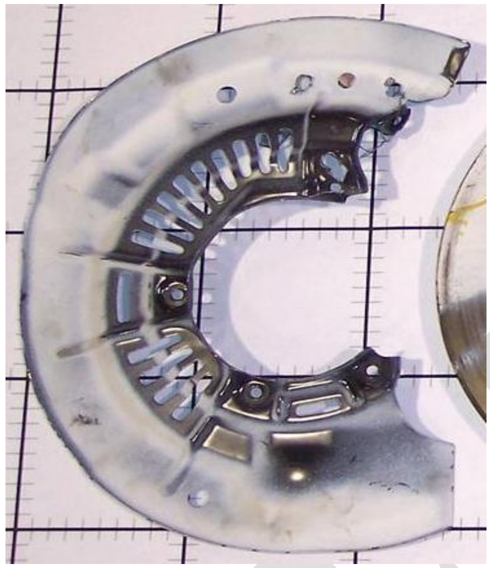


Image F.7-5: Front Splash Shield Current Component

(Source: FEV Inc photo)

F.7.1.3.3 Caliper Assembly

The baseline OEM Toyota Venza Front Caliper Assembly is a multi-piece assembly with the major components being made from cast iron and has a mass of 5.957kg. Traditionally caliper assemblies, **Image F.7-6**, are comprised of several components. These include: Housing, Mounting, Mounting Attachment Bolts (2), Inboard Brake Pad & Shim Plate, Outboard Brake Pad & Shim Plate, Pistons (2), Piston Seal Ring (2), Piston Seal Boots (2), Mounting Slide Pins (2), Mounting Slide Pin Boots (2), Housing Bleeder Valve and Housing Bleeder Valve Cap.

Image F.7-6: Front Caliper Current Assembly

(Source: http://cdn0.autopartsnetwork.com/images/catalog/brand/centric/640/14144280.jpg)

F.7.1.3.3.1 *Housings*

The baseline OEM Toyota Venza Front Caliper Housing is a single piece cast iron design and has a mass of 3.832kg. Traditionally caliper housings, **Image F.7-7**, have been made from various grades of cast iron. This allowed for adequate strength while also acting as a heat sink to assist in the brake cooling function. Now with advances in materials and processing methods, other choices are available and being utilized in aftermarket and high performance applications as well as OEM vehicle markets. Among some of these alternate mediums are Al, Ti, Steel, Mg and MMC. Forming methods now include sand cast, semi-permanent metal molding, die casting and machining from billet.

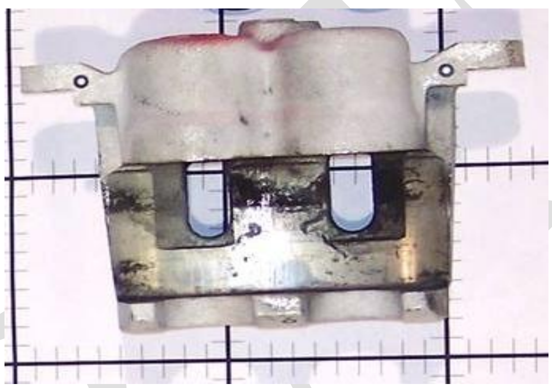


Image F.7-7: Front Caliper Housing Current Component

(Source: FEV Inc photo)

While these alternatives now are designed with the strength and performance required, they do add a significant cost-versus-mass increase. However the weight savings achieved is quite substantial and assists with reducing vehicle requirements for suspension loads, handling, ride quality, engine hp requirements, etc. Other advanced development includes using bulk molding compound using long randomly oriented carbon fiber continues to be of interest due to the ability to easily mold it into complex shapes. However, temperature extremes encountered by brake components and the current cost of the material will be serious challenges for some time to come.

F.7.1.3.3.2 *Mountings*

The baseline OEM Toyota Venza Front Caliper Mounting (or Bracket) is a single piece cast iron design and has a mass of 1.671kg. Caliper mountings (**Image F.7-8**) have normally been made from various grades of cast iron for adequate strength and function. Now with advances in materials and processing methods other choices are available and being utilized in aftermarket and high performance applications as well as OEM vehicle markets. Among some of these alternate mediums are Al, Ti, Steel and Mg. Forming and fabrication methods include casting and billet machining.

Image F.7-8: Front Caliper Mounting Current Component

(Source: FEV Inc photo)

F.7.1.3.3.3 *Pistons*

The baseline OEM Toyota Venza Front Caliper Pistons are a single piece phenolic glass-filled design and have a mass of 0.127kg. Caliper pistons (**Image F.7-9**) commonly are made from various alloys of steel for function and heat resistance. Now advances alternative materials and processing methods allow new choices to be available. Rather than metallics only (Al, Steel, Ti) being utilized there are Phenolic glass-filled plastics that are used in high volume by OEMs. These are molded to near net shape with minimal machining required, saving both material and processing time while saving significant mass.

Image F.7-9: Front Caliper Piston Current Components

(Source: FEV, Inc. photo)

F.7.1.3.3.4 *Brake Pads*

The baseline OEM Toyota Venza Front Caliper Brake Pads are of standard construction with steel backing plates and friction pad materials. They have a mass of 0.957kg. The brake pads, **Image F.7-10**, has had little change in design, materials or processing in recent years. Most have steel backing plates with a molded friction material attached to them. Various size braking surfaces and molded shapes are the common variations across different vehicle platforms. Most material differences are focused only in the friction material going from traditional asbestos now to semi-metallic and full metallics as well as various ceramic compounds. While these friction materials greatly affect performance and vehicle stopping distances under various conditions, little is accomplished in saving mass and reducing material weight.

Image F.7-10: Front Caliper Brake Pad Current Components

(Source: FEV Inc. photo)

F.7.1.4 Summary of Mass-Reduction Concepts Considered

Table F.7-4 shows the mass reduction ideas considered from the brainstorming activity for the Front Rotor/Drum and Shield Subsystem and their various components. These ideas include part modifications, material substitutions, processing and fabrication differences, and use of alternative parts currently in production and used on other vehicles and applications.

Component/ Assembly	Mass Reduction Idea	Estimated Impact	Risk & Trade-offs and/or Benefits
Front Rotor/Drum and Shield Subsystem			
Rotor	Vent (slot) front rotors	0-5% wt save	Low production - auto
	Cross-Drill front rotors	10-20% wt save	In Production - Most Auto Makers
	Rotor Downsizing based on vehicle mass reduction (34%) (9 of 10)	30-40% wt save	Lower Cost. In production - auto
	Two piece Rotor - Al light-weight center (hat) with Iron/Steel/CF outer surface (disc) w/ T-nut fasteners	20-30% wt save	In Production - Merc, BMW, Audi
	Change Material for Rotors - Al/MMC	40-50% wt save	High Cost. In Production - racing / aftermarket
	Downsizing based on Rotor fins	0-5% wt save	Low production - auto
	Clearance mill openings (rotor ID scalloping) around hat perimeter on rotor disc ID	20-30% wt save	In Production - Merc, BMW, Audi
	Clearance mill space (rotor OD scalloping) around disc OD perimeter	10-20% wt save	In Production - Motorcycles
	Clearance drill holes in rotor top hat surface to reduce wt (5 - 9/16" dia. X.25DP)	5-10% wt save	In Production - Merc, BMW, Audi
	Increase slots around rotor hat perimeter (OD) 50% (10 - .625Wide x 1.125Long x .25 Dp)	0-5% wt save	In Production - Most Auto Makers
	Chg from straight to directional vanes btwn rotor disc surfaces	0-5% wt save	In Production - Merc, BMW, Audi
	Make brake rotors out of ceramic	50-60% wt save	In Production - racing
	Replace from 2008 Toyota Prius (mass:17.820-12.811 & cost:0.96)	30-40% wt save	Lower Cost. In Production - Toyota
	Combine 16, 18, 41, 45, 52, 51, 60, 62, 64 & 66. Modify rotors with slotting, cross-drilling, 2-pc design, Al Hat, downsize from Prius, chg mat'l to Al/MMC, chg fin design (directional), rotor ID & OD scalloping, holes in rotor top hat surface & side perimeter.	60-70% wt save	High Cost. Various partial combinations in production by various high performance sports car manufacturers
Splash Shield	Replace from 2008 Toyota Prius (mass:0.893-0.388 & cost:0.93)	50-60% wt save	Lower cost. In Production - Toyota
	Make splash shield out of plastic	60-70% wt save	Low Cost. Low production - auto
	Combination. Replace from Prius & make out of plastic.	70-80% wt save	Lower Cost. Need development
	Make splash shield out of HSS	10-20% wt save	Higher Cost. Low production - auto
	Make splash shield out of Aluminum	30-40% wt save	Higher Cost. Low production - auto
	Make splash shield out of Titanium	20-30% wt save	High Cost. In Production - racing

Table F.7-4 continued on next page

Brake Pads	Replace from 2008 Toyota Prius (mass:2.004-1.377 & cost:0.98)	30-40% wt save	In Production - Toyota
	Combination. Replace from Prius and use thinner pad materials	40-50% wt save	Lower Cost. Low production - auto
	Make brake pad wear material thinner	5-10% wt save	Low production - auto
Calipers	Caliper Downsizing based on vehicle mass reduction	10-20% wt save	In Production - Most Auto Makers
	Change Material for selectively reinforced calipers (Al/MMC)	20-30% wt save	High Cost. In Production - racing
	Make caliper assembly out of cast magnesium	40-50% wt save	High Cost. In Production - auto
	Make caliper assembly out of cast aluminum	20-30% wt save	Higher Cost. In production - auto
	Make caliper assembly out of forged aluminum	30-40% wt save	Higher Cost. In production - auto
	Replace from 2008 Toyota Prius (mass:12.071-7.413 & cost:0.96)	30-40% wt save	Lower cost. In Production - Toyota
	Combination. Replace from Prius, downsize for mass reduction & chg mat'l to cast Mg	60-70% wt save	High Cost. Low production - auto
Caliper Mounting Bracket	Caliper Downsizing based on vehicle mass reduction	10-20% wt save	In Production - Most Auto Makers
	Change Material for selectively reinforced calipers (Al/MMC)	20-30% wt save	High Cost. In Production - racing
	Make caliper assembly out of titanium	40-50% wt save	High Cost. In Production - racing
	Make caliper assembly out of cast magnesium	40-50% wt save	High Cost. In Production - auto
	Make caliper assembly out of cast aluminum	20-30% wt save	Higher Cost. In production - auto
	Make caliper assembly out of forged aluminum	30-40% wt save	Higher Cost. In production - auto
	Replace from 2008 Toyota Prius (mass:12.071-7.413 & cost:0.96)	30-40% wt save	Lower cost. In Production - Toyota
	Combination. Replace from Prius, downsize for mass reduction & chg mat'l to cast Mg	60-70% wt save	High Cost. Low production - auto

Table F.7-4: Summary of Mass-Reduction Concepts Initially Considered for the Front Rotor / Drum and Shield Subsystem

F.7.1.5 Selection of Mass Reduction Ideas

Table F.7-5 shows the mass reduction ideas for the Front Rotor/Drum and Shield subsystem that were selected for detailed evaluation of both the mass savings achieved and the cost to manufacture them. Several ideas suggest plastics and magnesium as alternate materials. Also, included are part substitutions from other vehicle designs such as those currently in use on the Toyota Prius (as determined in the March 2010 Lotus Report).

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
06	**03**	**00**	**Front Rotor/Drum and Shield Subsystem**	
06	03	00	Rotor	Combination. Modify rotors with slotting, cross-drilling, 2-pc design, Al Hat, downsize from Prius, chg mat'l to Al/MMC, chg fin design (directional), rotor ID & OD scalloping, holes in rotor top hat surface & side perimeter.
06	03	00	Splash Shield	Combination. Replace from Prius & make out of plastic.
06	03	00	Brake Pads	Combination. Replace from Prius and use thinner pad materials
06	03	00	Calipers	Combination. Replace from Prius, downsize for mass reduction & chg mat'l to cast Al
06	03	00	Caliper Mounting Bracket	Combination. Replace from Prius, downsize for mass reduction & chg mat'l to cast Al

Table F.7-5: Mass-Reduction Ideas Selected for the Detailed Front Rotor / Drum and Shield Subsystem Analysis

F.7.1.5.1 Rotors

The solution(s) chose to be implemented on the final Front Rotor Assembly (**Image F.7-22**) was the combination of multiple individual brainstorming ideas. These ideas included the following modifications to component design, material utilized and processing methods required:

- Two-piece Assembled Rotor Design, **Image F.7-11**

- Hat Fastened to Rotor Disc w/ T-Nuts and Bolts

  (Increased Process Time but Allows Better Hat Material Choices for Mass Savings)

- Manufacturers and OEMs include: Chevy, Mercedes, Audi, BMW, Wilwood, Brembo

Image F.7-11: Front Rotor Mass Reduced Component

(Source: http://www.wilwood.com/Pdf/Catalogs/TechCatalog.pdf)

- Al Hat (Material Substitution), **Image F.7-12**
  - Die Cast to Near-Net Shape

    (Mass Savings even with increased material volume of 20-30%, Decreased Processing Time, Rapid and Increased Heat Dissipation)

  - Manufacturers and OEMs include: Chevy, Mercedes, Audi, BMW, Wilwood, Brembo, Motorcycles

Image F.7-12: Front Rotor Mass Reduced Component

(Source: http://www.wilwood.com/Pdf/Catalogs/TechCatalog.pdf)

- Al / MMC Disc Surfaces (Material Substitution), **Image F.7-13**
  - SPMM Cast to Near-Net Shape

    (Drastic Mass Savings even with increased material volume of 10-20%, Heat Resistant, Improved Rotor Life, Reduced Cracking and Deformation)
  - Manufacturers and OEMs include: GM EV1, Plymouth Prowler Mercedes, Audi, BMW, Porsche, Ferrari, Lamborghini, Lotus, Wilwood, Brembo, Motorcycles

Image F.7-13: Front Rotor Mass Reduced Component

(Source: http://www.wilwood.com/Pdf/Catalogs/TechCatalog.pdf)

- Cast Directional Cooling Fins Between Disc Surfaces, **Image F.7-14**
  - Casting Process Change. Enhanced Disc Cooling.

    (Acts as Centrifuge Air Pump: Maximum Air Circulation for Increased Cooling. This is Required Due to Less Rotor Material Mass Available to Absorb Heat.)
  - Manufacturers and OEMs include: Mercedes, Audi, BMW, Porsche, Ferrari, Lamborghini, Wilwood, Brembo

Image F.7-14: Front Rotor Mass Reduced Component

(Source:http://www.highperformancepontiac.com/tech/hppp_1101_brake_rotor_guide/photo_03.html)

- Disc Surface Slotting, **Image F.7-15**
    - Slight Mass Savings and Improved Brake Pad Performance

      (Release Trapped Heat, Gas, and Dust from Disc Surface)
    - Manufacturers and OEMs include: Chevy, Pontiac, Cadillac, Mercedes, Audi, BMW, Porsche, Ferrari, Lamborghini, Wilwood, Brembo, Motorcycles

Image F.7-15: Front Rotor Mass Reduced Component

(Source: http://www.highperformancepontiac.com/tech/hppp_1101_brake_rotor_guide/photo_13.html)

- Disc Surface Cross-Drilling, **Image F.7-16**
  - Improved Disc Cooling and Mass Savings

    (Disperse Built-Up Heat and Gases)
  - Manufacturers and OEMs include: Chevy, Pontiac, Cadillac, Mercedes, Audi, BMW, Porsche, Ferrari, Lamborghini, Wilwood, Brembo, Motorcycles

Image F.7-16: Front Rotor Mass Reduced Component

(Source: http://www.pap-parts.com/products.asp?dept=2732)

- Down-sizing Based on the Scaling Utilizing the 2008 Toyota Prius, **Image F.7-17**
  - Ratio Vehicle Net Mass and Rotor Size versus Prius Specs (Lotus) to Reduce Rotor Size and Material Usage.

    (Mass Savings Due to Less Material Usage)

Image F.7-17: Front Rotor Size Normalization Mass Reduced Component

(Source: FEV, Inc. photo)

- Scallop Rotor OD, **Image F.7-18**
    - Improve Braking Performance and Mass Savings
    - Manufacturers and OEMs include: Wilwood, Brembo, Numerous Motorcycle Applications

Image F.7-18: Front Rotor Mass Reduced Component

(Source: http://www.wilwood.com/Pdf/Catalogs/TechCatalog.pdf)

- Scallop Rotor ID, **Image F.7-19**
    - Improve Braking Performance and Mass Savings
    - Manufacturers and OEMs include: Audi, Mercedes, BMW, Wilwood, Brembo, Numerous Motorcycle Applications

Image F.7-19: Front Rotor Mass Reduced Component

(Source: http://www.clubcobra.com/forums/kirkham-motorsports/)

- Cross-Drill Hat OD, **Image F.7-20**
  - Improved Drum Surface Cooling and Mass Savings

Image F.7-20: Front Rotor Mass Reduced Component

(Source http://forums.tdiclub.com/showthread.php?t=238563)

- Drill Holes in Hat Top Surface, **Image F.7-21**
  - Improved Drum Surface Cooling & Mass Savings
  - Manufacturers and OEMs include: Audi, Mercedes, BMW, Wilwood, Brembo

Image F.7-21: Front Rotor Mass Reduced Component

(Source: http://www.pic2fly.com/Wilwood+Rotor+Hats.html)

The final Front Rotor Assembly (**Image F.7-22**) is the approximate design configuration based on the above combined ideas. This redesigned Front Rotor solution has a calculated mass of 4.552kg. Although nearly all of these individual mass reduction ideas have been implemented by plenty of manufactures and OEMs individually, none have been utilized all at once in a single vehicle application. Therefore, the appropriate amount of industry testing and validation must be performed by any vehicle manufacturer in order to fit this design to a particular vehicle application. Concerns to be addressed would include the normal list of topics that are determined with any braking system. These would include some of the following requirements:

- Cracking and Deformation Resistance
- Degassing, Glazing and Debris Control
- Brake Pad Wear
- Cooling (Heat Dissipation) Performance
- Disc Heat Capacity versus Warping
- Quality & Geometric Tolerance:
    - Dimensioning, Surface Finish, Lateral Runout, Flatness, Perpendicularity & Parallelism
- Rotor Braking Surface Wear

- Rotor Life and Durability vs. Warranty
- Braking Performance vs. Component Longevity
- NVH Testing vs. Functional Performance
- Rotor Assembly (Disc & Hat) Balancing

Image F.7-22: Front Rotor Mass Reduced Component Example

(Source: http://www.dsmtuners.com/forums/blogs/secongendsm/2176-wilwood-brake-kit.html)

F.7.1.5.2 Splash Shields

The solution(s) chose to be implemented on the Front Splash Shields (**Image F.7-23**) was the combination of two individual brainstorming ideas. This redesigned Toyota Venza Splash Shield solution has a calculated mass of 0.075kg. These ideas included the following modifications to design, materials and processing:

- Plastic Glass-Filled, Ribbed and Webbed Shield (Material Substitution)
    - Injection Molded to Near-Net Shape and Combining Components (Mass Savings even with increased material volume of 20-30%, Component Simplification and Assembly Reduction)
- Down-sizing Based on the Scaling Utilizing the 2008 Toyota Prius
    - Ratio Vehicle Net Mass & Rotor Size vs. Prius Specs (Lotus)

Image F.7-23: Front Splash Shield Mass-Reduced Component Examples

(Source: http://www.motorcycle-superstore.com)

F.7.1.5.3 Caliper Assembly

The redesigned Toyota Venza Front Caliper Assembly is still a multi-piece assembly comprised of the same components and design function. The major components are now being made from cast Al and the assembly has a new reduced mass calculated to be 2.563kg. The Front Caliper Assembly (**Image F.7-24** and **Image F.7-25**) is still comprised of the same components and design function. These include: Housing, Mounting, Mounting Attachment Bolts (2), Inboard Brake Pad & Shim Plate, Outboard Brake Pad & Shim Plate, Pistons (2), Piston Seal Ring (2), Piston Seal Boots (2), Mounting Slide Pins (2), Mounting Slide Pin Boots (2), Housing Bleeder Valve, and Housing Bleeder Valve Cap.

Image F.7-24: Front Caliper Mass Reduced Assembly Example

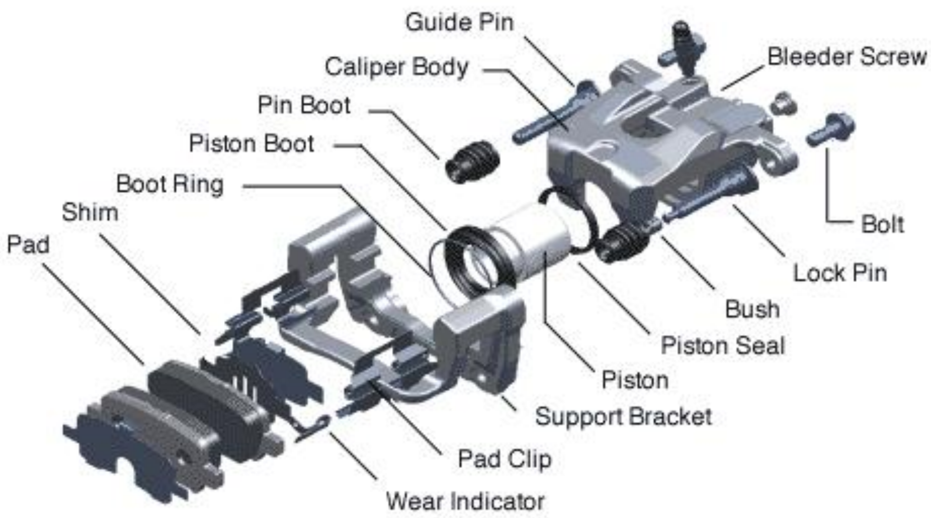


Image F.7-25: Front Caliper Assembly Component Diagram Example

(Source: http://www.brakewarehouse.com/)

F.7.1.5.3.1 *Housings*

The Front Caliper Housing (**Image F.7-26**) has been changed from a cast iron design to a die cast Al design. Additional material volume of 70-80% was added to improve strength and increase mass surface to assist in the brake cooling function. This technology is available and being utilized in aftermarket and high performance applications as well as a few OEM vehicle markets. Some manufacturers and vehicle applications include: BMC (Chrylser, Mini-Cooper), AP (Pontiac Grand Am, Ford Lotus, Honda NSX, Mk3 Titan, Fulvia, and various motorcycles), Lockheed (Can Am race cars, Honda autos, BMW autos, Lotus autos, and many various motorcycles), and Brembo (Ducatii and Bimota motorcycles).

Image F.7-26: Front Caliper Housing Mass Reduced Component example

(Source:http://www.peterverdone.com/wiki/index.php?title=PVD_Land_Speed_Record_Bike#Caliper)

While these alternatives now are designed with the strength and performance required they do add a significant cost while providing a large mass decrease. However the weight savings achieved is quite substantial. This redesigned Front Caliper Housing solution has a calculated mass of 1.470kg. This mass decrease assists with reducing vehicle requirements for suspension loads, handling, ride quality, engine hp requirements, etc.

F.7.1.5.3.2 <u>Mountings</u>

The Front Caliper Mounting, **Image F.7-27**, was changed from cast iron to a die cast Al design. While additional material volume of 70-80% was added to improve strength, the mass savings achieved was still significant. This redesigned Front Caliper Mounting solution has a calculated mass of 0.640kg. This upgraded material design is used in many aftermarket and high performance applications. Some manufacturers and vehicle applications include: AP (Pontiac autos, Lotus autos, and various motorcycles), Lockheed (Honda autos, BMW autos, and many various motorcycles) and Brembo (Ducatii motorcycles).

Image F.7-27: Front Caliper Mounting Mass Reduced Component Example

(Source: http://www.gforcebuggies.com/Parts)

F.7.1.5.3.3 *Brake Pads*

The Brake Pads, **Image F.7-28**, had had little change in their design and the materials and processing remains the same. Still utilizing steel backing plates with a molded friction material attached. The variation in mass savings achieved was by utilizing slightly smaller and thinner brake pads. These redesigned Toyota Venza Front Caliper Brake Pad solutions have a calculated mass of 0.60kg. Most material differences are focused only in the friction material going from traditional asbestos now to semi-metallic and full metallics as well as various ceramic compounds. While these friction materials greatly affect performance and vehicle stopping distances under various conditions, little is accomplished in saving mass and reducing material weight.

Image F.7-28: Front Caliper Brake Pad Mass Reduced Components

(Source: http://cdn0.autopartsnetwork.com/images/catalog/wp/full/W01331833409NPN.JPG)

The final Front Brake Corner assembly shown below, **Image F.7-29**, is the approximate design configuration based on the above combined ideas. This redesigned Toyota Venza Front Brake Corner Assembly solution has a calculated mass of 15.888kg. Again, nearly all of these individual mass reduction ideas have been implemented by many manufactures and OEMs individually, but none have been utilized at once in a single vehicle application. Therefore, the appropriate amount of industry testing and validation must be performed by any vehicle manufacturer in order to fit this design to a particular vehicle application.

Image F.7-29: Front Brake System Mass Reduced Assembly Example

(Source: http://www.wilwood.com/Pdf/Catalogs/TechCatalog.pdf)

F.7.1.6 Calculated Mass-Reduction & Cost Impact Results

Table F.7-6 shows the results of the mass reduction ideas that were evaluated for the Front Rotor / Drum and Shield subsystem. This resulted in a subsystem overall mass savings of 16.599kg and a cost increase differential of $-6.07.

System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys/ Sub-Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
				Net Value of Mass Reduction Idea					
06	**03**	**00**	**Front Rotor/Drum and Shield Subsystem**						
06	03	01	Front Rotor and Shield	D	9.098	-$34.66	-$3.81	48.08%	0.53%
06	03	02	Front Caliper, Anchor and Attaching Components	A	7.500	$28.58	$3.81	53.86%	0.44%
				A	**16.599**	**-$6.07**	**-$0.37**	**50.34%**	**0.97%**
					(Decrease)	(Increase)	(Increase)		

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.7-6: Mass-Reduction and Cost Impact for the Front Rotor / Drum and Shield Subsystem

Table F.7-7 shows the ideas for the Front Rotor / Drum and Shield Subsystem with the Brake Rotors achieving the greatest mass reduction, 8.738kg, along with some cost increase of $38.57. The Caliper Housing was the next largest mass savings realized with 4.724kg and a significant cost reduction of $27.50.

System	Subsystem	Sub-Subsystem	Component / Assembly Description	Mass Reduction "kg" (1)	Cost Impact "$" (1)	Cost/ Kilogram $/kg
				Mass Reduction Results		
06	**03**	**00**	**Front Rotor/Drum and Shield Subsystem**			
06	03	01	Rotor	8.378	-$38.57	-$4.60
06	03	01	Splash Shield	0.720	$3.91	$5.43
06	03	02	Caliper Housing	4.724	$27.50	$5.82
06	03	02	Brake Pads	0.714	-$4.32	-$6.05
06	03	02	Caliper Mounting Bracket	2.063	$5.41	$2.62

(1) "+" = decrease, "-" = increase

Table F.7-7: Calculated Mass-Reductions and Cost Impact Results for the Front Rotor / Drum Components and Shield Subsystem Components

F.7.2 Rear Rotor / Drum and Shield Subsystem

F.7.2.1 Subsystem Content Overview

This pictorial diagram, **Image F.7-30**, represents the major brake components in the Rear Rotor / Drum and Shield Subsystem and their relative location and position relevant to one another as located on the vehicle rear corner.

Image F.7-30: Rear Rotor / Drum and Shield Subsystem Relative Location Diagram

(Source: Lotus – 2010 March EPA Report)

As seen in **Image F.7-31**, the Rear Rotor/Drum and Shield subsystem consists of the following major components: Rear Rotor, Rear Splash Shield, Rear Caliper Assembly, Rear Caliper Mounting, and Miscellaneous Anchor and Attaching Components.

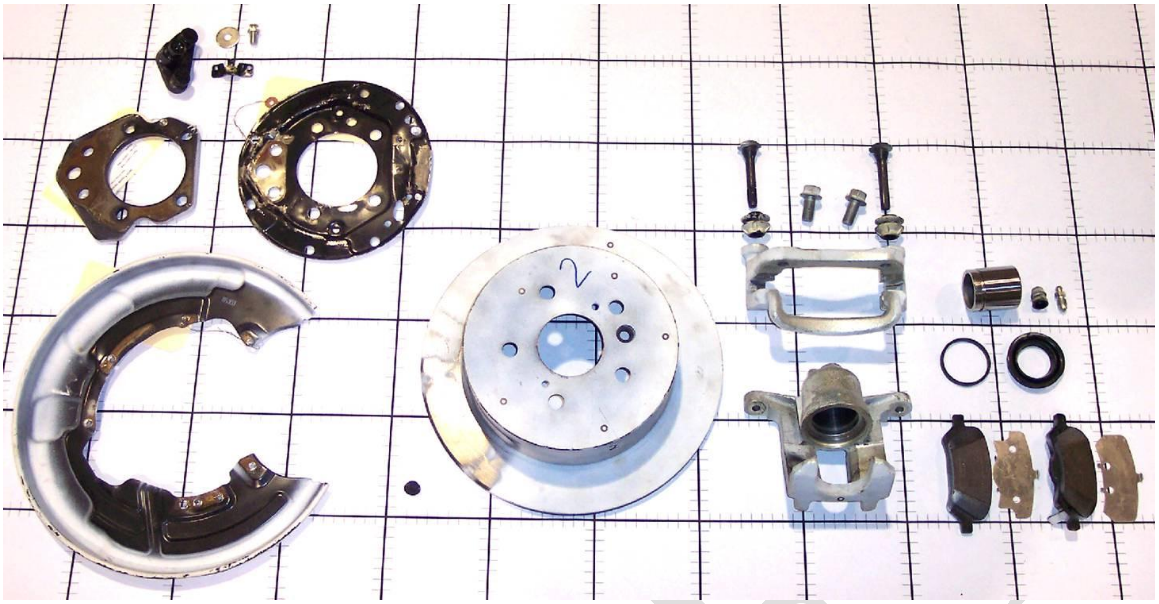


Image F.7-31: Rear Rotor / Drum and Shield Subsystem Current Major Components

(Source: FEV Inc photo)

Table F.7-8 indicates the two (2) sub-subsystems that make-up the Rear Rotor/Drum and Shield subsystem. These are the Rear Rotor & Shield sub-subsystem and the Anchor and Attaching Components sub-subsystem. The most significant contributor to the mass within this subsystem was found to be within the Rear Rotor and Shield sub-subsystem (approx 66.3%).

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
06	**04**	**00**	**Rear Rotor/Drum and Shield Subsystem**	**--**
06	04	01	Rear Rotor and Shield	14.893
06	04	02	Rear Caliper, Anchor and Attaching Components	7.578
			Total Subsystem Mass =	**22.470**
			Total System Mass =	**85.740**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**26.21%**
			System Mass Contribution Relative to Vehicle =	**1.31%**

Table F.7-8: Mass Breakdown by Sub-subsystem for the Rear Rotor / Drum and Shield Subsystem

F.7.2.2 Toyota Venza Baseline Subsystem Technology

As with the Front Brake subsystems previously discussed, the Toyota Venza's Rear Rotor and Shield subsystem (**Image F.7-32**) follows typical industry standards. Rotors (**Image F.7-33**) are single piece design cast out of grey iron and manufactured to SAE specifications. The Splash Shields (**Image F.7-34**) are typical stamped and welded steel fabrications. The Caliper Assembly (**Image F.7-35**) is composed of several components. These include: Caliper Housings (**Image F.7-36**) are high nickel content cast iron with the appropriate machining. The Caliper Mountings (**Image F.7-37**) are cast iron and machined. The Brake Caliper houses the Brake Pads and Pistons. The Caliper Piston (**Image F.7-38**) is drawn, machined and coated steel with standard seal configurations. The Brake Pads (**Image F.7-38**) are of standard construction with steel backing plates and friction pad materials. The current OEM Toyota Venza Rear Brake Corner Assembly has a mass of 11.235kg.

Image F.7-32: Rear Brake System Assembly Example

(Source: http://www.wheels24.co.za/News/General_News/Scooby-STI-goes-auto-20090225)

F.7.2.3 Mass-Reduction Industry Trends

F.7.2.3.1 <u>Rotors</u>

The baseline OEM Toyota Venza Rear Rotor (**Image F.7-33**) is a single piece design cast out of grey iron and has a mass of 5.742kg. Many high-performance and luxury vehicle models have began utilizing alternate rotor designs in order to improve both performance and economy. Two-piece rotor assemblies are now able to be found in many Mercedes', BMW's, Audi's, Corvette's, Porches', etc across many platforms and vehicle models. This two-piece configuration was also mentioned in the March 2010 Lotus Report. Besides OEM's, there are aftermarket suppliers that use this design. Brembo and Wilwood are two such companies that have used this rotor design in various production applications. This two-piece design usually utilizes an Aluminum center hub (or hat) along with a disc braking surface (typically cast iron or steel).

Image F.7-33: Rear Rotor Current Component

(Source: http://www.bestvalueautoparts.com/Replacement_Parts/TOYOTA))

The Rotor Center (Hat) can be made from several material choices including Aluminum (Al), Titanium (Ti), Magnesium (Mg), Grey Iron or Steel (Fe) and manufactured from cast forms or billet machined from solid.

The Rotor disc surfaces are also able to be made from various materials and processing methods. These include Aluminum Metal Matrix Composites (Al/MMC), MMC, Ti and Fe. Even Carbon/Ceramic matrices have been used to produce rotors of less mass. Processing includes casting vented or solid disc plates and the machining cross-drilled plates, slotted plates and scalloped disc (both ID and OD) profiles.

Some race cars and airplanes use brakes with carbon fiber discs and carbon fiber pads to reduce weight. For these systems, wear rates tend to be high, and braking may be poor or "grabby" until the brake is heated to the proper operating temperature. Again, this technology adds substantial costs if considered for regular high volume automotive production capacities.

F.7.2.3.2 Splash Shields

The baseline OEM Toyota Venza Rear Splash Shield is a multi- piece welded design, stamped of common steel and has a mass of 1.624kg. A majority of splash shields (or dust shields) (**Image F.7-34**) are made from stamped light gage steel. Some are vented or slotted for reduced material and increased weight savings. Alternative materials are now beginning to be examined for use to further reduce weight contribution. These include Al, high-strength steels, and even various reinforced plastics.

Image F.7-34: Rear Splash Shield Current Component

(Source: FEV Inc photo)

F.7.2.3.3 Caliper Assembly

The baseline OEM Toyota Venza Rear Caliper Assembly is a multi-piece assembly with major components made from cast iron and has a mass of 3.250kg. Traditional caliper assemblies (**Image F.7-35**) are comprised of several components. These include: Housing, Mounting, Mounting Attachment Bolts (2), Inboard Brake Pad and Shim Plate, Outboard Brake Pad and Shim Plate, Piston, Piston Seal Ring, Piston Seal Boot, Mounting Slide Pins (2), Mounting Slide Pin Boots (2), Housing Bleeder Valve, and Housing Bleeder Valve Cap.

Image F.7-35: Rear Caliper Current Assembly

(Source: http://cdn2.autopartsnetwork.com/images/catalog/brand/centric/640/14144640.jpg)

F.7.2.3.3.1 *Housings*

The baseline OEM Toyota Venza Rear Caliper Housing is a single piece cast iron design and has a mass of 1.896kg. Traditional caliper housings (**Image F.7-36**) have been made from various grades of cast iron. This allowed for adequate strength while also acting as a heat sink to assist in the brake cooling function. Now with advances in materials and processing methods, other choices are available and being utilized in aftermarket and high performance applications as well as OEM vehicle markets. Among some of these alternate mediums are Al, Ti, Steel, Mg and MMC. Forming methods now include sand cast, semi-permanent metal molding, die casting and machining from billet.

Image F.7-36: Rear Caliper Housing current component.

(Source: FEV Inc photo)

While these alternatives now are designed with the strength and performance required they do add a significant cost-versus-mass increase. However, the weight savings achieved is quite substantial and assists with reducing such vehicle requirements for suspension loads, handling, ride quality, and engine hp requirements. Other advanced development includes using bulk molding compound using long randomly oriented carbon fiber continues to be of interest due to the ability to easily mold it into complex shapes. However, temperature extremes encountered by brake components and the current cost of the material will be serious challenges for some time to come.

F.7.2.3.3.2 *<u>Mountings</u>*

The baseline OEM Toyota Venza Rear Caliper Mounting is a single piece cast iron design and has a mass of 0.934kg. Caliper mountings, **Image F.7-37**, have normally been made from various grades of cast iron for adequate strength and function. Now with advances in materials and processing methods other choices are available and being utilized in aftermarket and high performance applications as well as OEM vehicle markets. Among some of these alternate mediums are Al, Ti, Steel and Mg. Forming and fabrication methods include casting and billet machining.

Image F.7-37: Rear Caliper Mounting Current Component

(Source: FEV Inc photo)

F.7.2.3.3.3 *<u>Piston</u>*

The baseline OEM Toyota Venza Rear Caliper Pistons are a single piece steel drawn design and have a mass of 0.219kg. Caliper piston (**Image F.7-**

38) commonly are made from various alloys of steel for function and heat resistance. Now advances alternative materials and processing methods allow new choices to be available. Rather than utilizing metallics only (Al, Steel, Ti), there are phenolic glass-filled plastics that are used in high volume by OEMs. These are molded to near net shape with minimal machining required, saving both material and processing time while saving significant mass.

Image F.7-38: Rear Caliper Piston Current Component

(Source: FEV Inc photo)

F.7.2.3.3.4 Brake Pads

The baseline OEM Toyota Venza Rear Caliper Brake Pads are of standard construction with steel backing plates and friction pad materials. They have a mass of 0.487kg. The brake pads (**Image F.7-39**) had had little change in design, materials or processing in recent years. Most have steel backing plates with a molded friction material attached to them. Various sized braking surfaces and molded shapes are common variations across different vehicle platforms. Most material differences are focused only in the friction material going from traditional asbestos now to semi-metallic and full metallic as well as various ceramic compounds. While these friction materials greatly affect performance and vehicle stopping distances under various conditions, little is accomplished in saving mass and reducing material weight.

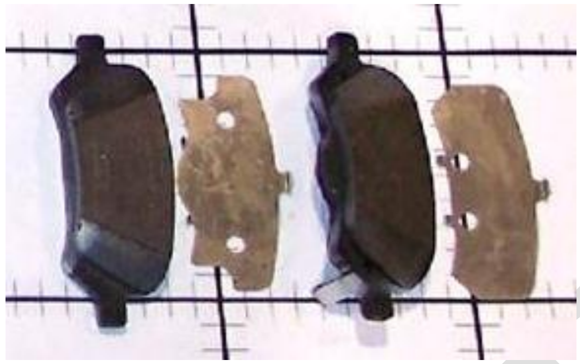


Image F.7-39: Rear Caliper Brake Pad Current Components

(Source: FEV Inc photo)

F.7.2.4 Summary of Mass-Reduction Concepts Considered

Table F.7-9 shows the mass reduction ideas considered from the brainstorming activity for the Rear Rotor/Drum and Shield Subsystem and their various components. These ideas include part modifications, material substitutions, processing and fabrication differences, and use of alternative parts currently in production and used on other vehicles and applications

Component/ Assembly	Mass Reduction Idea	Estimated Impact	Risk & Trade-offs and/or Benefits
Rear Rotor/Drum and Shield Subsystem			
Rotor	Vent (slot) front rotors	0-5% wt save	Low production - auto
	Cross-Drill front rotors	10-20% wt save	In Production - Most Auto Makers
	Rotor Downsizing based on vehicle mass reduction	30-40% wt save	Lower Cost. In production - auto
	Two piece Rotor - Al light-weight center (hat) with Iron/Steel/CF outer surface (disc) w/ T-nut fasteners	20-30% wt save	In Production - Merc, BMW, Audi
	Change Material for Rotors - Al/MMC	40-50% wt save	High Cost. In Production - racing / aftermarket
	Downsizing based on Rotor fins	0-5% wt save	Low production - auto
	Clearance mill openings (rotor ID scalloping) around hat perimeter on rotor disc ID	20-30% wt save	In Production - Merc, BMW, Audi
	Clearance mill space (rotor OD scalloping) around disc OD perimeter	10-20% wt save	In Production - Motorcycles
	Clearance drill holes in rotor top hat surface to reduce wt (5 - 9/16" dia. X.25DP)	5-10% wt save	In Production - Merc, BMW, Audi
	Increase slots around rotor hat perimeter (OD) 50% (10 - .625Wide x 1.125Long x .25 Dp)	0-5% wt save	In Production - Most Auto Makers
	Chg from straight to directional vanes btwn rotor disc surfaces	0-5% wt save	In Production - Merc, BMW, Audi
	Make brake rotors out of ceramic	50-60% wt save	In Production - racing
	Replace from 2008 Toyota Prius (mass:17.820-12.811 & cost:0.96)	30-40% wt save	Lower Cost. In Production - Toyota
	Combination. Modify rotors with slotting, cross-drilling, 2-pc design, Al Hat, downsize from Prius, chg mat'l to Al/MMC, chg fin design (directional), rotor ID & OD scalloping, holes in rotor top hat surface & side perimeter.	60-70% wt save	High Cost. Various partial combinations in production by various high performance sports car manufacturers

Table F.7-9 continued next page

Splash Shield	Vent rear splash shield like front shield	10-20% wt save	Lower cost. In Production - most automakers
	Make splash shield out of plastic	60-70% wt save	Low Cost. Low production - auto
	Make splash shield out of High Strength Steel	10-20% wt save	Higher Cost. Low production - auto
	Make splash shield out of Aluminum	30-40% wt save	Higher Cost. Low production - auto
	Make splash shield out of Titanium	20-30% wt save	High Cost. In Production - racing
	Integrate (3) splash shield plates into (1)	20-30% wt save	Lower cost. In Production
	Eliminate thick backing plate. Attach directly to axle	10-20% wt save	Lower cost. In Production
	Replace from 2008 Toyota Prius (mass:3.189-0.715 & cost:0.25)	60-70% wt save	Lower cost. In Production - Toyota
	Combinination. Replace from Prius, Vent, Al Mat'l, Combine 3 plates into 1.	70-80% wt save	Moderate Cost
Access Plug	Eliminate shoe brake access plug	100% wt save	Low production - auto
	Make shoe access plug out of plastic	10-20% wt save	Low production - auto
Hose	Replace from 2008 Toyota Prius (mass:0.313-0.228 & cost:0.97)	20-30% wt save	In Production - Toyota

Brake Pads	Replace from 2008 Toyota Prius (mass:2.004-1.377 & cost:0.98)	30-40% wt save	In Production - Toyota
	Combination. Replace from Prius and use thinner pad materials	40-50% wt save	Lower Cost. Low production - auto
	Make brake pad wear material thinner	5-10% wt save	Low production - auto
Calipers	Caliper Downsizing based on vehicle mass reduction	10-20% wt save	In Production - Most Auto Makers
	Change Material for selectively reinforced calipers (Al/MMC)	20-30% wt save	High Cost. In Production - racing
	Make caliper assembly out of cast magnesium	40-50% wt save	High Cost. In Production - auto
	Make caliper assembly out of cast aluminum	20-30% wt save	Higher Cost. In production - auto
	Make caliper assembly out of forged aluminum	30-40% wt save	Higher Cost. In production - auto
	Replace from 2008 Toyota Prius (mass:12.071-7.413 & cost:0.96)	30-40% wt save	Lower cost. In Production - Toyota
	Combination. Replace from Prius, downsize for mass reduction & chg mat'l to cast Mg	60-70% wt save	High Cost. Low production - auto

Table F.7-9 continued next page

Caliper Mounting Bracket	Caliper Downsizing based on vehicle mass reduction	10-20% wt save	In Production - Most Auto Makers
	Change Material for selectively reinforced calipers (Al/MMC)	20-30% wt save	High Cost. In Production - racing
	Make caliper assembly out of titanium	40-50% wt save	High Cost. In Production - racing
	Make caliper assembly out of cast magnesium	40-50% wt save	High Cost. In Production - auto
	Make caliper assembly out of cast aluminum	20-30% wt save	Higher Cost. In production - auto
	Make caliper assembly out of forged aluminum	30-40% wt save	Higher Cost. In production - auto
	Replace from 2008 Toyota Prius (mass:12.071-7.413 & cost:0.96)	30-40% wt save	Lower cost. In Production - Toyota
	Combination. Replace from Prius, downsize for mass reduction & chg mat'l to cast Mg	60-70% wt save	High Cost. Low production - auto
Piston, Caliper	Make piston body from magnesium vs machined steel	50-60% wt save	High Cost. Low production
	Make piston body from molded plastic composite (phenolic) vs machined steel	60-70% wt save	In Production - Most Auto Makers
	Make piston body from cast aluminum vs machined steel	30-40% wt save	Higher Cost. In production - auto
	Make piston body from forged aluminum vs machined steel	40-50% wt save	Higher Cost. In production - auto
	Make piston body from HSS vs machined steel	10-20% wt save	In Production - Auto
	Make piston body from forged SS vs machined steel	5-10% wt save	Higher Cost. In Production - Auto
	Make piston body from titanium vs machined steel	40-50% wt save	Low production - racing / aftermarket

Table F.7-9: Summary of Mass-Reduction Concepts Initially Considered for the Rear Rotor / Drum and Shield Subsystem

F.7.2.5 Selection of Mass Reduction Ideas

Table F.7-10 shows the mass reduction ideas for the Rear Rotor/Drum and Shield subsystem that were selected for detailed evaluation of both the mass savings achieved and the cost to manufacture. Several ideas suggest plastics and magnesium as alternate materials. Also included are part substitutions from other vehicle designs such as those currently in use on the Toyota Prius (as determined in the March 2010 Lotus Report).

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
06	**04**	**00**	**Rear Rotor/Drum and Shield Subsystem**	
06	04	00	Rotor	Combination. Modify rotors with slotting, cross-drilling, 2-pc design, Al Hat, downsize from Prius, chg mat'l to Al/MMC, chg fin design (directional), rotor ID & OD scalloping, holes in rotor top hat surface & side perimeter.
06	04	00	Splash Shield	Combination. Replace from Prius, Vent, Al Mat'l, Combine 3 plates into 1.
06	04	00	Access Plug	Make shoe access plug out of plastic
06	04	00	Hose	Replace from 2008 Toyota Prius (mass:0.313-0.228 & cost:0.97)
06	04	00	Brake Pads	Combination. Replace from Prius and use thinner pad materials
06	04	00	Calipers	Combination. Replace from Prius, downsize for mass reduction & chg mat'l to cast Al
06	04	00	Caliper Mounting Bracket	Combination. Replace from Prius, downsize for mass reduction & chg mat'l to cast Al
06	04	00	Piston, Caliper	Make piston body from molded plastic composite (phenolic) vs machined steel

Table F.7-10: Mass-Reduction Ideas Selected for the Detailed Rear Rotor/Drum and Shield Subsystem Analysis

F.7.2.5.1 Rotors

The solution(s) chosen to be implemented on the final Rear Rotor Assembly (**Image F.7-50**) was the combination of multiple individual brainstorming ideas. These ideas included the following modifications to component design, material utilized and processing methods required:

- Two-piece Assembled Rotor Design, **Image F.7-40**
    - Hat Fastened to Rotor Disc w/ T-Nuts and Bolts

(Increased Process Time but Allows Better Hat Material Choices for Mass Savings)

- Manufacturers and OEMs include: Chevy, Mercedes, Audi, BMW, Wilwood, Brembo

Image F.7-40: Rear Rotor Mass Reduced Component

(Source: http://www.hrpworld.com/client_images/ecommerce/client_39/products/5862_1_tn.jpg)

- Al Hat (Material Substitution), **Image F.7-41**
  - Die Cast to Near-Net Shape

    (Mass Savings even with increased material volume of 20-30%, Decreased Processing Time, Rapid and Increased Heat Dissipation)
  - Manufacturers and OEMs include: Chevy, Mercedes, Audi, BMW, Wilwood, Brembo, Motorcycles

Image F.7-41: Rear Rotor Mass Reduced Component

(Source: http://www.wilwood.com/Pdf/Catalogs/TechCatalog.pdf)

- Al / MMC Disc Surfaces (Material Substitution) **Image F.7-42**
    - SPMM Cast to Near-Net Shape

      (Drastic Mass Savings even with increased material volume of 10-20%, Heat Resistant, Improved Rotor Life, Reduced Cracking and Deformation)
    - Manufacturers and OEMs include: Mercedes, Audi, BMW, Porsche, Ferrari, Lamborghini, Wilwood, Brembo, Motorcycles

Image F.7-42: Rear Rotor Mass Reduced Component

(Source: http://www.wilwood.com/Pdf/Catalogs/TechCatalog.pdf)

- Disc Surface Slotting, **Image F.7-43**
    - Slight Mass Savings and Improved Brake Pad Performance

      (Release Trapped Heat, Gas and Dust from Disc Surface)
    - Manufacturers & OEMs include: Chevy, Pontiac, Cadillac, Mercedes, Audi, BMW, Porsche, Ferrari, Lamborghini, Wilwood, Brembo, Motorcycles

Image F.7-43: Rear Rotor Mass Reduced Component

(Source: http://www.highperformancepontiac.com/tech/hppp_1101_brake_rotor_guide/photo_13.html)

- Disc Surface Cross-Drilling, **Image F.7-44**
  - Improved Disc Cooling and Mass Savings

    (Disperse Built-Up Heat & Gases)
  - Manufacturers and OEMs include: Chevy, Pontiac, Cadillac, Mercedes, Audi, BMW, Porsche, Ferrari, Lamborghini, Wilwood, Brembo, Motorcycles

Image F.7-44: Rear Rotor Mass Reduced Component

(Source: http://www.pap-parts.com/products.asp?dept=2732)

- Down Sizing Based on the Scaling Utilizing the 2008 Toyota Prius, **Image F.7-45**
    - Ratio Vehicle Net Mass and Rotor Size vs. Prius Specs (Lotus) to Reduce Rotor Size and Material Usage.

      (Mass Savings Due to Less Material Usage)

Image F.7-45: Rear Rotor Size Normalization Mass Reduced Component

- Scallop Rotor OD, **Image F.7-46**
    - Improve Braking Performance and Mass Savings
    - Manufacturers and OEMs include: Wilwood, Brembo, Numerous Motorcycle Applications

Image F.7-46: Rear Rotor Mass Reduced Component

(Source: http://www.wilwood.com/Pdf/Catalogs/TechCatalog.pdf)

- Scallop Rotor ID, **Image F.7-47**
    - Improve Braking Performance and Mass Savings
    - Manufacturers and OEMs include: Audi, Mercedes, BMW, Wilwood, Brembo, Numerous Motorcycle Applications

Image F.7-47: Rear Rotor Mass Reduced Component

(Source: http://www.clubcobra.com/forums/kirkham-motorsports/)

- Cross-Drill Hat OD, **Image F.7-48**
    - Improved Drum Surface Cooling & Mass Savings

Image F.7-48: Rear Rotor Mass Reduced Component

(Source http://forums.tdiclub.com/showthread.php?t=238563)

- Drill Holes in Hat Top Surface, **Image F.7-49**

- Improved Drum Surface Cooling & Mass Savings
- Manufacturers & OEMs include: Audi, Mercedes, BMW, Wilwood, Brembo

Image F.7-49: Rear Rotor Mass Reduced Component

(Source: http://www.pic2fly.com/Wilwood+Rotor+Hats.html)

The final Rear Rotor Assembly (**Image F.7-50**) is the approximate design configuration based on the above combined ideas. This redesigned Toyota Venza Rear Rotor Assembly solution has a calculated mass of 4.596kg. Although nearly all of these individual mass reduction ideas have been implemented by many manufactures and OEMs individually, none have been utilized all at once in a single vehicle application. Therefore the appropriate amount of industry testing and validation must be performed by any vehicle manufacturer in order to fit this design to a particular vehicle application. Concerns to be addressed include the normal list of topics determined with any braking system. These would include some of the following requirements:

- Cracking and Deformation Resistance
- Degassing, Glazing and Debris Control
- Brake Pad Wear
- Cooling (Heat Dissipation) Performance
- Disc Heat Capacity vs. Warping
- Quality & Geometric Tolerancing:
    - Dimensioning, Surface Finish, Lateral Runout, Flatness, Perpendicularity & Parallelism

- Rotor Braking Surface Wear
- Rotor Life and Durability vs. Warranty
- Braking Performance vs. Component Longevity
- NVH Testing vs. Functional Performance
- Rotor Assembly (Disc and Hat) Balancing

Image F.7-50: Rear Rotor Mass Reduced Component Example

(Source: http://www.dsmtuners.com/forums/blogs/secongendsm/2176-wilwood-brake-kit.html)

F.7.2.5.2 Splash Shields

The solution(s) chosen to be implemented on the Rear Splash Shields (**Image F.7-51**) was the combination of two individual brainstorming ideas. This redesigned Toyota Venza Rear Splash Shield solution has a calculated mass of 0.496kg. These ideas included the following design, materials and processing modifications:

- Aluminum Fabrication (Material Substitution)
  - One piece forging design to Near-Net Shape and Combining Components (Mass Savings even with increased material volume of 120-130%, Component Simplification and Assembly Reduction)
- Vented Design (done in forging strikes).
  - (Mass Reduction from Less Material)

- Down Sizing Based on the Scaling Utilizing the 2008 Toyota Prius
    - Ratio Vehicle Net Mass & Rotor Size vs. Prius Specs (Lotus)

Image F.7-51: Rear Splash Shield Mass Reduced Component Example

(Source: http://www.rjays.com/Superbell/SB_images/3513.jpg)

F.7.2.5.3 Caliper Assembly

The redesigned Toyota Venza Rear Caliper Assembly is also a multi-piece assembly comprised of the same components and design function. The major components are now being made from cast Al and the assembly has a new reduced mass calculated to be 1.406kg. The Rear Caliper Assembly (**Image F.7-52** and **Image F.7-53**) is still comprised of the same components and design function: Housing, Mounting, Mounting Attachment Bolts (2), Inboard Brake Pad and Shim Plate, Outboard Brake Pad and Shim Plate, Piston, Piston Seal Ring, Piston Seal Boot, Mounting Slide Pins (2), Mounting Slide Pin Boots (2), Housing Bleeder Valve, and Housing Bleeder Valve Cap.

Image F.7-52: Rear Caliper Mass Reduced Assembly Example

(Source: http://www.sillbeer.com/blog/category/brakes)

Image F.7-53: Rear Caliper Assembly Component Diagram Example

(Source: http://www.brakewarehouse.com/remanufactured_brake_calipers.asp)

F.7.2.5.3.1 *Housings*

The Rear Caliper Housing (**Image F.7-54**) has been changed from a cast iron design to a die cast Al design. Additional material volume of 10-20% was added to improve strength and increase mass surface to assist in the brake cooling function. This technology is available and being utilized in aftermarket and high performance applications as well as a few OEM vehicle markets. Some manufacturers and vehicle applications include: BMC (Mini-Cooper), AP (Pontiac Grand Am, Ford Lotus, Honda NSX, Mk3 Titan, Fulvia, and various motorcycles), Lockheed (Can Am race cars, Honda autos, BMW autos, Lotus autos, and many various motorcycles) and Brembo (Ducatii and Bimota motorcycles).

Image F.7-54: Rear Caliper Housing Mass Reduced Component Example

(Source: http://www.sillbeer.com/blog/category/brakes)

While these alternatives now are designed with the strength and performance required they do add a significant cost while providing a large mass decrease. However the weight savings achieved is quite substantial. This redesigned Toyota Venza Rear Caliper Housing solution has a calculated mass of 0.727kg. This mass decrease assists with reducing such vehicle requirements as suspension loads, handling, ride quality, and engine hp requirements.

F.7.2.5.3.2 *Mountings*

The Rear Caliper Mounting, **Image F.7-55**, was changed from cast iron to a die cast Al design. While additional material volume of 20-30% was added to improve strength, the mass savings achieved was still significant. This redesigned Toyota Venza Rear Caliper Mounting solution has a calculated mass of 0.363kg. This upgraded material design is used in many aftermarket and high performance applications. Some manufacturers and vehicle applications include: AP (Pontiac autos, Lotus autos, and various motorcycles), Lockheed (Honda autos, BMW autos, and many various motorcycles) and Brembo (Ducatii motorcycles).

Image F.7-55: Rear Caliper Mounting Mass Reduced Component Example

(Source: http://www.gforcebuggies.com/Parts)

F.7.2.5.3.3 Piston

The Toyota Venza Rear Caliper Pistons have been changed from a steel drawn design to a phenolic glass-filled design and now have a reduced mass of 0.114kg. A material volume increase of approximately 110-120% was to compensate for the strength of the steel being replaced. This design of Caliper Pistons (**Image F.7-56**) commonly used by many different OEM manufacturers in high volume applications, as well as being used by multiple aftermarket suppliers. These OEMs include Toyota as well as all the other major car manufacturers. These are molded to near net shape with minimal machining required, saving both material and processing time while saving significant mass.

Image F.7-56: Rear Caliper Piston Mass Reduced Component

(Source: FEV Inc photo)

F.7.2.5.3.4 Brake Pads

The Rear Brake Pads (**Image F.7-57**) had had little change in their design and the materials and processing remains the same. Still utilizing steel backing plates with a molded friction material attached. The variation in mass savings achieved was by utilizing slightly smaller and thinner brake pads. These redesigned Toyota Venza Rear Caliper Brake Pad solutions have a calculated mass of 0.306kg. Most material differences are focused only in the friction material going from traditional asbestos now to semi-metallic and full metallic as well as various ceramic compounds. While these friction materials greatly affect performance and vehicle stopping distances under various conditions, little is accomplished in saving mass and reducing material weight.

Image F.7-57: Rear Caliper Brake Pad Mass Reduced Components

(Source: http://cdn1.autopartsnetwork.com/images/catalog/wp/full/W01331833410NPN.JPG)

The final Rear Brake Corner Assembly shown below (**Image F.7-58**) is the approximate design configuration based on the above combined ideas. This redesigned Toyota Venza Rear Brake Corner Assembly solution has a calculated mass of 11.531kg. To reiterate, nearly all of these individual mass reduction ideas have been implemented by plenty of manufactures and OEMs individually, but none have been utilized all at once in a single vehicle application. Therefore the appropriate amount of industry testing and validation must be performed by any vehicle manufacturer in order to fit this design to a particular vehicle application.

Image F.7-58: Rear Brake System Mass Reduced Assembly Example

(Source: http://www.wilwood.com/Pdf/Catalogs/TechCatalog.pdf)

F.7.2.6 Calculated Mass-Reduction & Cost Impact Results

Table F.7-11 shows the results of the mass reduction ideas that were evaluated for the Rear Rotor/Drum and Shield subsystem. This resulted in a subsystem overall mass savings of 9.676kg and a cost savings differential of $6.08.

System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys/ Sub-Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
				Net Value of Mass Reduction Ideas					
06	04	00	**Rear Rotor/Drum and Shield Subsystem**						
06	04	01	Rear Rotor and Shield	D	4.565	-$14.09	-$3.09	20.32%	0.27%
06	04	02	Rear Caliper, Anchor and Attaching Components	A	5.110	$20.17	$3.95	22.74%	0.30%
				A	**9.676** (Decrease)	**$6.08** (Decrease)	**$0.63** (Decrease)	**43.06%**	**0.57%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.7-11: Mass-Reduction and Cost Impact for the Rear Rotor/Drum and Shield Subsystem

Table F.7-12 shows the redesigned components for the Rear Rotor/Drum and Shield subsystem. The Rear Brake Rotors achieve the greatest mass reduction, 2.293kg, along with some cost expense of $13.05. The Caliper Housing is the next largest mass savings, with 2.337kg and a significant cost reduction of $14.54.

System	Subsystem	Sub-Subsystem	Component / Assembly Description	Mass Reduction "kg" (1)	Cost Impact "$" (1)	Cost/ Kilogram $/kg
				Mass Reduction Results		
06	03	00	**Rear Rotor/Drum and Shield Subsystem**			
06	04	01	Rear Brake Rotor (Disc)	2.293	-$13.05	-$5.69
06	04	01	Access Plug - Rear Brake Rotor (Disc)	0.016	$0.01	$0.47
06	04	01	Rear Brake Shield	2.256	-$1.06	-$0.47
06	04	02	Hose	0.085	$0.26	$3.02
06	04	02	Caliper Housing (Rear)	2.337	$14.54	$6.22
06	04	02	Pad Kit, Disc Brake, Rear (2 Inner & 2 Outer Pads)	1.336	$0.21	$0.16
06	04	02	Mounting, Caliper (Rear)	1.142	$2.40	$2.10
06	04	02	Piston, Caliper (Rear)	0.210	$2.77	$13.19

(1) "+" = decrease, "-" = increase

Table F.7-12: Calculated Subsystem Mass-Reductions and Cost Impact Results for the Rear Rotor / Drum Components and Shield Subsystem Components

F.7.3 Parking Brake and Actuation Subsystem

F.7.3.1 Subsystem Content Overview

Image F.7-59 represents the major parking brake components in the Parking Brake and Actuation subsystem, which includes: the Parking Brake Pedal Actuator Sub-assembly, the Parking Brake Shoes and Associated Hardware, and the Actuation Cable Assemblies, and Guides and Brackets that are located on the vehicle from the engine firewall (front of vehicle) all the way to the rear wheels.

Image F.7-59: Parking Brake and Actuation Subsystem Current Sub-assemblies

(Source: Lotus – 2010 March EPA Report)

The Parking Brake and Actuation subsystem (**Table F.7-13**) consists of the Parking Brake Controls and the Parking Brake Cables and Attaching Components, including the Parking Brake Shoes and Hardware. The most significant contributor to mass is the Parking Brake

Shoes and Hardware (approximately 56.69%) followed by the Parking Brake Controls (approximately 27.52%).

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
06	**05**	**00**	**Parking Brake and Actuation Subsystem**	**--**
06	05	01	Parking Brake Controls	3.689
06	05	02	Parking Brake Cables and Attaching Components	2.117
06	05	03	Parking Brake Shoes and Hardware	7.599
			Total Subsystem Mass =	**13.405**
			Total System Mass =	**85.740**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**15.63%**
			System Mass Contribution Relative to Vehicle =	**0.78%**

Table F.7-13: Mass Breakdown by Sub-subsystem for the Parking Brake and Actuation Subsystem

F.7.3.2 Toyota Venza Baseline Subsystem Technology

The Toyota Venza's Parking Brake subsystem, **Image F.7-60**, follows typical industry standards. The Venza uses a cable operated "drum-in-hat" rear parking brake system. The system consists of a hat-shaped rotor with a small drum on the inside for the parking brake shoe interface, and a flange or rotor disc surface on the outside diameter for the normal caliper, disc brake action. This entire unit is engaged by a pedal actuator located under the instrument panel against the engine firewall. The mass of this entire Parking Brake and Actuator sub-subsystem is 13.405kg.

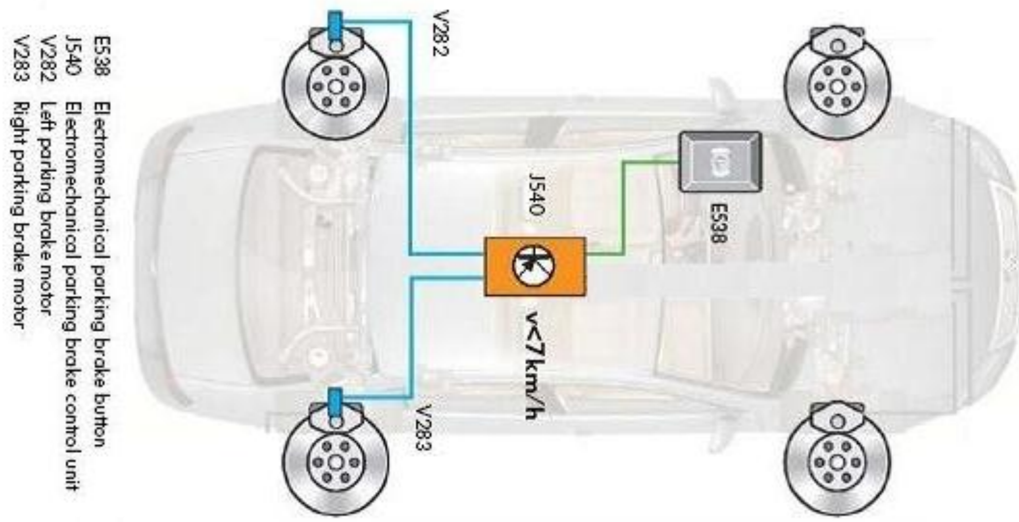


Image F.7-60: Parking Brake and Actuation Subsystem Layout and Configuration

(Source: http://www.volkspage.net/technik/ssp/ssp/SSP_346.pdf)

F.7.3.3 Mass-Reduction Industry Trends

Alternatives to cable-operated parking brake systems are focused on hydraulic, electrical, and electro-mechanical components to actuate the parking brake system at the rear wheels. The use of push-button switches and console touch screens can eliminate the need for hand levers or foot pedals in the cabin interior. Electrical wiring and actuators can provide input controls to initiate the clamping force at the rear wheels. This allows the reduction (if not the elimination) in the length and number of cable assemblies routed under and along the vehicle floor pan and sub-frame structures.

TRW offers a front and rear wheel Electric Park Brake system (**Image F.7-61**) that provides four-wheel park brake capability with associated claims of improved safety. VW has utilized an Electro-Hydraulic Park Brake system (**Image F.7-62**) that is initiated by an electric motor that drives a geared actuator providing direct hydraulic pressure influence by pushing directly on the caliper piston inside the caliper housing. Other designs offer a compromise of a hybrid approach, still using electronic actuation and motor-driven systems but integrating them into the existing rear cable systems already present on most vehicles.

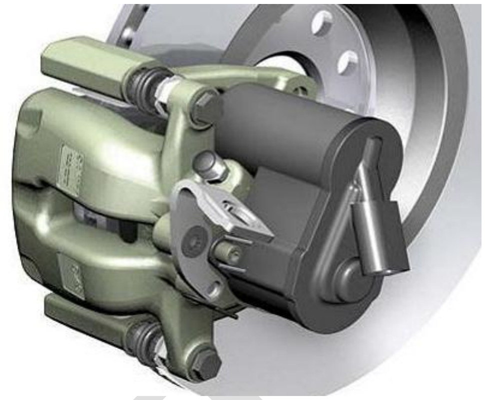


Image F.7-61: TRW Park Brake System **Image F.7-62: VW Park Brake System**

(Image F.7-61 Source : http://www.buzzbox.com/news/2010-09-29/gas:technology/?clusterId=2019488)
(Image F.7-62 Source: http://www.volkspage.net/technik/ssp/ssp/SSP_346.pdf)

F.7.3.3.1 Pedal Frame and Arm Sub-Assembly

The baseline OEM Toyota Venza Pedal Frame & Arm Sub-assembly (**Image F.7-63**) is a multi-piece design of stamped steel fabrication welded into a sub-assembly with various bushings and reinforcements added. This overall sub-assembly has a mass of 2.112kg. Many high-performance and luxury vehicle models have began utilizing alternate materials and designs in order to improve mass and expense. Another option being implemented by many OEMs is to use electronics and button actuators in order to engage the parking brake system. This allows for a complete elimination of pedal and hand lever sub-assemblies for vehicle cab interiors, maximizing mass savings. This electronic actuation configuration was also mentioned in the March 2010 Lotus Report.

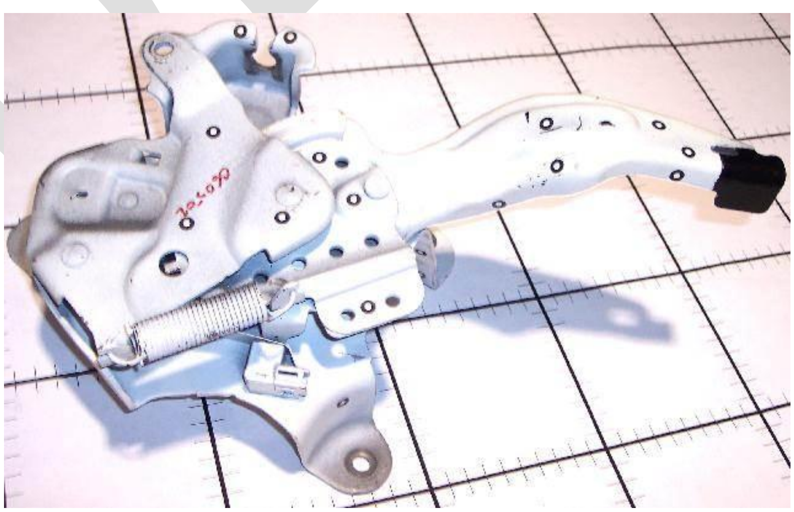


Image F.7-63: Pedal Frame Current Sub-assembly

(Source: FEV, Inc photo)

F.7.3.3.2 Cable System Sub-Assembly

The baseline OEM Toyota Venza Cable Assemblies (**Image F.7-64**) are multi-piece designs of wound steel and sleeved poly shields into sub-assemblies with brackets and fasteners added. This sub-subsystem has a mass of 2.117kg. Many high-performance and luxury vehicle models utilize alternate cable configurations with hand lever actuators located in the center console between the front seats. This allows for a shorter path to the rear parking brakes, therefore requiring less cable length (and weight).

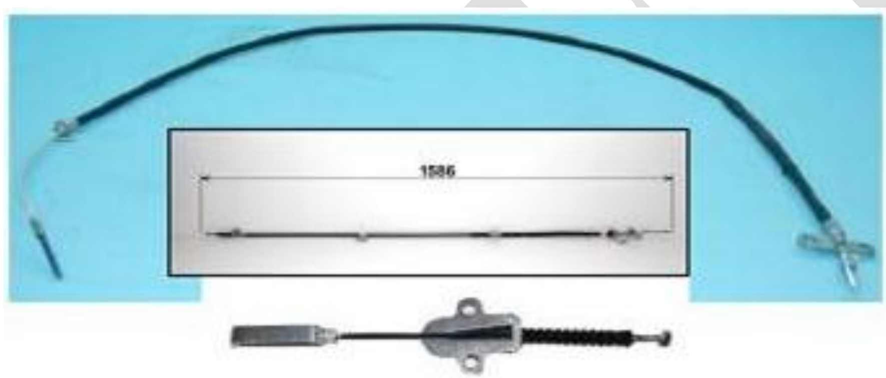


Image F.7-64: Cable System Current Sub-assemblies

(Source: Lotus – 2010 March EPA Report)

F.7.3.3.3 Brake Shoes and Attachments Sub-Assembly

The baseline OEM Toyota Venza Parking Brake Shoes and Attachment Hardware (located inside the rear rotor hat) is a multi-piece design of stamped steel fabricated components, springs, pins, levers and fasteners along with dual, semi-circular friction brake shoes, **Image F.7-65**. All of these various components and the brake shoes are housed as an assembly inside the rear rotor hat drum area, **Image F.7-66**. This sub-assembly has a mass of 3.80kg.

Image F.7-65: Brake Shoe and Attachment Hardware Current Sub-assembly Example

(Source: http://www.autopartsnetwork.com/catalog/2010/Toyota/Venza/Brake)

Image F.7-66: Brake Shoe and Attachment Hardware Current Sub-assembly Example

(Source: http://1965econolinepickup.blogspot.com/2007/11/rear-brake-assembly.html)

While this design is extremely common, there are some high performance and luxury vehicle models that have started utilizing alternate designs. These include single-piece brake shoes that span a larger area on one frame piece while still utilizing two friction pad surfaces, while others are trying to incorporate the existing brake calipers and caliper brake pads so as to be able to remove all of the hardware and shoes inside the rotor hat drum. This replacement configuration was also mentioned in the March 2010 Lotus Report. Besides OEMs, there are aftermarket suppliers that use this design.

F.7.3.4 Summary of Mass-Reduction Concepts Considered

Table F.7-14 shows mass reduction ideas from our brainstorming activity for the Parking Brake and Actuation subsystem. Ideas include part modifications, material substitutions, and use of parts currently in production on other vehicles.

Component/ Assembly	Mass Reduction Idea	Estimated Impact	Risk & Trade-offs and/or Benefits
Parking Brake and Actuation Subsystem			
Park Brake Actuator	Hand operated parking brake instead of foot operated (shorten cable No 1 length, actuator asm wash)	5-10% wt save	In production - most automakers
Park Brake Lever & Frame	Make parking brake lever & frame out of a stamping	5-10% wt save	In production - most automakers
Park Brake Lever & Frame	Make parking brake lever & frame out of HSS	10-20% wt save	Low production - auto
Park Brake Lever & Frame	Make parking brake lever & frame out of Aluminum	30-40% wt save	Low production - auto
Park Brake Lever & Frame	Make parking brake lever & frame out of Magnesium	50-60% wt save	Low production - racing / aftermarket
Park Brake Lever & Frame	Make parking brake lever & frame out of Plastic Composite (PA6 GF30)	50-60% wt save	In Production - Chrysler, Honda
Park Brake Lever & Frame	Make parking brake lever & frame out of Titanium	40-50% wt save	High Cost. Low production - racing / aftermarket
Pivot Pin Mount (on splash shield)	Make parking brake pivot pin mount out of cast aluminum instead of steel	30-40% wt save	Higher Cost. Low production.
Shoes	Replace from 2008 Toyota Prius (mass:2.517-0.000 & cost:x)	100% wt save	Low cost. In Production - Toyota
Park Brake System	Integrate Cadillac CTS park brake system	5-10% wt save	In Production - GM
Actuation Switch	Incorporated into LCD control screen	0-5% wt save	In production - most automakers
Electronic Park Brake System	Add actuation to LCD Infotain_Module	5-10% wt save	In production - most automakers
Electronic Park Brake System	Incorporate park brake-by-wire	2-30% wt save	Low production. Consideration for system reduncies
Electronic Park Brake System	Combination. Replace from 2005 VW Passat elect PB act & LCD touch screen actuator.	70-80% wt save	Low cost. In Production - Toyota
Park Brake System	Use one park brake	40-50% wt save	not analyzed - validation & perf concerns from OEM
Park Brake System	Integrate mechanical park brake into caliper	30-40% wt save	not analyzed - included in idea X2 (need mass of solenoid actuator, wiring & switches from Lotus to add back in)

Table F.7-14: Summary of Mass-Reduction Concepts Initially Considered for the Parking Brake and Actuation Subsystem

F.7.3.5 Selection of Mass Reduction Ideas

Table F.7-15 shows one mass reduction idea for the Parking Brake and Actuation subsystem that we selected for detail evaluation.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
06	**05**	**00**	**Parking Brake and Actuation Subsystem**	
06	05	00	Electronic Park Brake System	Combination. Replace from 2005 VW Passat elect PB act & LCD touch screen actuator.

Table F.7-15: Mass-Reduction Idea Selected for the Detailed Parking Brake and Actuation Subsystem Analysis

The chosen solution to implement for this study was the electro-mechanical parking brake system utilized on the VW Passat. The use of a push-button switch on the console eliminates the need for the foot pedal actuator in the cabin interior. Electrical wiring and a control module will provide input controls to initiate the clamping force at the rear wheels. This also allows the elimination of the cable assemblies routed under the vehicle as well as removal of all of the hardware and brake shoes inside the rotor hat drum location. The mass reduced redesign of this entire Parking Brake and Actuator Sub-subsystem is now reduced to 3.77kg.

VW has utilized an Electronic Parking Brake (EPB) system (**Image F.7-66**) that is initiated by an electric motor that drives a geared actuator providing direct hydraulic pressure influence by pushing directly on the caliper piston inside the caliper housing. This allows the use of the already present rear brake calipers to apply pressure directly on the rotor disc surfaces, as occurs already under normal operator use of the vehicle.

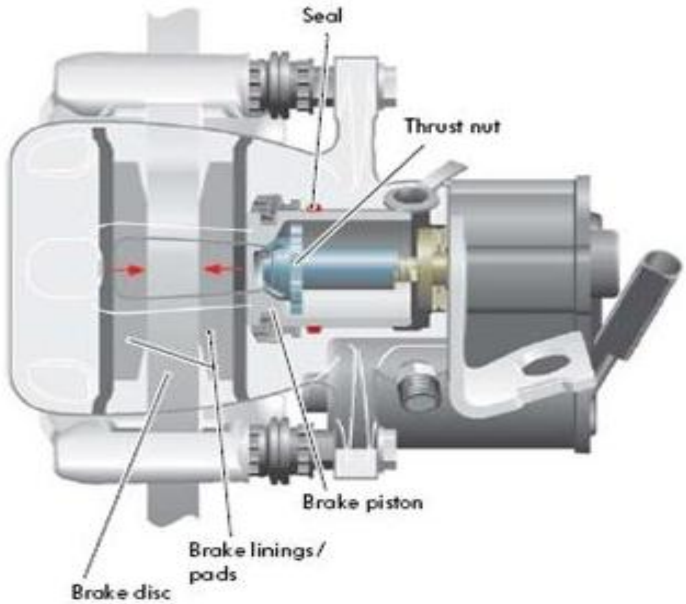


Image F.7-66: VW Electro-Mechanical Park Brake System

(Source: http://www.volkspage.net/technik/ssp/ssp/SSP_346.pdf)

F.7.3.5.1 Actuator Button Sub-Assembly

The Pedal Frame and Arm Sub-assembly was changed from a multi-piece design of stamped steel welded into a sub-assembly to a push-button actuator (**Image F.7-67**). Even though wiring harnesses and a control module (**Image F.7-68**) are required, the mass savings achieved is still substantial. This redesigned Toyota Venza Parking Brake Actuator system assembly has a calculated mass of 1.202kg. This upgraded actuator design is used in many aftermarket and high-performance vehicles. It allows not only the complete elimination of the pedal and hand lever sub-assemblies for vehicle cab interiors, but also significant reduction or even elimination of the cable actuation sub-assemblies.

Image F.7-67: Actuator Button System **Image F.7-68: EPB Control Module**

(Source: http://www.volkspage.net/technik/ssp/ssp/SSP_346.pdf)

F.7.3.5.2 Cable System Sub-Assembly

The cable assemblies are now eliminated and no longer required due to the implementation of the push-button actuation system described above in **Section F.7.3.5.1**. The elimination of these cable sub-assemblies allows for a mass savings of 2.117kg.

F.7.3.5.3 Caliper Motor Actuator Sub-Assembly

The Parking Brake Shoes and Attachment Hardware is now eliminated and replaced with the multi-piece design of a geared motor actuator (**Image F.7-69**) that attaches to the back of the rear of the caliper housing. This new electro-mechanical sub-assembly unit has a new net mass of 1.284kg.

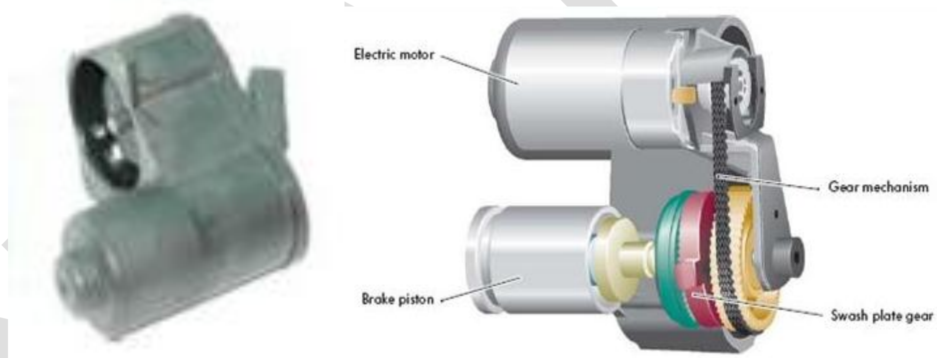


Image F.7-69: Caliper Motor Actuator mass reduced sub-assembly

(Source: http://www.volkspage.net/technik/ssp/ssp/SSP_346.pdf)

A close examination of the EPB unit shows it attaching to the back of the rear caliper housing and when engaged (**Image F.7-70**) it drives a spindle rod into the back of the caliper piston. This engagement utilizes a 50:1 gear drive ratio to apply the amount of force necessary to close the caliper brake pads on both sides of the rotor disc surface-locking the rear wheels.

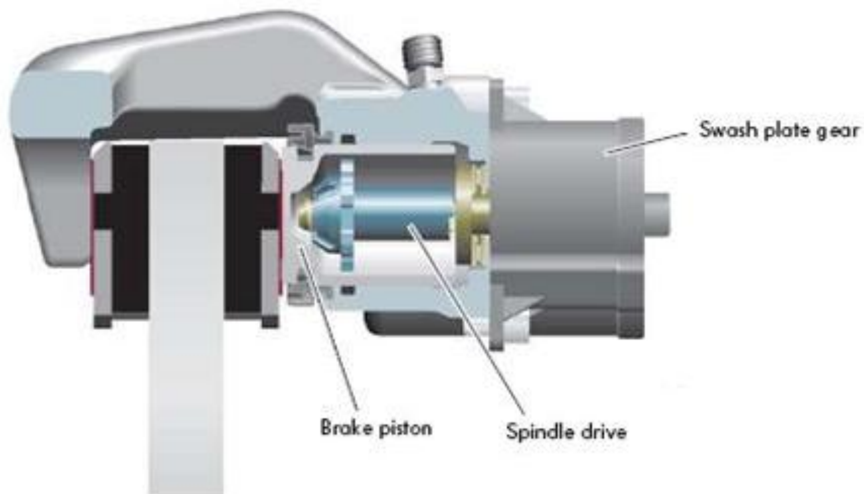


Image F.7-70: EPB System Engaging the Caliper and Rotor Components

(Source: http://www.volkspage.net/technik/ssp/ssp/SSP_346.pdf)

F.7.3.6 Calculated Mass-Reduction & Cost Impact Results

Table F.7-16 shows the results of the mass-reduction ideas evaluated for the Parking Brake and Actuation subsystem. The idea for an Electronic Park Brake system shows good estimated mass reduction with a significant cost reduction. This resulted in a subsystem overall mass savings of 9.635kg and a cost savings differential of $82.98.

				Net Value of Mass Reduction Ideas					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys/ Sub-Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
06	**05**	**00**	**Parking Brake and Actuation Subsystem**						
06	05	01	Parking Brake Controls	A	2.487	$18.16	$7.30	18.55%	0.15%
06	05	02	Parking Brake Cables and Attaching Components	A	2.117	$29.90	$14.12	15.79%	0.12%
06	05	03	Parking Brake Shoes and Hardware	A	5.031	$34.92	$6.94	37.53%	0.29%
				A	**9.635**	**$82.98**	**$8.61**	**71.88%**	**0.56%**
					(Decrease)	(Decrease)	(Decrease)		

(1) **"+" = mass decrease, "-" = mass increase**
(2) **"+" = cost decrease, "-" = cost increase**

Table F.7-16: Mass-Reductions and Cost Impact for the Parking Brake and Actuation Subsystem

F.7.4 Brake Actuation Subsystem

F.7.4.1 Subsystem Content Overview

Image F.7-71 represents the major sub-assemblies components in the Brake Actuation subsystem. These include the Brake Pedal Actuator Sub-assembly, the Accelerator Pedal Actuator Sub-assembly, Master Cylinder, Master Cylinder Reservoir and various Brake Lines, Hoses, and associated Brackets & Fasteners located on the vehicle that run to each brake corner assembly at each wheel.

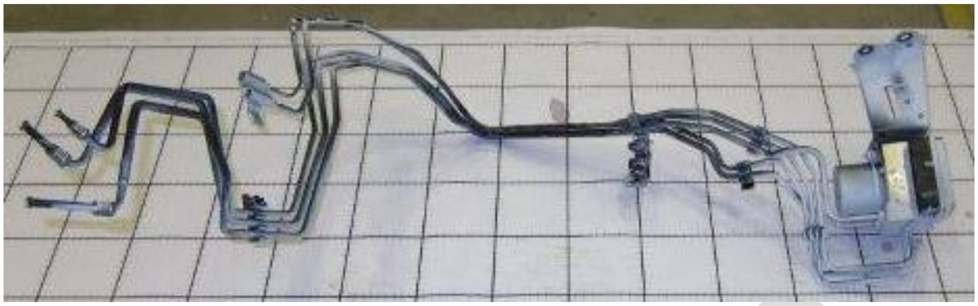


Image F.7-71: Brake Actuation Subsystem Major Components and Sub-assemblies

(Source: FEV Inc photos)

As seen in **Table F.7-17**, the Brake Actuation Subsystem consists of the Master Cylinder and Reservoir, Actuator Assemblies (Brake and Accelerator), and the Brake Lines and Hoses. The most significant contributors to the mass are the Actuator Assemblies (approximately 42.9%) followed by the Brake Lines and Hoses (approximately 42.2%).

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
06	**06**	**00**	**Brake Actuation Subsystem**	**--**
06	06	01	Master Cylinder and Reservoir	0.823
06	06	02	Actuator Assemblies	2.378
06	06	03	Brake Lines and Hoses	2.335
			Total Subsystem Mass =	**5.536**
			Total System Mass =	**85.740**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**6.46%**
			System Mass Contribution Relative to Vehicle =	**0.32%**

Table F.7-17: Mass Breakdown by Sub-subsystem for the Brake Actuation Subsystem

F.7.4.2 Toyota Venza Baseline Subsystem Technology

The Toyota Venza's Brake Actuation subsystem follows typical industry standards. The Venza uses a typical multi-zone Master Cylinder (**Image F.7-72**) with conventional ABS controls and steel tubing (**Image F.7-73**) to each of the wheel brake systems. The Brake Pedal Actuator sub-assembly (**Image F.7-74**) is made of conventional stamped steel construction with welded assembly. It consists of multiple components that are detailed below. The Accelerator Pedal Actuator system (**Image F.7-78**) is a set of plastic injection molded components that are assembled together. The current OEM Toyota Venza Brake Actuation subsystem assembly has a mass of 4.658kg.

F.7.4.3 Mass-Reduction Industry Trends

F.7.4.3.1 Master Cylinder and Reservoir

The baseline OEM Toyota Venza Master Cylinder and Reservoir sub-assembly (**Image F.7-72**) is a multi-piece design of cast aluminum and machined fabrication assembled with various valving and sealing components. This overall sub-assembly has a mass of 0.823kg. This system is already highly optimized for design and materials (Al & plastic) and therefore no further changes or solutions for mass reductions were identified for implementation.

Image F.7-72: Master Cylinder and Reservoir Current Sub-assembly

(Source: http://www.autopartsnetwork.com/catalog/2010/Toyota/Venza/Brake)

F.7.4.3.2 Brake Lines and Hoses

The baseline OEM Toyota Venza Brake Lines and Hoses (**Image F.7-73**) are conventional tubing designs with steel walls and flared ends with threaded line fittings and appropriate brackets and fasteners added. This sub-subsystem has a mass of 2.335kg. This system is very conventional, but no newer designs or systems were identified for replacement or improvement. The best solution choice for these components is to shorten the length of the brake lines required by optimizing the routing paths.

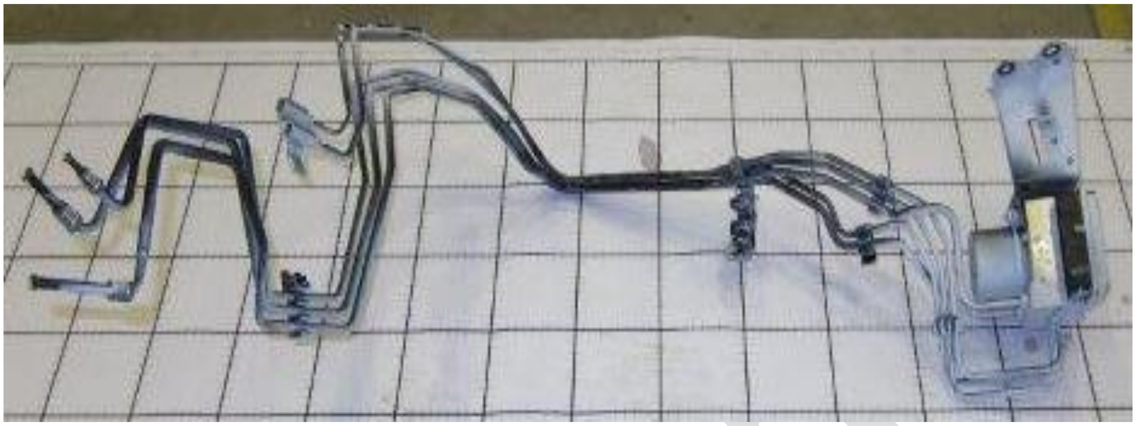


Image F.7-73: Brake Lines and Hoses Current Sub-assemblies

(Source: FEV, Inc. photo)

F.7.4.3.3 Brake Pedal Actuator Sub-Assembly

The baseline OEM Toyota Venza Brake Pedal Actuator Sub-assembly (**Image F.7-74**) is a multi-piece design of stamped steel fabricated components welded together as an assembly along with springs, pins, levers, and fasteners. These components have a sub-assembly mass of 2.104kg. This is a standard design configuration by nearly all OEMs allowing for adequate function while using a proven design and simple materials and processes. It is, however, not mass or cost efficient but instead is industry driven by allowing the continued utilization of existing capital equipment, tooling and reusing previous process/component designs.

Image F.7-74: Brake Pedal Actuator Current Sub-assembly

(Source: FEV, Inc. photo)

F.7.4.3.3.1 *<u>Brake Pedal Arm Frame Sub-Assembly</u>*

While this steel brake pedal frame design is extremely common, there are some high-performance and luxury vehicle models that have begun utilizing alternate designs. These include new designs for the Pedal Frame and Housing Sub-assembly (**Image F.7-75**). The new design utilizes a plastic framing and housing structure around the brake pedal arm sub-assembly. These injection molded frames simplify design by reducing components, ease assembly by eliminating welding and provide substantial weight savings. Other possible solutions use similar processing but different materials including AL, HSS, Mg and even Ti. This current welded sub-assembly has a net mass of 0.903kg.

Image F.7-75: Brake Pedal Arm Frame Current Sub-assembly

(Source: FEV, Inc. photo)

F.7.4.3.3.2 *<u>Brake Pedal Arm Ratio Lever</u>*

While this steel Brake Pedal Arm Ratio Lever (**Image F.7-76**) design is common there are some high performance and luxury vehicle models that began to utilize alternate designs. These redesigns make use of lighter materials that allow a weight savings. Materials that are considered include: Al, Ti, Mg and HSS. These pieces are fabricated and machined to simplify design as provide substantial weight savings. This current sub-assembly has a net mass of 0.471kg.

Image F.7-76: Brake Pedal Arm Frame Current Sub-assembly

(Source: FEV Inc photo)

F.7.4.3.3.3 *Brake Pedal Arm Assembly*

This steel Brake Pedal Arm (**Image F.7-77**) design is very common among OEMs. There are however, some high-performance and luxury vehicle models that have began utilizing alternate designs. These include redesigns for material substitutions for the use of Al, Ti, Mg, HSS and reinforced plastics. These new arms used simplified designs to reduce components and use light materials to provide substantial weight savings. This current welded sub-assembly has a net mass of 0.615kg.

Image F.7-77: Brake Pedal Arm Current Sub-assembly

(Source: FEV Inc photo)

F.7.4.3.4 Accelerator Pedal Actuator Sub-Assembly

The baseline OEM Toyota Venza Accelerator Pedal Actuator Sub-assembly (**Image F.7-78**) is a multi-piece design of injection molded components, springs, pins, levers and fasteners that are assembled together. This sub-assembly has a mass of 0.267kg.

Image F.7-78: Accelerator Pedal Actuator Current Sub-assembly

(Source: FEV Inc photo)

This configuration is very common in the automotive industry and used by nearly all OEMs. After researching for new designs, there were no significant mass reductions solutions that were found to be able to replace this unit and achieve any appreciable savings.

F.7.4.4 Summary of Mass-Reduction Concepts Considered

Table F.7-18 shows mass-reduction ideas that were brainstormed and considered for the Brake Actuation subsystem. These ideas include part modifications, material substitutions, and use of parts currently in production on other vehicles.

Component/ Assembly	Mass Reduction Idea	Estimated Impact	Risk & Trade-offs and/or Benefits
Brake Actuation Subsystem			
Master Cylinder	Replace from 2008 Toyota Prius (mass:0.468-0.985 & cost:1.08)	wt increase	In Production - Toyota. Not implemented due to wt increase
Reservoir	Replace from 2008 Toyota Prius (mass:0.147-0.336 & cost:0.85)	wt increase	In Production - Toyota. Not implemented due to wt increase
Support	Replace from 2008 Toyota Prius (mass:0.00-0.296 & cost:x)	wt increase	In Production - Toyota. Not implemented due to wt increase
Cap	Replace from 2008 Toyota Prius (mass:0.028-0.030 & cost:0.99)	wt increase	In Production - Toyota. Not implemented due to wt increase
Reservoir Asm	Replace from 2008 Toyota Prius (mass:0.175-0.662 & cost:x)	wt increase	In Production - Toyota. Not implemented due to wt increase
Accelerator Pedal	Composite with Mucell® for lever, frame & pad	10-20% wt save	Low vol production - auto
Brake Pedal Pad	Brake Pedal pad composite with Mucell®	10-20% wt save	Low vol production - auto
Brake Pedal Arm	Hollow plastic brake pedal and plastic arm (PA6-GF33)	30-40% wt save	In development - auto
	Brake pedal arm from HSS	5-10% wt save	Low vol production - auto
	Brake pedal arm from forged Aluminum	30-40% wt save	Higher Cost. Low vol production auto
	Brake pedal arm from Magnesium	60-70% wt save	High Cost. Low vol production - auto
	Brake pedal arm from Titanium	40-50% wt save	High Cost. Low production - racing / aftermarket
Brake Pedal Ratio Lever	Variable Ratio Mechanism either eliminated or simplified.	unknown	not investigated due to validation requirements
	Brake pedal Ratio Lever from HSS	5-10% wt save	Higher Cost. Low vol production
	Brake pedal Ratio Lever from forged Aluminum	20-30% wt save	Higher Cost. Low vol production
	Brake pedal Ratio Lever from Magnesium	40-50% wt save	Development required
	Brake pedal Ratio Lever from Titanium	40-50% wt save	High Cost. Low production - racing / aftermarket
Brake Pedal	Add parking brake functions to service brake pedal	5-10% wt save	not evaluated due to poor ranking

Table F.7-18 continued on next page

Brake Pedal Bracket	Aluminum Support Bracket (includes 2 sides, top, lower spacer & sensor brkt)	30-40% wt save	Higher Cost. Low vol production
	Magnesium Support Bracket (includes 2 sides, top, lower spacer & sensor brkt)	40-50% wt save	High Cost. Low vol production - auto
	HSS Support Bracket (includes 2 sides, top, lower spacer & sensor brkt)	10-20% wt save	Higher Cost. Low vol production
	Plastic (PA6 GF30) Support Bracket (includes 2 sides, top, lower spacer & sensor brkt)	50-60% wt save	Lower Cost. In production - many auto makers
	Replace from 2008 Toyota Prius (mass:0.000-0.400 & cost:x)	wt increase	In Production - Toyota. Not implemented due to wt increase
Brake Line System	Replace from 2008 Toyota Prius (mass:2.362-0.813 & cost:0.34)	50-60% wt save	In Production - Toyota
Distribution Block	Replace from 2008 Toyota Prius (mass:0.000-0.601 & cost:x)	wt increase	In Production - Toyota. Not implemented due to wt increase

Table F.7-18: Summary of Mass-Reduction Concepts Initially Considered for the Brake Actuation Subsystem

F.7.4.5 Selection of Mass Reduction Ideas

Table F.7-19 shows the mass-reduction ideas for the major components of the Brake Actuation subsystem that were selected for detail evaluation. There are six components or sub-assemblies being redesigned and changed in order to achieve mass reductions.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
06	**06**	**00**	**Brake Actuation Subsystem**	
06	06	00	Accelerator Pedal	Composite with Mucell® for lever, frame & pad
06	06	00	Brake Pedal Pad	Brake Pedal pad composite with Mucell®
06	06	00	Brake Pedal Arm	Hollow plastic brake pedal and plastic arm (PA6-GF33)
06	06	00	Brake Pedal Ratio Lever	Brake pedal Ratio Lever from Magnesium
06	06	00	Brake Pedal Bracket	Plastic (PA6 GF30) Support Bracket (includes 2 sides, top, lower spacer & sensor brkt)
06	06	00	Brake Line System	Replace from 2008 Toyota Prius (mass:2.362-0.813 & cost:0.34)

Table F.7-19: Mass-Reduction Ideas Selected for the Detailed Brake Actuation Subsystem Analysis

The mass saving solutions selected for the various components within the Brake Actuation Sub-subsystem vary greatly and are summarized in greater detail below.

F.7.4.5.1 Master Cylinder and Reservoir

The baseline Toyota Venza Master Cylinder and Reservoir Sub-assembly is already highly optimized for design and materials and therefore no further changes or solutions for mass reductions were identified.

F.7.4.5.2 Brake Lines and Hoses

The OEM Toyota Venza Brake Lines and Hoses Sub-assemblies are of conventional design. The March 2010 Lotus Report suggests a direct replacement and size normalization using the 2008 Toyota Prius Brake Line system as reference. This results in a reduction of the amount of brake lines being required and lowers the mass of the new routing paths. This redesign sub-subsystem has a reduced mass of 0.794kg.

F.7.4.5.3 Brake Pedal Actuator Sub-Assembly

The baseline Venza Brake Pedal Actuator Sub-assembly is currently a multi-piece steel design. The major components within this assembly have been redesigned and now have a new sub-assembly net mass of 0.545kg. The example below, **Image F.7-79**, is from a new design and production method developed by Trelleborg. This brake pedal design utilizes advanced water injection technology allowing very strong design function while still using light weight glass fiber reinforced plastic materials to achieve significant mass reductions. Due to the replacement of steel with an over-molded plastic, an additional material volume of 60-80% was made.

Image F.7-79: Brake Pedal Actuator Mass Reduced Sub-assembly Example

(Source: http://www.torquenews.com/auto-sector-stocks?page=27)

Another similar brake actuator system design has also been developed by BMW (**Image F.7-80**) for use in some of their high end luxury and performance vehicles. This unit utilizes plastic framing and pedal arms as well in order to reduce mass significantly.

Image F.7-80: Brake Pedal Actuator Mass Reduced Sub-assembly Example

(Source http://www.worldcarfans.com/111040531267/bmw-reveals-lightweight-component-innovations)

F.7.4.5.3.1 Brake Pedal Arm Frame Sub-Assembly

The conventional steel Brake Pedal Frame (**Image F.7-81**) design has been replaced with a PA6-GF sub-assembly. Due to the replacement of steel with plastic, an additional material volume of 80-90% was made. This solution is becoming more common in some OEM base level model vehicles as well as many high performance and luxury vehicle models. This includes OEMs such as GM, Chrysler, Ford, and Honda. The new design utilizes a plastic framing and housing structure around the brake pedal arm sub-assembly. These injection-molded frames simplify design by reducing components and easing assembly while also providing substantial weight savings. The sub-assembly shown here is from the brake pedal frame in a 2011 Chrysler Minivan. This redesigned plastic sub-assembly has a reduced mass of 0.230kg.

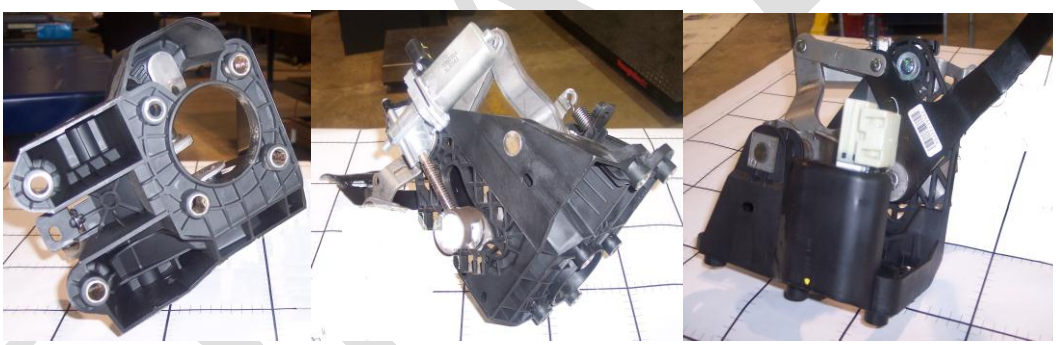


Image F.7-81: Brake Pedal Arm Frame Mass Reduced Sub-assembly Example

(Source: FEV Inc photo)

F.7.4.5.3.2 Brake Pedal Arm Ratio Lever

This steel Brake Pedal Arm Ratio Lever (**Image F.7-82**) has been redesigned to make use of Die Cast Mg. Due to the replacement of steel with Mg, an additional material volume of 60-70% was made. These new designs allow a substantial weight savings for a new reduced mass of 0.041kg.

Image F.7-82: Brake Pedal Arm Frame Reduced Mass Sub-assembly Example

F.7.4.5.3.3 Brake Pedal Arm Assembly

The steel Brake Pedal Arm (**Image F.7-83**) design is now being changed to a redesign allowing the use PA6-GF. Due to the replacement of steel with an over-molded plastic, an additional material volume of 60-70% was made. This design configuration is becoming more common among OEMs and provides simple processing by injection molding and enabling a simplified design and substantial weight savings. This particular example shows a hollow insert being over-molded to further decrease weight and improve strength. This new mass reduced sub-assembly has a net mass of 0.164kg.

Image F.7-83: Brake Pedal Arm Mass Reduced Sub-assembly Example

(Source: http://www.torquenews.com/auto-sector-stocks?page=27)

F.7.4.5.4 Accelerator Pedal Actuator Sub-Assembly

The current design Accelerator Pedal Actuator Sub-assembly (**Image F.7-84**) is already a good design regarding mass impact. This configuration is now very common in the automotive industry and used by nearly all OEMs. After researching for new designs, there are no significant mass reductions solutions found that could achieve any appreciable savings. However, the use of MuCell® technology during the injection molding process of some of the larger plastic components does allow for a small weight savings of approximately 10% with almost no cost penalty. This newly processed sub-assembly results in a reduced net mass of 0.243kg.

Image F.7-84: Accelerator Pedal Actuator Mass Reduced Sub-assembly Example

(Source: http://www.thetruthaboutcars.com/2010/02)

The net result of all of these changes within the Brake Actuation Sub-subsystem results a new total mass of 1.530kg.

F.7.4.6 Calculated Mass-Reduction & Cost Impact Results

Table F.7-20 shows the results of the mass-reduction ideas that were evaluated for the Brake Actuation subsystem. The implemented solutions resulted in a subsystem overall mass savings of 2.984kg and a cost savings differential of $31.90.

System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys/ Sub-Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
				Net Value of Mass Reduction Ideas					
06	06	00	**Brake Actuation Subsystem**						
06	06	01	Master Cylinder and Reservoir	A	0.000	$0.00	$0.00	0.00%	0.00%
06	06	02	Actuator Assemblies	A	1.443	$5.99	$4.15	26.06%	0.08%
06	06	03	Brake Lines and Hoses	A	1.541	$25.91	$16.81	27.84%	0.09%
				A	**2.984**	**$31.90**	**$10.69**	**53.90%**	**0.17%**
					(Decrease)	(Decrease)	(Decrease)		

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.7-20: Mass-Reduction and Cost Impact for the Brake Actuation Subsystem

Table F.7-21 shows the results for the Brake Actuation subsystem. The Brake Line Sub-assemblies show the best estimated mass reduction, 1.541kg, with a significant cost reduction of $25.91. The Brake Pedal Frame/Bracket accounted for the next largest mass savings realized with 0.673kg and a cost reduction of $1.36.

System	Subsystem	Sub-Subsystem	Component / Assembly Description	Mass Reduction "kg" (1)	Cost Impact "$" (1)	Cost/ Kilogram $/kg
				Mass Reduction Results		
06	06	00	**Brake Actuation Subsystem**			
06	06	02	Accelerator Pedal	0.027	$0.08	$2.91
06	06	02	Brake Pedal Arm	0.451	$3.82	$8.48
06	06	02	Brake Pedal Pad	0.006	$0.03	$5.33
06	06	02	Brake Pedal Ratio Lever	0.286	$0.70	$2.43
06	06	02	Brake Pedal Bracket	0.673	$1.36	$2.03
06	06	03	Brake Line System	1.541	$25.91	$16.81

(1) "+" = decrease, "-" = increase

Table F.7-21: Calculated Subsystem Mass-Reduction and Cost Impact Results for the Brake Actuation Subsystem Components

F.7.5 Power Brake Subsystem (for Hydraulic)

F.7.5.1 Subsystem Content Overview

As seen in **Table F.7-22**, the Power Brake subsystem consists of the Vacuum Booster assembly.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
06	07	00	**Power Brake (for hydraulic)**	--
06	07	01	Vacuum Booster System Asm	2.829
			Total Subsystem Mass =	**2.829**
			Total System Mass =	**85.740**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**3.30%**
			System Mass Contribution Relative to Vehicle =	**0.17%**

Table F.7-22: Mass Breakdown by Sub-subsystem for the Power Brake (for Hydraulic) Subsystem

F.7.5.2 Toyota Venza Baseline Subsystem Technology

The Toyota Venza's Power Brake subsystem (**Image F.7-85**) follows typical industry standards in using a vacuum-actuated booster. The booster is a metal canister that contains a valve and diaphragm and uses vacuum from the engine to multiply the force a driver's foot applies to the master cylinder. A rod going through the center of the canister connects to the master cylinder's piston on one side and to the pedal linkage on the other. The booster also includes a check valve that maintains vacuum in the booster when the engine is turned off, or if a leak forms in a vacuum hose. The vacuum booster has to be able to provide enough volume and pressure within the brake line system for a driver to make several stops in the event that the engine stops running.

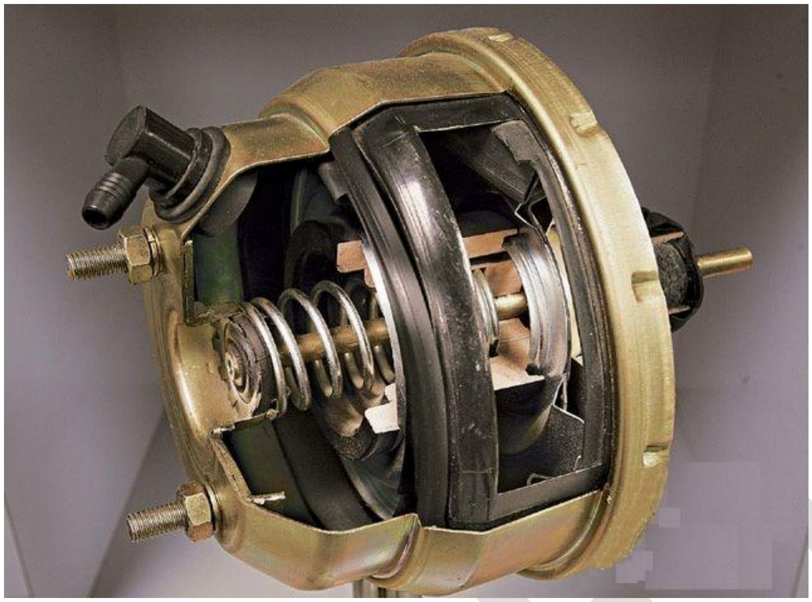


Image F.7-85: Brake Power Brake Subsystem Major Sub-assembly Example

(Source:http://www.superchevy.com/technical/chassis/brakes/sucp_0901_power_brake_boosters)

F.7.5.3 Mass-Reduction Industry Trends

Some manufacturers have begun to implement a new design of system that utilizes solenoids and valves in order to maintain system pressure during various driving conditions. This allows for removal of the typical conventional vacuum booster system configuration. This smaller, but much more expensive system, usually requires the addition of wiring harnesses and control modules to process I/Os and regulate the system operation. But this small addition of materials is minor when compared to the overall mass saved by removing the booster unit. The result of this system exchange results in a significant weight savings. This electro-mechanical system (**Image F.7-86**) configuration is utilized in the 2008 Toyota Prius. Another example of this technology is the Hyperbrake™ system (**Image F.7-87**) by Janel Hydro. It claims to completely eliminate the vacuum booster by use of pistons and cylinders to amplify the hydraulic pressure of the brake fluid.

Image F.7-86: Toyota Prius Hydraulic Pressure Booster

(Source: Lotus – 2010 March EPA Report)

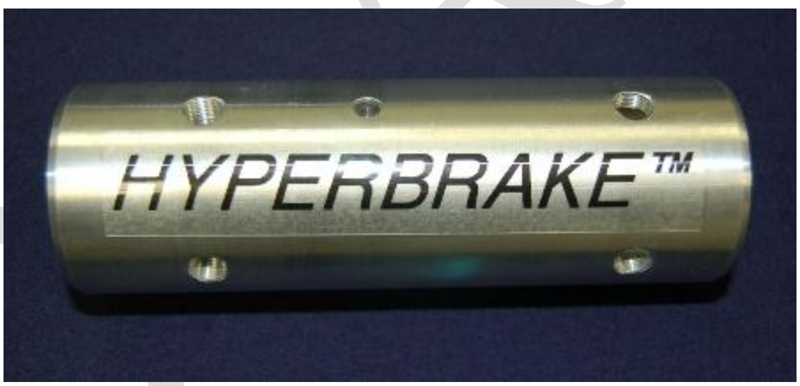


Image F.7-87: Janel Hyperbrake Hydraulic Pressure Booster

(Source: http://www.janelhydro.com/)

F.7.5.3.1 Vacuum Booster Sub-Assembly

The baseline Venza Power Brake Sub-assembly (**Image F.7-88**) is a multi-piece steel design. The major components within this assembly are made from stamped steel (Front Shell – **Image F.7-89**; Rear Shell – **Image F.7-90**; Mount Stiffener – **Image F.7-91**; Diaphragm Backing Plate – **Image F.7-92**), small fabricated steel parts (Clevis Pin and Bracket, Center Plunger, Actuator Shaft, Mounting Studs) and a few plastic and rubber molded pieces (Plunger Boot, Diaphragm, Piston Housing). These components are then assembled with various processing methods and fasteners into the vacuum booster system. Together these components have a net sub-assembly mass of 1.725kg.

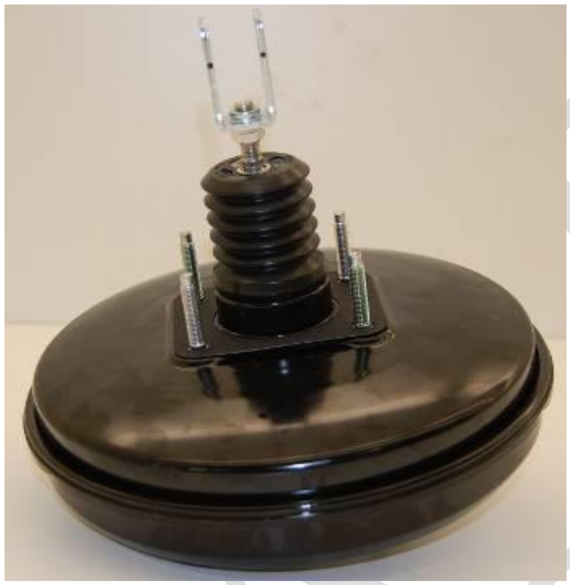


Image F.7-88: Brake Pedal Actuator Mass Current Sub-assembly

(Source: Lotus – 2010 March EPA Report)

F.7.5.3.1.1 *Front Shell*

This Booster Front Shell (**Image F.7-89**) is of a standard design configuration. It is fabricated from a one-piece sheet metal stamping and painted for corrosion resistance. There are a few alternate designs that have been tried in other vehicles. These new designs utilize different materials including molded reinforced plastics, spun Al, and HSS stampings. These alternative materials allow for simple manufacturing while still providing substantial weight savings. The current steel Front Shell has a mass of 0.537kg.

Image F.7-89: Vacuum Booster Front Shell Current Component

(Source: FEV, Inc photo)

F.7.5.3.1.2 *Rear Shell*

The current Booster Rear Shell (**Image F.7-90**) is a typical design used by many OEM manufacturers. It is a fabricated one piece sheet metal stamping, painted for corrosion resistance. There are some alternate designs that have been tried in other applications. These other configurations utilize different materials including molded reinforced plastics, spun Al and HSS stampings. These materials provide weight savings while still allowing for simple manufacturing processes. The Venza Rear Shell has a mass of 0.462kg.

Image F.7-90: Vacuum Booster Rear Shell Current Component

(Source: FEV, Inc. photo)

F.7.5.3.1.3 *Plate Mount Stiffener*

The stamped steel Plate Mount Stiffener (**Image F.7-91**) design is very common among OEMs. There are other material alternatives that allow for mass savings. These include redesigns for material substitutions for the use of - Al, Ti, Mg, HSS and reinforced plastics. The Venza Plate Mount Stiffener component has a mass of 0.064kg.

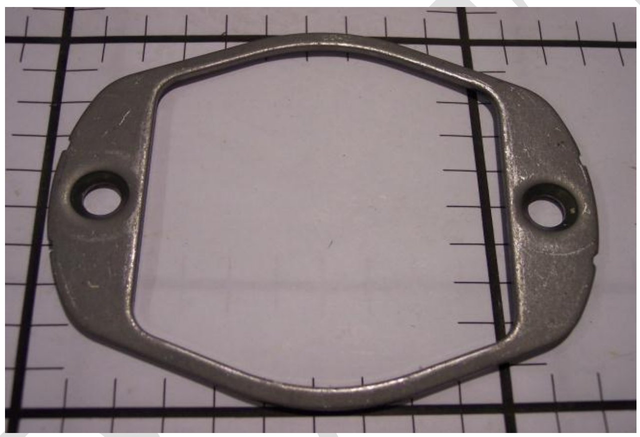


Image F.7-91: Vacuum Booster Plate Mount Stiffener Current Component

(Source: FEV, Inc. photo)

F.7.5.3.1.4 *Backing Plate, Diaphragm*

The baseline OEM Toyota Venza Diaphragm Backing Plate, **Image F.7-92**, is a single-piece, stamped steel design. The plastic molded sleeve is not included in this part's mass solution. This Venza Backing Plate component has a mass of 0.328kg.

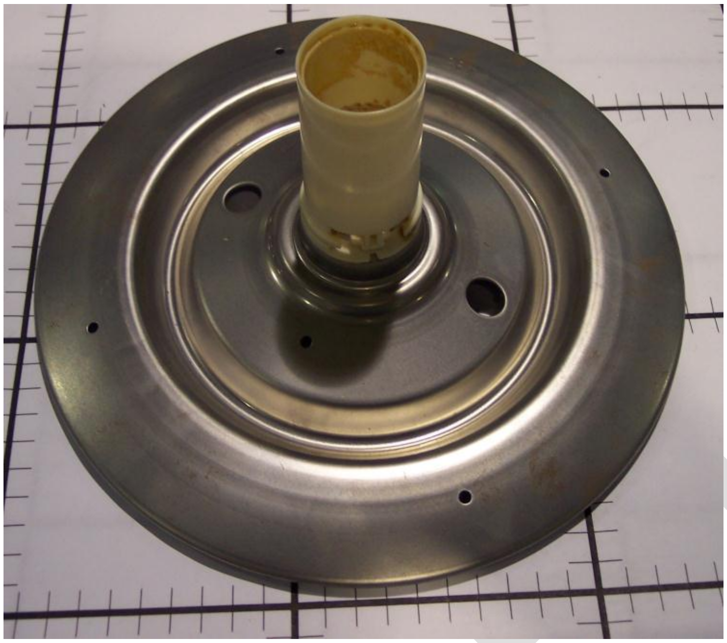


Image F.7-92: Vacuum Booster Backing Plate, Diaphragm Current Component

(Source: FEV, Inc. photo)

F.7.5.4 Summary of Mass-Reduction Concepts Considered

Table F.7-23 shows mass-reduction ideas that were brainstormed and considered for the Power Brake subsystem. Ideas include part modifications and material substitutions for eleven different components.

Component/ Assembly	Mass Reduction Idea	Estimated Impact	Risk & Trade-offs and/or Benefits
Power Brake (for hydraulic)			
Booster Clevis Pin	Make booster clevis pin out of aluminum	30-40% wt save	Higher Cost. In Production - auto.
	Make booster clevis pin out of HSS	10-20% wt save	Higher Cost.
	Make booster clevis pin out of Titanium	40-50% wt save	High Cost. Not done.
Booster Clevis Bracket	Make booster clevis bracket (nut) out of aluminum	30-40% wt save	Higher Cost. In Production - auto.
	Make booster clevis bracket (nut) out of HSS	10-20% wt save	Higher Cost. Low volume.
	Make booster clevis bracket (nut) out of Titanium	40-50% wt save	High Cost. Low production - auto racing
Vacuum Brake Booster Shell - Front	Make vacuum brake booster shell (front) out of spun aluminum	30-40% wt save	Higher Cost. In production - auto.
	Make vacuum brake booster shell (front) out of HSS	10-20% wt save	Higher Cost. Low vol production
	Make vacuum brake booster shell (front) out of die cast Magnesium	50-60% wt save	High Cost. Development
	Make vacuum brake booster shell (front) out of Titanium	40-50% wt save	High Cost. Not produced.
	Make vacuum brake booster shell (front) out of molded & ribbed PA6 GF30	60-70% wt save	Lower Cost. Development.
Vacuum Brake Booster Shell - Rear	Make vacuum brake booster shell (rear) out of spun aluminum	30-40% wt save	Higher Cost. In production - auto.
	Make vacuum brake booster shell (rear) out of HSS	10-20% wt save	Higher Cost. Low vol production
	Make vacuum brake booster shell (rear) out of die cast Magnesium	50-60% wt save	High Cost. Development
	Make vacuum brake booster shell (rear) out of Titanium	40-50% wt save	High Cost. Not produced.
	Make vacuum brake booster shell (rear) out of molded & ribbed PA6 GF30	60-70% wt save	Lower Cost. Development.
Vacuum Fitting	Make vacuum fitting out of plastic	60-70% wt save	Lower Cost. In production - auto
Piston, Actuator	Make booster piston, actuator out of forged aluminum	30-40% wt save	Higher Cost. In production - auto
	Make booster piston, actuator out of HSS	10-20% wt save	Higher Cost. Development
	Make booster piston, actuator out of Magnesium	50-60% wt save	High Cost. Development
	Make booster piston, actuator out of Titanium	40-50% wt save	High Cost. Not produced.

Table F.7-23 continued on next page

Plate, Mount Stiffener	Make booster plate, mount stiffener out of forged aluminum	30-40% wt save	Higher Cost. Development
	Make booster plate, mount stiffener out of HSS	10-20% wt save	Higher Cost. Low production
	Make booster plate, mount stiffener out of glass filled plastic	60-70% wt save	Lower Cost. R&D required.
	Make booster plate, mount stiffener out of Magnesium	50-60% wt save	High Cost. Development
	Make booster plate, mount stiffener out of Titanium	40-50% wt save	High Cost. Not produced.
Studs - Long, MC to BM	Make studs - long out of forged aluminum	30-40% wt save	Higher Cost. Low vol production
	Make studs - long out of HSS	10-20% wt save	Higher Cost. Not produced
	Make studs - long out of Titanium	40-50% wt save	High Cost. Production - auto racing
Shaft (threaded), Center Plunger - Valve, Metering	Make shaft, center plunger out of forged aluminum	30-40% wt save	Higher Cost. Low vol production
	Make shaft, center plunger out of HSS	10-20% wt save	Higher Cost.
	Make shaft, center plunger out of Titanium	40-50% wt save	High Cost. Not produced
Backing Plate, Diaphram - Vacuum Booster	Make backing plate out of stamped aluminum	30-40% wt save	Higher Cost. Low production
	Make backing plate out of HSS	10-20% wt save	Higher Cost. Development
	Make backing plate out of ABS plastic	60-70% wt save	Lower Cost. R&D required
	Make backing plate out of magnesium	50-60% wt save	High Cost. Not produced
Level Sensor (Reservoir)	Replace from 2008 Toyota Prius (mass:0.007-0.009 & cost:1.00)	Lotus idea - wt increase	Not analyzed - wt increase

Table F.7-23: Summary of Mass-Reduction Concepts Initially Considered for the Power Brake (for Hydraulic) Subsystem

F.7.5.5 Selection of Mass Reduction Ideas

Table F.7-24 shows mass-reduction ideas for the Power Brake subsystem that were selected as final solutions for detailed evaluation for both mass and cost.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
06	**07**	**00**	**Power Brake (for Hydraulic) Subsystem**	
06	07	00	Booster Clevis Pin	Make booster clevis pin out of aluminum
06	07	00	Booster Clevis Bracket	Make booster clevis bracket (nut) out of aluminum
06	07	00	Vacuum Brake Booster Shell - Front	Make vacuum brake booster shell (front) out of molded & ribbed PA6 GF30
06	07	00	Vacuum Brake Booster Shell - Rear	Make vacuum brake booster shell (rear) out of spun aluminum
06	07	00	Vacuum Fitting	Make vacuum fitting out of plastic
06	07	00	Piston, Actuator	Make booster piston, actuator out of Magnesium
06	07	00	Plate, Mount Stiffener	Make booster plate, mount stiffener out of glass filled plastic
06	07	00	Studs - Long, MC to BM	Make studs - long out of forged aluminum
06	07	00	Shaft (threaded), Center Plunger - Valve, Metering	Make shaft, center plunger out of forged aluminum
06	07	00	Backing Plate, Diaphram - Vacuum Booster	Make backing plate out of ABS plastic

Table F.7-24: Mass-Reduction Ideas Selected for Detailed Power Brake (for Hydraulic) Subsystem Analysis

F.7.5.5.1 Vacuum Booster Sub-Assembly

The new Brake Vacuum Booster Sub-assembly (**Image F.7-93**) is still a multi-piece design as the original was but now using optimized, mass reduced components where applicable. With these 11 new component designs assembled together, this new booster sub-assembly now has a reduced mass of 0.528kg.

Image F.7-93: Vacuum Booster Mass Reduced Sub-assembly Example

(Source: http://www.autohausaz.com/vw-auto-parts/vw-brake_booster-replacement.html)

F.7.5.5.1.1 *Front Shell*

The conventional steel Vacuum Booster Front Shell (**Image F.7-94**) design has been replaced with a PA6-GF sub-assembly. The piece is webbed and ribbed, as needed, for maximum reinforcement as well as having over-molded inserts in key areas. Due to the replacement of steel with plastic, an additional material volume of 30-40% was made. This design is not currently in any high-production applications, but should become more accepted in lighter applications in future model releases. This injection-molded shell retains a simplified design and manufacturing process while also providing substantial weight savings. This redesigned plastic component has a reduced mass of 0.087kg.

Image F.7-94: Vacuum Booster Front Shell Mass Reduced Component Example

(Source: Lotus – 2010 March EPA Report)

F.7.5.5.1.2 Rear Shell

The steel Vacuum Booster Rear Shell (**Image F.7-95**) design has been replaced with a single-piece forged Al component. Due to the replacement of steel with Al, an additional material volume of 20-30% was made. This design is not commonly used by OEMs but can easily be utilized in many current applications. This forged shell retains a simplified design and uses a common manufacturing process while still allowing for reasonable weight savings. This redesigned component has a reduced mass of 0.239kg.

Image F.7-95: Vacuum Booster Rear Shell Reduced Mass Component Example

(Source: http://www.walkertool.com/part17.htm)

F.7.5.5.1.3 *Mounting Plate*

The steel Mounting Plate design is now being replaced with a PA6-GF sub-assembly. The piece is webbed and ribbed for reinforcement using over-molded inserts in key areas. Due to the replacement of steel with an over-molded plastic, an additional material volume of 30-40% was made. Bendix (**Image F.7-96**) is one such major manufacturer that utilizes plastic material for this type of design. Delphi (**Image F.7-97**) also has a new design that utilizes Hytel® material and includes over-molded inserts. This configuration provides simple processing through injection molding and enables a simplified design with substantial weight savings. This new mass reduced part now being utilized has weight of 0.012kg.

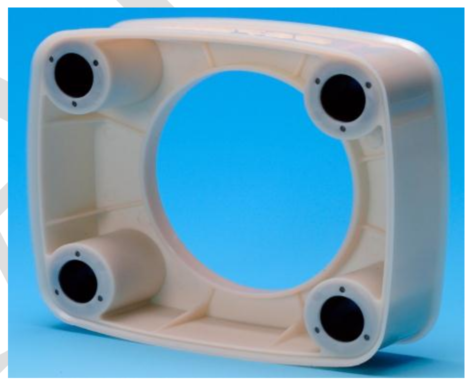


Image F.7-96: Bendix Mounting Plate **Image F.7-97: Delphi Mounting Plate**

(Image F.7-95- Source: http://www.hooverautoparts.com/index.php?cruising=products&category=Brake%20Parts)
(Image F.7-96 - Source: http://www2.dupont.com/Automotive/en_US/news_events/article20040126.html)

F.7.5.5.1.4 *Diaphragm Plate*

The stamped steel Diaphragm Plate (**Image F.7-98**) is being redesigned to allow the use PA6-GF. Due to the replacement of steel with an over-molded plastic, an additional material volume of 30-40% was made. This new design can be simply processed with injection molding and enables a simplified design with substantial weight savings. This new mass-reduced component has a resulting mass of 0.057kg.

Image F.7-98: Vacuum Booster Diaphragm Backing Plate Mass Reduced Component Example

F.7.5.6 Calculated Mass-Reduction & Cost Impact Results

Table F.7-25 shows the results of the mass reduction ideas that were evaluated and implemented for the Power Brake subsystem. This included redesigns and modifications being made to 10 different components. The implemented solutions resulted in a subsystem overall mass savings of 1.1964kgs and a cost savings differential of $1.35.

				Net Value of Mass Reduction Ideas					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys/ Sub-Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
06	**07**	**00**	**Power Brake (for Hydraulic) Subsystem**						
06	07	01	Vacuum Booster System Asm	A	1.196	$1.35	$1.13	42.25%	0.07%
				A	**1.196** (Decrease)	**$1.35** (Decrease)	**$1.13** (Decrease)	**42.25%**	**0.07%**

(1) **"+" = mass decrease, "-" = mass increase**
(2) **"+" = cost decrease, "-" = cost increase**

Table F.7-25: Mass-Reduction and Cost Impact for the Power Brake (Hydraulic) Subsystem

Table F.7-26 shows the results for the various components that were redesigned for weight savings. The Front and Rear Booster Shells show the largest calculated mass reductions (83.8% and 48.3%, respectively) along with a small total cost reduction for each.

System	Subsystem	Sub-Subsystem		Component / Assembly Description	Mass Reduction Results			
						Mass Reduction "kg" (1)	Cost Impact "$" (1)	Cost/ Kilogram $/kg
06	**07**	**00**		**Power Brake (for Hydraulic) Subsystem**				
06	07	01		Booster Clevis Pin		0.006	-$0.12	-$22.00
06	07	01		Booster Clevis Bracket		0.033	-$0.05	-$1.44
06	07	01		Vacuum Brake Booster Shell - Front		0.450	$0.66	$1.47
06	07	01		Vacuum Brake Booster Shell - Rear		0.223	$0.01	$0.06
06	07	01		Vacuum Fitting		0.032	$1.02	$31.77
06	07	01		Piston, Actuator		0.021	$0.10	$5.03
06	07	01		Plate, Mount Stiffener		0.052	$0.25	$4.79
06	07	01		Studs - Long, MC to BM		0.078	-$0.54	-$6.89
06	07	01		Shaft, Center Plunger - Valve, Metering		0.030	-$0.22	-$7.48
06	07	01		Backing Plate, Diaphragm - Vacuum Booster		0.271	$0.24	$0.90

(1) "+" = decrease, "-" = increase

Table F.7-26: Calculated Subsystem Mass-Reduction and Cost Impact Results for the Power Brake (for Hydraulic) Subsystem

F.8 Frame & Mounting System

As shown in **Table F.8-1**, the Frame & Mounting system is made up of six subsystems: Frame, Body Mounting, Engine Transmission Mounting, Towing and Coupling Attachments, Spare Tire Mounting (Chassis), and Rolling Chassis Modules. The Frame is the only subsystem applicable to this study. The Frame subsystem is comprised primarily of the front and rear frames (carriages) and associated brackets.

Comparing the six sub-systems, it is clear that the mass is located in the Frame subsystem.

System	Subsystem	Sub-Subsystem	Description	System & Subsystem Mass "kg"
07	**00**	**00**	**Frame and Mounting System**	
07	01	00	Frame Subsystem	43.729
07	02	00	Body Mounting Subsystem	0.000
07	03	00	Engine Transmission Mounting Subsystem	0.000
07	04	00	Towing and Coupling Attachments Subsystem	0.000
07	05	00	Spare Tire Mounting (Chassis) Subsystem	0.000
07	08	00	Rolling Chassis Modules	0.000
			Total System Mass =	**43.729**
			Total Vehicle Mass =	**1711**
			System Mass Contribution Relative to Vehicle =	**2.56%**

Table F.8-0-3: Baseline subsystem breakdown for Frame & Mounting System

Table F.8-2 shows the calculated mass-reduction results for the ideas generated related to the Frame and Mounting system. A mass savings of 16.498kg was realized with a cost increase of $3.66, resulting in a cost increase of $0.22/kg.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
07	**00**	**00**	**Frame and Mounting System**						
07	01	00	Frame Sub System	B	16.498	-$3.66	-$0.22	37.73%	0.96%
07	02	00	Body Mounting Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
07	03	00	Engine Transmission Mounting Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
07	04	00	Towing and Coupling Attachments Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
07	05	00	Spare Tire Mounting (Chassis) Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
07	08	00	Rolling Chassis Modules		0.000	$0.00	$0.00	0.00%	0.00%
				B	**16.498** (Decrease)	**-$3.66** (Increase)	**-$0.22** (Increase)	**37.73%**	**0.96%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.8-0-4: Calculated Mass-Reduction and Cost Impact for Frame & Mounting System

F.8.1 Frame Subsystem

F.8.1.1 Subsystem Content Overview

As seen in **Table F.8-3**, the Frame subsystem is comprised of the Full Frame, Special Protective Structures, Body Isolators, Front Strut Frame (**Image F.8-1**), Rear Strut Frame (**Image F.8-2**), and Miscellaneous Components sub-subsystems. The major components within these sub-subsystems are the front and rear cradles, frame brackets, cushions, and associated hardware. The most significant contributor to the mass of the Frame subsystem is the Front Strut Frame.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
07	**01**	**00**	**Frame Subsystem**	
07	01	01	Full Frame	0.000
07	01	02	Special Protective Structures (Engine Under Cover)	0.062
07	01	03	Body Isolators (Front & Rear Stopper, Front Suspension Member Body Mntg)	0.774
07	01	04	Front Strut Frame (Frame Asm, Cushions, Brackets)	32.549
07	01	05	Rear Strut Frame (Rear Cradle, Cushions, Brackets)	10.345
07	01	99	Miscellaneous	0.000
			Total Subsystem Mass =	**43.729**
			Total System Mass =	**43.729**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**100.00%**
			Subsystem Mass Contribution Relative to Vehicle =	**2.56%**

Table F.8-0-5: Mass Breakdown by Sub-subsystem for Frame Subsystem

Image F.8-1: Front Frame Assembly

(Source: Lotus Report)

Image F.8-2: Rear Frame Assembly

(Source: Lotus Report)

F.8.1.2 Toyota Venza Baseline Subsystem Technology

The Toyota Venza Frame & Mounting system follows typical industry standards as it has nothing new, out of the ordinary, or unique. The Frame & Mounting system's Front Cradle (**Image F.8-3**) and Rear Cradle (**Image F.8-4**), consists of several formed steel components welded together. This is a common design across Toyota platforms. Several parts, including the Front Suspension Brackets (**Image F.8-5**), Front Damper Assembly (**Image F.8-6**), Frame Side Rail Brackets (**Image F.8-7**), and Rear Suspension Brackets

(**Image F.8-8**), are bolted on to attach and/or provide support for other components (including the radiator) to the body.

F.8.2 Mass-Reduction Industry Trends

Magnesium is a material that is making interesting inroads into automotive design. It has a mass that is two-thirds that of aluminum for equivalent volumes of material. Specifically of interest for the Frame & Mounting system is a magnesium engine cradle/frame that was manufactured for the 2006 Chevrolet Corvette Z06 in a joint venture between Hydro Magnesium and Meridian Technologies Inc.

Aluminum Rheinfelden in Germany developed Magsimal-59®, an aluminum alloy that has the chemical composition AlMg5Si2Mn. The casting capabilities of this alloy produce parts with less mass than conventional aluminum casting alloys. Used in high-pressure die casting, suspension components have been made for Porsche and BMW with wall thickness as thin as 2.5 mm.

Another emerging technology is NanoMAG, which will eventually become very attractive for many automotive applications. This patent-pending process features isotropic, fine-grained strengthening of magnesium sheet stock. A combined effort of NanoMAG LLC and the University of Michigan has produced ultra-fine-grain “nanocrystalline” magnesium sheet, which has properties superior to those of conventional materials such as steel, aluminum, and titanium. Thixomolding® technology produces a sheet bar that is put through secondary thermo-mechanical heat processing. Precise control of the microstructure increases the yield strength of the original Thixomolded® stock by more than 200% to more than 250 MPa along with 10% elongation. The result is an advanced magnesium sheet/plate with a superior strength-to-weight ratio. Current uses of Nano MAG are limited to low-volume applications such as defense. Therefore, automotive applications are anticipated in the future.

F.8.2.1 Front Frame

The Front Frame (**Image F.8-3**) consists of approximately 34 individual steel stampings welded together to form a single frame.

Image F.8-3: Front Frame

(Source: FEV, Inc. photo)

F.8.2.2 Rear Frame

The Rear Frame (**Image F.8-4**) consists of approximately six individual steel stampings welded together to form a single rear frame.

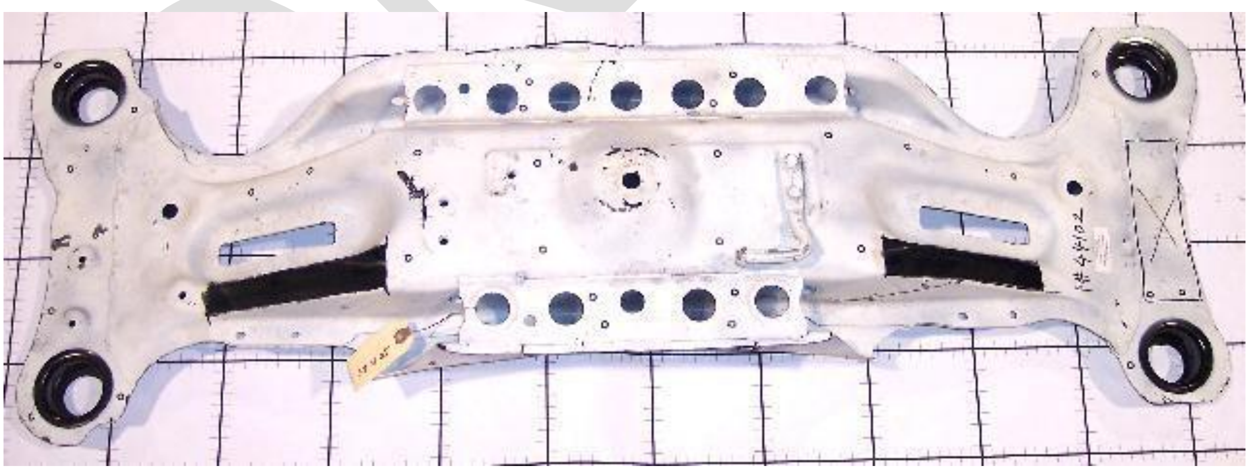


Image F.8-4: Rear Frame

(Source: FEV, Inc. photo)

F.8.2.3 Front Suspension Brackets

The Front Suspension Bracket (**Image F.8-5**) is made of two different steel stampings that are welded together.

Image F.8-5: Front Suspension Bracket

(Source: FEV, Inc. photo)

F.8.2.4 Front Damper Assembly

The Front Damper Assembly (**Image F.8-6**) consists of one steel stamping and one forging molded together to form the assembly.

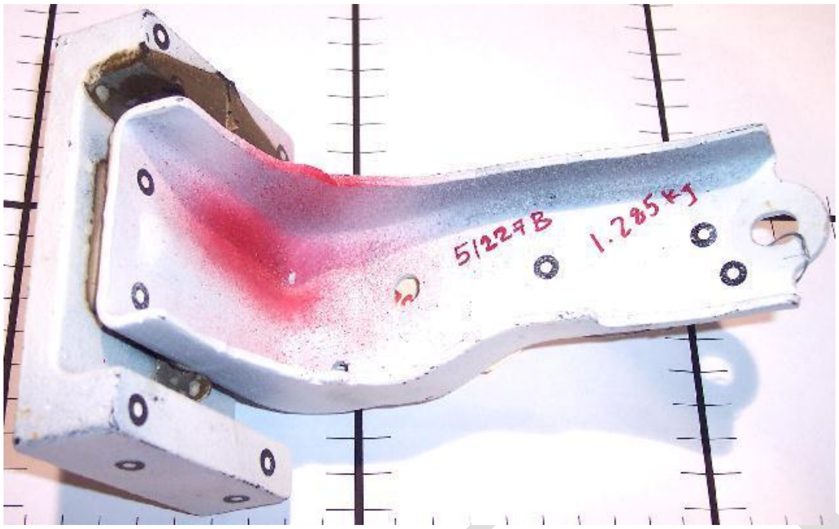


Image F.8-6: Front Damper Assembly

(Source: FEV, Inc. photo)

F.8.2.5 Frame Side Rail Brackets

The Venza Frame Side Rail Bracket (**Image F.8-7**) is formed by two different steel stampings that are spot-welded together.

Image F.8-7: Frame Side Rail Bracket

(Source: FEV, Inc. photo)

F.8.2.6 RearSuspension Stopper Brackets

The Rear Suspension Stopper Bracket (**Figure 5.8-8**) is formed by two different steel stampings that are spot-welded together.

Image F.8-8: Rear Suspension Stopper Bracket

(Source: FEV, Inc. photo)

F.8.3 Summary of Mass-Reduction Concepts Considered

Table F.8-4 is the Frame & Mounting system summary chart for mass reduction concepts. The ideas suggest substitutions of polymer material, aluminum, high strength steel, magnesium, Magsimal-59®, and applications observed on the 2005 VW Passat.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
BRACKET SUB-ASSY, FRONT SUSPENSION MEMBER, RH (51023A)	Make out of Nylon 66 - 60% GF	60% Mass Reduction	Cost savings due to reduced cycle time
	Normalize to 2005 VW Passat	15% Mass Reduction	Cost savings due to reduction in material usage
BRACKET SUB-ASSY, FRONT SUSPENSION MEMBER, LH (51024A)	Make out of Nylon 66 - 60% GF	60% Mass Reduction	Cost savings due to reduced cycle time
	Normalize to 2005 VW Passat	15% Mass Reduction	Cost savings due to reduction in material usage
Stopper, Rear Suspension Member, Lower RH (52273A)	Make out of Nylon 66 - 60% GF	60% Mass Reduction	Cost savings due to reduced cycle time
Stopper, Rear Suspension Member, Lower LH (52274A)	Make out of Nylon 66 - 60% GF	60% Mass Reduction	Cost savings due to reduced cycle time
Member Sub-Asm, Rear Suspension (51206A)	Normalize to 2005 VW Passat	25% Mass Reduction	Cost savings due to reduction in material usage
DAMPER, FRONT SUSPENSION MEMBER DYNAMIC (51227B)	Normalize to 2005 VW Passat	15% Mass Reduction	Cost savings due to reduction in material usage
PLATE SUB-ASSY, FRAME SIDE RAIL, RH (51035)	Normalize to 2005 VW Passat	15% Mass Reduction	Cost savings due to reduction in material usage
	Make out of Stamped Aluminum	40% Mass Reduction	Cost increase due to more expensive material substition
PLATE SUB-ASSY, FRAME SIDE RAIL, LH (51036)	Normalize to 2005 VW Passat	15% Mass Reduction	Cost savings due to reduction in material usage
	Make out of Stamped Aluminum	40% Mass Reduction	Cost increase due to more expensive material substition
Isolator Bushings	Eliminate bushing cans from isolator bushings	No Mass Savings	Minimal Cost Impact, No known current application
Front Frame Assy	Cast from Magsimal® -59	50% Mass Reduction	Significant Cost Increase
	Use High Strength Steel	10% Mass Reduction	Significant Cost Increase
	Fabricate from Titanium	40% Mass Reduction	Significant Cost Increase, No known current application
	Cast out of Magnesium	50% Mass Reduction	Cost Increase, Currently used on high end vehicles
Member Sub-Asm, Rear Suspension (51206A)	Cast out of Magnesium	50% Mass Reduction	Significant Cost Increase
	Tailor Rolled Blanks	10% Mass Reduction	Significant Cost Increase. Not recommended by supplier
	Use High Strength Steel	10% Mass Reduction	Significant Cost Increase
	Fabricate from Titanium	40% Mass Reduction	Significant Cost Increase, No known current application
	Cast out of Magnesium	50% Mass Reduction	Cost Increase, Currently used on high end vehicles

Table F.8-4: Summary of mass-reduction concepts initially considered for the Frame Subsystem.

F.8.3.1 Selection of Mass Reduction Ideas

Table F.8-5 shows the selected mass reduction ideas for the Frame subsystem for detailed evaluation of both the mass savings achieved and manufacturing cost. Several ideas suggest plastics as alternate materials. Also, included are part substitutions from other vehicle designs such as those currently in use on the VW Passat (as determined in the March 2010 Lotus Report).

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
07	01	00	Frame Subsystem	
07	01	04	Bracket, Front Suspension, RH (51023A)	Normalize to 2005 VW Passat
			Bracket, Front Suspension, RH (51023A)	Make out of Nylon 66 - 60% GF
			Bracket, Front Suspension, LH (51024A)	Normalize to 2005 VW Passat
			Bracket, Front Suspension, LH (51024A)	Make out of Nylon 66 - 60% GF
			Stopper, Rear Suspension, Lower RH (52273A)	Make out of Nylon 66 - 60% GF
			Stopper, Rear Suspension, Lower RH (52274A)	Make out of Nylon 66 - 60% GF
			Damper, Front Suspension (51227B)	Normalize to 2005 VW Passat
			Bracket, Frame Side Rail, RH (51035)	Normalize to 2005 VW Passat
			Bracket, Frame Side Rail, RH (51035)	Make out of Nylon 66 - 60% GF
			Bracket, Frame Side Rail, LH (51036)	Normalize to 2005 VW Passat
			Bracket, Frame Side Rail, LH (51036)	Make out of Nylon 66 - 60% GF
			Front Frame Assy	Cast out of Magnesium
07	01	05	Rear Frame Assy (51206A)	Normalize to 2005 VW Passat

Table F.8-5: Mass-Reduction Ideas Selected for Front Drive Housed Axle Subsystem Analysis

F.8.3.2 Front Suspension Brackets

The solution chosen for implemention on the Front Suspension Bracket (**Image F.8-9**) is to ratio the Venza vehicle net mass and bracket size versus the VW Passat specs (Lotus) to reduce the bracket size and then change the material from steel to Nylon (PA66 – 60% GF).

Image F.8-9: Front Suspension Bracket

(Source: FEV photo)

F.8.3.3 Rear Suspension Stopper Brackets

The solution chosen to be implemented on the Rear Suspension Stopper Bracket (**Image F.8-10**) is to change the material from steel to Nylon (PA66 – 60% GF).

Image F.8-10: Rear Suspension Stopper Bracket

(Source: FEV, Inc. photo)

F.8.3.4 Front Damper Assembly

The solution chosen to be implemented on the Front Damper Assembly (**Image F.8-11**) is to ratio the Venza vehicle net mass and damper size versus the VW Passat specs (Lotus) to reduce the Damper size.

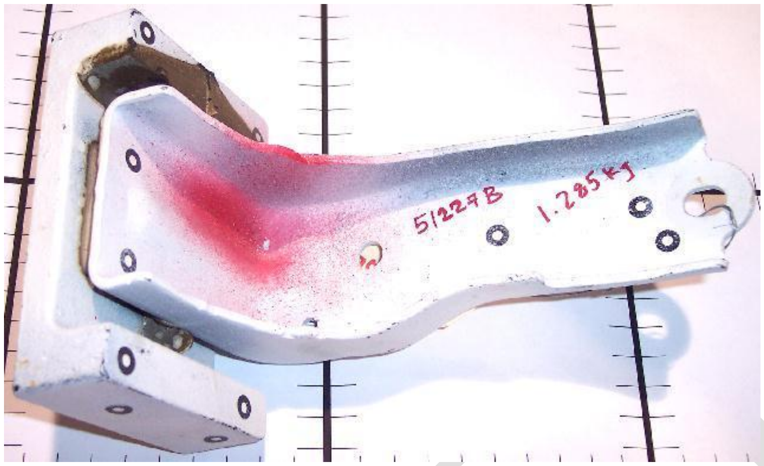


Image F.8-11: Front Damper Assembly

(Source: FEV photo)

F.8.3.5 Front Damper Assembly

The solution chosen for implementation on the Frame Side Rail Bracket (**Image F.8-12**) is to ratio the Venza vehicle net mass and bracket size versus the VW Passat specs (Lotus) to reduce the bracket size and then change the material from steel to Nylon (PA66 – 60% GF).

Image F.8-12: Frame Side Rail Bracket

(Source: FEV photo)

F.8.3.6 Front Frame Assembly

The solution chosen to be implemented on the Front Frame Assembly (**Image F.8-13**) is to change the material from a stamped steel construction to a cast magnesium structure.

Image F.8-13: Front Frame Assembly

Source: A2MAC1 -http://a2mac1.com/AutoReverse/reversepart.asp?productid=64&clientid=1&producttype=2

F.8.3.7 Rear Frame Assembly

The solution chosen for implementation on the Rear Frame Assembly (**Image F.8-14**) is to ratio the Venza vehicle net mass and Rear Frame size versus the VW Passat specs (Lotus) to reduce the Rear Frame size.

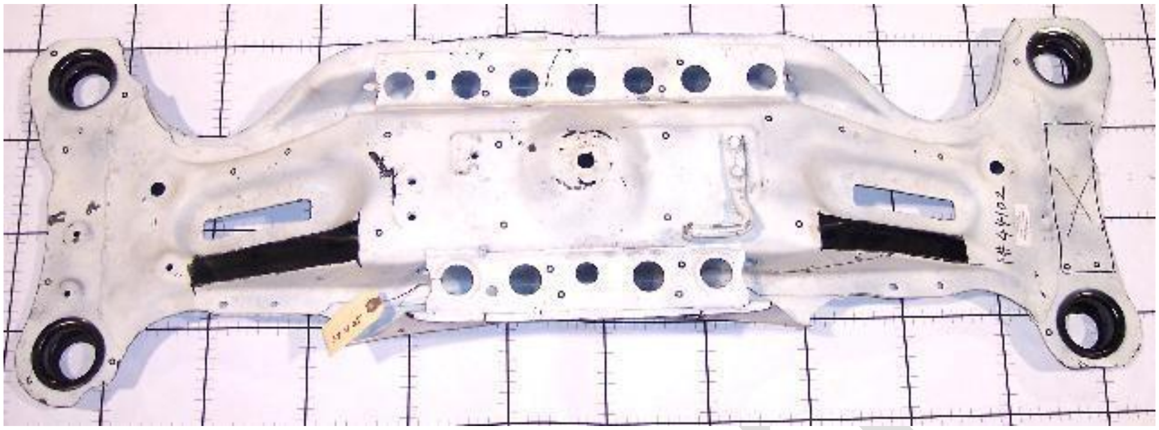


Image F.8-14: Rear Frame Assembly

(Source: FEV photo)

F.8.4 Calculated Mass-Reduction & Cost Impact Results

Table F.8-6 shows the results of the mass reduction ideas that were evaluated for the Frame subsystem. This resulted in a subsystem overall mass savings of 16.498kgs and a cost increase of $3.66.

The Front Strut Frame sub-subsystem includes the Front Frame which was changed to a die-casted magnesium part versus a multiple steel stamping construction. This action accounts for 71% of the 13.959 kg weight save. The Front Strut Frame sub-subsystem also includes (2) Suspension Brackets, (2) Radiator Support Brackets, and (1) Damper Assembly. These brackets are made from a steel stamping construction which has been changed to an injection mold process. The Suspension Bracket changes account for 10% of the mass savings. The Radiator Support Bracket changes account for 2% of the mass savings and finally, the Damper Assembly which was downsized based on a Lotus idea to normalize it to a 2005 VW Passat Damper Assembly accounts for 8% of the mass savings. The cost of these changes increases the cost of the sub-subsystem by $1.43

The Rear Strut Frame sub-subsystem includes the Rear Frame, which was downsized based on a Lotus idea to normalize it to a 2005 VW Passat and (2) Stopper Brackets which were changed from a steel stamping construction to an inject mold process. The cost of these mass reduction ideas raises the cost of this sub-subsystem by $2.23.

System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
				Net Value of Mass Reduction Idea					
07	**01**	**00**	**Frame Subsystem**						
07	01	04	Front Strut Frame	B	13.959	-$1.43	-$0.10	42.89%	0.82%
07	01	05	Rear Strut Frame	B	2.538	-$2.23	-$0.88	24.54%	0.15%
				B	**16.498** (Decrease)	**-$3.66** (Increase)	**-$0.22** (Increase)	**37.73%**	**0.96%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.8-6: Calculated Subsystem Mass-Reduction and Cost Impact Results for Frame Subsystem

F.9 Exhaust System

An exhaust system is tubing used to guide reaction exhaust gases away from a controlled combustion inside an engine. The entire system conveys burnt gases from the engine, expelling these toxic and/or noxious gases through one or more exhaust pipes. Depending on the overall system design, the exhaust gas may flow through one or more of the following: cylinder head and exhaust manifold; a turbocharger (to increase engine power); a catalytic converter (to reduce air pollution); a muffler (to lessen noise). **Image F.9-1** shows the Toyota Venza muffler.

Image F.9-1 : Toyota Venza Muffler

(Source: FEV, Inc. photo)

The Exhaust ystem is comprised of the Acoustical Control Components and Exhaust Gas Treatment Components Subsystem (see **Table F.9-1**).

System	Subsystem	Sub-Subsystem	Description	System & Subsystem Mass "kg"
09	00	00	Exhaust System	
09	01	00	Acoustical Control Components Subsystem	11.743
09	02	00	Exhaust Gas Treatment Comp. Subsystem	14.874
			Total System Mass =	26.617
			Total Vehicle Mass =	1711
			System Mass Contribution Relative to Vehicle =	1.56%

Table F.9-1: Mass Breakdown by Subsystem for Exhaust System.

(Reference **Table F.9-2**) Mass and cost impact for the exhaust subsystem.

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsystem/ Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
09	00	00	Exhaust System						
09	01	00	Acoustical Control Components Subsystem	B	2.789	-$0.21	-$0.07	23.75%	0.16%
09	02	00	Exhaust Gas Treatment Comp. Subsystem	A	4.729	$2.68	$0.57	31.79%	0.28%
				A	7.518 (Decrease)	$2.47 (Decrease)	$0.33 (Decrease)	28.25%	0.44%

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.9-2: Mass-Reduction and Cost Impact for Exhaust Subsystem

F.9.1 Acoustical Control Components Subsystem

F.9.1.1 Subsystem Content Overview

As seen in **Table F.9-3**, the Acoustic Control Component sub-subsystem is included in the Acoustical Control Components subsystem. This sub-subsystem is the only driver in the subsystem.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
09	**01**	**00**	**Acoustical Control Components Subsystem**	
09	01	01	Acoustic Control Components	11.743
			Total Subsystem Mass =	**11.743**
			Total System Mass =	**26.617**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**44.12%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.69%**

Table F.9-3: Mass Breakdown by Sub-subsystem for Acoustical Control Components Subsystem

F.9.1.2 Toyota Venza Baseline Subsystem Technology

For the Acoustic Control Components sub-subsystem, the total 11.74kg weight does not include the muffler: It includes only the front and center pipe sections, which include one catalytic converter, one baffle, and one resonator made from stainless steel. The 4-cylinder engine's pipe lengths and diameter are the same as the 6-cylinder equipped with a dual-tipped muffler. This makes the 4-cylinder exhaust systems pipes and muffler larger than required for the volume of exhaust expelled. Using the larger system for the 4-cylinder is a good idea from the carry-over and manufacturing aspect; however, for the overall system weight and the resultant effect on gas mileage for the 4-cylinder, this may not be an effective trade-off. The Venza's other technologies include EDPM hangers and welded- and bolted-on hollow hanger brackets. **Images 5.9-2** and **5.9-3** show a section view of the Toyota Venza exhaust and the pipe as a whole.

Image F.9-2 : Toyota Venza Exhaust

(Source: FEV, Inc. photo)

Image F.9-3 : Toyota Venza Exhaust Pipe

(Source: FEV, Inc. photo)

F.9.1.3 Mass-Reduction Industry Trends

Industry trends vary for exhaust systems, ranging from mild steel, titanium, special grades of stainless steel, and magnesium in race cars to low-production vehicles. There are many different types of SS that can be considered for exhaust systems. The use of tailor-welded blanks of different types of stainless steel allows for thicker and thinner areas of SS as needed. A common type is austenitic stainless such as 304. It is difficult to fabricate, however, owing to the rate of strain hardening. If very severe bending is required, it may be necessary to stress-relieve the material by annealing the pipe part of the way through the forming process. There are other stainless materials available in the 300 Series stainless family, but they are more brittle and have a poorer thermal shock performance than 409 Series stainless, which is most often used in today's OEM stainless systems.

Titanium is widely used for exhausts on motorcycles, the automotive industry has largely shunned this material, and for good reason: The bending stresses from forming Titanium sheets requires extra supports to prevent cracking at high stress areas. Titanium's main advantage, however, is its low density: approximately 40% lower density than stainless steel. Since 2006, the use of titanium alloys for automotive exhaust systems manufacturing has increased for the high-end market vehicles. Titanium alloys used for exhaust system fabrication use additional alloying elements, as aluminum, copper, niobium, silicon, and iron. The addition of these elements significantly increases the oxidation resistance and mechanical properties of the alloy.

Other trends for exhaust systems include the use of different materials for the hangers; EDPM or Rubber is used by most OEM's today.

F.9.1.4 Summary of Mass-Reduction Concepts Considered

Ideas considered for the exhaust weight reduction were a titanium system, welded-on exhaust hangers and hollow hangers, and using optional materials for the exhaust rubber hanger grommets. The Venza implemented some of these ideas already, so a closer look in to the weight reduction was needed (**Table F.9-4**).

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Front and Center Pipes	Titanium Alloy	20 to 30% Mass Reduction	High cost, slower cycle time in manufacturing
Front and Center Pipes	304 Stainless Steel	NA	High cost, Harder to work with, may require added operations
Front and Center Pipes	Tailored Welded Blanks	15 to 20% Mass Reduction	Higher cost of laser welding and added capital cost
Front and Center Pipes	Mubea Tailored Rolled Tubes TRT®	20 to 25% Mass Reduction	Small increase for manufacturing
Front and Center Pipes	Down size to 2.4L Toyota Matrix	20 to 25% Mass Reduction	Cost savings due to less material & manufacturing
Front and Center Pipes	Weld on Hanger Brkts	5 to 10% Mass Reduction	Already implemented
Front and Center Pipes	Hollow Hanger Brkts	1 to 5% Mass Reduction	Already implemented
Front and Center Pipes Rubber Grommets	SGF™ Rubber Grommets	30% Mass Reduction	Low cost due to removal of the amount of grommets and hangers

Table F.9-4: Summary of mass-reduction concepts initially considered for the Acoustical Control Components Subsystem

F.9.1.5 Selection of Mass-Reduction Ideas

Table F.9-5 includes the mass-reduction ideas that were selected for the exhaust system center and front pipes.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
09	**01**	**00**	**Acoustical Control Components Subsystem**	
09	01	01	Acoustic Control Components	Mubea Tailored Rolled Tubes TRT®
				SGF™ Rubber Grommets

Table F.9-5: Mass-Reduction Ideas Selected for Acoustical Control Components Subsystem

Applying the Mubea Tailor Rolled Tubes (TRT®) process of continuous rolling to varying thicknesses ranging from 1.1mm to .7mm on the Toyota Venza's 1.2mm exhaust pipes rather than laser welding flat blanks created additional weight savings. The Mubea process offers a major weight savings of 28% – or 2.099kg. Savings on the center pipe section. In the front pipe section, by also using the Mubea TRT® process, the savings is 28% (.476kg). Mubea has a few different process's such as Tailor Rolled Tubes TRT®, Tailor Rolled Products TRP®, Tailor Rolled Blanks TRB® and all are highly innovative as it can also be applied to a number of different body parts, such as A- and B-pillars, roof members, bumpers, and structure parts. **Figure F.9-1** shows in detail the basic Mubea rolling process.

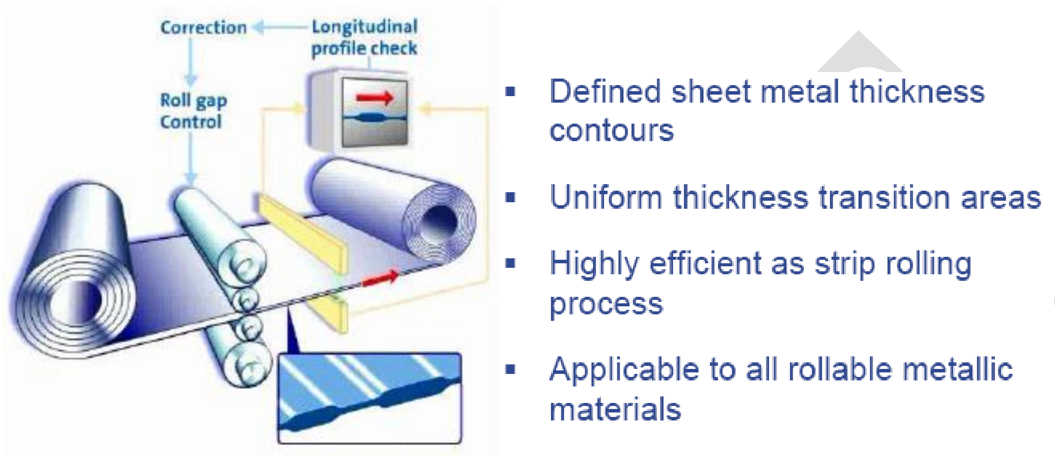
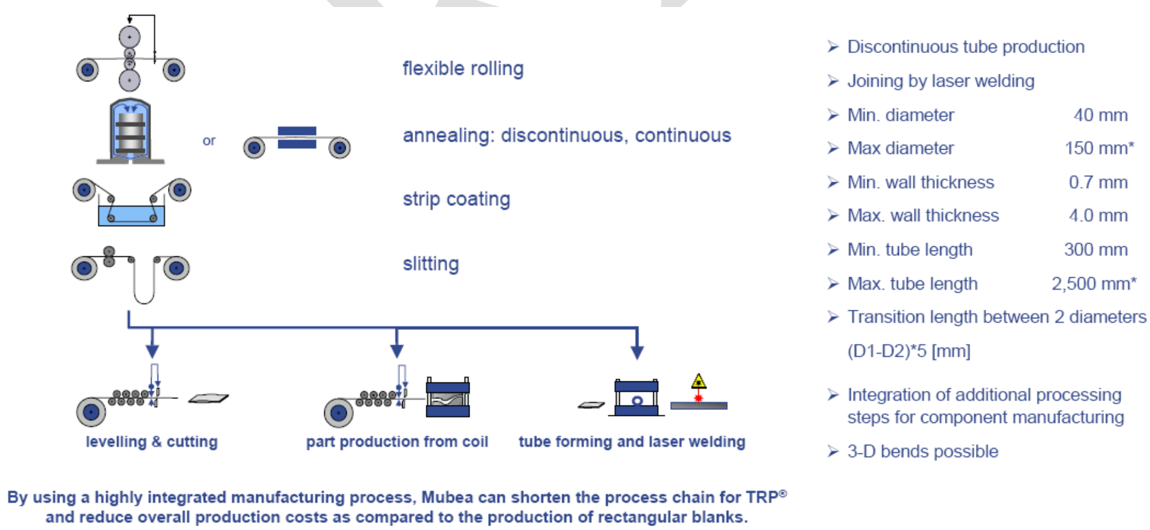
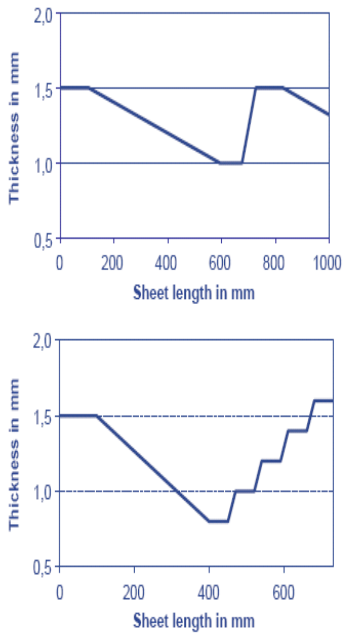


Figure F.9-1: Basic Mubea® Process

Below is the Mubea TRB® exhaust pipe manufacturing process (**Figure F.9-2**).





- Varying sheet metal thickness with smooth transitions
- 50 % max. thickness reduction
- Slope between 1/3000 up to 1/100
- Narrow thickness tolerances
- Optimized sheet thickness adapted to component load
- The cost of the component does not depend on number of thickness steps
- Reduction of sheet and component weight

- Annual series production capacity of 60,000 tons
- Product range:
  Tailor Rolled Blanks - TRB®
  Tailor Rolled Products - TRP®
  Tailor Rolled Tubes - TRT®
- Numerous application studies prove a weight saving potential of 10 kg for body structure and 5 kg for chassis applications
- Supply contracts with Audi, BMW, Chrysler, Daimler AG, Ford GM/Opel, Porsche, PSA, Skoda & VW
- More than 30 million TRB® delivered for series production to date

Thanks to Flexible Rolling, components with varying thickness profiles can be produced without additional costs.

Tailor Rolled Tubes – TRT®
Fully Automated Tube Production Line

Figure F.9-2: Mubea TRB® Exhaust Pipe Manufacturing Process

(Presentation material and information provided by Mubea)

SGF® exhaust hangers were also selected as a means of mass reduction. Advantages of the SGF® hangers include:

- Weight reduction, up to 37% lighter than competitor's models.
- Very high load capacity in X, Y, and Z directions
- Reduce the number of hangers and hanger brackets
- Packaging: Due to becoming 40% more narrow, hangers can be positioned tight to the exhaust system
- Up to 21 times the life cycles of competitors' models
- Extreme durability, including high- and low-temperature performance
- The hangers do not need to be changed over the lifetime of the car

- High break load: 10 kN
- Use of EPDM instead of expensive silicon rubber
- Cord inlay for strength

Using the SGF® hangers reduced the number of hangers and hanger brackets on the car side as well as the pipe side.

A recommendation by SGF® to remove three hangers on the existing exhaust system would require the new hangers and brackets to be relocated, as **Table F.9-6** shows.

Weight, Material, Dimension

	SGF LS000-E077-002	Toyota 17565-0P041
Weight and number of parts:	45 grams/ 3pcs	68 grams/ 6 pcs
Size (y-axis)	25 mm	34 mm
Material	EPDM	EPDM
Bolt diameter	10mm	12mm

Durability, Testing Conditions and Results

	SGF LS000-E077-002	Toyota 17565-0P041
120ºC; Z=45N +- 180N		Failed at 42000 cycles
120ºC; Z=90N +- 360N	4 Parts, stopped without any fault at 800000 cycles	Specimen No 1:Failed at 1600 cycles 2:Failed at 2379 cycles

Table F.9-6: SGF Existing Exhaust System Recommendation

Image F.9-4 shows how the SGF® hangers, which are smaller in size with more strength, result in an up to 37% lighter product. Note that the hanger strength comes from the cord inlay reinforcement.

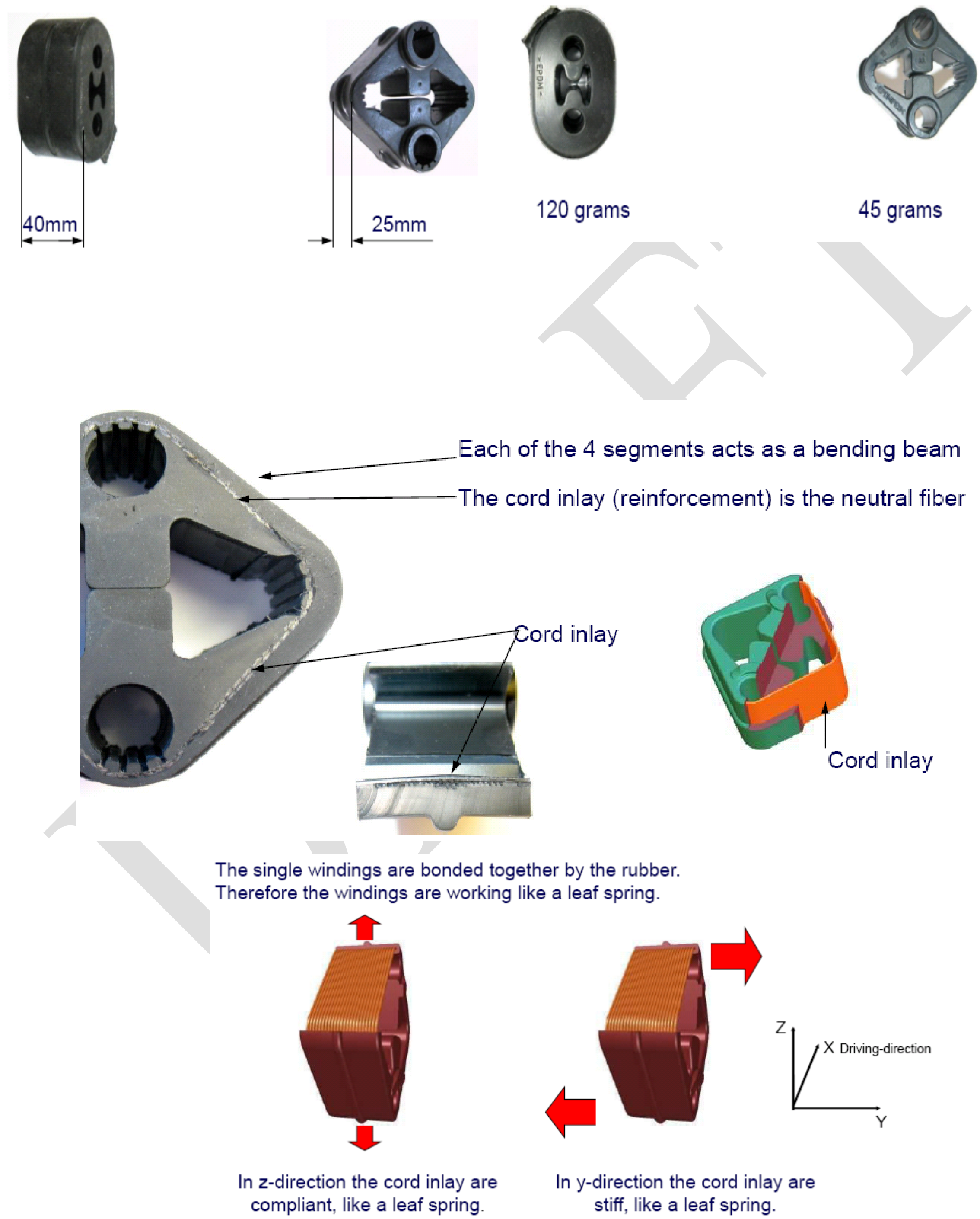


Image F.9-4: SGF® Hangers

(All presentation material and information provided by SGF®)

F.9.1.6 Mass-Reduction & Cost Impact

Table F.9-7 shows the weight and cost reductions per sub-subsystem. In the sub-subsystem Acoustic Control Components, the Mubea Tailored Rolled Tubes TRT® process was used to provide varying thickness in the exhaust front pipe assembly for a weight savings of .476kg. This TRT® was also used on the exhaust center pipe assembly for a weight savings of 2.099kg and a cost increase of $.56 The TRT® are slightly higher in manufacturing costs, but that cost is off set by the material weight savings.

The SGF® exhaust hangers are a lighter product then the typical EDPM hanger the hangers by themselves are slightly more in cost to the typical EDPM exhaust hangers, but the SGF® hanger's superior strength and quality allows the system to reduce the amount of hangers needed for an over all weight and cost savings. On the Acoustic Control Components sub-subsystem, two exhaust hangers were originally used. With the SGF® system, one hanger in this sub-subsystem can be removed along with the steel hanger brackets attached to the pipe and car side. The car side and exhaust hanger being removed saves .122kg with a cost savings of $.55 Removing one rubber hanger and replacing the other one with the SGF hanger reduces the weight by .091kg but with a cost increase of $.19 this still comes out as a total SGF® system savings .213kg and $.36 cost savings.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
09	**01**	**00**	**Acoustical Control Components Subsystem**						
09	01	01	Acoustic Control Components	B	2.789	-$0.21	-$0.07	23.75%	0.16%
				B	**2.789** (Decrease)	**-$0.21** (Increase)	**-$0.07** (Increase)	**7.17%**	**0.16%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.9-7: Sub-Subsystem Mass-Reduction and Cost Impact for Acoustical Control Components Subsystem.

F.9.2 Exhaust Gas Treatment Components Subsystem

F.9.2.1 Subsystem Content Overview

As shown in **Table F.9-8,** within the Exhaust Gas Treatment Components subsystem is the Emission Control Components sub-subsystem – the only mass reduction driver in this subsystem.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
09	**02**	**00**	**Exhaust Gas Treatment Comp. Subsystem**	
09	02	01	Emission Control Components	14.874
			Total Subsystem Mass =	**14.874**
			Total System Mass =	**26.617**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**55.88%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.87%**

Table F.9-8: Mass Breakdown by Sub-subsystem for Exhaust Gas Treatment Components Subsystem

F.9.2.2 Toyota Venza Baseline Subsystem Technology

Mufflers are installed along the exhaust pipe as part of the exhaust system of an internal combustion engine. The muffler reduces exhaust noise by absorption of the exhaust sound waves and is routed through a series of passages and chambers lined with woven fiberglass wool. The resonating chambers tuned to cause destructive interference wherein opposite sound waves cancel each other out, and Catalytic converters also have a muffling effect.

The Toyota Venza's exhaust system muffler is larger than required for the I4 motor version due to it being common component for the dual exhaust used in the 6-cylinder engine option. Although the Venza does have some innovations, the exhaust is stainless steel for reduced weight and corrosion resistance and the hanger tubes are hollow allowing for additional weight reductions. The hangers are also welded to the BIW which eliminates the need for nuts and bolts.

For Emission Control Components sub-subsystem, the total weight of 14.87kg does not include the muffler pipes. This sub-subsystem only includes the muffler.

Image 5.9-5: Toyota Venza Muffler

(Source: FEV photo)

F.9.2.3 Mass-Reduction Industry Trends

Industry trends for weight reduction vary quite a bit for exhaust systems. The most common is to use stainless steel for the weight and corrosion resistance. Other ideas like hollow hangers welded to the BIW and lightweight rubber hanger grommets are used on the Toyota Venza.

F.9.2.4 Summary of Mass-Reduction Concepts Considered

Some ideas considered for the exhaust mass reduction were a titanium system, welded exhaust hangers, hollow hangers, and using new materials for the exhaust rubber hanger grommets. Due to the Venza already having some of these ideas implemented, a closer look in to the weight reduction was required (**Table F.9-9**).

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Muffler	Titanium Alloy	20 to 30% Mass Reduction	High cost, slower cycle time in manufacturing
Muffler	304 Stainless Steel	NA	High cost, Harder to work with, may require added operations
Muffler	Tailored Welded Blanks	15 to 20% Mass Reduction	Higher cost of laser welding and added capital cost
Muffler	Mubea™ Tailored Rolled Blanks	20 to 25% Mass Reduction	Small increase for manufacturing
Muffler	Down size to 2.4L Toyota Matrix	20 to 25% Mass Reduction	Cost savings due to less material & manufacturing
Muffler	Weld on Hanger Brkts	5 to 10% Mass Reduction	Already implemented
Muffler	Hollow Hanger Brkts	1 to 5% Mass Reduction	Already implemented
Muffler Rubber Grommets	SGF™ Rubber Grommets	30% Mass Reduction	Low cost due to removal of the amount of grommets and hangers

Table F.9-9: Summary of mass-reduction concepts initially considered for the Exhaust Gas Treatment Components Subsystem

F.9.2.5 Selection of Mass Reduction Ideas

The Toyota Venza system is partially optimized for weight and cost. A look at some of the optional technologies used in the industry today (**Table F.9-10**), however, shows there are more mass reduction ideas that can be applied. By downsizing the exhaust system to the comparable Toyota Matrix system (which uses a 2.4L engine), a 2.334kg weight savings can be realized. In addition, by using the Mubea® tailor rolled blank process a 24% (1.3kg) weight savings can be attributed too the muffler. The SGF® grommet process on the rubber hanger grommets can achieve a 52% (1.092kg) savings by removing two original rubber grommets and the four hanger brackets. All Mubea® and SGF® processes can be seen in the above Acoustical Control Components subsystem.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
09	**02**	**00**	**Exhaust Gas Treatment Comp. Subsystem**	
09	02	01	Emission Control Components	Mubea™ Tailored Rolled Blanks
				Down size to 2.4L Toyota Matrix
				SGF™ Rubber Grommets

Table F.9-10: Mass-Reduction Ideas Selected for Exhaust Gas Treatment Components Subsystem

F.9.2.6 Mass-Reduction & Cost Impact

Table F.9-11 shows the weight and cost reductions per sub-subsystem. The reduction for the sub-subsystem “Emission Control Components” were to down-size the muffler from the Toyota Venza that has a common muffler for the 4 & 6 cylinder models to the Toyota Matrix 2.4L engine muffler. This represents a 2.334kg weight save and a $1.24 cost savings.

Then apply a Mubea TRB® process. The muffler will save 1.303kg with a cost increase of $.49

Even though the SGF® exhaust hangers are a lighter product then the typical EDPM hanger the hangers by themselves are slightly more in cost to the typical EDPM exhaust hangers, but the SGF® hanger's superior strength and quality allows the system to reduce the amount of hangers needed for an over all weight and cost savings. On the Emission Control Components, four exhaust hangers were originally used. With the SGF® system, two in this sub-subsystem can be removed along with the steel hanger brackets attached to the muffler and car side. The car side and exhaust hanger being removed saves .909kg with a cost savings of $2.32 Removing 2 rubber hanger and replacing the other one with the SGF hanger reduces the weight by .183kg but with a cost increase of $.39 this still comes out as a total SGF® system savings 1.092kg and $1.93 cost savings.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
09	**02**	**00**	**Exhaust Gas Treatment Comp. Subsystem**						
09	02	01	Emission Control Components	A	4.729	$2.68	$0.57	31.79%	0.28%
				A	**4.729** (Decrease)	**$2.68** (Decrease)	**$0.57** (Decrease)	**17.77%**	**0.28%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.9-11 Sub-Subsystem Mass-Reduction and Cost Impact for Exhaust Gas Treatment Components Subsystem.

F.10 Fuel System

The Fuel Tank and Lines subsystem is comprised primarily of the fuel tank and associated fuel lines between the fuel filler neck and the fuel tank. The fuel lines between the fuel tank and fuel pump are also included in this subsystem. The Fuel Vapor Management subsystem is comprised of a charcoal/vapor canister and the connecting lines between the fuel tank and the charcoal canister. In comparing the sub-systems under the fuel system, the greatest opportunity for mass reduction falls under the Fuel Tank and Lines subsystem (**Table F.10-1**).

System	Subsystem	Sub-Subsystem	Description	System & Subsystem Mass "kg"
10	**00**	**00**	**Fuel System**	
10	01	00	Fuel Tank and Lines Subsystem	21.018
10	02	00	Fuel Vapor Management Subsystem	3.259
			Total System Mass =	**24.276**
			Total Vehicle Mass =	**1711**
			System Mass Contribution Relative to Vehicle =	**1.42%**

Table F.10-1: Baseline Subsystem Breakdown for Fuel System

Table F.10-2 shows the calculated mass-reduction results for the ideas generated related to the Fuel system. A mass savings of 6.804Kgs was realized with a cost reduction of $3.91 which results in a cost savings of $0.57 per kg.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
10	**00**	**00**	**Fuel System**						
10	01	00	Fuel Tank And Lines Subsystem	A	6.307	$2.70	$0.43	30.01%	0.37%
10	02	00	Fuel Vapor Management Subsystem	A	0.497	$1.21	$2.44	15.26%	0.03%
				A	**6.804** (Decrease)	**$3.91** (Decrease)	**$0.57** (Decrease)	**28.03%**	**0.40%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.10-2: Calculated Mass-Reduction and Cost Impact Results for Fuel System.

F.10.1 Fuel Tank & Lines Subsystem

F.10.1.1 Subsystem Content Overview

Table F.10-3 shows the three sub-subsystems that make up the Fuel Tank and Lines subsystem. These are the Fuel Tank Assembly, Fuel Distribution, and Fuel Filler sub-

subsystem. The most significant contributor to the mass of the Fuel Tank and Lines subsystem is the Fuel Tank Assembly. This includes the tank, baffles, fuel pump, sending unit and exterior tank mounting brackets.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
10	**01**	**00**	**Fuel Tank And Lines Subsystem**	
10	01	01	Fuel Tank Assembly (Fuel Tank, Fuel Pump, Sending Unit)	18.783
10	01	03	Fuel Distribution (Fuel Lines)	0.519
10	01	04	Fuel Filler (Refueling) (Filler Pipes & Hoses)	1.716
			Total Subsystem Mass =	**21.018**
			Total System Mass =	**24.276**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**86.58%**
			Subsystem Mass Contribution Relative to Vehicle =	**1.23%**

Table F.10-3: Mass Breakdown by Sub-subsystem for Fuel Tank and Lines Subsystem.

F.10.1.2 Toyota Venza Baseline Subsystem Technology

The Toyota Venza Fuel system follows typical industry standards for steel tanks. There is nothing new, out of the ordinary, or unique. The fuel tank (**Image F.10-1**) is a welded sheet metal construction with thinner gauge metal on its upper half versus the bottom. The fuel pump (**Image F.10-2**), is retained by an outer retaining ring, Figure 1-6, and (8) M5 x .80 fasteners (**Image F.10-3**). Due to this being a saddle tank design, fuel from one side of the tank must be pumped to the other via the fuel pump. A sending unit (**Image F.10-4**) detects the total fuel level. The sending unit is retained by (6) M5 x .80 fasteners (**Image F.10-5**). The tank is held in place by a steel strap (**Image F.10-6**), which is edge-protected by an extruded rubber edging material (**Image F.10-7**). Finally, the fuel delivery system consists of a steel fuel filler tube assembly (**Image F.10-8**). Several brackets (**Images 5.10-9, -10, -11**) clamp the vapor tube to the fuel filler pipe, as well as clamping the entire assembly to the vehicle.

F.10.2 Mass-Reduction Industry Trends

F.10.2.1 Fuel Tank

Steel fuel tank construction is a common technology used by Toyota. However, it is no longer the norm for the automotive industry.

Image F.10-1: Venza Fuel Tank

(Source: FEV, Inc. photo)

Some industry reports indicate more than 95% of the fuel tanks produced in Europe are made from plastics. Plastic tanks have become the primary material of choice in Europe and North America for many reasons:

1. A plastic tank system weighs two-thirds less than an average steel tank system. Advantages of the blow molding process used to make fuel tanks:
    a. Sheet polymer material for blow molding is high density polyethylene (HDPE), which has a lower density than water and is very chemically resistant.
    b. HDPE can be treated or laminated with barrier materials such as LLDPE which provides very effective emission control, rupture resistance, and extended temperature range.
    c. Tooling for blow molding is lower cost and is not stressed as heavily as tooling for steel parts.

d. The main peripheral welded seam for the steel tank is eliminated with blow molding of HDPE. Components like filler necks can be welded to the HDPE tank to seal and secure, and it will use much less energy than steel welding.

2. Plastics offer design flexibility for complex shapes, which are difficult to attain with steel. This includes integral connection features for attaching other fuel system components such as the vapor canister.

3. Impact and corrosion resistance is provided without secondary operations. No painting or coating is required.

Although not priced in our cost reduction estimates, life cycle total energy costs are also reduced using plastic:

- Plastic materials can be created and processed at lower temperatures than steel.
- Lower energy levels are required to recycle plastic than steel.

Regarding environmental concerns, feedstock for HDPE made from bio materials will be produced in at least one manufacturing plant (Braskem).which will help reduce our dependence on petroleum. Braskem is a Brazilian petrochemical company headquartered in São Paulo. The company is the largest petrochemical in the Americas by production capacity and the fifth largest in the world. By revenue it is the fourth largest in the Americas and the 17th in the world.

F.10.2.2 Fuel Pump

The Toyota Venza Fuel Pump (**Image F.10-2**) is inserted into the fuel tank and held in place by an outer retaining ring (**Image F.10-3**) and (8) M5 x .80 fasteners (**Image F.10-4**).

Image F.10-2: Fuel Pump

(Source: FEV, Inc. photo)

Image F.10-3: Retaining Ring

(Source: FEV, Inc. photo)

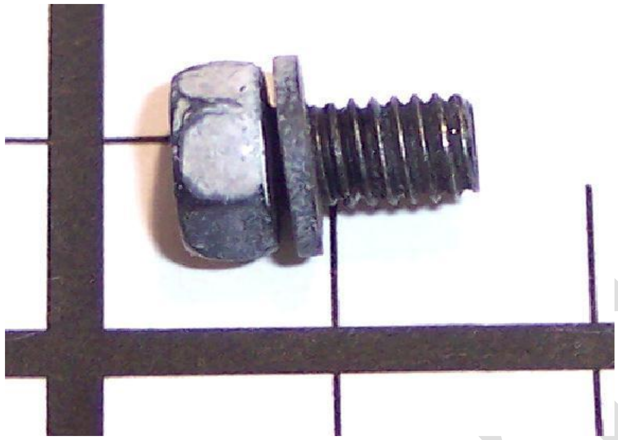


Image F.10-4: Fuel Pump Retaining Fastener

(Source: FEV, Inc. photo)

F.10.2.3 Sending Unit

The Toyota Venza Sending Unit (**Image F.10-5**) is constructed from a heavy gauge stamped sheet metal mounting plate which is riveted to a lighter gauge stamped sheet metal switch bracket. The switch assembly is attached to the switch bracket via stamped locking features. The sending unit is inserted into the fuel tank and held in place by (6) M5 x .80 fasteners (**Image F.10-6**).

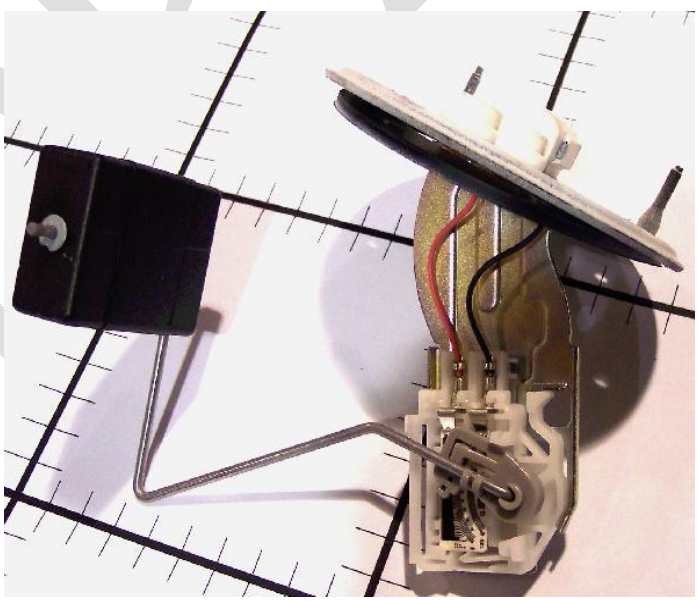


Image F.10-5: Sending Unit

(Source: FEV, Inc. photo)

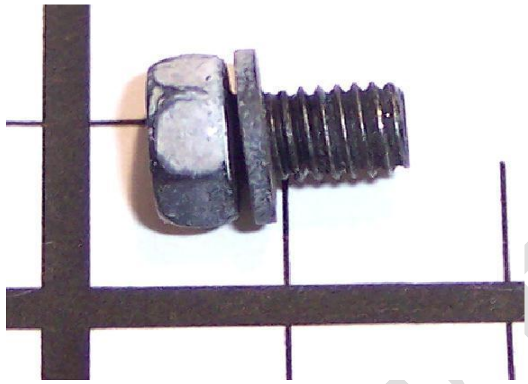


Image F.10-6: Sending Unit Retaining Fastener

(Source: FEV, Inc. photo)

F.10.2.4 Fuel Tank Mounting Straps

The mounting straps (**Image F.10-7**), which hold the fuel tank in place, are made of light gauge stamped sheet metal with an extruded rubber protective edging, (**Image F.10-8**). The protective edging is required to prevent the edge of the sheet metal straps from wearing away the anti-corrosion material applied to the outer surfaces of the fuel tank.

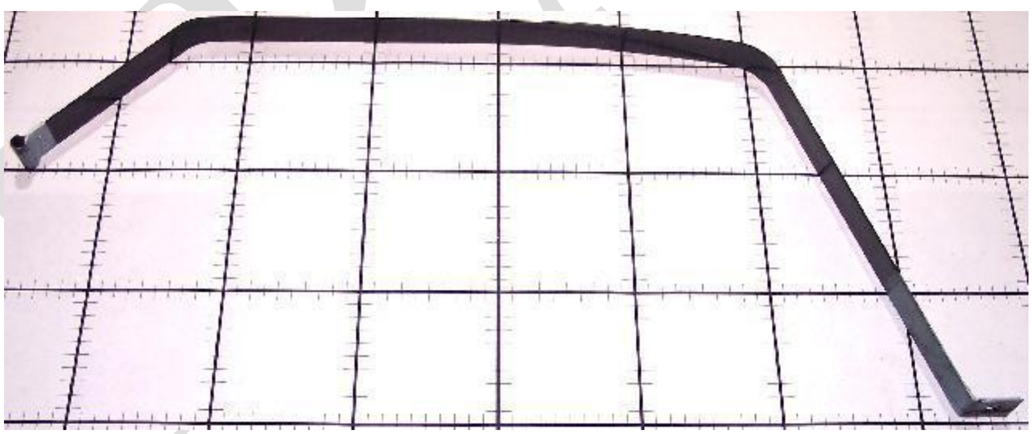


Image F.10-7: Fuel Tank Mounting Strap

(Source: FEV, Inc. photo)

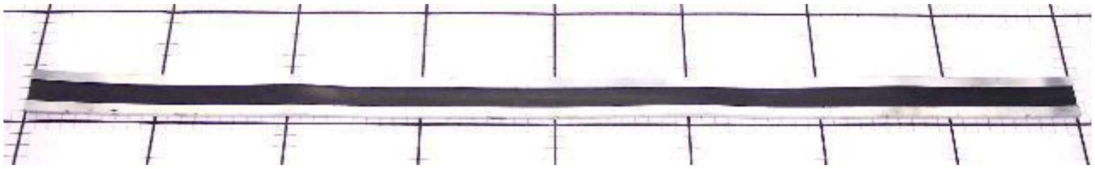


Image F.10-8: Protective Edging

(Source: FEV, Inc. photo)

F.10.2.5 Fuel Filler Tube Assembly

The Fuel Filler Tube Assembly (**Image F.10-9**) is an extruded steel tube extending from the fuel fill neck to the fuel tank. Also running alongside the fuel fill tube is the vapor return line.

Image F.10-9: Fuel Filler Tube Assembly

(Source: FEV, Inc. photo)

F.10.3 Summary of Mass-Reduction Concepts Considered

The Fuel Tanks and Lines summary chart, shown in **Table F.10-4**, demonstrates the clear move from steel to plastic. The fuel tank offers the greatest mass reduction opportunity as mentioned above. Plastics offer weight reduction benefits for other fuel system components. Brainstorming activities generated all of the ideas in the chart below. There are several suppliers and websites supporting the use of plastics for the fuel tank and other components within the fuel system.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Fuel Tank	Make out of HDPE	50% Weight Save	Low Cost, in production on Chrysler Town & Country
Fuel Tank	Size Reduction	10% Weight Save	Low Cost, in production on Saab 9-3 1.9 TiD Linear (2005)
Fuel Tank	Eliminate Saddle Tank Design	40% Weight Save	Risk of Insufficient Fuel Quantity
Fuel Tank	Make Fuel Tank Baffles out of Plastic	5% Weight Save	Increased Manufacturing Cost
Fuel Tank	Make fuel tank out of Dupont plastic/metalic material	10% Weight Save	Low Cost, Reduce Hydrocarbon Emissions up to 98%
Fuel Filler Tubes	Make out of HDPE	20% Weight Save	Low Cost, in production on Saab 9-3 1.9 TiD Linear (2005)
FPU Mounting Bracket	Use twist lock to eliminate Fasteners	100% Weight Save	Low Cost, in production on Chrysler Town & Country
Fuel Tank Mounting Pins	Use T-Slot attachment to eliminate pins	100% Weight Save	Low Cost
Fuel Tank Mounting Straps	Eliminate Rubber Protection	100% Weight Save	Low Cost, in production on Chrysler Town & Country
Fuel Sender Bracket	Make out of >POM< instead of steel	80% Weight Save	Low Cost
Fuel Sender Mounting Bracket	Use twist lock to eliminate Fasteners	100% Weight Save	Low Cost
Fuel Filler Tube Brackets	Eliminate brackets with Blow molded Filler & Vapor Tubes	100% Weight Save	Low Cost, in production on Saab 9-3 1.9 TiD Linear (2005)
Fuel Tank Cross Over Tube	Make out of Plastic	80% Weight Save	Low Cost Increase

Table F.10-4: Summary of mass-reduction concepts initially considered for the Fuel Tank & Lines Subsystem.

F.10.4 Selection of Mass-Reduction Ideas

We chose most of the ideas generated from the brainstorming activities for detail evaluation as shown in **Table F.10-5**. In our team approach to idea generation, we consider all components regardless of how big or small the opportunity.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
10	00	00	**Fuel Tank & Lines Subsystem**	
10	01	01	Cross Over Tube	Make cross over tube out of plastic
			Fuel Tank	Make blow molded fuel tank
			Fuel Tank	Reduce plastic tank size by 12% (based on a 20% vehicle mass reduction)
			Mounting Pin	Eliminate fuel tank mounting pin and use T-slot bracket design instead
			Retaining Ring	Make FPU retaining ring with locking features to eliminate (8) fasteners
			Tank Straps	Eliminate rubber from tank straps
			Gage Asm, Fuel Sender, No 2 (Secondary)	Make sender unit bracket out of plastic instead of steel
			Gage Asm, Fuel Sender, Bracket (new)	Use twist lock bracket & eliminate fasteners
			Shield, Large	Eliminate Steel Fill Tubes with Blow Molded Tubes
			Protector, Fuel Fill Pipe	Eliminate Protector Bracket with Blow Molded Tubes
			Support Bracket	Eliminate shield (77246C) & fastener (11327) with Blow Molded Tank
10	01	03	N/A	N/A
10	01	04	Fill tubes	Make fuel fill tubes a one-piece blow molded design

Table F.10-5: Mass-Reduction Ideas Selected for Fuel Tank & Lines Subsystem Analysis

F.10.4.1 Cross-Over Tube Assembly

The solution chosen to be implemented for the Cross-Over Tube Assembly is to make it out of plastic instead of steel.

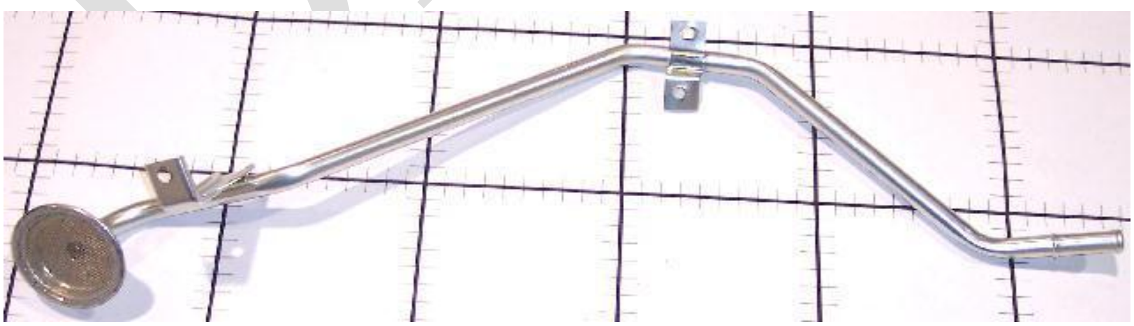


Image F.10-10: Cross-over Tube Assembly

(Source: FEV, Inc. photo)

F.10.4.2 Fuel Tank

The solution chosen to be implemented for the Fuel Tank is to make it out of a blow molded HDPE plastic (**Image F.10-11**) and to reduce the size of the fuel tank 12% taking advantage of the overall weight reduction ideas implemented over the entire vehicle.

Image F.10-11: Plastic (HDPE) Fuel Tank

(Source: A2MAC1 - http://a2mac1.com/AutoReverse/reversepart.asp?productid=222&clientid=1&producttype=2)

F.10.4.3 Fuel Tank Mounting Pins (Eliminated)

The solution chosen to be implemented for the Fuel Tank Mounting Pins is to eliminate them in lieu of a new strap configuration utilizing a Tee-slot design (**Image F.10-12**). Instead of pinning the end of the strap, this design locks the strap end without the need of a pin.

Image F.10-12: Fuel Tank Mounting Strap Assy

(Source: BTM Corp - http://www.btmcorp.com/tlapps.html)

F.10.4.4 Fuel Pump Retaining Ring

The solution(s) chosen to be implemented for the Fuel Pump Retaining Ring (**Image F.10-13**) is to make it a "twist lock" design, thus eliminating the need for fasteners.

Image F.10-13: Fuel Pump Retaining Bracket "Twist Lock" Design

(Source: FEV, Inc. photo)

F.10.4.5 Fuel Sending Unit Retaining Bracket

The solution(s) chosen to be implemented for the Fuel Sending Unit Retaining Bracket (**Image F.10-14**) is make the bracket out of plastic instead of stamped steel and making it a "twist lock" design, thus eliminating the need for fasteners.

Image F.10-14: Sending Unit Mounting Bracket

(Source: FEV, Inc. photo)

F.10.4.6 Large Bracket (Eliminated)

The solution chosen to be implemented for the Large Bracket (**Image F.10-15**) is to eliminate the bracket due to the blow molded Fuel Fill Tube Assembly. This bracket will no longer be needed because the Fuel Fill Tube and the Vapor Tube will be connected via the blow mold process.

Image F.10-15: Large Shield (Eliminated)

(Source: FEV, Inc. photo)

F.10.4.7 Protector Bracket (Eliminated)

The solution chosen to be implemented for the Protector Bracket (**Image F.10-16**) is to eliminate the bracket due to the blow molded Fuel Fill Tube Assembly. This bracket will no longer be needed because the Fuel Fill Tube and the Vapor Tube will be connected via the blow mold process.

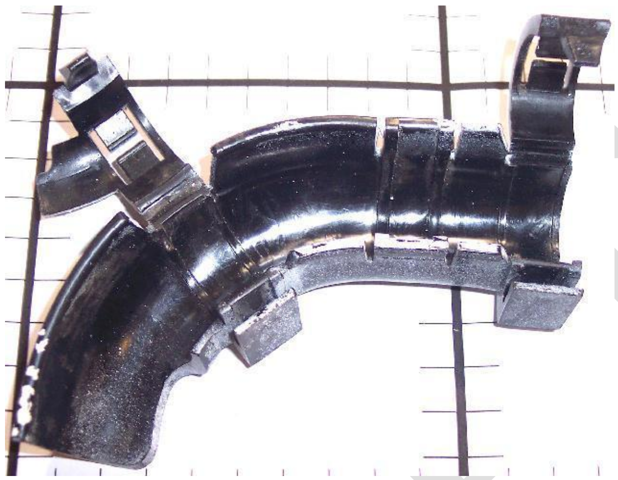


Image F.10-16: Protector (Eliminated)

(Source: FEV, Inc. photo)

F.10.4.8 Small Shield Bracket (Eliminated)

The solution(s) chosen to be implemented for the Support Bracket (**Image F.10-17**) is to eliminate the bracket due to the blow molded Fuel Fill Tube Assembly. This bracket will no longer be needed because the Fuel Fill Tube and the Vapor Tube will be connected via the blow mold process.

Image F.10-17: Support Bracket (Eliminated)

(Source: FEV, Inc. photo)

F.10.4.9 Fuel Filler Tube Assembly

The solution chosen to be implemented for the Fuel Filler Tube Assembly **Image F.10-18** is to make the tubes out of HDPE using a blow mold process.

Image F.10-18: Fuel Filler Tube Assembly

(Source: Inergy Automotive - http://www.inergyautomotive.com/innovativesystems/pfs/pfp/Pages/pfp.aspx)

F.10.5 Calculated Mass-Reduction & Cost Impact Results

Table F.10-6 shows the results of the mass reduction ideas that were evaluated for the Fuel Tank & Lines subsystem. This resulted in a subsystem overall mass savings of 6.307kgs and a cost savings differential of $2.70.

The Fuel Tank Assembly sub-subsystem ideas account for the entire cost savings which was only slightly reduced by the small cost hit created by the Fuel Filler sub-subsystem ideas. The Fuel Tank Assembly sub-subsystem includes the Fuel Tank, which was changed from a steel construction tank to a HDPE blow-molded tank and accounts for 88% of the 6.307 kg weight save. The remaining 12% of the mass reduction was reduced by small miscellaneous changes.

The Fuel Filler sub-subsystem raises the cost of this sub-subsystem slightly by $0.20, but the cost of the entire subsystem is still reduced to $2.70 because of the $2.90 savings realized in the Fuel Tank Assembly sub-subsystem.

System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
				Net Value of Mass Reduction Idea					
10	00	00	**Fuel Tank & Lines Subsystem**						
10	01	01	Fuel Tank Assembly (Fuel Tank, Fuel Pump, Sending Unit)	A	5.759	$2.90	$0.50	30.66%	0.34%
10	01	03	Fuel Distribution (Fuel Lines)		0.000	$0.00	$0.00	0.00%	0.00%
10	01	04	Fuel Filler (Refueling) (Filler Pipes & Hoses)	B	0.548	-$0.20	-$0.37	31.95%	0.03%
				A	**6.307** (Decrease)	**$2.70** (Decrease)	**$0.43** (Decrease)	**30.01%**	**0.37%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.10-6: Calculated Subsystem Mass-Reduction and Cost Impact Results for Fuel Tank & Lines Subsystem.

F.10.6 Fuel Vapor Management Subsystem

F.10.6.1 Subsystem Content Overview

In **Table F.10-7**, the Fuel Vapor Canister Assembly is identified as the most significant contributor to the mass of the total fuel system. The Fuel Vapor Canister Assembly includes the canister housing, charcoal, valves, fittings, and hoses.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
10	02	00	**Fuel Vapor Management Subsystem**	
10	02	01	Fuel Vapor Canister Asm (Vapor Canister, Brackets, Lines)	3.259
			Total Subsystem Mass =	**3.259**
			Total System Mass =	**24.276**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**13.42%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.19%**

Table F.10-7: Mass Breakdown by Sub-subsystem for Fuel Vapor Management Subsystem.

F.10.6.2 Toyota Venza Baseline Subsystem Technology

The Toyota Venza Fuel Vapor Management Subsystem shows characteristics of the latest development of these systems. There is nothing new, out of the ordinary, or unique compared to other vehicles.

The EVAP (evaporative control system) is simple but quite sophisticated. The function of the EVAP is to trap, store and dispense evaporative emissions from the gas tank to the engine. A canister (**Image F.10-19**) is used to trap the fuel vapors, which adhere to activated charcoal in the canister until the engine is started. This system has to be completely sealed including the gas tank filler cap to meet current and future emission standards. A purge valve controls the vapor flow into the engine based on commands from the ECM (electronic engine control module). While the engine is running, and if a predetermined condition is met, the purge valve is opened by the ECM to release stored fuel vapors in the canister into the intake manifold. The ECM changes the duty cycle of the purge valve to control purge flow volume. The Canister to mounted to the underbody between the fuel tank and the exhaust muffler and is protected by a Canister Cover (**Image F.10-20**).

A “key off” monitor checks for system leaks and canister pump module malfunctions. The monitor starts five hours after the ignition switch is turned off. At least five hours are required for the fuel to cool down to stabilize the EVAP pressure, thus making the EVAP system monitor more accurate.

F.10.6.3 Mass-Reduction Industry Trends

No industry trends have been noted for the Fuel Vapor Management subsystem beyond what is seen in the Venza system. Advances in engine and vehicle electronic control continue with significant concern regarding complete control and elimination gasoline vapors. The hardware of the Fuel Vapor Management subsystem will continue to be developed for functionality with few, if any, major opportunities for size and weight reduction short of smaller fuel tank size, which would reduce vapor generation.

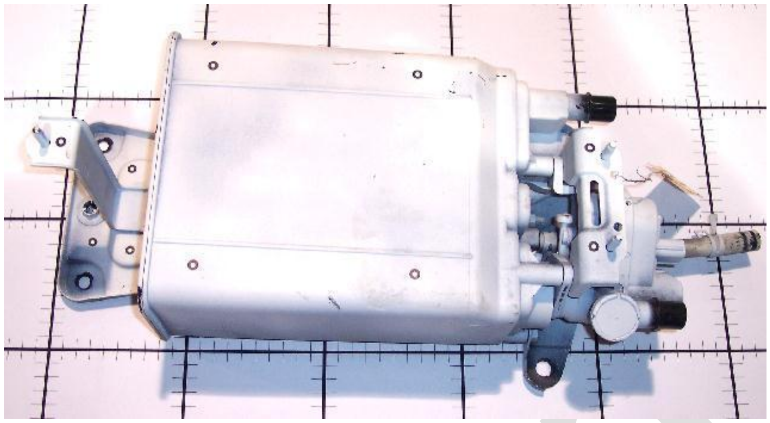


Image F.10-19: Vapor Canister

(Source: FEV, Inc. photo)

Image F.10-20: Vapor Canister Cover

(Source: FEV, Inc. photo)

F.10.6.4 Summary of Mass-Reduction Concepts Considered

Table F.10-8 shows the Fuel Vapor Management summary chart and shows a few mass reduction ideas dealing primarily with moving from steel bracket to plastic and utilizing the MuCell® Microcellular Foaming Technology.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Canister Cover	Make Charcoal Canister Cover using MuCell® Microcellular Foaming Technology	10% Weight Save	Cost Neutral
Charcoal Canister	Make Charcoal Canister using MuCell® Microcellular Foaming Technology	10% Weight Save	Cost Neutral
Bracket, Large	Make large bracket out of Polypro w/30% Glass Fill	80% Weight Save	Cost Savings
Bracket, Medium	Make medium charcoal canister bracket out of Polypro w/30% Glass Fill	80% Weight Save	Cost Savings
Bracket, Small	Make small charcoal canister bracket out of Polypro w/30% Glass Fill	80% Weight Save	Cost Savings

Table F.10-8: Summary of mass-reduction concepts initially considered for the Fuel Vapor Management Subsystem.

F.10.6.5 Selection of Mass Reduction Ideas

Most of the ideas generated from the brainstorming activities for the Fuel Vapor subsystem were utilized in this report as shown in **Table F.10-9**. In our team approach to idea generation, we consider all components regardless of how big or small the opportunity.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
10	02	00	**Fuel Vapor Management Subsystem**	
10	02	01	Canister Cover	Make using MuCell® Microcellular Foaming Technology
			Charcoal Canister	Make using MuCell® Microcellular Foaming Technology
			Bracket, Large	Make out of Polypro w/30% Glass Fill
			Bracket, Medium	Make out of Polypro w/30% Glass Fill
			Bracket, Small	Make out of Polypro w/30% Glass Fill

Table F.10-9: Mass-Reduction Ideas Selected for Fuel Vapor Management Subsystem Analysis.

F.10.6.6 Canister Housing & Canister Cover

The solution(s) chosen to be implemented on the Vapor Canister Housing (**Image F.10-21**) and the Canister Cover (**Image F.10-22**) is to use the MuCell® Microcellular Foaming Technology during the injection molding process.

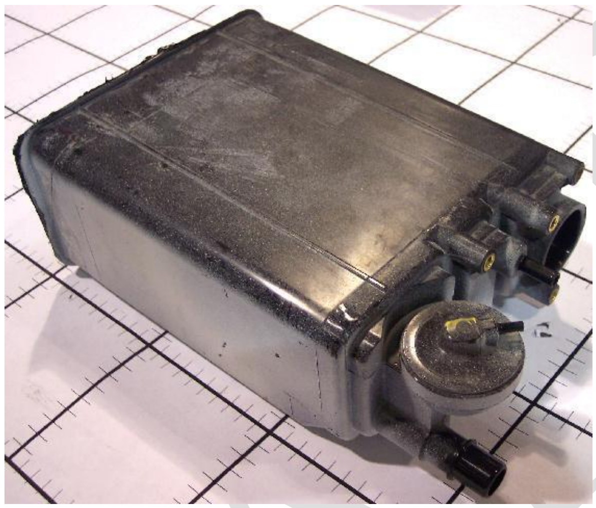


Image F.10-21: Vapor Canister Housing

(Source: FEV, Inc. photo)

Image F.10-22: Vapor Canister Cover

(Source: FEV, Inc. photo)

F.10.6.7 Canister Brackets

The solution chosen to be implemented on the Large Canister Bracket (**Image F.10-23**) Medium Canister Bracket (**Image F.10-24**) and the Small Canister Bracket (**Image F.10-25**) is to redesign the brackets out of plastic instead of stamped steel.

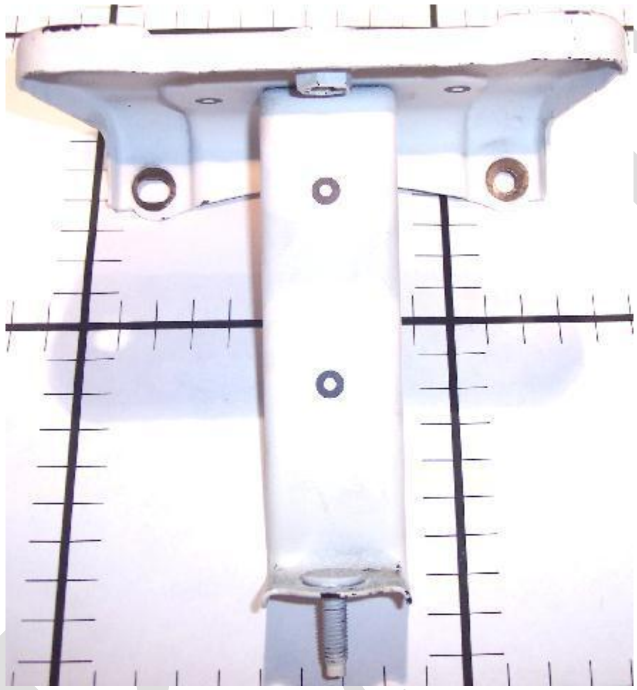


Image F.10-23: Large Canister Bracket

(Source: FEV, Inc. photo)

Image F.10-24: Medium Canister Bracket

(Source: FEV, Inc. photo)

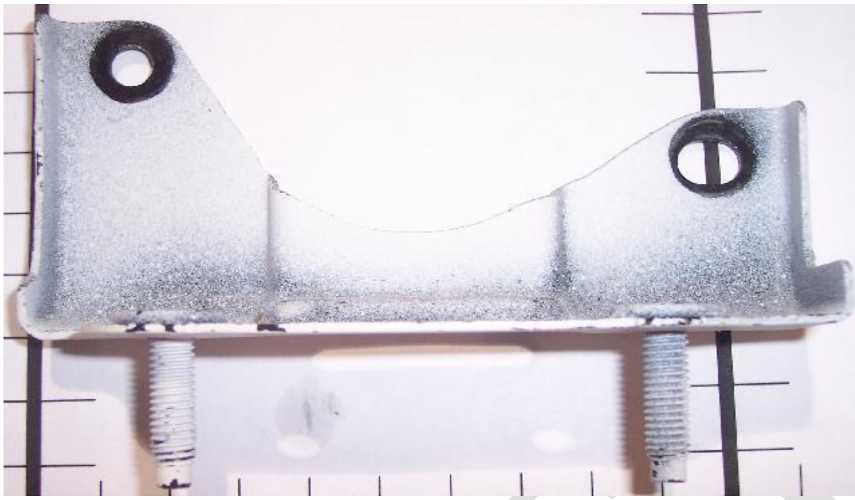


Image F.10-25: Small Canister Bracket

(Source: FEV, Inc. photo)

F.10.6.8 Calculated Mass-Reduction & Cost Impact Results

Table F.10-10 shows the results of the mass reduction ideas that were evaluated for the Fuel Vapor Management subsystem. This resulted in a subsystem overall mass savings of .497 kg and a cost savings differential of $1.21.

The Fuel Vapor Canister sub-subsystem includes the Vapor Canister and its associated Brackets. The Vapor Canister Brackets are made from stamped steel construction. 76% of the .497 kg mass savings came from changing the brackets from steel to plastic. The remaining mass savings was realized by applying the MuCell® Foaming Technology to the Vapor Canister Housing and the Vapor Canister Cover.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
10	**02**	**00**	**Fuel Vapor Management Subsystem**						
10	02	01	Fuel Vapor Canister Asm	A	0.497	$1.21	$2.44	15.26%	0.03%
				A	**0.497** (Decrease)	**$1.21** (Decrease)	**$2.44** (Decrease)	**15.26%**	**0.03%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.10-10: Preliminary Ballpark Subsystem Mass-Reduction and Cost Impact Estimates for Fuel Vapor Management Subsystem.

F.11 Steering System

The Toyota Venza uses an electric power steering system. Electric power steering systems have an advantage in fuel efficiency: there is no belt-driven hydraulic pump constantly running, whether steering assistance is required or not. This is a major reason for electric power steering systems' introduction. Another key advantage is the elimination of a belt-driven engine accessory, and several high-pressure hydraulic hoses between the hydraulic pump (which is mounted on the engine) and the steering gear (mounted on the chassis). This greatly simplifies manufacturing and maintenance.

Included in the Steering system are the Steering Gear, Power Steering, Steering Column, Steering Column Switches, and Steering Wheel subsystems. The Steering Gear subsystem is the greatest weight contributing subsystem at 8.82kg (see **Table F.11-1**).

System	Subsystem	Sub-Subsystem	Description	System & Subsystem Mass "kg"
11	**00**	**00**	**Steering System**	
11	01	00	Steering Gear Subsystem	8.825
11	02	00	Power Steering Subsystem	7.477
11	04	00	Steering Column Subsystem	5.083
11	05	00	Steering Column Switches Subsystem	0.554
11	06	00	Steering Wheel Subsystem	2.288
			Total System Mass =	**24.227**
			Total Vehicle Mass =	**1711**
			System Mass Contribution Relative to Vehicle =	**1.42%**

Table F.11-1: Mass Breakdown by Subsystem for Steering System

The Steering Gear, Steering Column, and Steering Wheel subsystems were used for mass reduction. The Steering Column subsystem offered the greatest weight savings, as shown in **Table F.11-2**.

System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
				Net Value of Mass Reduction Idea					
11	00	00	**Steering System**						
11	01	00	Steering Gear Subsystem	A	0.123	$0.24	$1.99	1.39%	0.01%
11	02	00	Power Steering Subsystem	A	0.210	$0.10	$0.46	2.81%	0.01%
11	04	00	Steering Column Subsystem	A	1.148	$10.39	$9.05	22.58%	0.07%
11	05	00	Steering Column Switches Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
11	06	00	Steering Wheel Subsystem	A	0.336	$0.32	$0.94	14.69%	0.02%
				A	**1.817** (Decrease)	**$11.05** (Decrease)	**$6.08** (Decrease)	**7.50%**	**0.11%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.11-2: Mass-Reduction and Cost Impact for Steering System

F.11.1 Steering Gear Subsystem

F.11.1.1 Subsystem Content Overview

As shown in **Table F.11-3**, the Steering Gear subsystem includes the Steering Gear sub-subsystem.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
11	01	00	**Steering Gear Subsystem**	
11	01	01	Steering Gear	8.825
			Total Subsystem Mass =	**8.825**
			Total System Mass =	**24.227**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**36.43%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.52%**

Table F.11-3: Mass Breakdown by Sub-subsystem for Steering Gear Subsystem

F.11.1.2 Toyota Venza Baseline Subsystem Technology

The Toyota Venza uses a conventional steering gear setup. **Image F.11-1** shows the Toyota Venza steering gear. **Image F.11-2** is a close-up of the tie rod end.

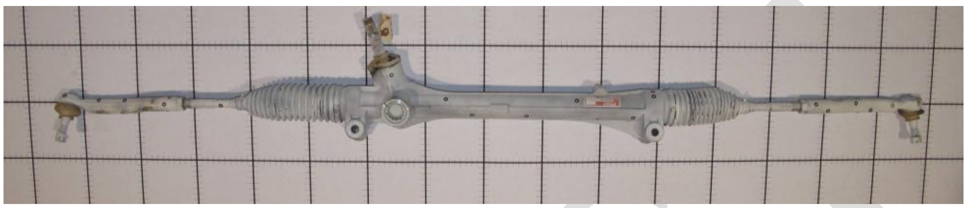


Image F.11-1 : Toyota Venza Steering Gear

(Source: FEV, Inc. photo)

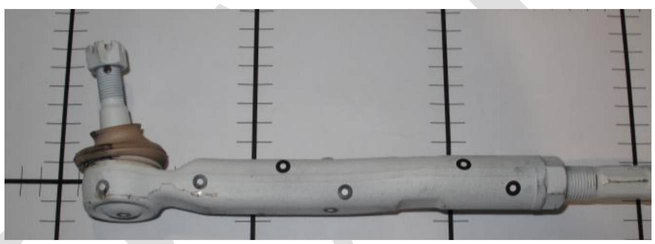


Image F.11-2: Toyota Venza Tie Rod End

(Source: FEV, Inc. photo)

F.11.1.3 Mass-Reduction Industry Trends

No mass reduction industry trends stand out on the Toyota Venza. Some weight savings have been identified when comparing the Venza to other vehicles of the same class and size.

F.11.1.4 Summary of Mass-Reduction Concepts Considered

Table F.11-4 shows weight deductions taken for the Steering Gear subsystem.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Tie Rod	Use Tubing Swedged to Inner Ball Joint Rather Than Solid Rod for Tie Rod	20% Mass Reduction	Needs Engineering
Ball Joint & Tie Rod	Shorten Forging for the Ball Joint and Lengthen the Tie Rod End - Used 2011 Chrysler Mini Van as Direct Comparison	15 to 20% Mass Reduction	Less over all material
Ball Joint	Stamped Ball Joints	20 to 25% Mass Reduction	Leak and Rust

Table F.11-4: Summary of mass-reduction concepts initially considered for the Steering Gear Subsystem

F.11.1.5 Selection of Mass Reduction Ideas

The weight deduction used for the Steering Gear subsystem was to shorten the ball joint ends and lengthen the threaded part of the tie rod end. The current Chrysler mini van has a shorter ball joint end and it was selected and used as a basis for this analysis (**Table F.11-5**). Using this can result in a 1% .123kg savings.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
11	**01**	**00**	**Steering Gear Subsystem**	
11	01	01	Steering Gear	Shorten Forging for the Ball Joint and Lengthen the Tie Rod End - Used 2011 Chrysler Mini Van as Direct Comparison

Table F.11-5: Mass-Reduction Ideas Selected for the Steering Gear Subsystem

F.11.1.6 Mass-Reduction & Cost Impact Estimates

Table F.11-6 shows the weight and cost reductions per Steering Gear sub-subsystem. In the change to shorten the forged ball joint end and lengthen the tie rod end, mass was reduced from the ball joint forging based on the 2011 Chrysler mini van. This resulted in a mass savings of .261kg and $.52 in cost savings. With shortening the ball joint end the tie rod end had to be lengthened, this contributed an increase of .138kg and an increase in cost of $.28 both these changes netted a mass savings of .123kg and a cost save of $.24

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
11	01	00	Steering Gear Subsystem						
11	01	01	Steering Gear	A	0.123	$0.24	$1.99	1.39%	0.01%
				A	0.123 (Decrease)	$0.24 (Decrease)	$1.99 (Decrease)	0.51%	0.01%

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.11-6: Sub-Subsystem Mass-Reduction and Cost Impact for Steering Gear Sub-Subsystem

F.11.2 Power Steering Subsystem

F.11.2.1 Subsystem Content Overview

As seen in (**Table F.11-7**), included in the Power Steering subsystem is the Power Steering Electronic Controls sub-subsystem.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
11	02	00	Power Steering Subsystem	
11	02	01	Power Steering Electronic Controls	7.477
			Total Subsystem Mass =	7.477
			Total System Mass =	24.227
			Total Vehicle Mass =	1711
			Subsystem Mass Contribution Relative to System =	30.86%
			Subsystem Mass Contribution Relative to Vehicle =	0.44%

Table F.11-7: Mass Breakdown by Sub-subsystem for the Power Steering Subsystem

F.11.2.2 Toyota Venza Baseline Subsystem Technology

The Toyota Venza uses an advanced power steering system with power steering assist and electronic stability control.

F.11.2.3 Mass-Reduction Industry Trends

The Toyota Venza follows industry norms for the mass reductions trends on the power steering system.

F.11.2.4 Summary of Mass-Reduction Concepts Considered

Table F.11-8 shows the Power Steering subsystem and the ideas reviewed.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Control Module	Build Control Module into Assist Motors Aluminum Housing for Heat Sink and Cut Mass	5 to 10% Mass Reduction	Needs Engineering
Assist Module	Replace Steel Worm Gear with Composite	2 to 5% Mass Reduction	One gear is composite already and the other is metal, This means that the engineering has already been done
Assist Module	Replace Metal Motor Housing with Composite	15 to 20% Mass Reduction	Due to EMF Engineering would be needed
Assist Module	Use Resolver Based Sensor	NA	No Weight Save
EPS Control Unit	Change Steel Brkt to Composite	20 to 30% Mass Reduction	Material and Manufacturing savings

Table F.11-8: Summary of Mass-Reduction Concepts Initially Considered for the Power Steering Subsystem

F.11.2.5 Selection of Mass Reduction Ideas

The weight deduction used for the subsystem power steering was to mold the EPS steel mounting brackets out of PA6- GF30-35, using the MuCell® gas foaming process to reduce the weight of the plastic by 10% (**Table F.11-9**).

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
11	**02**	**00**	**Power Steering Subsystem**	
11	02	01	Power Steering Electronic Controls	Make EPS Steel Brkt Out of Composite and Then MuCell® for Added Weight Reduction

Table F.11-9: Mass-Reduction Ideas Selected for the Power Steering Subsystem

F.11.2.6 Mass-Reduction & Cost Impact

Table F.11-10 shows the weight and cost reductions for the Power Steering Electronic Controls sub-subsystem.

Taking the EPS Brkts from 1010/1008 steel and making them out of PA6 glass filled 30-35 plastic, then MuCell® the parts provided a mass savings of .21kg and a cost savings of $.10

The MuCelling of the parts contributed .021kg of the over all .21kg even though the PA6 with class filled 30-35 with MuCell is more expensive then 1010/1008 steel, the mass reduction from steel to plastic and the reduced cycle time and the parts not needing a deburring and washing operation after the stamping ending up as a costs savings.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
11	**02**	**00**	**Power Steering Subsystem**						
11	02	01	Power Steering Electronic Controls	A	0.210	$0.10	$0.46	2.81%	0.01%
				A	**0.210** (Decrease)	**$0.10** (Decrease)	**$0.46** (Decrease)	**0.87%**	**0.01%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Figure 5.10-10: Mass-Reduction and Cost Impact Estimates for Power Steering Electronic Controls Sub-Subsystem.

F.11.3 Steering Column Subsystem

F.11.3.1 Subsystem Content Overview

Table F.11-11 shows the Steering Column Assembly sub-subsystem included in the Steering Column subsystem, contributing 5.083 kg mass.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
11	**04**	**00**	**Steering Column Subsystem**	
11	04	01	Steering Column Assembly	5.083
			Total Subsystem Mass =	**5.083**
			Total System Mass =	**24.227**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**20.98%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.30%**

Table F.11-11: Mass Breakdown by Sub-subsystem for the Steering Column Subsystem

F.11.3.2 Toyota Venza Baseline Subsystem Technology

A steering column performs the following secondary functions: Energy dissipation management in the event of frontal collision. The column also provides a mounting surface for the multi-function switch, column lock, column wiring, column shrouds, transmission gear selector, gauges or other instruments as well as the electro motor and gear units, height and/or length adjustments.

Steering columns may contain universal joints, which may be part of the collapsible steering column design, to allow the column to deviate somewhat from a straight line. **Images F.11-3** and **F.11-4** are the Toyota Venza steering shaft.

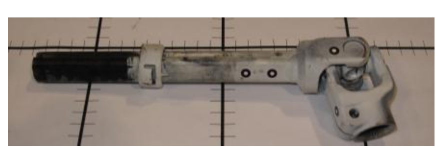


Image F.11-3: Toyota Venza Steering Shaft

(Source: FEV Photo)

Image F.11-4: Toyota Venza Steering Shaft

(Source: FEV Photo)

F.11.3.3 Mass-Reduction Industry Trends

Mass-reduction industry trends include using aluminum or magnesium casting to replace the steel shaft. Another is a grommet "only" design in which the steering column goes through the fire wall.

F.11.3.4 Summary of Mass-Reduction Concepts Considered

Table F.11-12 shows the weight deductions taken from the Steering Column Assembly sub-subsystem.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Lower Cover	Change Firewall Steering Boot (3 Piece) Design to 1 Piece Grommet Design	5 to 10% Mass Reduction	Eliminate stamped steel retainer ring, 3 bolts, 3 weld nuts on BIW
Intermediate Shaft	Replace Yoke Forgings with Stamped Weld	15 to 20% Mass Reduction	Engineering needed to verify
Intermediate Shaft	Change Forgings to Die Cast Aluminum	30 to 40% Mass Reduction	Less material and manufacturing cost
Intermediate Shaft	Replace Forged Couplers with Flexible Stanly TW241F10 50%-GR PA4/6	20 to 25% Mass Reduction	Engineering needed to verify
Steering Adjustment Lever	MuCell®	5 to 10% Mass Reduction	Part is too small

Table F.11-12: Summary of mass-reduction concepts initially considered for the Steering Column subsystem

F.11.3.5 Selection of Mass Reduction Ideas

Weight reductions used for the Steering Column subsystem are listed in **Table F.11-13**.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
11	**04**	**00**	**Steering Column Subsystem**	
11	04	01	Steering Column Assembly	Change Firewall Steering Boot (3 Piece) Design to 1 Piece Grommet Design
				Change Intermediate Shaft Steel Forgings to Die Cast Aluminum

Table F.11-13: Mass-reduction ideas selected for the Steering Column subsystem

F.11.4 Mass-Reduction & Cost Impact

Table F.11-14 shows the total weight reduction for the Steering Column Assembly sub-subsystem.

Changing the intermediate shaft from a forged steel part to a die cast aluminum shaft allowed for fewer operations and no assembly/welding of the yoke to the shaft. Less material was also required to move from steel to aluminum, even though aluminum is more expensive. The mass reduction for the female intermediate shaft was .442kg and a cost save of $4.04 and the male intermediate shaft mass savings was .635 and a cost save of $5.69 for a total intermediate shaft mass savings of 1.076kg and a cost save of $9.73.

Changing the fire wall boot design for the intermediate shaft also reduced mass with a cost save. The original design was to have a rubber boot on held onto the engine side of the fire wall by a metal ring with 3 nuts and 3 bolts. Using a grommet design with .03kg of added material to allow it to fit around the fire wall cut out opening allowed us remove the steel ring and the 3 nuts and 3 bolts to be eliminated. This resulted in a mass savings of .072kg and a cost savings of $.67

The overall subsystem mass savings was 1.148kg and a cost savings of $10.40

System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
				Net Value of Mass Reduction Idea					
11	04	00	**Steering Column Subsystem**						
11	04	01	Steering Column Assembly	A	1.148	$10.39	$9.05	22.58%	0.07%
				A	**1.148** (Decrease)	**$10.39** (Decrease)	**$9.05** (Decrease)	**4.74%**	**0.07%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.11-14: Sub-subsystem mass-reduction and cost impact for the Steering Column subsystem

F.11.5 Steering Column Switches Subsystem

F.11.5.1 Subsystem Content Overview

As displayed in **Table F.11-15**, the Steering Column Switches subsystem includes the Steering Column and Shroud-Mounted Switches and Clockspring sub-subsystem and the Steering Column Control Module and Sensors sub-subsystem.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
11	05	00	**Steering Column Switches Subsystem**	
11	05	01	Steering Col. Shroud/Switches & Clockspring	0.554
11	05	02	Steering Column Control Module and Sensors	0.000
			Total Subsystem Mass =	**0.554**
			Total System Mass =	**24.227**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**2.29%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.03%**

Table F.11-15: Mass Breakdown by Sub-subsystem for the Steering Column Switches Subsystem

F.11.5.2 Toyota Venza Baseline Subsystem Technology

The Toyota Venza's clockspring is a special rotary electrical connector that allows a vehicle's steering wheel to turn while still making an electrical connection between the steering wheel airbag and/or the vehicle's horn and other devices. The clockspring is located between the steering wheel and the steering column.

Clocksprings generally consist of a flat multicore-conductor cable wound in a spiral shape similar to a clock spring (hence the name). The name, however, is also given to devices fulfilling the same function but use spring-loaded brushes contacting concentric slip rings.

F.11.5.3 Mass-Reduction Industry Trends

There are no mass-reduction trends for the clockspring or the multifunction stalk.

F.11.5.4 Summary of Mass-Reduction Concepts Considered

No weight reduction concepts were able for consideration in the Steering Column Switches subsystem (see **Table F.11-16**).

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Angle Transmitter	MuCell®	2 to 5% Mass Reduction	Not able to do due to transmitter is part of clock spring
Ignition Switch Assy	MuCell®	2 to 5% Mass Reduction	Not able to do due to being part of the dash
Ignition Switch Assy	Replace with Keyless Go	NA	Already done

Table F.11-16: Summary of mass-reduction concepts initially considered for the Steering Column Switches subsystem

F.11.5.5 Selection of Mass Reduction Ideas

No mass-reductions ideas were chosen for the Steering Column Switches subsystem.

F.11.6 Steering Wheel Subsystem

F.11.6.1 Subsystem Content Overview

Table F.11-17 shows that Steering Wheel subsystem includes the Steering Wheel, Steering Wheel Mounted Switches, Steering Wheel Air Bag, Steering Wheel Trim sub-subsystems.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
11	**06**	**00**	**Steering Wheel Subsystem**	
11	06	01	Steering Wheel	2.000
11	06	02	Steering Wheel Mounted Switches	0.182
11	06	03	Steering Wheel Airbag ((Part of Safty System))	0.000
11	06	04	Steering Wheel Trim	0.106
			Total Subsystem Mass =	**2.288**
			Total System Mass =	**24.227**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**9.45%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.13%**

Table F.11-17: Mass Breakdown by Sub-subsystem for the Steering Wheel Subsystem

F.11.6.2 Toyota Venza Baseline Subsystem Technology

The Venza steering wheel is a die cast magnesium rim with polyurethane over molding. In addition, the steering wheel has the audio system, telephone and voice control included as part of the steering wheel. **Figure F.11-5** and **Figure F.11-6** show the Toyota Venza steering wheel and the trim cover, respectively.

Figure F.11-5: Toyota Venza Steering Wheel

(Source: FEV Photo)

Figure F.11-6: Steering Wheel Trim Cover

(Source: FEV Photo)

F.11.6.3 Mass-Reduction Industry Trends

Industry trends for steering wheels have been to die cast a lightweight material such as magnesium or aluminum and over mold polyurethane for the grip. The steering wheel grip can also be made of wood, carbon fiber, leather, or cloth. For high-end vehicles, emblems made out of wood, plastic, and aluminum can be added. Steering-mounted switches and heated grips are options sometimes added. The automotive system company Takata, in conjunction with plastics supplier Sabic, has developed a steering wheel out of a Lexan copolymer resin. This steering wheel has passed all OEM testing and will soon be added into a production vehicle. The Lexan steering wheel can save over 20% depending on the design and application. **Figure F.11-7** shows options that can be added to the steering wheel, such as elements for a heated steering wheel and that material such as wood or carbon can be made into steering wheels.

Heating elements **Wood & Carbon**

Figure F.11-7

(Source: FEV, Inc. photo)

Figure 5.11-8 shows the cross-section view of a steering wheel.

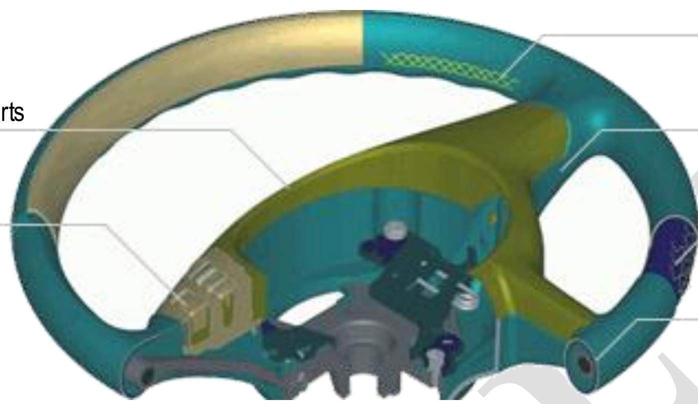


Figure 5.11-8: Steering Wheel Cross-Section View

Image Courtesy of Takata website (http://www.takata.com/en/products/steeringwheel.html)

F.11.6.4 Summary of Mass-Reduction Concepts Considered

Table F.11-18 shows the ideas that were considered for weight reductions in the Steering Wheel subsystem.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Rear Trim Cover	Use Polyone®	10% Mass Reduction	Manufacturing and Material savings
Steering Wheel	Make out of Carbon Fiber	15 to 20% Mass Reduction	High material and processing cost
Steering Wheel	Make out of Die Cast Aluminum	10 to 15% Mass Reduction	Current steering wheel is made of Magnesium and this would add weight
Steering Wheel	Make out of Lexan	20 to 25% Mass Reduction	Material and process save

Table F.11-18: Summary of mass-reduction concepts initially considered for the Steering Wheel subsystem

F.11.6.5 Selection of Mass Reduction Ideas

Table F.11-19 shows the weight reductions idea used for the Steering Wheel subsystem.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
11	**06**	**00**	**Steering Wheel Subsystem**	
11	06	01	Steering Wheel	Replace Steering Wheel with Lexan Composite Wheel
11	06	04	Steering Wheel	PolyOne® Trim Cover

Table F.11-19: Mass-reduction ideas selected for the Steering Wheel subsystem

F.11.6.6 Reduction & Cost Impact

Table F.11-20 shows the weight and cost reductions per sub-subsystem of the Steering Wheel subsystem.

Changing the steering wheel from a typical die cast aluminum over molded with Polyurethane Rubber to a new lexan composite steering wheel reduced the mass by 20% or .326kg with the lexan plastic as a new blend of plastic the cost to manufacture it is high, so the savings that would normally been seen with reducing the amount of process and material weight is off set to some degree by the cost of the lexan material. The cost reduction is $.27

The steering wheel rear trim covers mass was also reduced by 10% using the PolyOne CFA® foaming process for injection molding. The mass savings was.011kg and a cost savings of $.04

The combined changes amounted to a total mass save of .336kg and a cost savings of $.32

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
11	**06**	**00**	**Steering Wheel Subsystem**						
11	06	01	Steering Wheel	A	0.326	$0.27	$0.84	14.23%	0.02%
11	06	02	Steering Wheel Mounted Switches		0.000	$0.00	$0.00	0.00%	0.00%
11	06	03	Steering Wheel Airbag		0.000	$0.00	$0.00	0.00%	0.00%
11	06	04	Steering Wheel Trim	A	0.011	$0.04	$4.04	0.46%	0.00%
				A	**0.336** (Decrease)	**$0.32** (Decrease)	**$0.94** (Decrease)	**1.39%**	**0.02%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.11-20: Sub-subsystem mass-reduction and cost impact for Steering Wheel subsystem.

F.12 Climate Control System

The breakdown of the Climate Control system into its four subsystems is displayed in **Table F.12-1**. As shown, the Air Handling/Body Ventilation subsystem contributes the majority of the mass. This is largely due to the Main HVAC Unit, which resides in that subsystem. The Main HVAC Unit includes the blower and all passages and door flaps that control the speed, temperature, and location of the air as it is distributed throughout the vehicle's cabin. It also houses two aluminum heat exchangers (the Heater Core and the Evaporator).

System	Subsystem	Sub-Subsystem	Description	System & Subsystem Mass "kg"
12	00	00	**Climate Control System**	
12	01	00	Air Handling/Body Ventilation Subsystem	12.813
12	02	00	Heating/Defrosting Subsystem	1.033
12	03	00	Refrigeration/Air Conditioning Subsystem	1.331
12	04	00	Controls Subsystem	0.485
			Total System Mass =	**15.662**
			Total Vehicle Mass =	**1711**
			System Mass Contribution Relative to Vehicle =	**0.92%**

Table F.12-1: Baseline Subsystem Breakdown for the Climate Control System

Table F.12-2 shows a total of 2.436 kg was reduced from the Climate Control system, accompanied by a cost savings of $9.34. The Air Handling/Body Ventilation subsystem contributed most significantly from a weight savings perspective. There were no mass reduction ideas applied to the Refrigeration/Air Conditioning subsystem.

Lotus Engineering applied MuCell® extensively throughout the Climate Control system in their study. This analysis included the use of MuCell®, PolyOne's Chemical Foaming Agents, and Zotefoams' Azote® foam. FEV and Lotus applied mass-reduction to a lot of similar components in the Climate Control system.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
12	00	00	**Climate Control System**						
12	01	00	Air Handling/Body Ventilation Subsystem	A	2.034	$7.27	$3.58	15.88%	0.12%
12	02	00	Heating/Defrosting Subsystem	A	0.393	$2.03	$5.16	38.03%	0.02%
12	03	00	Refrigeration/Air Conditioning Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
12	04	00	Controls Subsystem	A	0.009	$0.04	$4.21	1.84%	0.00%
				A	**2.436** (Decrease)	**$9.34** (Decrease)	**$3.83** (Decrease)	**15.55%**	**0.14%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.12-2: Mass Reduction and Cost Impact for the Climate Control System

F.12.1 Air Handling/Body Ventilation Subsystem

F.12.1.1 Subsystem Content Overview

The mass breakdown of the Air Handling/Body Ventilation subsystem is shown in **Table F.12-3**. The largest mass contributor, not only for this subsystem, but for the entire Climate Control system, is the HVAC Main Unit. Weighing approximately 10 kg, the HVAC Main Unit includes the Heater Core and the Evaporator as well as all flaps and motor/gearboxes to control where the air is distributed.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
12	**01**	**00**	**Air Handling/Body Ventilation Subsystem**	
12	01	02	Air Distribution Duct Components (Duct Manifolds)	1.855
12	01	03	Body Air Outlets (Dash Vents)	0.906
12	01	04	HVAC Main Unit: Air Distribution Box/ Heater Core & Evaporator	10.052
			Total Subsystem Mass =	**12.813**
			Total System Mass =	**15.662**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**81.81%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.75%**

Table F.12-3: Mass Breakdown by Sub-subsystem for the Air Handling/Body Ventilation Subsystem

F.12.1.2 Toyota Venza Baseline Subsystem Technology

The Venza contains high-density polyethylene (HDPE) blow-molded air duct components. This is the most common material and manufacturing technique for these types of parts. The Venza's Main Air Duct Manifold is shown in **Image F.12-1**. Floor air ducts that distribute air from the Main HVAC Unit to the rear passenger area are shown in **Image F.12-2**.

Image F.12-1: Toyota Venza Main Air Duct Manifold

(Source: FEV, Inc. Photo)

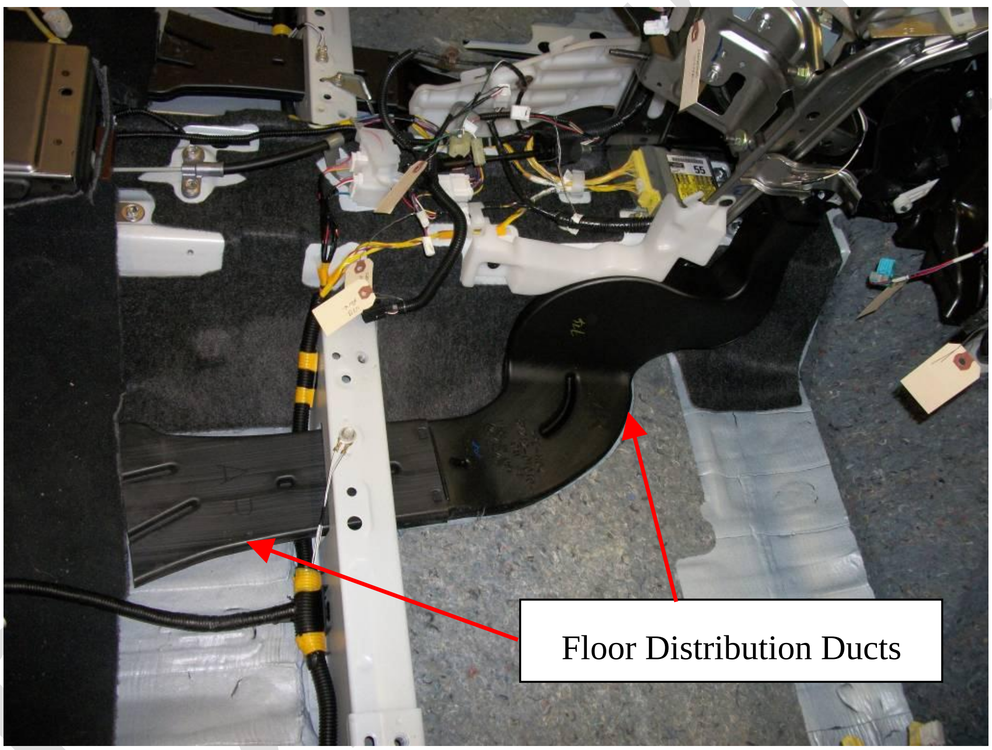


Image F.12-2: View of Toyota Venza's stripped-down interior (Front Passenger Side), showing Floor Distribution Ducts

(Source: FEV, Inc. Photo)

The HVAC Main Unit was bolted to the Cross-Car Beam under the Instrument Panel in the Venza (**Image F.12-3**). The assembly is shown out of the vehicle in **Image F.12-4**. This module is the heart of the Climate Control system. It is the primary output controlled by the user when the HVAC controls are input on the Instrument Panel. The HVAC Main Unit connects to the A/C tubes in the engine compartment, which run through the A/C compressor and through the condenser heat exchanger (mounted flush with the engine's radiator). The refrigerant then travels through tubing and enters the expansion valve, which is contained within the HVAC main unit along with the evaporator. Likewise, it connects to the radiator system to bring warm fluid into the heater core heat exchanger when the heat is being used. The air is forced through the ducts by the blower motor, which is housed in the HVAC main unit. A series of ducts and flaps controlled by the user's inputs allow the air to pass to the appropriate compartments. This HVAC main unit assembly contains mostly talc-filled polypropylene parts. There are numerous electric motors with gear boxes as well in the main unit to control vent flaps and direct air flow. The evaporator and the heater core heat exchangers are constructed of aluminum.

Image F.12-3: Toyota Venza Instrument Panel with Interior Trim Removed

(Source: FEV, Inc. Photo)

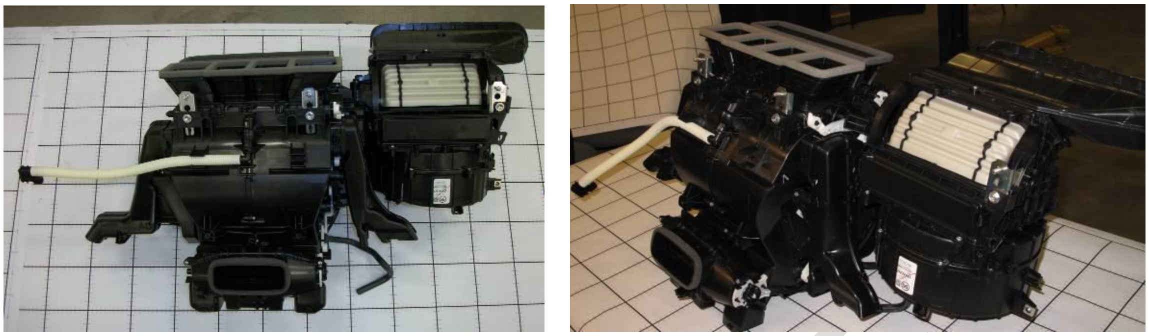


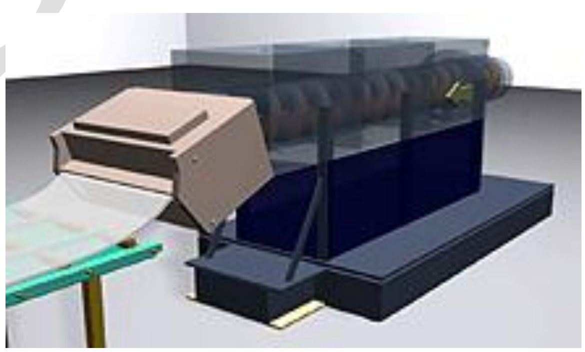
Image F.12-4: Toyota Venza HVAC Main Unit

(Source: FEV, Inc. Photo)

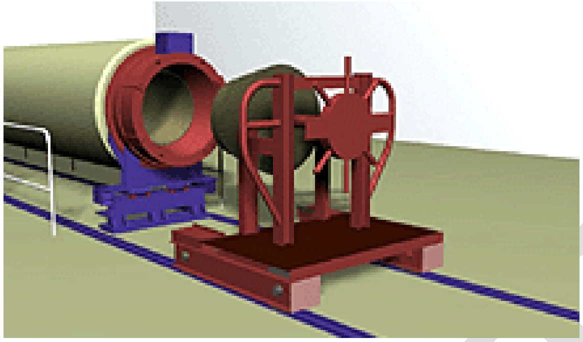
F.12.1.3 Mass-Reduction Industry Trends

Zotefoams, Inc. is a UK-based company that uses a unique manufacturing process to reduce the mass of plastics, essentially converting them into a foam-like substance. This material has found use in, among other applications, climate control air ducts. Zotefoams' material is extremely lightweight and all their foams are cross-linked. Depending on the grade, high-density polyethylene (HDPE) Zotefoam can have a density between 0.03 to 0.115 g/cm^3. The density of regular HDPE is 0.95 g/cm^3. If the volume of a component is constant and the material is changed from standard HDPE to a Zotefoams' grade, a weight reduction of 88% to 97% is possible based on the densities. In reality, the volume of the part increases some, decreasing the actual weight reduction to around 80%, which is still quite substantial.

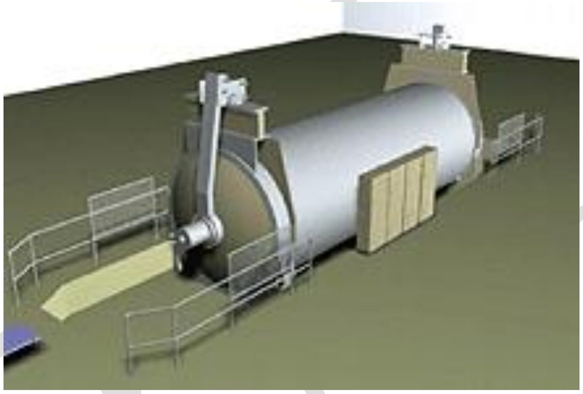
The process starts with an extruded sheet of polyethylene. The extrusion step is shown in illustration (a) of **Image F.12-5**. Next, in illustration (b), the extruded slabs are put into a high-pressure autoclave and impregnated with nitrogen in a high-temperature, high-pressure environment. In the final step, the nitrogen is allowed to expand in a low-pressure autoclave, picture (c). When the slabs come out they are a foam-like substance.



(a) Extrusion



(b) Nitrogen saturation in high pressure autoclave.



(c) Nitrogen expansion in low pressure autoclave.

Image F.12-5: Zotefoams Manufacturing Process

(Source: Zotefoams http://zotefoams.com/pages/US/manufacturing-process.asp)

Once the foam slabs are produced, they can be manufactured into useable components. In the case of the HVAC ducts, twin sheet molding is used. This process uses heat and air pressure to force two separate sheets of foam to either side of a mold thereby forming them to the desired shape. The edges of the sheets are then welded together resulting in a one-piece duct.

An example of an air duct manifold manufactured from Zotefoams' Azote® is shown in **Image F.12-6**. A side-by-side comparison of the Zotefoams' duct with the baseline Venza duct is shown in **Image F.12-7**. This illustrated similarity provides a pre-validation of feasibly applying such a material to the Air Duct Manifold of the Toyota Venza.

(a) Close-up View of Zotefoams Duct

(b) Zotefoams Front Air Duct Manifold

Image F.12-6: Air Duct Manifold manufactured from a Zotefoams' foam

(Source: Part Courtesy of Zotefoams, Inc.; FEV, Inc. photo)

(a) Zotefoams Duct

(b) Toyota Venza Duct

Image F.12-7: Comparison of Air Duct Manifolds

(Source: FEV, Inc. photo)

Zotefoams currently has products in high-volume production in the automotive industry for exterior wing mirror gaskets, but not for HVAC parts. Outside of the automotive industry, however, all of the Environmental Control systems ducting on Boeing’s 787 Dreamliner® are made from Zotefoams’ material.

WEMAC style vents (**Image F.12-8**) are an option for automotive HVAC vents. Currently used in airplanes, WEMAC vents allow for more user control of airflow direction and speed while providing simplified design and a reduced number of assembly components. Since there are fewer parts, there is a possibility for weight reduction as well as a potential cost savings.

Image F.12-8: Examples of WEMAC Vent Styles

(Source: Chief Aircraft http://www.chiefaircraft.com/aircraft/windshields-vents/air-vents.html)

General Motors' Cadillac Ciel concept car integrates the dash vents behind a portion of the instrument panel (**Image F.12-9**). This is not yet in production and it is not clear as to whether this feature is for aesthetics, mass reduction, or both. It may, however, pose some mass savings depending on what parts are needed to control airflow direction and permit user control.

Image F.12-9: Cadillac Ciel Concept Car Interior with Air Duct Vents Integrated Behind IP

(Source: Auto Style Corner http://autostylecorner.blogspot.com/2011/10/2011-cadillac-ciel-concept-design.html)

F.12.1.4 Summary of Mass-Reduction Concepts Considered

Table F.12-4 shows the mass reduction ideas considered for the Air Handling/Body Ventilation subsystem. Industry trends mentioned in the previous section were all considered. In addition, Trexel's MuCell® process and PolyOne's Chemical Foaming Agents are listed as they could be applied to many of the plastic components. For more information on these processes, reference **Section F.4B.1.2**.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
HVAC Ducts	Zotefoams Azote® Foam	50-80% mass reduction	Moderate cost or cost save depending on application, currently used on ducting in Boeing 787 Dreamliner®
HVAC Main Unit Housings & Flaps	MuCell®	10% mass reduction	Low cost, MuCell® used in high volume production by Ford
Dash Vent Covers	PolyOne CFA	10-15% mass reduction	Low cost, CFA for PP currently under test for use in high volume production vehicles
Dash Vents	Replace with WEMAC vents used in airplanes	0-10% mass reduction	Low cost, used in production for aircrafts
Dash Vents	Eliminate air vents and integrate behind instrument panel and gauges	0-20% mass reduction	Low cost, on Cadillac Ciel (concept car) not currently in production

Table F.12-4: Summary of Mass-Reduction Concepts Initially Considered for the Air Handling/Body Ventilation Subsystem

F.12.1.5 Selection of Mass Reduction Ideas

The mass reduction ideas applied to the Climate Control system within the Air Handling/Body Ventilation subsystem are shown in **Table F.12-5**. Sub-subsystems that did not have any mass-reduction ideas are denoted by an "n/a" designation. Trexel's MuCell® technology and PolyOne's CFAs were applied to many plastic components, mainly in the HVAC Main Unit. Zotefoams' Azote® was used for the air distribution ducts.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
12	**01**	**00**	**Air Handling/Body Ventilation Subsystem**	
12	01	02	Air Distribution Duct Components (Duct Manifolds)	Zotefoams Azote® material to replace blow-molded HDPE ducts.
12	01	03	Body Air Outlets (Dash Vents)	PolyOne CFA on Class A parts, MuCell® on non-Class A parts, and Zotefoams Azote® on ducts.
12	01	04	HVAC Main Unit: Air Distribution Box/ Heater Core & Evaporator	MuCell® applied to applicable housings and flaps.

Table F.12-5: Mass-Reduction Ideas Selected for Detail Analysis of the Air Handling/Body Ventilation Subsystem

F.12.1.6 Mass-Reduction & Cost Impact Results

Applying Azote® to the ducts in the Air Distribution Duct Components sub-subsystem yielded the greatest mass reduction (1.454 kg), as shown in the first line of **Table F.12-6**. A weight reduction of 80% is applied to these ducts as that is the realistic guideline provided by Zotefoams. The cost was significantly decreased, resulting in a savings of $6.45 for all of the parts in the sub-subsystem. The baseline HDPE parts were blow-molded, which is an expensive process. The twin sheet molding machinery used for the Azote® parts is much less expensive than blow-molding equipment. Even though Azote® material is more expensive than standard HDPE, this increase in material cost did not compare to the drastic reduction in machine burden. The overall manufacturing cost was therefore lower. The reason that Zotefoams is not currently used in production for automotive HVAC ducts, even though it is lighter and less expensive, is because it is still relatively new to the industry. There is prevailing criteria from the past that is still imposed by OEMs on new materials like Zotefoams'. To date, hesitancy on the part of the manufacturer's design centers has limited the opportunity for entry, let alone consideration.

There were two smaller ducts in the Body Air Outlets sub-subsystem that are injection-molded parts. These parts were converted to Azote® for the redesign, however there is a cost increase for this sub-subsystem because injection molding, contrary to blow molding, is an inexpensive process and was even more inexpensive than the twin sheet forming used for the Azote® duct.

MuCell® and PolyOne's CFAs account for the rest of the weight savings. These are applied to the HVAC Main Unit's plastic components as well as the Dash Vents, totaling a mass reduction of 0.581 kg. For these components, MuCell® and CFAs saved money. The cost of MuCell® in this study includes licensing fees. None of the costs include tooling. Overall, the Air Handling/Body Ventilation subsystem saved $7.27.

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
12	01	00	**Air Handling/Body Ventilation Subsystem**						
12	01	02	Air Distribution Duct Components (Duct Manifolds)	A	1.454	$6.45	$4.43	78.35%	0.08%
12	01	03	Body Air Outlets (Dash Vents)	X	0.103	-$0.62	-$6.02	11.36%	0.01%
12	01	04	HVAC Main Unit: Air Distribution Box/ Heater Core & Evaporator	A	0.478	$1.45	$3.03	4.75%	0.03%
				A	**2.034** (Decrease)	**$7.27** (Decrease)	**$3.58** (Decrease)	**15.88%**	**0.12%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.12-6: Mass-Reduction and Cost Impact for the Air Handling/Body Ventilation Subsystem

F.12.2 Heating/Defrosting Subsystem

F.12.2.1 Subsystem Content Overview

The Heating/Defrosting subsystem includes the Defroster Ducts (Front Window/Windshield Defrosting sub-subsystem) and Heater Hoses (Supplementary Heat Source sub-subsystem). This subsystem only contributes 6.59% of the Climate Control system's total mass, as seen in **Table F.12-7**.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
12	02	00	**Heating/Defrosting Subsystem**	
12	02	01	Front Window/Windshield Defrosting	0.510
12	02	07	Supplementary Heat Source	0.523
			Total Subsystem Mass =	**1.033**
			Total System Mass =	**15.662**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**6.59%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.06%**

Table F.12-7: Mass Breakdown by Sub-subsystem for the Heating/Defrosting Subsystem

F.12.2.2 Toyota Venza Baseline Subsystem Technology

The Defroster Duct assembly is shown in **Image F.12-10**. It is made up of four parts. The two side ducts are blow-molded HDPE. The two parts that make up the center manifold are an injection-molded blend of PP and PE. The assembly is snapped together (no fasteners are required).

Image F.12-10: Toyota Venza's Defroster Duct Assembly Including Two Center Manifolds and Two Side Ducts

(Source: FEV, Inc. Photo)

F.12.2.3 Mass-Reduction Industry Trends

Zotefoams' Azote® material, as described in **Section F.12.1.3**, is also applicable to this subsystem, particularly the Defroster Duct Assembly. MuCell® and PolyOne's CFAs are also industry trends that could be applied to reduce dthe mass of this subsystem, however, the baseline HDPE blow-molded part is by far what is most common in the industry currently.

F.12.2.4 Summary of Mass-Reduction Concepts Considered

Mass reduction ideas considered are shown in **Table F.12-8**. The four-component assembly shown in **Image F.12-10** could potentially be combined into one piece and made out of a twin sheet forming process using Azote®.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Defroster Ducts	Merge into one part and use Zotefoams Azote® Foam	50-80% mass reduction	Moderate cost or cost save depending on application, currently used on ducting in Boeing 787 Dreamliner®

Table F.12-8: Summary of Mass-Reduction Concepts Initially Considered for the Heating/Defrosting Subsystem

F.12.2.5 Selection of Mass Reduction Ideas

Zotefoams' Azote® was chosen for the Heating/Defrosting subsystem (**Table F.12-9**). It was merged into one piece.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
12	**02**	**00**	**Heating/Defrosting Subsystem**	
12	02	01	Front Window/Windshield Defrosting	Four-piece assembly merged into one piece using Zotefoams Azote® material.
12	02	07	Supplementary Heat Source	n/a

Table F.12-9: Mass-Reduction Ideas Selected for Detail Analysis of the Heating/Defrosting Subsystem

F.12.2.6 Mass-Reduction & Cost Impact Results

The results of the mass reduction for the Heating/Defrosting subsystem are shown in **Table F.12-10**. As seen, 0.393 kg was saved at a cost decrease of $2.03. The two side ducts were blow-molded, so money was saved going to the twin sheet forming process; however, some money was also spent converting the two injection molding pieces to Azote® using twin sheet forming. These parts would still be supplied to the OEM and while no tooling costs were included in this analysis, the OEM would still provide the tooling as is the case with most OEM-supplier relationships.

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
12	02	00	**Heating/Defrosting Subsystem**						
12	02	01	Front Window/Windshield Defrosting	A	0.393	$2.03	$5.16	76.99%	0.02%
12	02	07	Supplementary Heat Source		0.000	$0.00	$0.00	0.00%	0.00%
				A	**0.393** (Decrease)	**$2.03** (Decrease)	**$5.16** (Decrease)	**38.03%**	**0.02%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.12-10: Mass-Reduction and Cost Impact for the Heating/Defrosting Subsystem

F.12.3 Controls Subsystem

F.12.3.1 Subsystem Content Overview

The breakdown of the Controls subsystem is shown in **Table F.12-11**. The Mechanical Control Head sub-subsystem includes the user controls for the HVAC and is mounted in the instrument panel. The Electronic Climate Control Unit sub-subsystem includes a circuit board with a harness connector enclosed in a housing. Overall, the Controls subsystem only accounts for approximately 3% of the system mass.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
12	04	00	**Controls Subsystem**	
12	04	02	Mechanical Control Head	0.326
12	04	03	Electronic Climate Control Unit	0.159
			Total Subsystem Mass =	**0.485**
			Total System Mass =	**15.662**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**3.09%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.03%**

Table F.12-11: Mass Breakdown by Sub-subsystem for the Controls Subsystem

F.12.3.2 Toyota Venza Baseline Subsystem Technology

The climate control operating switches, which is the primary assembly in the Mechanical Control Head sub-subsystem is shown in **Image F.12-11**.

Image F.12-11: Toyota Venza HVAC User Controls

(Source: FEV, Inc. Photo)

F.12.3.3 Mass-Reduction Industry Trends

An industry trend concerning the HVAC user controls is to integrate them into a touch screen. Touch screens are currently the main interface in most luxury cars and are making their way into non-luxury cars as well. Touch screens can be costly, however, in both development and hardware costs.

F.12.3.4 Summary of Mass-Reduction Concepts Considered

This Electronic Unit (not pictured) is a circuit board enclosed in a plastic (ABS) housing. It is possible to apply MuCell® to this housing, as shown for consideration in **Table F.12-12**. Also, integration of the HVAC user controls into a touch screen was considered.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Climate Control Unit Housing	MuCell®	10% mass reduction	Low cost, MuCell® used in high volume production by Ford
HVAC User Controls	Integrate into touch screen	10% mass reduction	High cost, in production on many luxury cars

Table F.12-12: Summary of Mass-Reduction Concepts Initially Considered for the Controls Subsystem

F.12.3.5 Selection of Mass Reduction Ideas

MuCell® was selected to reduce the weight of the Climate Control Unit's Housing (**Table F.12-13**). Integrating the HVAC user controls into a touch screen was not applied in this analysis as the weight savings was not significant enough to overcome the cost increase.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
12	**04**	**00**	**Controls Subsystem**	
12	04	02	Mechanical Control Head	n/a
12	04	03	Electronic Climate Control Unit	MuCell® applied to Control Unit Housing.

Table F.12-13: Mass-Reduction Ideas Selected for Detail Analysis of the Controls Subsystem

F.12.3.6 Mass-Reduction & Cost Impact Results

The results of lightweighting the Electronic Climate Control Unit Housing are shown in **Table F.12-14**. MuCell was the only idea applied and it resulted in a $0.04 cost save.

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
12	**04**	**00**	**Controls Subsystem**						
12	04	02	Mechanical Control Head		0.000	$0.00	$0.00	0.00%	0.00%
12	04	03	Electronic Climate Control Unit	A	0.009	$0.04	$4.21	5.62%	0.00%
				A	**0.009** (Decrease)	**$0.04** (Decrease)	**$4.21** (Decrease)	**1.84%**	**0.00%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.12-14: Mass-Reduction and Cost Impact for the Controls Subsystem

F.13 Info, Gage & Warning Device System

The Info, Gage & Warning Device system typically includes five subsystems: instrument cluster, horn, clock/timekeeping, parking or reversing aid, and non-automotive driver information subsystems. The Toyota Venza contains mass in two of these subsystems – the instrument cluster and horn subsystems, as seen in **Table F.13-1**. The clock/timekeeping components were included in the In-Vehicle Entertainment system. From the data shown, the instrument cluster subsystem is the biggest weight contributor in this system. The Toyota Venza has a light weight horn subsystem for which there is currently no better option in the market that can be applied to the vehicle (note: the horn subsystem includes the horn mechanism itself and not the components used to activate the horn in the steering wheel, which are in the Occupant Restraining Device subsystem of the Body system). Therefore, the weight reduction analysis will focus on the instrument cluster subsystem.

System	Subsystem	Sub-Subsystem	Description	System & Subsystem Mass "kg"
13	00	00	**Info, Gage & Warning Device System**	
13	01	00	Instrument Cluster Subsystem	1.399
13	06	00	Horn Subsystem	0.500
13	07	00	Clock/Timekeeping Subsystem	n/a
13	13	00	Parking or Reversing Aid Subsystem	n/a
13	21	00	Non-Automotive Driver Information Subsystem	n/a
			Total System Mass =	**1.899**
			Total Vehicle Mass =	**1711**
			System Mass Contribution Relative to Vehicle =	**0.11%**

Table F.13-0-6: Baseline Subsystem Breakdown for Info, Gage & Warning Device System

As **Table F.13-2** shows, weight reduction ideas were applied to the instrument cluster subsystem. The ideas reduced the system weight by 0.076kg which is a 4% system mass reduction.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
13	00	00	**Info, Gage & Warning Device System**						
13	01	00	Instrument Cluster Subsystem	A	0.076	$0.19	$2.45	5.44%	0.004%
13	06	00	Horn Subsystem		0.000	$0.00	$0.00	0.00%	0.000%
13	07	00	Clock/Timekeeping Subsystem		0.000	$0.00	$0.00	0.00%	0.000%
13	13	00	Parking or Reversing Aid Subsystem		0.000	$0.00	$0.00	0.00%	0.000%
13	21	00	Non-Automotive Driver Information Subsystem		0.000	$0.00	$0.00	0.00%	0.000%
				A	**0.076** (Decrease)	**$0.19** (Decrease)	**$2.45** (Decrease)	**4.01%**	**0.004%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.13-0-7: Preliminary Mass-Reduction and Cost Impact for Info, Gage & Warning Device System

F.13.1 Instrument Cluster Subsystem

F.13.1.1 Subsystem Content Overview

The two sub-subsystems within the Instrument Cluster subsystem are pictured in **Image F.13-1** and **Image F.13-2**. They are the driver information center and the IP cluster.

Image F.13-1: Driver Information Center **Image F.13-2: IP Cluster**

(Source: FEV, Inc. Photo)

As seen in **Table F.13-3**, the most significant contributor to the mass of the Instrument Cluster subsystem is the IP cluster. This includes the cluster lense, cluster mask assembly, and the cluster rear housing assembly.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
13	**01**	**00**	**Instrument Cluster Subsystem**	
13	01	01	Driver Information Center	0.447
13	01	02	IP Cluster	0.952
			Total Subsystem Mass =	**1.399**
			Total System Mass =	**1.899**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**73.67%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.08%**

Table F.13-0-8: Mass Breakdown by Sub-subsystem for Instrument Cluster Subsystem

F.13.1.2 Toyota Venza Baseline Subsystem Technology

The driver information center (DIC) is approximately 335mm long, 90mm wide, and 120mm in height. The IP cluster also follows the industry convention. It is approximately 360mm long, 180 mm wide, and 140mm in height. Both sub-subsystems contain a lense, lense mask, rear housing, circuit board and display assembly. The majority of the material is PP (polypropylene). The lenses are made of PMMA.

F.13.1.3 Mass-Reduction Industry Trends

The industry is beginning to use advanced technology for plastic material weight savings. A few pioneers are Trexel and PolyOne. Trexel's MuCell® process and PolyOne's Chemical Foaming Agents (CFAs) are detailed further in **Section F.4B.1.2**.

F.13.1.4 Summary of Mass-Reduction Concepts Considered

Comparing the options in the industry, both MuCell® and PolyOne's CFAs were considered in the mass reduction brainstorming process as **Table F.13-4** shows. In the Lotus report, they suggested MuCell® as the weight reduction idea for instrument cluster subsystem.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Instrument Cluster Subsystem	MuCell®	10-20% weight save	Low cost, MuCell® used in high volume production by Ford
Instrument Cluster Subsystem	PolyOne CFA	10-15% weight save	Low cost, CFA for PP currently under test for use in high volume production vehicles

Table F.13-0-9: Summary of mass-reduction concepts initially considered for the Instrument Cluster Subsystem

F.13.1.5 Selection of Mass Reduction Ideas

MuCell® was selected for cost analysis because all eligible parts in this subsystem had non-Class A surfaces. That is, MuCell® was applied to parts that the customer cannot see. Components such as the driver information center screen or info. plate were not applicable for MuCell®. There were no eligible Class A surface finish parts for

PolyOne's CFAs to be applied. Also, MuCell® is best applied to plastic parts that have a thickness of 2mm or above. The ideas were applied to the components shown in **Table F.13-5**. Each of these components is pictured in **Images F.13-3** through **F.13-8**.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
13	**00**	**00**	**Info, Gage & Warning Device System**	
13	01	01	Circuit Board Support	MuCell®
13	01	01	DIC Housing	MuCell®
13	01	01	DIC Lense Mask	MuCell®
13	01	02	Cluster Rear Housing	MuCell®
13	01	02	Display Housing	MuCell®
13	01	02	Cluster Mask Assy	MuCell®

Table F.13-0-10: Mass-Reduction Ideas Selected for Detail Info Instrument Cluster Subsystem Analysis

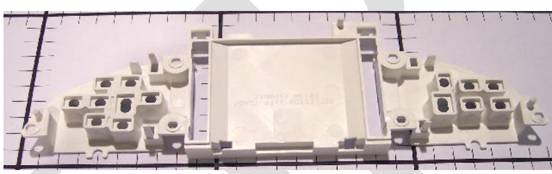
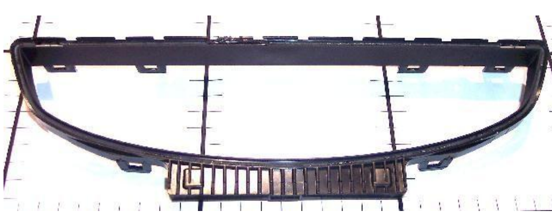


Image F.13-3: Circuit Board Support

(Source: FEV, Inc. Photo)

Image F.13-4: DIC Housing

(Source: FEV, Inc. Photo)



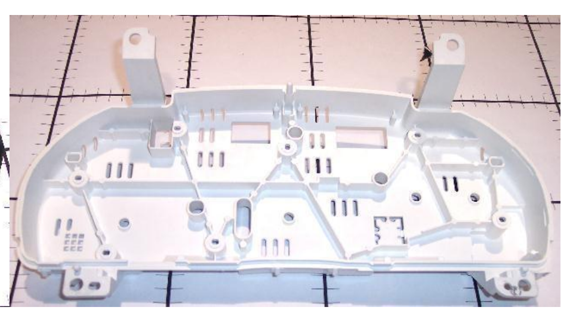


Image F.13-5: DIC Lense Mask

Image F.13-6: Cluster Rear Housing

(Source: FEV, Inc. Photo) *(Source: FEV, Inc. Photo)*

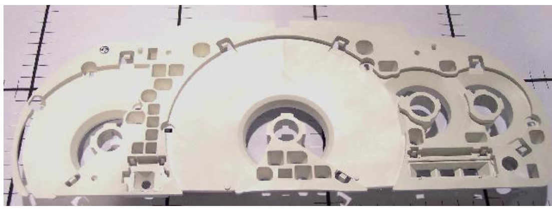


Image F.13-7: Display Housing

(Source: FEV, Inc. Photo)

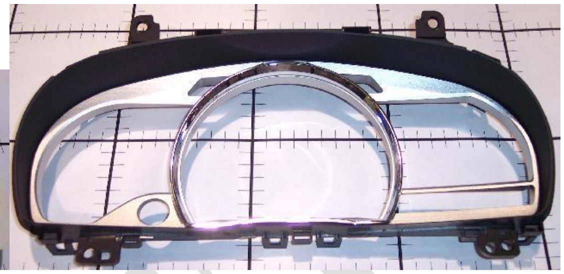


Image F.13-8: Cluster Mask Assembly

(Source: FEV, Inc. Photo)

F.13.1.6 Mass-Reduction & Cost Impact

Table F.13-6 shows a summary of the overall cost impact driven by the weight reduction applied to the instrument cluster subsystem. The 0.076kg saved is 100% a result of the MuCell® applied to the six parts listed in **Table F.13-5**. Applying MuCell® to these components resulted in a cost savings of $0.19.

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
13	**01**	**00**	**Instrument Cluster Subsystem**						
13	01	01	Driver Information Center	A	0.027	$0.15	$5.32	6.10%	0.002%
13	01	02	IP Cluster	A	0.049	$0.04	$0.84	5.13%	0.003%
				A	**0.076** (Decrease)	**$0.19** (Decrease)	**$2.45** (Decrease)	**15.21%**	**0.004%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.13-0-11: Calculated Subsystem Mass-Reduction and Cost Impact Results for Instrument Cluster Subsystem

F.14 In-Vehicle Entertainment System

Toyota Venza has a baseline entertainment system with a basic radio, CD, and MP3 input connection with a sum mass of 4.472 kg (**Table F.14-1**).

System	Subsystem	Sub-Subsystem	Description	System & Subsystem Mass "kg"
15	**00**	**00**	**In-Vehicle Entertainment System**	
15	01	00	Receiver and Audio Media Subsystem	3.145
15	02	00	Antenna Subsystem	0.159
15	03	00	Speaker Subsystem	1.281
			Total System Mass =	**4.586**
			Total Vehicle Mass =	**1711**
			System Mass Contribution Relative to Vehicle =	**0.27%**

Table F.14-0-1: Baseline Subsystem Breakdown for In-Vehicle Entertainment System

Image F.14-1:Toyota Venza Radio

(Source: FEV photo)

The days of listening to radio, CD players, or even just singing out loud for entertainment in the car are long gone. Today's auto buyers are moving into high-tech entertainment with top trends to outfit their vehicles, including satellite radio, DVDs on overhead screens, and even video game console hooked up in the backseat. In-vehicle computers and entertainment systems are just a few components of the $56 billion market for in-vehicle entertainment.

Portable entertainment systems are quickly becoming a necessity for families of all sizes. It is not only luxury cars that are installed with premium entertainment accessories such as MP3 jacks, surround-sound audio, and video players with cinematic options: new fleets of cars and minivans are already equipped with the latest DVD player and overhead TV screens.

Table F.14-2 shows the areas found in which mass weight reduction is available without loss of functionality.

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	System/ Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
15	00	00	**In-Vehicle Entertainment System**						
15	01	00	Receiver and Audio Media Subsystem	A	1.024	$1.74	$1.70	32.55%	0.06%
15	02	00	Antenna Subsystem	A	0.049	$0.69	$14.17	30.82%	0.00%
15	03	00	Speaker Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
				A	1.073 (Decrease)	$2.43 (Decrease)	$2.27 (Decrease)	23.39%	0.06%

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.14-0-2: Mass-Reduction and Cost Impact for Body System Group

F.14.1 In-Vehicle Receiver and Audio Media Subsystem

As seen in **Table F.14-3**, the steel case enclosures of the Radio, CD player, XM receiver, and Antenna components are the most significant contributors to the Receiver and Audio Media subsystem mass.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
15	**01**	**00**	**Receiver and Audio Media Subsystem**	
15	01	01	Enclosures	1.206
15	01	02	Electronic Boards	1.036
15	01	03	Plastic Enclosure	0.648
15	07	00	Multimedia Interface (USB)	0.256
			Total Subsystem Mass =	**3.145**
			Total System Mass =	**4.586**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**68.59%**
			System Mass Contribution Relative to Vehicle =	**0.18%**

Table F.14-0-3: Mass Breakdown by Sub-subsystem for Receiver and Audio Media Subsystem.

F.14.1.1 Toyota Venza Baseline Subsystem Technology

Toyota's quality and interior design over the past 10 years gives other automakers something to consider and compete with in the marketplace. Celebrating the 10-year anniversary of its Prius clearly shows that the company can certainly lead the industry when it wants – just not so much with advanced infotainment and Smartphone integration. Toyota previously lagged behind its competitors' technologies that respond to spoken commands, such as Ford's SYNC and General Motors' MyLink. Through spoken commands, motorists can use these systems without taking their hands off the wheel or their eyes off the road. Most automakers are trying to make sure that they display things in a safe, secure manner and that these options do not distract motorists.

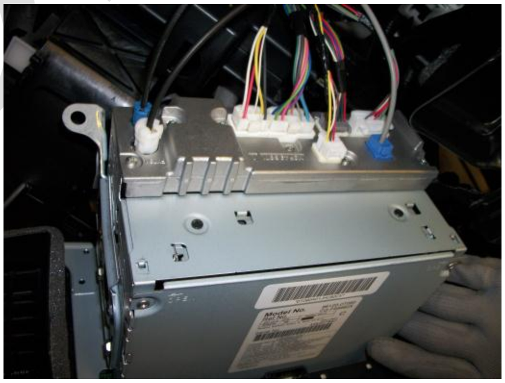


Image F.14-2:Toyota Venza Radio source

(Source: FEV photo)

Entune™ is Toyota's next-generation infotainment system, integrating aspects of navigation with media and other fun stuff, too. Like much of its competition, Toyota is offering smartphone integration, hitting all the major bases with support for BlackBerry™, Android™, and iPhone. Users will need to download and install an application to their phones, which will then provide all the data their car needs. The car itself does not have an onboard modem or a separate data plan, so vehicle owners will need to pay for one.

A benefit is that the system is said to be easily upgradeable via software update, providing some degree of "future-proofing" – that is, trying to anticipate future developments. This is something, at this point, fairly rare in the infotainment business, and a rather nice thing to provide.

There are a variety of apps that work with Entune™, the biggest being Bing™, MovieTickets.com™, OpenTable®, and Pandora® Internet radio. However, the standard apps will not be upgraded to include Entune™ support: separate versions will be required. This potentially means users will need two copies of Pandora installed on their phones, which is a decidedly unfortunate deal if a user is tight on storage.

F.14.1.2 Mass-Reduction Industry Trends

In-car entertainment, sometimes referred to as ICE, is a collection of hardware devices installed into automobiles and other forms of transportation to provide audio or visual (sometimes both) entertainment and satellite navigation systems (SatNav). This includes playing media such as CDs, DVDs, Free view/TV, USB and/or other optional surround sound, or DSP systems. Also increasingly common are the incorporation of video game consoles into the vehicle. In-car entertainment is becoming more widely available due to reduced costs of devices such as LCD screen/monitors and the consumer cost of the converging media playable technologies: single hardware units are capable of playing CD, MP3, WMA, DVD. Mass weight reduction in these components is high on the design priority list when combining these options.

F.14.1.3 Summary of Mass-Reduction Concepts Considered

Table F.14-7 compiles the mass reduction ideas considered for the Receiver and Audio Media subsystem. Lotus Engineering did not apply any mass reduction ideas to the In-Vehicle Entertainment system. The plastic case replaces a formed sheet metal case assembled with screws and cooled with fans. The new plastic case achieves required EMI and RFI shielding by completely enclosing electronics with a mesh Faraday cage that is insert molded. (The Faraday cage is named for English scientist Michael Faraday, who invented it in 1836.)

For a radio, Faraday cages shield external electromagnetic radiation if the conductor is thick enough and the holes that create the mesh are significantly smaller than the radiation's wavelength. Electrical charges within the cage's conducting material will redistribute so as to cancel the field's effects in the cage's interior. This phenomenon is also employed to protect electronic equipment from lightning strikes and other electrostatic discharges.

Component/ Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Steel case enclosures	replace with Aluminum	10% weight save	Integrity and strength compromised
Steel case enclosures	replace with Plastic	50% weight save	Extensive engineering hurdles to overcome
CD Player Modual	replace CD player with USB & AUX jack	30% weight save	Low risk moderate cost increase
Aluminum Case Assemb	Carbon fiber material rep	50% weight save	Extensive engineering hurdles to overcome
Aluminum Case Assemb	Magnesium material repl	30% weight save	Low risk moderate cost increase

Table F.14-4: Summary of Mass-Reduction Concepts Initially Considered for the Receiver and Audio Media Subsystem

F.14.1.4 Magnetic Tooling

The cutting, folding, and the eventual insertion of the mesh into the mold requires innovative magnetic tooling and the use of robots to transfer the formed mesh into the mold.

The new plastic case provides better shielding than the previously used metal cases. There are lower emissions over a range of 150 Hz to 430 MHz. OEMs are seeking improved electromagnetic interference to avoid any internal cross talk, such as interference with electronic engine controls.

The system cost to assemble the radio is reduced by one-third with the new technology. Twenty-nine screws are completely eliminated. Use of injection molding allowed incorporation of design features not possible with the sheet metal case. For example, Delphi designed slide lock and snap lock features that allow fast snap assembly. Other mechanical features are also integrated into the design. Mechanical part reduction includes ESD grounding clips, fasteners and main board grounding. Assembly parts eliminated included a separate assembly fixture and use of torque feedback screwdrivers.

As a result, the case is also more rigid, reducing rattle noises. There is also a significant increase in natural frequency. Natural frequency is the frequency at which a system naturally vibrates once it has been set into motion. Vibration testing on the new plastic case radio showed a 25% increase in natural frequency.

F.14.1.5 Recycled Plastic

Delphi is using reprocessed plastic to make the case. MRC Polymers of Chicago supplies 16 percent glass-filled PC/ABS for the part, which is produced by Amity Mold of Tipp City, OH. The plastic comes from post industrial and post consumer sources. The PC/ABS blend had to be optimized to meet environmental requirements and reduce warping.

The design of the plastic case lowered the internal temperature. One reason for the improved thermal management is insulation of the heat sink from the interior of the radio. The cooling fan was eliminated due to the isolative properties of the plastic. As a result, electric current used is also reduced, improving vehicle mileage.

Other advantages include:

- Weight is reduced in the structural support for the radio
- Safety is improved with reduced injuries from metal cuts: protective gloves are not required for assembly
- Condensation is eliminated during temperature cycling: dew-point temperature is not achieved so no moisture drops on the circuit board
- Lower dust intrusion during standard testing

The Plastic Case design is ultimately going to be used across the board at Delphi. Wherever it is currently using sheet metal, it will instead use this technology. Its application is quite broad-based and can be used as a competitive advantage for all of their product lines.

Another Delphi innovation is how the cage is placed in a mold cavity and then held in position while plastic is injected at high pressures. Many specifics of the manufacturing technology are proprietary and covered by 29 U.S. patents pending.

F.14.1.6 Widespread Application

Applicable to any automotive interior electronic packaging, the same advantages apply: part and weight reductions, integration of mechanical and electrical features, and improved air cooling with no loss of shielding. Delphi is also exploring non-automotive consumer applications.

The Delphi plastic radio case could replace a wide range of shielding approaches besides sheet metal cases. These include die cast metal cases, conductive coatings (paints and plating), board-level shielding for individual metal cases, conductive plastics, and conductive additives.

F.14.1.7 Selection of Mass-Reduction Ideas

The mass reduction idea selected replaces a formed sheet metal case assembled with screws and cooled with fans. The new plastic case achieves required EMI and RFI shielding by completely enclosing electronics with a mesh Faraday cage that is insert molded. Cost benefit and mass reduction benefit a total win.

Eliminating the CD player and replacing it with ether a USB or AUX jack to allow interface with phones or MP3 players for prerecorded or streamed music was not selected at this time: there is still demand from many customers for the capability to play their favorite CDs.

System	Subsystem	Sub-Subsystem	Description	Mass-Reduction Ideas Selected for Detail Evaluation
15	**1**	**00**	**Receiver and Audio Media Subsystem**	
15	01	01	Infotainment Enclosure	Replace 1018 steel farecation with Premier A240-HTHF molded enclosure

Table F.14-5: Mass-Reduction Idea Selected for Receiver and Audio Media Subsystem Analysis

F.14.1.8 Mass-Reduction & Cost Impact Estimates

The greatest mass reduction came as a result of replacing steel cases with plastic on the Venza Infotainment system as seen in **Table F.14-9**.

Image F.14-3: Delphi Ultra Light Radio source

(Source: Google images)

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	System/ Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
15	**00**	**00**	**In-Vehicle Entertainment System**						
15	01	00	Receiver and Audio Media Subsystem	A	1.024	$1.74	$1.70	32.55%	0.06%
15	02	00	Antenna Subsystem	A	0.049	$0.69	$14.17	30.82%	0.00%
15	03	00	Speaker Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
				A	**1.073** (Decrease)	**$2.43** (Decrease)	**$2.27** (Decrease)	**23.39%**	**0.06%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.14-6: Subsystem Mass-Reduction and Cost Impact for Receiver and Audio Media Subsystem

F.14.2 Antenna Subsystem

The Antenna subsystem is a miniature copy of the radio package, with a small steel enclosure, a circuit board, and the required connection to receive a signal from the antenna and send it on to the radio.

The Antenna enclosure, like that of the radio, is a steel construction and is another good opportunity for the molded plastic configuration. The simplicity of the molded component and the easy of assembly makes this a good conversion for this application. **Table F.14-7** shows the mass of the Antenna subsystem

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
15	**02**	**00**	**Antenna Subsystem**	
15	02	01	Infotainment Antennas and Cables	0.159
			Total Subsystem Mass =	**0.159**
			Total System Mass =	**4.586**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**3.47%**
			System Mass Contribution Relative to Vehicle =	**0.01%**

Table F.14-7: Mass Breakdown by Sub-subsystem for Antenna Subsystem.

The cost related to the Antenna subsystem is all related to the conversion of the enclosure from steel to plastics using the same material and snap fit design as the radio described being used by General Motors in their new model vehicles across the board. I am sure that we will see more utilization of this kind of material and molded construction in the future.

Table F.14-8 will show the cost implication of using a RFI molded case in this subsystem.

			Net Value of Mass Reduction Idea					
Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
02	**00**	**Antenna Subsystem**						
02	01	Infotainment Antennas and Cables	A	0.049	$0.69	$14.17	30.82%	0.00%
			A	**0.049** (Decrease)	**$0.69** (Decrease)	**$14.17** (Decrease)	**30.82%**	**0.00%**

"+" = mass decrease, "-" = mass increase
"+" = cost decrease, "-" = cost increase

Table F.14-8: Cost Summary by Sub-subsystem for Antenna Subsystem

F.14.3 Speaker Subsystem

The Speaker subsystem was inspected and evaluated with similar automotive and other comparative sound systems in the market today. We found no mass weight or quality of sound advantage in trying to replace to present components.

F.14.4 Total Mass Reduction and Cost Impact

In a vehicle that weighs 1711 kg, the Infotainment system is a small percentage of that mass. With the use of today's new, innovative materials and process methodologies that change the norm of assembly, however, we can improve the end result.

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	System/ Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
15	00	00	**In-Vehicle Entertainment System**						
15	01	00	Receiver and Audio Media Subsystem	A	0.896	$1.81	$2.02	28.48%	0.05%
15	02	00	Antenna Subsystem	A	0.049	$0.69	$14.17	30.82%	0.00%
15	03	00	Speaker Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
				A	**0.945** (Decrease)	**$2.51** (Decrease)	**$2.65** (Decrease)	**20.60%**	**0.06%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.14-9: Mass-Reduction and Cost Impact for In-Vehicle Entertainment

F.15 Lighting System

The Lighting system, broken down in **Table F.15-1**, is largely made up of the Venza's exterior light assemblies, which are most notably, the Front Headlamp assemblies and Rear Tail Lamp assemblies. Four interior lighting switches are also included, but are not a significant mass contributor. There is no mass for the Interior Lighting subsystem as these components were kept with their respective interior assemblies (e.g., Instrument Panel or Door Trim).

System	Subsystem	Sub-Subsystem	Description	System & Subsystem Mass "kg"
17	**00**	**00**	**Lighting System**	
17	01	00	Front Lighting Subsystem	6.090
17	02	00	Interior Lighting Subsystem	0.000
17	03	00	Rear Lighting Subsystem	3.827
17	05	00	Lighting Switches Subsystem	0.127
			Total System Mass =	**10.044**
			Total Vehicle Mass =	**1711**
			System Mass Contribution Relative to Vehicle =	**0.59%**

Table F.15-1: Baseline Subsystem Breakdown for the Lighting System

The Front Lighting subsystem was the only subsystem with weight reduction applied as seen in **Table F.15-2**, which resulted in 0.531 kg of mass saved with a cost increase of $0.76. The Rear Lighting subsystem did not lend itself to mass reduction ideas due to the configuration of the assembly. A foaming agent could not be applied to the Rear Tail Lamp Housings because it would reduce the aesthetic quality of the reflective coating. The Front Headlamp Housings did not have such a coating on the housings (since the Front Headlamps had separate reflector components).

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
17	**00**	**00**	**Lighting System**						
17	01	00	Front Lighting Subsystem	C	0.531	-$0.76	-$1.42	8.73%	0.03%
17	02	00	Interior Lighting Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
17	03	00	Rear Lighting Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
17	05	00	Lighting Switches Subsystem		0.000	$0.00	$0.00	0.00%	0.00%
				C	**0.531** (Decrease)	**-$0.76** (Increase)	**-$1.42** (Increase)	**5.29%**	**0.03%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.15-2: Mass-Reduction and Cost Impact for the Lighting System

Lotus Engineering did not apply any mass reduction ideas to the Lighting system.

F.15.1 Front Lighting Subsystem

F.15.1.1 Subsystems Content Overview

A breakdown of the Front Lighting subsystem is shown in **Table F.15-3**. This subsystem makes up approximately 60% of the Lighting system's mass and most of that is from the Headlamp Cluster Assembly sub-subsystem. This includes the Front Headlamps of the vehicle. The Supplemental Front Lamps subsystem includes the front Fog Lamps.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
17	**01**	**00**	**Front Lighting Subsystem**	
17	01	01	Headlamp Cluster Assy	5.563
17	01	04	Supplemental Front Lamps	0.527
17	01	05	Side Repeater / Marker Lamps	0.000
17	01	99	Misc.	0.000
			Total Subsystem Mass =	**6.090**
			Total System Mass =	**10.044**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**60.63%**
			Subsystem Mass Contribution Relative to Vehicle =	**0.36%**

Table F.15-3: Mass Breakdown by Sub-subsystem for the Front Lighting Subsystem

F.15.1.2 Toyota Venza Baseline System Technology

The Toyota Venza's headlamps are relatively large since they include halogen incandescent lights, projector lights, and the traditional turn signal. A Venza Front Headlamp assembly is shown in **Image F.15-1**. The Front Headlamps have a polypropylene housing (**Image F.15-2**), polycarbonate lens, and reflectors made of a bulk molding compound (BMC) pointed out in **Image F.15-3**.

Image F.15-1: Toyota Venza Front Headlamp Assembly Example

(Source: ebay http://www.ebay.com/itm/Toyota-Venza-Headlight-Head-Lamp-Halogen-RH-/390285376072?item=390285376072&vxp=mtr)

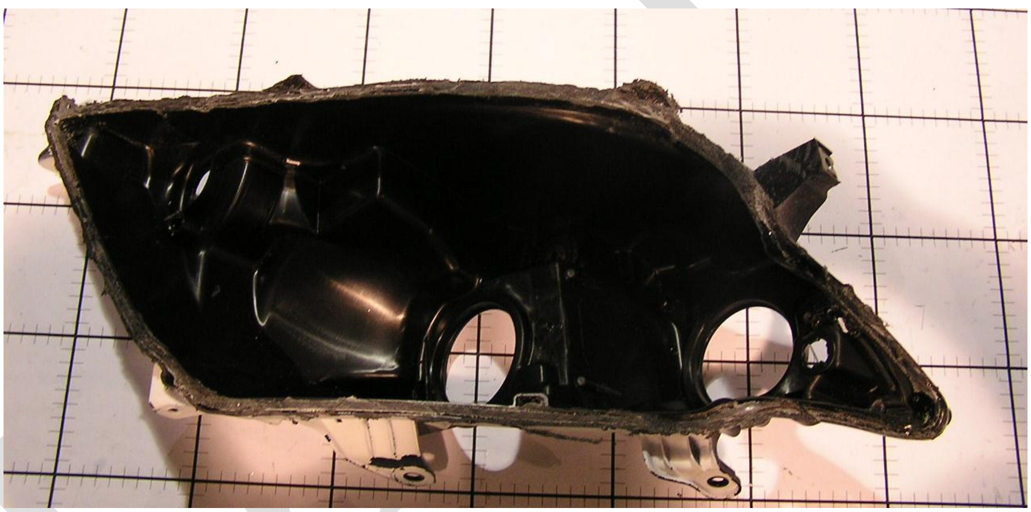


Image F.15-2: Toyota Venza Front Headlamp Housing

(Source: FEV, Inc. Photo)

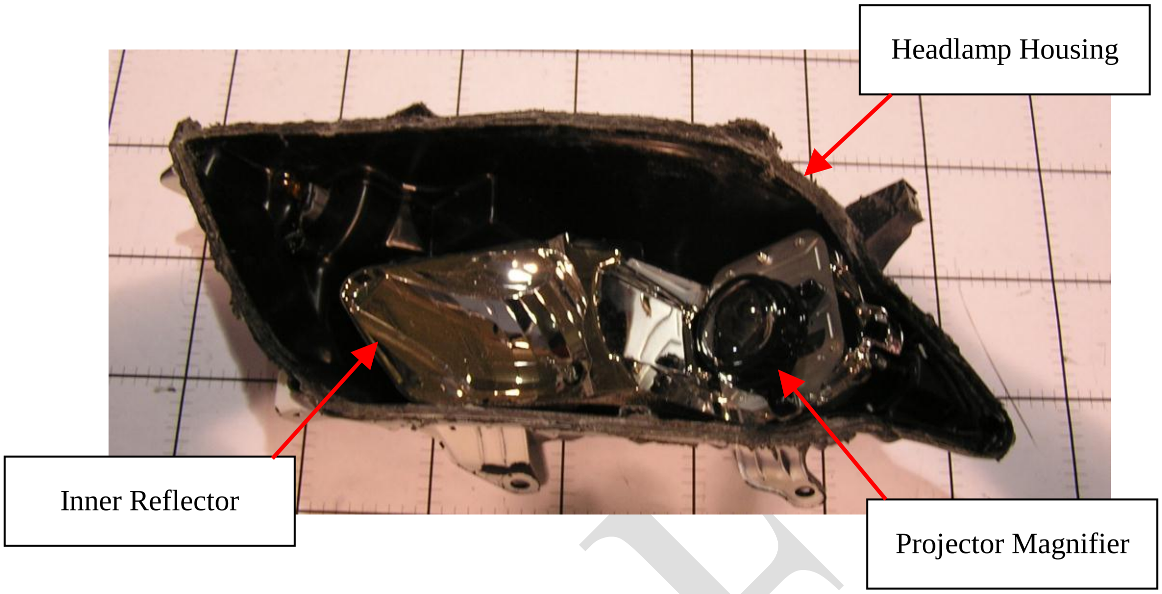


Image F.15-3: Toyota Venza Front Headlamp Housing with Inner Reflector & Project Magnifier

(Source: FEV, Inc. Photo)

The Inner Reflector in **Image F.15-3** reflects the light produced by the halogen bulb. Behind the Projector Magnifier in **Image F.15-3** there is a Projector Reflector which reflects the light produced by the projector light. This Projector Reflector is shown by itself in two views in **Image F.15-4**.

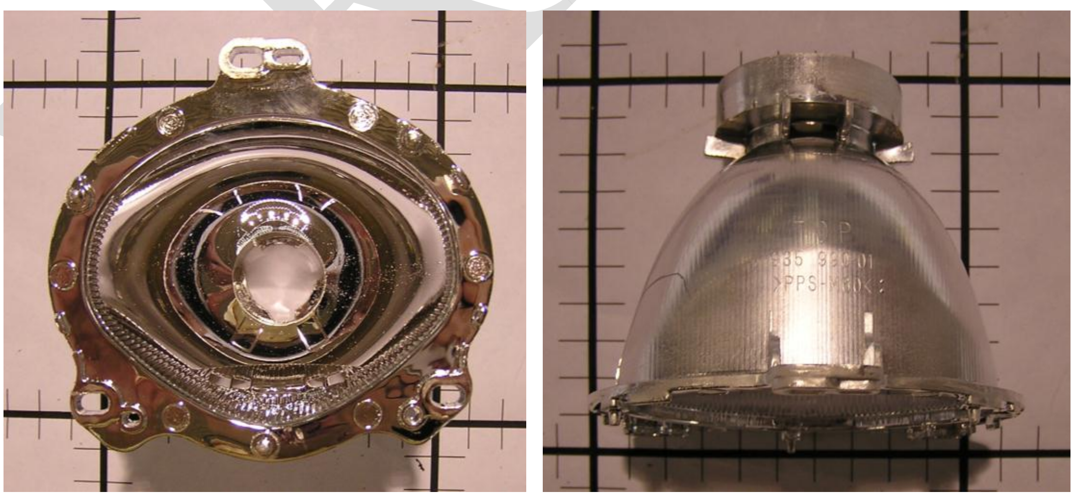


Image 5-17.4: Toyota Venza Projector Reflector

(Source: FEV, Inc. Photo)

The Front Fog Lights have a multi-piece housing made of various types of plastic, one of which has a chrome Physical Vapor Deposition (PVD) coating for light reflectance.

F.15.1.3 Mass-Reduction Industry Trends

Various types of plastics are used in headlamp assemblies depending on their application and purpose. The reflector component helps illuminate the light output of the bulbs and is a relatively dense plastic because of the high heat requirements it needs to maintain. Often times, a Bulk Molding Compound (BMC) is used for the reflectors, which is capable of enduring the elevated temperatures. BMCs have a relatively high density compared to other plastics. SABIC has a product line called Ultem® for this specific application, which is a type of polyetherimide (PEI). These plastics are specifically developed and used for headlamp reflectors so they possess the necessary thermal requirements plus have a lower density compared to BMCs. Typical BMCs have a density of 2 g/cm^3 and Ultem® PEI has a density of approximately 1.3 g/cm^3. In addition, Ultem® PEI can be molded in thinner wall sections. SABIC's Ultem® material has been used in production and a few examples are shown in **Image F-1F.6.**

Image F.15-5: SABIC Ultem® Production Application Examples.

(Photo Courtesy of SABIC)

Although more expensive from a material standpoint, Ultem® saves some cost on processing. As shown in **Image F.15-6**, when using a PEI such as Ultem®, the part can go directly from its injection molding step to metalizing, saving on surface preparation costs. The metalizing often takes place through a process called Physical Vapor Deposition (PVD) for headlamp reflectors.

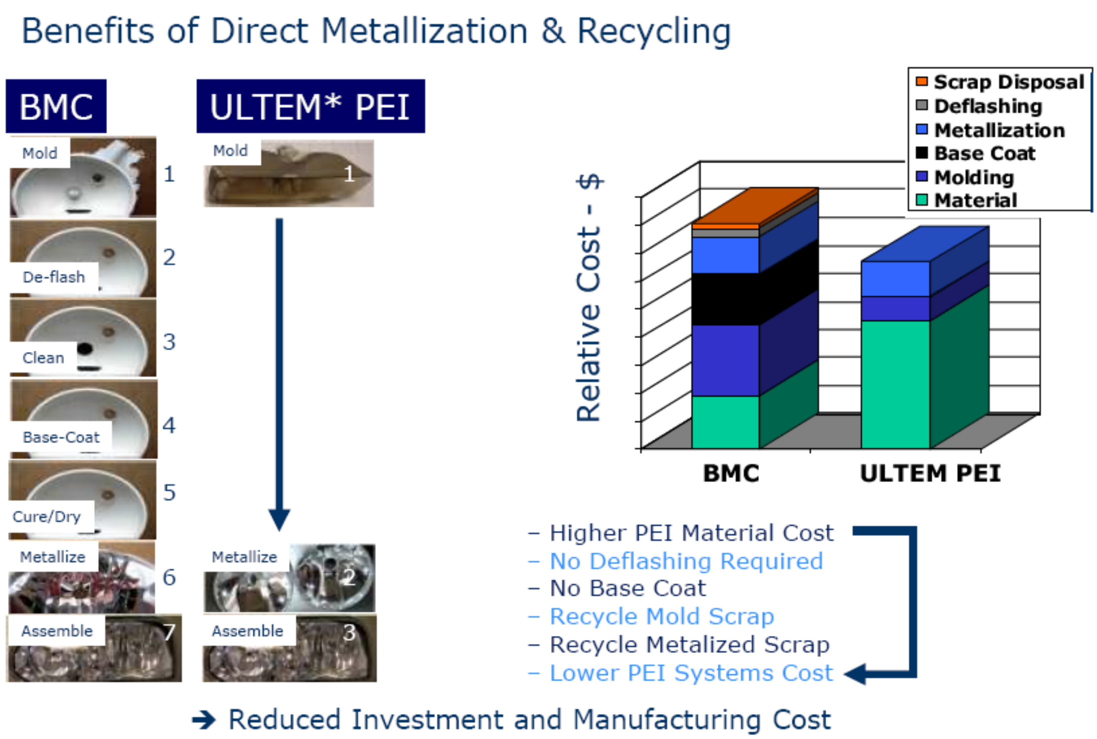


Image F.15-6: Processing Comparison between BMC and Ultem® PEI

(Image Courtesy of SABIC)

Other recent industry trends with headlights concern the actual light source and output. Transitioning from the traditional halogen bulbs to High Intensity Discharge (HID) and LED lights are becoming popular choices both for visibility and for styling. These alternative lights, however, do not necessarily offer mass reduction. HID lights require a ballast, which adds weight. LEDs, although known for not emitting much heat at the light output, do give off considerable heat at the light source and often require additional heat sinks or cooling fans to keep from overheating. The addition of these cooling mechanisms will ultimately increase the mass of the headlamp as well.

Using LEDs can have a favorable effect on fuel economy in an indirect manner, however. Hewlett-Packard performed a study using LEDs for just the turn signal lamps. The study indicates that the alternator may be able to be down-sized due to a reduced power consumption since LEDs are more efficient than incandescent bulbs. Also, a lighter weight wiring harness may be implemented.[1]

Reducing the size of the headlamp is another option; however, doing this will require an increase in material elsewhere. That is, if the headlamp volume was reduced, then the surrounding sheet metal on the car would have to increase in volume, thus actually increasing the overall weight of the car as opposed to decreasing it.

F.15.1.4 Summary of Mass-Reduction Concepts Considered

The mass reduction ideas considered for the Front Lighting subsystem are compiled in **Table F.15-4**. Trexel's MuCell® process is considered for use on applicable plastic housings along with PolyOne's Chemical Foaming Agents, reference **Section F.4B.1.2** for more information on these technologies. In addition, the Ultem® PEI material was considered as discussed in the previous section. For the Rear Tail Lamp Reflectors, PEI was not applicable as those components were already made of a lightweight PBT plastic.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
Front Headlamp Housing	MuCell®	10% mass reduction	Low cost, MuCell® used in high volume production by Ford
Front Headlamp Inner Reflector	SABIC Ultem®	40-50% mass reduction	High Cost, used on Cadillac CTS, Audi A1, and Toyota Sienna
Front Headlamp Projector Reflector	SABIC Ultem®	20-25% mass reduction	High Cost, used on Cadillac CTS, Audi A1, and Toyota Sienna
Headlamp Cluster Assembly	Use LED lights instead of halogen bulbs	Potential mass increase	Used in high volume production on numerous Audi and Mercedes-Benz models, may increase mass due to required heat sink or fan

Table F.15-4: Summary of Mass-Reduction Concepts Initially Considered for the Front Lighting Subsystem

F.15.1.5 Selection of Mass Reduction Ideas

The mass reduction ideas that were selected for the Front Lighting subsystem are listed in **Table F.15-5**. Ultem® PEI was used for the Front Headlamp Inner Reflectors and Projector Reflectors. MuCell® was applied to the Front Headlamp Housings. LEDs were not selected to replace the halogen bulbs do to the additional required cooling parts.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
17	**01**	**00**	**Front Lighting Subsystem**	
17	01	01	Headlamp Cluster Assy	MuCell® applied to Headlamp Housings. SABIC's Ultem® replace BMC material on Front Headlamp Reflectors.
17	01	04	Supplemental Front Lamps	n/a
17	01	05	Side Repeater / Marker Lamps	n/a
17	01	99	Misc.	n/a

Table F.15-5: Mass-Reduction Ideas Selected for Detail Analysis of the Front Lighting Subsystem

F.15.1.6 Mass-Reduction & Cost Impact Results

The mass reductions that resulted for the Front Lighting subsystem, and thus the entire Lighting system itself since this was the only subsystem that had weight reduction ideas applied to it, are shown in **Table F.15-6**. Of the 0.531 kg of mass reduced from the subsystem, 73% is a result of using the Ultem® PEI for the reflectors and the remaining 27% is caused by applying MuCell® to the Front Headlamp Housings. From a cost standpoint, the use of Ultem® PEI increased the cost differential by $1.09, but MuCell® decreased the cost by $0.33 resulting in the overall $0.76 cost hit.

Using Ultem® PEI more than doubled the material cost for the inner reflectors. PEI reduced, however, the processing cost. With the bulk molding compound, it was necessary to wash, base coat, and allow curing time before PVD could occur. With Ultem® PEI, however, the reflector can go directly from injection molding to PVD. This should be the only change in cost seen by the OEM (i.e., there are already manufacturing facilities setup who can handle the volume and there are no special licensing fees or price premium for this material).

System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Sub-Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
				Net Value of Mass Reduction Idea					
17	01	00	**Front Lighting Subsystem**						
17	01	01	Headlamp Cluster Assy	C	0.531	-$0.76	-$1.42	9.55%	0.03%
17	01	04	Supplemental Front Lamps		0.000	$0.00	$0.00	0.00%	0.00%
17	01	05	Side Repeater / Marker Lamps		0.000	$0.00	$0.00	0.00%	0.00%
17	01	99	Misc.		0.000	$0.00	$0.00	0.00%	0.00%
				C	**0.531** (Decrease)	**-$0.76** (Increase)	**-$1.42** (Increase)	**8.73%**	**0.03%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.15-6: Mass-Reduction and Cost Impact for the Front Lighting Subsystem.

Works Cited

1. http://chemlinks.beloit.edu/BlueLight/pages/hp/an1155-2.pdf

F.16 Electrical Distribution and Electronic Control System

Cable harnesses are usually designed according to geometric and electrical requirements. The wires are first cut to the desired length, usually using a special wire-cutting machine. The wires may also be printed on by a special machine during the cutting process or later on a separate machine. After this, the ends of the wires are stripped to expose the metal of the wires, which are fitted with any required terminals and/or connector housings. The cables are assembled and clamped together on a special workbench or to a pin board (according to design specification) to form the cable harness. After fitting any protective sleeves, conduit, the harness is either fitted directly in the vehicle or shipped. In spite of increasing automation, in general, cable harnesses continue to be manufactured by hand, and this will likely remain the case for the immediate future. This is due in part to the many different processes involved, which are clearly difficult to automate. Nevertheless, these processes can be learned relatively quickly, even without professional qualifications. **Figure F.16-1** shows the process for manufacturing some different types of wire, from raw metal compounds to solid and braded wire with or without shielding.

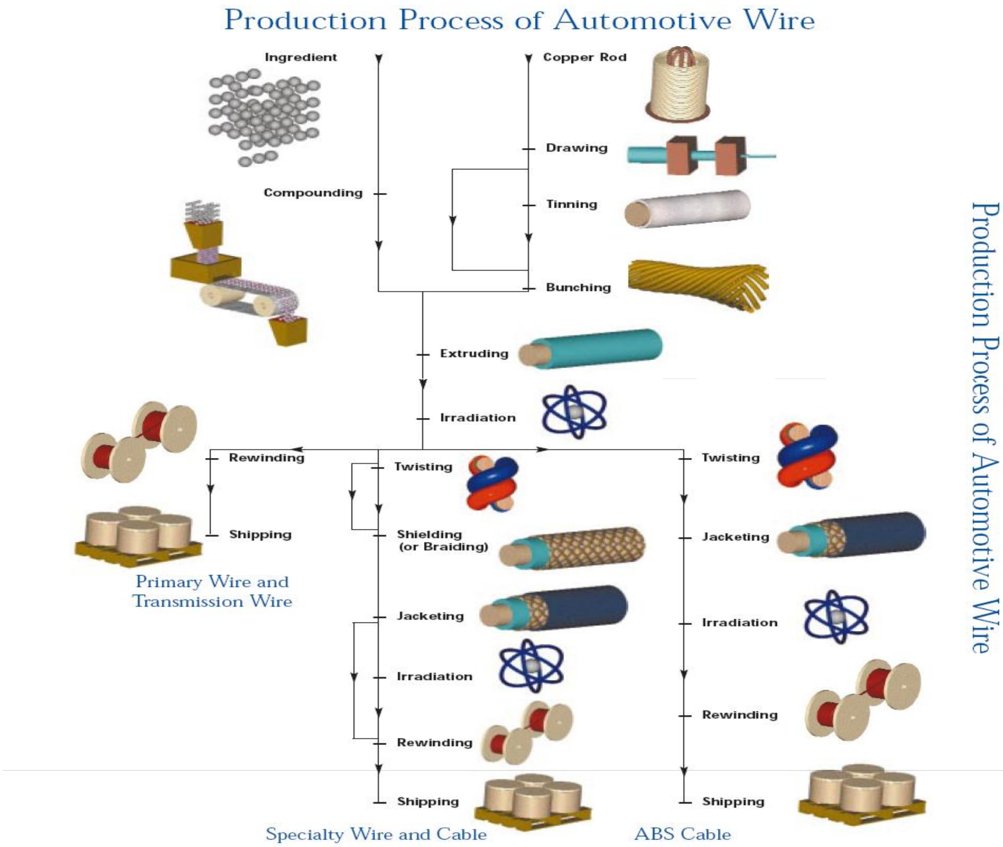


Figure F.16-1: Production Process of Automotive Wire

The Electrical Distribution and Electronic Control system is made up of the Electrical Wiring and Circuit Protection subsystem. As shown in **Table F.16-1**, this makes up the total system.

System	Subsystem	Sub-Subsystem	Description	System & Subsystem Mass "kg"
18	00	00	Electrical Distribution and Electronic Control System	
18	01	00	Electrical Wiring and Circuit Protection Subsystem	23.944
			Total System Mass =	23.944
			Total Vehicle Mass =	1711
			System Mass Contribution Relative to Vehicle =	1.40%

Table F.16-1: Mass Breakdown by Subsystem for Electrical System.

Electrical Wiring and Circuit Protection system (**Table F.16-2**).

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction Idea: Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Subsys./ Subsys. Mass Reduction "%"	Vehicle Mass Reduction "%"
18	00	00	Electrical Dis. and Electronic Control System						
18	01	00	Electrical Wiring and Circuit Protection Subsystem	A	0.889	$1.47	$1.66	3.71%	0.05%
				A	0.889 (Decrease)	$1.47 (Decrease)	$1.66 (Decrease)	3.71%	0.05%

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table 5.16-2: Mass-Reduction and Cost Impact for Electrical System

F.16.1 Electrical Wiring and Circuit Protection Subsystem

F.16.1.1 Subsystem Content Overview

Image F.16-3 shows the structure of the subsystem Electrical Wiring and Circuit Protection. The included sub-subsystems, Front End and Engine Compartment Wiring, Instrument Panel Harness, Body and Rear End Wiring, Battery Cables, Engine and Transmission Wiring and Seat Harness. **Image F.16-1** shows an instrument panel wiring harness.

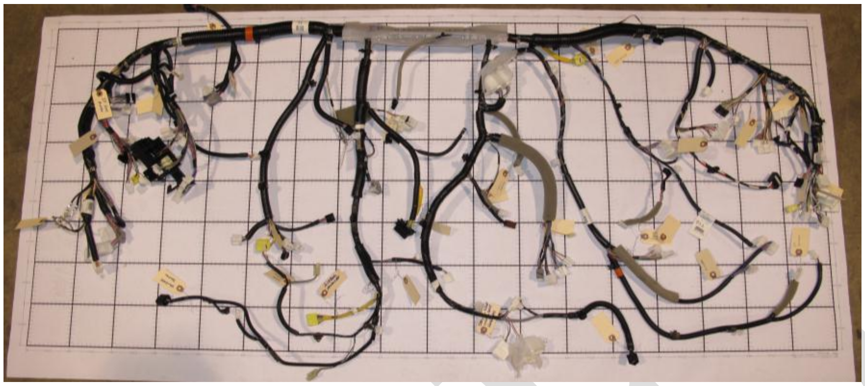


Image F.16-1: Instrument Panel Wiring Harness

(Source: FEV, Inc. Photo)

The most significant contributor to the mass of the Electrical Wiring and Circuit Protection subsystem is the Front End and Engine Compartment Wiring sub-subsystem at 7.525kg. **Table F.16-3** shows the mass contribution of all included sub-subsystems.

System	Subsystem	Sub-Subsystem	Description	Subsystem & Sub-subsystem Mass "kg"
18	**01**	**00**	**Electrical Wiring and Circuit Protection Subsystem**	
18	01	01	Front End and Engine Compartment Wiring	7.525
18	01	02	Instrument Panel Harness	6.133
18	01	03	Body and Rear End Wiring	6.599
18	01	04	Battery Cables	0.682
18	01	05	Engine and Transmission Wiring	2.671
18	01	06	Seat Harness	0.333
			Total Subsystem Mass =	**23.944**
			Total System Mass =	**23.944**
			Total Vehicle Mass =	**1711**
			Subsystem Mass Contribution Relative to System =	**100.00%**
			Subsystem Mass Contribution Relative to Vehicle =	**1.40%**

Table F.16-3: Mass Breakdown by Sub-subsystem for Electrical Wring and Circuit Protection Subsystem

F.16.1.2 Toyota Venza Baseline Subsystem Technology

The Toyota Venza's electrical systems follow an industry norm with copper wire contained in PVC insulation. Wire gauge sizes are optimized for current capacities.

F.16.1.3 Mass-Reduction Industry Trends

Industry trends for automotive wiring systems allow for a variety for wire and wire sheathing options. The wire compositions come in many combinations, annealed bare copper, silver tin and nickel-plated copper, copper clad steel, copper clad aluminum, copper clad magnesium, stranded, single core and flat cables. Reviewing today's market options, each wire type is found to have its different pros and cons. For this study, cost and weight were the most closely examined in order to determine the final selection for mass weight reduction.

Wire sheathing used since the 1970s has been mostly PVC. With new PPO and PPE polymers, however, insulation manufactures are making improvements in wire sheathing cost, weight, and the recyclability.

F.16.1.4 Summary of Mass-Reduction Concepts Considered

The many aspects and variety of new concepts for automotive wiring can be debated for hours to determine the best way forward. For this study, all the previously mentioned concepts were reviewed and given consideration with three key areas in mind: cost, weight, and recycling capability. Companies such as Delphi, Sumitomo, and Leoni produce large amounts of automotive wiring and are moving toward providing new products such as copper-clad aluminum and aluminum wire. Each wiring has respective advantages and disadvantages relating to usage and manufacturing processes, with weight a hot-button issue. As this relates directly to increasing mileage, more OEMs and suppliers are thinking outside the box. Sumitomo has developed an aluminum wire harness being used in the 2011 Toyota Yaris.

Some of the ideas evaluated, but not considered, included: flexible printed circuit, extruded flat wire, replacing wiring troughs where applicable with BIW, replacing copper conductors with copper-coated aluminum (CCA) conductors, replacing stamped module housings with conductive plastics and/or plating for EMI, eliminating or reducing empty connector cavities, replacing low current and signal wires with copper magnesium

(CuMg) alloy conductors, replacing signal leads with Brass FLRMSY conductors, and using a fiber optic network. The summary of mass-reduction technologies considered is detailed in **Table F.16-4**.

Component/Assembly	Mass-Reduction Idea	Estimated Impact	Risks & Trade-offs and/or Benefits
All Harness's	PPO Coating	20 to 30% Mass Reduction	Lower material and processing cost
All Harness's	Copper Clad Aluminum-CCA Wire	20 to 30% Mass Reduction	Lower material cost and processing needed for connection issue
All Harness's	Aluminum Wire	20 to 30% Mass Reduction	Lower material cost and processing needed for connection issue
Eng Harness Cable Trays	MuCell® gas foaming process for non-class "A" surfaces	10% Mass Reduction	Added capital, lower material usage, faster cycle time, smaller press size
Eng Harness Brkts	From Steel to Composite	10 to 25% Mass Reduction	Lower material and processing cost

Table F.16-4: Summary of mass-reduction concepts initially considered for the Electrical Wring and Circuit Protection Subsystem

F.16.1.5 Selection of Mass Reduction Ideas

Following the review of today's market innovations and trends, FEV has opted to use 8000 series aluminum wire for the battery ground cables & ground strap, this is not claded wire but aluminum only wire, and use GE PPO sheathing on all wire harnesses. With these two methods a significant weight and cost savings can be achieved.

Image F.16-2: Aluminum Stranded wire

(Source: Google Images)

There continue to be some issues with using aluminum wiring, of which aluminum oxidation, coefficient of expansion, creep, and lack of North American aluminum wire production are the most common. With the use of newer aluminum alloys, however, these concerns are likely mitigated to the point that the commercial use of aluminum wire for automotive applications is under consideration with several OEM's.

An approximately 60% increase in cross-section for aluminum wire is required to provide the equivalent conductivity provided by a copper conductor it would replace, the weight reduction is still about a third.

Engineers at BMW, in conjunction with the University of Munich (TUM), are working to find solutions for a number of challenges using aluminum; not just for conventional autos, but for electric vehicle (EV) applications where current demands and temperatures command a robust electrical control system.

The BMW/TUM team is devoting considerable work into connection boundaries and developing innovative solutions that it believes will provide reliable wiring configurations over a minimum 10-year vehicle life span. The Sumitomo Group developed a light-weight wiring harness using thin aluminum wires with twisted wire structures to ensure electrical connection reliability. It is probable that automotive wiring will become a major driver of aluminum consumption in the years ahead.

If aluminum wire was able to be used today for this study and could be applied to all the wiring harnesses, an approximate additional weight savings of 5.7kgs and a cost savings of approx $44, or $7.8 per kg, could be achieved.

Wire sheathing is another area in which automotive wire affect cost and weight. Polyvinyl chloride (PVC) is a thermoplastic polymer that is the most commonly used wire sheathing today. The advantages of using PVC are that it is inexpensive and effective. Heat, however, is an issue with PVC. PVC can only be used in 60% of automotive wiring harness applications. For high heat areas, such as the engine compartment, cross-linked polyethylene is used. PVC and cross-linked polyethylene both have environmental drawbacks as well, such as toxic halogens that can cause dioxin release and recycling issues. New products being developed by polymer manufactures such as GE will be the next generation of wire sheathing. GE has developed a PPO product that is thinner, lighter, and stronger than PVC – plus, it is recyclable.

The PPO coating is a GE Advanced Material Based on GE's polyphenylene oxide (PPO) and an olefin. This new Flexible Noryl wire coating lacks the halogens and the potential for dioxin release – which have given PVC a bad name. PPO coating has an inherent weight advantage when the two materials are used equally.

Based on this advantage, savings come from the ability to use less PPO to match or even beat the performance of PVC. For example, on wires up to 1.5 mm^2, Delphi would typically use a 0.4-mm-thick PVC coating to meet its customers' requirements. The corresponding PPO thickness, by contrast, would be just 0.2 mm. PPO offers 7 to 10 times more pinch and abrasion resistance than an equal thickness of PVC. Plus, PPO, which has a glass transition temperature of 212 C, has already passed the industry's 110 C thermal tests for Class B wire. The confidence is that the material will soon pass 125 C tests as well.

The PPO weight advantage over PVC makes a strong case for its use in reducing the weight in wiring harnesses. The greater savings come from the better performance of PPO versus PVC. PPO, being thinner, reduces the overall size of the wire by 25%. This also reduces the harness bundle size.

Other technologies selected for wiring harness cable trays were Trexel's MuCell® Microcellular Foam Process. The MuCell® Microcellular Foam Technology brings significant weight reduction, energy reduction, and greenhouse gas emission benefits to a wide range of packaging products and applications produced by any of the three major manufacturing processes (injection molding, extrusion and extrusion blow molding). Microcellular foaming technology was originally conceptualized and invented at the Massachusetts Institute of Technology (MIT). The technologies used are listed in **Table F.16-5**.

System	Subsystem	Sub-Subsystem	Subsystem Sub-Subsystem Description	Mass-Reduction Ideas Selected for Detail Evaluation
18	01	00	**Interior Trim and Ornamentation Subsystem**	Aluminum wire for ground strap & battery ground cables
				GE™ PPO Sheathing
				Steel Brkts to Composite
				MuCell® composite brkts

Table F.16-5: Mass-Reduction Ideas Selected for Electrical Wring and Circuit Protection Subsystem

F.16.1.6 Mass-Reduction & Cost Impact

Table 5.16-6 shows the weight and cost reductions per sub-subsystem.

In the Front End and Engine Compartment Wiring sub-subsystem, the Front End/Engine Harness's PVC sheath was replaced with GE™ PPO. The cable tray brackets and the fuse box were lightened using MuCell®. The kg breakdown and cost per part for the Front End and Engine Compartment Wiring sub-subsystem is as follows:

	mass	cost
Front End/Engine Harness	0.099	(0.051)
Cable Tray #1	0.016	0.066
Cable Tray #2	0.006	0.030
Cable Tray #3	0.005	0.023
Cable Tray #4	0.007	0.025
Fuse Box	0.150	0.367
Front End and Engine Compartment Wiring - Sub total>	**0.283**	**0.461**

In the Instrument Panel Harness sub-subsystem, the IP Wiring Main Harness, IP Wiring Sub Harness B, IP Wiring #1 and IP Wiring #2 PVC sheathing was replaced with GE™ PPO. The main connector box and connector box harness brackets were lightened using MuCell®. The kg breakdown and cost per part for the Instrument Panel Harness sub-subsystem is as follows:

	mass	cost
IP Wiring Main Harness	0.064	(0.032)
IP Wiring Sub Harness B	0.021	(0.011)
IP Wiring #1	0.001	(0.000)
IP Wiring #2	0.002	(0.001)
Main connector box, Top, IP Wiring	0.003	0.019
Main connector box, Bottom, IP Wiring	0.007	0.027
Connector Box 1,Harness, IP	0.007	0.040
Connector Box 2,Harness, IP	0.003	0.009
Connector Box 3,Harness, IP	0.002	0.007
Instrument Panel Harness - Sub total>	**0.110**	**0.058**

In the Body and Rear End Wiring sub-subsystem, all the harness wiring PVC sheathing was replaced with GE™ PPO. The kg breakdown and cost per part for the Body and Rear End Wiring sub-subsystem is as follows:

	mass	cost
Harness Asm, Body Interior	0.103	(0.053)
Liftgate Harness #1	0.001	(0.001)
Liftgate Harness #2	0.006	(0.003)
Harness, LF Door	0.003	(0.001)
Harness, RF Door	0.006	(0.002)
Harness, RR Door	0.001	(0.000)
Harness, LR Door	0.002	(0.001)
HVAC Door Motor Harness	0.001	0.000
Body and Rear End Wiring - Sub total>	**0.123**	**(0.062)**

In the Battery Cables sub-subsystem, all the harness wiring PVC sheathing was replaced with GE™ PPO. Also the Battery Ground Cable is made of aluminum. The kg breakdown and cost per part for the Battery Cables sub-subsystem is as follows:

	mass	cost
Harness, Battery Ground Cable	0.100	0.698
Battery to starter	0.120	(0.001)
Battery Cables - Sub total>	**0.220**	**0.697**

In the Harness Assembly sub-subsystem, the engine harness wiring PVC sheathing was replaced with GE™ PPO. The cable tray brackets were lightened using MuCell®. The harness brackets were changed from steel to PA66 plastic and then MuCelled. Below shows the kg break down and cost per part for the Engine and Transmission Wiring sub-subsystem.

	mass	cost
Harness Asm, Engine	0.043	(0.022)
Cable Tray #1, Engine	0.015	0.055
Cable Tray #2, Engine	0.004	0.022
Cable Support, Harness	0.003	0.019
Bracket #1, Harness, Engine	0.041	0.141
Bracket #2, Harness, Engine	0.027	0.047
Bracket #3, Harness, Engine	0.011	0.007
Engine and Transmission Wiring - Sub total>	**0.143**	**0.269**

In the Seat Harness sub-subsystem, the harness wiring PVC sheathing was replaced with GE™ PPO. Also, the Ground Strap is made of aluminum. The kg breakdown and cost per part for the Seat Harness sub-subsystem is as follows:

	mass	cost
Harness Weight Sensing RF Seat	0.001	(0.001)
Ground Strap	0.008	0.053
Seat Harness - Sub total>	**0.009**	**0.052**

In total, the Electrical Wiring and Circuit Protection subsystem mass savings combining all of the sub-subsystems is .889kg with a cost savings of $1.47

				Net Value of Mass Reduction Idea					
System	Subsystem	Sub-Subsystem	Description	Idea Level Select	Mass Reduction "kg" (1)	Cost Impact "$" (2)	Average Cost/ Kilogram $/kg	Sub-Subs./ Sub-Subs. Mass Reduction "%"	Vehicle Mass Reduction "%"
18	**01**	**00**	**Electrical Wiring and Circuit Protect Subsystem**						
18	01	01	Front End and Engine Compartment Wiring	A	0.283	$0.46	$1.63	3.77%	0.02%
18	01	02	Instrument Panel Harness	A	0.110	$0.06	$0.52	1.79%	0.01%
18	01	03	Body and Rear End Wiring	B	0.123	-$0.06	-$0.50	1.86%	0.01%
18	01	04	Battery Cables	A	0.220	$0.70	$3.17	32.27%	0.01%
18	01	05	Engine and Transmission Wiring	A	0.143	$0.27	$1.87	5.37%	0.01%
18	01	06	Seat Harness	A	0.009	$0.05	$5.73	2.70%	0.00%
				A	**0.889** (Decrease)	**$1.47** (Decrease)	**$1.66** (Decrease)	**3.71%**	**0.05%**

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

Table F.16-6: Sub-Subsystem Mass-Reduction and Cost Impact for Electrical Wring and Circuit Protection Subsystem

F.17 Vehicle Systems Overview and Results

F.18 Comparison of Results

G. Conclusions & Recommendation

H. Appendix

This appendix contains the selected supporting figures and tables used in the cost analyses. The section is structured in the following manner:

- Appendix H.1: Main Sections of Manufacturing Assumption and Quote Summary Worksheet
- Appendix H.2: Executive Summary for the Phase 1 report "An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Program" submitted to the Internal Council on Clean Transportation, by Lotus Engineering (March 2010)
- Appendix H.3: List of Light-Duty Vehicle Mass-Reduction Published Articles, Papers, and Journals Used as Information Sources in the Analysis
- Appendix H.4: EPA Toyota Venza Cost Analysis Breakdown
- Appendix H.5: Suppliers Contributed in Study

H.1 Main Sections of Manufacturing Assumption and Quote Summary Worksheet

The MAQS worksheet, as shown in Error! Reference source not found. and **Figure H-2**, contains seven (7) major sections. At the top of every MAQS worksheet is an information header ***(Section A)***, which captures the basic project details along with the primary quote assumptions. The project detail section references the MAQS worksheet back to the applicable CBOM. The primary quote assumption section provides the basic information needed to put together a quote for a component/assembly. Some of the parameters in the quote assumption section are automatically referenced/linked throughout the MAQS worksheet, such as capacity planning volumes, product life span, and OEM/T1 classification. The remaining parameters in this section including facility locations, shipping methods, packing specifications, and component quote level are manually considered for certain calculations.

Two (2) parameters above whose functions perhaps are not so evident from their names are the “OEM/T1 classification” and “component quote level.”

The “OEM/T1 classification” parameter addresses who is taking the lead on manufacturing the end-item component, the OEM or Tier 1 supplier. Also captured is the OEM or Tier 1 level, as defined by size, complexity, and expertise level. The value entered into the cell is linked to the Mark-up Database, which will up-load the corresponding mark-up values from the database into the MAQS worksheet. For example, if “T1 High Assembly Complexity” is entered in the input cell, the following values for mark-up are pulled into the worksheet: Scrap = 0.70%, SG&A = 7%, Profit = 8.0% and ED&T = 4%. These rates are then multiplied by the TMC at the bottom of the MAQS worksheet to calculate the applied mark-up as shown in **Figure H-H-2**.

The process for selecting the classification of the lead manufacturing site (OEM or T1) and corresponding complexity (e.g., High Assembly Complexity, Moderate Assembly Complexity, Low Assembly Complexity) is based on the team’s knowledge of existing value chains for same or similar type components.

Figure H 1: Sample MAQS Costing Worksheet (Part 1 of 2)

FEV

SECTION A

Technology Level:	Downsized, Turbocharged, Gasoline Direct Inject (GDI) Engine/ Compact Vehicle Class	OEM Operating Pattern (Weeks/Year):	47
Vehicle Class:	Compact/Economy 2-4 Passenger	Annual Engine Volume (CPV):	450,000
Study Case#:	N0101 (N = New, 01 = Technology Package, 01 = Vehicle Class)	Components per Engine:	4
System Description:	2007 Mini Cooper S. 1.6L I4, 16V DOHC GDI Turbo	Annual Component Volume:	1,800,000
Component Description:	Fuel Injector Assembly - Solenoid, 7 Hole; Part Number: 1104-N0101-01	Weekly Component Volume:	38,298
Component Quote Level:	☑ Full Quote ☐ Modification Quote ☐ Differential Quote (Quote Summary includes	Estimated Product Life:	10

OEM Plant Location:	North America
Supplier Plant Location:	North America
OEM/T1 Classification:	T1 High Assembly Complexity
Shipping Method:	FOB Ship Point
Packaging Specification:	Returnable Container & Internal Dunnage

GENERAL COMPONENT INFORMATION / GENERAL MANUFACTURING INFORMATION

Reference #	Part Description	Part Number	QTY Per Assembly	Primary Process Description	OEM/Supplier Classification	Material Specification	Labor Classification	Burden Classification
Tier 1 Supplier or OEM Processing & Assembly (Full Cost mapping)								
1A	Fuel Injector Assembly	1104-N0101-01	1	Final Assembly	T1 Assembly, Mark-up Applied @ Bottom.	Not Applicable	Electromechanical Assembly	Mech Assembly, LC, Base
2A	Seal Injector Tip	1104-N0101-01-30	1	Overmold seal @ Injector Tip	T1 Assembly, Mark-up Applied @ Bottom.	Nylon-HT, Inject.	Electromechanical Assembly	Mech Assembly, MC, Base
3A	Solenoid Body preassembled	1104-N0101-01-10	1	Insert Windings, Ring Locator a	T1 Assembly, Mark-up Applied @ Bottom.	Nylon66-40FMR, Inject.	Electromechanical Assembly	Mech Assembly, HC, Base
4A	Needle Body Assembly	1104-N0101-01-50	1	Laser weld internal valve body (	T1 Assembly, Mark-up Applied @ Bottom.	Not Applicable	Electromechanical Assembly	Mech Assembly, MC, Base
5A	Needle Assembly	1104-N0101-01-11	1	Assemble & Press Sleeve	T1 Assembly, Mark-up Applied @ Bottom.	Not Applicable	Electromechanical Assembly	Mech Assembly, MC, Base
6A	Needle Injector	1104-N0101-01-13	1	Laser Weld Ball and Seat to Needle	T1 Assembly, Mark-up Applied @ Bottom.	Not Applicable	Electromechanical Assembly	Mech Assembly, MC, Base
7A	Metering Valve assembly	1104-N0101-01-16	1	Laser Weld Plate to Valve	T1 Assembly, Mark-up Applied @ Bottom.	Not Applicable	Electromechanical Assembly	Mech Assembly, MC, Base
Purchase Part - High Impact Item (Full Cost Mapping)								
1A	Body Injector Solenoid	1104-N0101-01-20	1	Machine Body	T2/T3 CNC Turning, MSMC	S-Steel-440C, Bar	CNC Operator	CNC Turning, MC
2A	Sleeve winding to inlet separator	1104-N0101-01-27	1	Machine and Roll Splines	T2/T3 CNC Turning, MSMC	S-Steel-440C, Bar	CNC Operator	CNC Turning, MC
3A	Sleeve Fuel Inlet	1104-N0101-01-28	1	Machine	T2/T3 CNC Turning, MSMC	S-Steel-440C, Bar	CNC Operator	CNC Turning, MC
4A	Body needle	1104-N0101-01-9	1	Machine and Roll Splines	T2/T3 CNC Turning, MSMC	S-Steel-440C, Bar	CNC Operator	CNC Turning, MC
5A	Inlet Tube	1104-N0101-01-21	1	Cut and Flare	T2/T3 Hydro/CNC Form, SSLC	S-Steel-304, Tube	Forging Operator	Cold Forge, LMC
6A	Spring Seat Lower	1104-N0101-01-14	1	Machine	T2/T3 CNC Turning, MSMC	S-Steel-440C, Bar	CNC Operator	CNC Turning, MC
7A	Needle valve	1104-N0101-01-24	1	Centerless Grind	T2/T3 CNC Turning, MSMC	Not Applicable	CNC Operator	CNC Turning, MC
Purchase Part - Low Impact Item (Partial Cost Mapping = Processed Raw Material Estimate + Actual Component Assembly Process)								
Purchase Part - Commodity (Value taken from Purchase Part Database)								
1A	Solenoid Windings	1104-N0101-01-22	1		S			
2A	Ring winding locator	1104-N0101-01-26	1		S			
3A	Spring - needle to metering valve	1104-N0101-01-15	1		S			
4A	Spring Needle Return	1104-N0101-01-12	1		S			
5A	Sleeve Screen Stop	1104-N0101-01-25	1		S			
6A	Screen Fuel Inlet	1104-N0101-01-6	1		S			
7A	circlip face seal retainer	1104-N0101-01-5	1		S			
8A	Compression limiter - oring	1104-N0101-01-3	1		S			
			0					
			0					

SECTION B

MANUFACTURING RATES / MANUFACTURING COSTS / MARK-UP COSTS / TOTAL COSTS / TOOLING & INVESTMENT

Reference #	Finished Pieces Per Hour	Number of Operators	Number of Lines	Parallel Processing Multiplier	Material Usage "lbs"	Material Cost $/lb (DB)	Labor Rate $/Hour (DB)	Burden Rate $/Hour (DB)	Applied Burden Rate $/Hour	Material Cost	Labor/ Part	Burden/ Part	Total 1 = Material + Labor + Burden	End Item Scrap Rate (DB)	SG&A Rate (DB)	Profit Rate (DB)	ED&T/ R&D Rate (DB)	Total Mark-up Rate	Total Mark-up Cost	Total 2 = Total 1 + Total Mark-up	Total 3 = Total 2 * Qty per Ass'y	Tooling Assumptions "x1000"	Investment Assumptions "x1000"
Tier 1 Supplier or OEM Processing & Assembly (Full Cost mapping)																							
1A	480	2	1	6	0.000	$0.00	$37.35	$15.00	$90.00	$0.00	$0.16	$0.19	$0.34	0.00%	0.00%	0.00%	0.00%	0.00%	$0.00	$0.34	$0.34		
2A	450	1	1	1	0.005	$4.00	$37.35	$30.00	$30.00	$0.02	$0.08	$0.07	$0.17	0.00%	0.00%	0.00%	0.00%	0.00%	$0.00	$0.17	$0.17		
3A	450	2	1	5	0.030	$1.54	$37.35	$45.00	$225.00	$0.05	$0.17	$0.50	$0.71	0.00%	0.00%	0.00%	0.00%	0.00%	$0.00	$0.71	$0.71		
4A	450	4	1.5	8	0.000	$0.00	$37.35	$30.00	$360.00	$0.00	$0.33	$0.80	$1.13	0.00%	0.00%	0.00%	0.00%	0.00%	$0.00	$1.13	$1.13		
5A	450	1	1	4	0.000	$0.00	$37.35	$30.00	$120.00	$0.00	$0.08	$0.27	$0.35	0.00%	0.00%	0.00%	0.00%	0.00%	$0.00	$0.35	$0.35		
6A	514	1	1	3	0.000	$0.00	$37.35	$30.00	$90.00	$0.00	$0.07	$0.18	$0.25	0.00%	0.00%	0.00%	0.00%	0.00%	$0.00	$0.25	$0.25		
7A	514	1	1	2	0.000	$0.00	$37.35	$30.00	$60.00	$0.00	$0.07	$0.12	$0.19	0.00%	0.00%	0.00%	0.00%	0.00%	$0.00	$0.19	$0.19		
Purchase Part - High Impact Item (Full Cost Mapping)																							
1A	500	0.5	5	1	0.140	$4.56	$35.70	$45.00	$225.00	$0.64	$0.04	$0.45	$1.12	0.50%	6.50%	6.00%	1.00%	14.00%	$0.16	$1.28	$1.28		
2A	491	0.5	4.5	1	0.074	$4.56	$35.70	$45.00	$202.50	$0.34	$0.04	$0.41	$0.79	0.50%	6.50%	6.00%	1.00%	14.00%	$0.11	$0.90	$0.90		
3A	485	0.5	3.5	1	0.041	$4.56	$35.70	$45.00	$157.50	$0.19	$0.04	$0.33	$0.55	0.50%	6.50%	6.00%	1.00%	14.00%	$0.08	$0.63	$0.63		
4A	460	0.5	5.5	1	0.043	$4.56	$35.70	$45.00	$247.50	$0.20	$0.04	$0.54	$0.77	0.50%	6.50%	6.00%	1.00%	14.00%	$0.11	$0.88	$0.88		
5A	360	0.5	1	1	0.010	$1.65	$38.52	$100.09	$100.09	$0.02	$0.05	$0.28	$0.35	0.30%	6.00%	4.00%	0.00%	10.30%	$0.04	$0.38	$0.38		
6A	450	0.25	1.5	1	0.0002	$4.56	$35.70	$45.00	$67.50	$0.00	$0.02	$0.15	$0.17	0.50%	6.50%	6.00%	1.00%	14.00%	$0.02	$0.19	$0.19		
7A	540	0.25	1.5	1	0.000	$0.00	$35.70	$45.00	$67.50	$0.00	$0.02	$0.13	$0.14	0.50%	6.50%	6.00%	1.00%	14.00%	$0.02	$0.16	$0.16		
Purchase Part - Low Impact Item																							
Purchase Part - Commodity																			Supplier Account Cost	Purchase Price/ Unit	Purchase Price Net, PIA	Purchase Price Net, End Item		
1A																		$0.00	$0.25	$0.00	$0.25		
2A																		$0.00	$0.08	$0.00	$0.08		
3A																		$0.00	$0.01	$0.00	$0.01		
4A																		$0.00	$0.03	$0.00	$0.03		
5A																		$0.00	$0.01	$0.00	$0.01		
6A																		$0.00	$0.05	$0.00	$0.05		
7A																		$0.00	$0.02	$0.00	$0.02		
8A																		$0.00	$0.03	$0.00	$0.03		
																		$0.00	$0.00	$0.00	$0.00		
																		$0.00	$0.00	$0.00	$0.00		

"S"=Indicates Component is Supplied directly to T1 or OEM for Final or Sub-Assembly.

"SAC"=(Supplier Accounted Costs) Indicates Component is Supplied directly to T1 or OEM for Final or Sub-Assembly. In addition component material cost is accounted for in T1 quote sheet. Thus component cost will only be included for Mark-up Calculations.

"Alpha-Numeric Character" = Indicates purchase parts are brought in by T2/T3 Supplier for Subassembly.

SECTION F

	Material	Labor	Burden	TMC	Scrap	SG&A	Profit	ED&T	Total Mark-up		Total	Tooling	Investment
										1	$10.95		
T1 or OEM Total Manufacturing Cost:	$2.16	$1.47	$6.44	$10.07	$0.03	$0.41	$0.38	$0.06	$0.89	3	$10.95		
T1 or OEM Mark-Up Rates:	----	----	----	----	0.70%	7.00%	8.00%	4.00%	19.70%				
(SAC) &T1 or OEM Mark-Up Values:	0.00	----	----	----	$0.08	$0.77	$0.88	$0.44	$2.16				
Base Cost Impact to Vehicle:	$2.16	$1.47	$6.44	$10.07	$0.11	$1.18	$1.26	$0.50	$3.05		$13.11	$0	$0
										Packaging Cost:	$0.01		
										Net Cost Impact to Vehicle:	$13.13		

Figure H-H-1: Sample MAQS Costing Worksheet (Part 2 of 2)

Costs Broken Out Into Categories with Quantity per Assembly Taken into Account

Manufacturing Cost				Mark-up Cost				
Material	Labor	Burden	Total Mfg'ing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)
$0.00	$0.16	$0.19	$0.34	$0.00	$0.00	$0.00	$0.00	$0.00
$0.02	$0.08	$0.07	$0.17	$0.00	$0.00	$0.00	$0.00	$0.00
$0.05	$0.17	$0.50	$0.71	$0.00	$0.00	$0.00	$0.00	$0.00
$0.00	$0.33	$0.80	$1.13	$0.00	$0.00	$0.00	$0.00	$0.00
$0.00	$0.08	$0.27	$0.35	$0.00	$0.00	$0.00	$0.00	$0.00
$0.00	$0.07	$0.18	$0.25	$0.00	$0.00	$0.00	$0.00	$0.00
$0.00	$0.07	$0.12	$0.19	$0.00	$0.00	$0.00	$0.00	$0.00
$0.64	$0.04	$0.45	$1.12	$0.01	$0.07	$0.07	$0.01	$0.16
$0.34	$0.04	$0.41	$0.79	$0.00	$0.05	$0.05	$0.01	$0.11
$0.19	$0.04	$0.33	$0.55	$0.00	[illegible]	$0.03	$0.01	$0.08
$0.20	$0.04	$0.54	$0.77	$0.00	$0.05	$0.05	$0.01	$0.11
$0.02	$0.05	$0.28	$0.35	$0.00	$0.02	$0.01	$0.00	$0.04
$0.00	$0.02	$0.15	$0.17	$0.00	$0.01	$0.01	$0.00	$0.02
$0.00	$0.02	$0.13	$0.14	$0.00	$0.01	$0.01	$0.00	$0.02
$0.25			$0.25					
$0.08			$0.08					
$0.01			$0.01					
$0.03			$0.03					
$0.01			$0.01					
$0.05			$0.05					
$0.02			$0.02					
$0.03			$0.03					
$0.00			$0.00					
$0.00			$0.00					
Material	Labor	Burden	TMC	Scrape	SG&A	Profit	ED&T	Mark-up Total
$2.16	$1.47	$6.44	$10.07	$0.03	$0.41	$0.38	$0.06	$0.89
							2	$10.95

SECTION C

Notes:
a) Items 1,2, & 3 must all equal same value otherwise there is a computation error.

MANUFACTURING ASSUMPTIONS

Process Information	Projected Operating Pattern						Minimum Calculated Cycles Time					Project Process Requirement									
Process & Equipment Assumptions	Days/ Week	Shifts/ Day	Hrs./ Shift	Hrs./ Wk	Wks./ Yr.	Hrs./ Yr.	Pcs./ Hr. (100% Eff.)	Cycle Time/Operation "Sec."	Efficiency %	Pcs./ Hr. @ Stated Efficiency	Cycle Time/Operation @ Stated Efficiency "Sec."	Lean Design Calculation for Complete Process Time "Sec."	Parallel Operations/Machine or Stations/Line	Piece/Cycle/Machine	Tack Time/Machine/Cycle "Seconds"	Multiplier, If Required for Parallel Processing (1=Nothing)	Number of Equivalent Machines Required	Resulting Pieces/Hour	Resulting Cycle Time/ Part "Sec.	Total Number of Direct Operators
Semi Automated Line with Operator load and unload. St#1, Operator load injector assembly w. face seal., St#2, install circlip face seal, S#3Press Screen Stop and filter, S#4 Install Compression Limiter Oring and Oring Injector, S#5, Install Bracket Hold Down, S# 6Test & Label, #7 Operator Unload & Pack	5	2	10	100	47	4700	383	9.40	85%	451	7.99	-	7	2	15	6.0	1.0	480	7.50	2.00
Operator Load and Unload, Single Station, tip seal install and size.	5	2	10	100	47	4700	383	9.40	85%	451	7.99	-	1	2	16	1.0	1.0	450	8.00	1.00
Linear Transfer line feeding 2 Vertical Injection Press. Both 4 Cavities (2x2). Linear Transfer Line, St#1 Press Needle Body Assembly into Solenoid Body, St#2, Insert Coil and Ring Locator and Press Home, St#3 Load into Mold, ST# 4 Overmold., ST#5 Transfer to secondary overmold.	5	2	10	100	47	4700	383	9.40	85%	451	7.99	-	5	2	16	5.0	1.0	450	8.00	2.00
Automated Rotary Laser weld table with operator load assist and unload. S# 1 & 2 load pallet, S# 3 Fixture & Weld, S5 Fixture&Weld, S#6 Cool, S#7 Re-orientate, S#8 Insert Valve Assembly/Spring and Sleeve, S#9 Install Inlet Tube, S#10 laser Weld, S#11 Cool, Station 12 Test and Pack.	5	2	10	100	47	4700	383	9.40	85%	451	7.99	-	12	1	12	8.0	1.5	450	8.00	4.00
Semi automated load to pallet, automatic fixture and press. Operator assistance on load and unload.	5	2	10	100	47	4700	383	9.40	85%	451	7.99	32	4	1	8	4.0	1.0	450	8.00	1.00
Automated component feed and laser weld assembly station (load, fixture & clamp, weld#1, weld#2, unload)	5	2	10	100	47	4700	383	9.40	85%	451	7.99	21	3	1	7	3.0	1.0	514	7.00	1.00
Automated component feed and laser weld assembly station (load, fixture&clamp, weld, unload)	5	2	10	100	47	4700	383	9.40	85%	451	7.99	13	2	1	7.0	2.0	1.0	514	7.00	1.00
Multi Spindle CNC Turning Machine + Batch Wash	5	2	10	100	47	4700	383	9.40	85%	451	7.99	46	1	1	36	1.0	5.0	500	7.20	0.50
Multi Spindle CNC Turning Machine + Batch Wash	5	2	10	100	47	4700	383	9.40	85%	451	7.99	43	1	1	33	1.0	4.5	491	7.33	0.50
Multi Spindle CNC Turning Machine + Batch Wash	5	2	10	100	47	4700	383	9.40	85%	451	7.99	36	1	1	26	1.0	3.5	485	7.43	0.50
Multi Spindle CNC Turning Machine + Batch Wash	5	2	10	100	47	4700	383	9.40	85%	451	7.99	53	1	1	43	1.0	5.5	460	7.82	0.50
Cold Form Press with automated part handling	5	2	10	100	47	4700	383	9.40	85%	451	7.99	33	4	1	10	1.0	1.0	360	10.00	0.50
Automated CNC, Feed and Machine, Batch Wash	5	2	10	100	47	4700	383	9.40	85%	451	7.99	-	1	1	12	1.0	1.5	450	8.00	0.25
Hopper feed to centerless grinding	5	2	10	100	47	4700	383	9.40	85%	451	7.99	-	3	1	10	1.0	1.5	540	6.67	0.25

SECTION D

PACKAGING CALCULATIONS:
Packaging Type: Option #3 Tote, 42 Totes/Pallet
Part Size: 90x55x25 mm
Parts/Layer per tote: 3 x 8
Number of Layers per tote: 9

	Cost per Piece		Total Amount	Lump Sum Payment (%)	Total # of Pieces/ Amortization Period	Number of Service Months	Interest Rate		Cost per Pallet /Rack	Total Number of Pallets/ Racks Required	Number of Parts per Pallet/ Rack	Supplier, Customer and In-transit Inventory	Supplier, Customer and In-transit Inventory
Rack/Pallet Investment Amortization:	$0.014		$106,680	0.00%	9,000,000	60	5.00%		$4,180	26	9072	6	229787
	Cost per Piece		Tier Pad Price Per	Tier Pads Pallet/Rack	Divider Pads, Price Per	Divider Pads Pallet/Rack	Other #1 Packaging Price Per	Other #1 Pads Pallet/ Rack	Other #2 Packaging Price Per	Other #2 Pads Pallet/ Rack	Other #3 Packaging. Price Per	Other #3 Pads Pallet/ Rack	
Expendable Packaging in Piece Cost:	$0.00		$0.00	0	$0.00	0	$0.00	0	$0.00	0	$0.00	0	
Packaging Cost Total:	$0.014												

SECTION E

OEM Operating Pattern (Weeks/Year):	47	OEM Plant Location:	North America
Annual Engine Volume (CPV):	450,000	Supplier Plant Location:	North America
Components per Engine:	4	OEM/T1 Classification:	T1 High Assembly Complexity
Annual Component Volume:	1,800,000	Shipping Method:	FOB Ship Point
Weekly Component Volume:	38,298	Packaging Specification:	Returnable Container & Internal Dunnage
Estimated Product Life:	10		

TMC

	Material	Labor	Burden	TMC	Scrap	SG&A	Profit	ED&T	Total Mark-up		$10.95
T1 or OEM Total Manufacturing Cost:	$2.16	$1.47	$6.44	$10.07	$0.03	$0.41	$0.38	$0.06	$0.89		$10.95
T1 or OEM Mark-Up Rates:	-----	-----	-----	-----	0.70%	7.00%	8.00%	4.00%	19.70%		
(SAC) &T1 or OEM Mark-Up Values:	0.00	-----	-----	-----	$0.08	$0.77	$0.88	$0.44	$2.16		
Base Cost Impact to Vehicle:	$2.16	$1.47	$6.44	$10.07	$0.11	$1.18	$1.26	$0.50	$3.05		$13.11
										Packaging Cost:	$0.01
										Net Cost Impact to Vehicle:	$13.13

Figure H-H-2: Excerpt Illustrating Automated Link between OEM/T1 Classification Input in MAQS Worksheet and the Corresponding Mark-up Percentages Uploaded from the Mark-up Database

The “component quote level” identifies what level of detail is captured in the MAQS worksheet for a particular component/assembly, full quote, modification quote, or differential quote. When the “full quote” box is checked, it indicates all manufacturing costs are captured for the component/assembly. When the “modification quote” box is checked, it indicates only the changed portion of the component/assembly has been quoted. A differential quote is similar to a modification quote with the exception that information from both technology configurations, is brought into the same MAQS worksheet, and a differential analysis is conducted on the input cost attributes versus the output cost attributes. For example, if two (2) brake boosters (e.g., HEV booster and baseline vehicle booster) are being compared for cost, each brake booster can have its differences quoted in a separate MAQS worksheet (modification quote) and the total cost outputs for each can be subtracted to acquire the differential cost. Alternatively in a single MAQS worksheet the cost driving attributes for the differences between the booster’s (e.g., mass difference on common components, purchase component differences, etc.) can be offset, and the differential cost calculated in a single worksheet. The differential quote method is typically employed those components with low differential cost impact to help minimize the number of MAQS worksheets generated.

From left to right, the MAQS worksheet is broken into two (2) main sections as the name suggests, a quote summary ***(Section B)*** and manufacturing assumption section ***(Section D).*** The manufacturing assumption section, positioned to the right of the quote summary section, is where the additional assumptions and calculations are made to convert the serial processing operations from Lean Design® into mass production operations.

Calculations made in this section are automatically loaded into the quote summary section. The quote summary section utilizes this data along with other costing database data to calculate the total cost for each defined operation in the MAQS worksheet.

Note "defined operations" are all the value-added operations required to make a component or assembly. For example, a high pressure fuel injector may have twenty (20) base level components which all need to be assembled together. To manufacture one (1) of the base level components there may be as many as two (2) or three (3) value-added process operations (e.g., cast, heat treat, machine). In the MAQS worksheet each of these process operations has an individual line summarizing the manufacturing assumptions and costs for the defined operation. For a case with two (2) defined operations per base level component, plus two (2) subassembly and final assembly operations, there could be as many as forty (40) defined operations detailed out in the MAQS worksheet. For ease of viewing all the costs associated with a part, with multiple value-added operations, the operations are grouped together in the MAQS worksheet.

Commodity based purchased parts are also included as a separate line code in the MAQS worksheet. Although there are no supporting manufacturing assumptions and/or calculations required since the costs are provided as total costs.

From top to bottom, the MAQS worksheet is divided into four (4) quoting levels in which both the value-added operations and commodity-based purchase parts are grouped: (1) Tier 1 Supplier or OEM Processing and Assembly, (2) Purchase Part – High Impact Items, (3) Purchase Part – Low Impact Items, and (4) Purchase Part – Commodity. Each quoting level has different rules relative to what cost elements are applicable, how cost elements are binned, and how they are calculated.

Items listed in the ***Tier 1 Supplier or OEM Processing and Assembly*** section are all the assembly and subassembly manufacturing operations assumed to be performed at the main OEM or T1 manufacturing facility. Included in manufacturing operations would be any on-line attribute and/or variable product engineering characteristic checks. For this quote level, full and detailed cost analysis is performed (with the exception of mark-up which is applied to the TMC at the bottom of the worksheet).

Purchase Part – High Impact Items include all the operations assumed to be performed at Tier 2/3 (T2/3) supplier facilities and/or T1 internal supporting facilities. For this quote level detailed cost analysis is performed, including mark-up calculations for those components/operations considered to be supplied by T2/3 facilities. T1 internal supporting facilities included in this category do not include mark-up calculations. As mentioned above, the T1 mark-up (for main and supporting facilities) is applied to the TMC at the bottom of the worksheet.

Purchase Part – Low Impact Items are for *higher priced* commodity based items which need to have their manufacturing cost elements broken out and presented in the MAQS sheet similar to high impact purchase parts. If not, the material cost group in the MAQS worksheet may become distorted since commodity based purchase part costs are binned to material costs. ***Purchase Part – Commodity Parts*** are represented in the MAQS worksheet as a single cost and are binned to material costs.

At the bottom of the MAQS worksheet ***(Section F)***, all the value-added operations and commodity-based purchase part costs, recorded in the four (4) quote levels, are automatically added together to obtain the TMC. The applicable mark-up rates based on the T1 or OEM classification recorded in the MAQS header are then multiplied by the TMC to obtain the mark-up contribution. Adding the TMC and mark-up contribution together, a subtotal unit cost is calculated.

Important to note is that throughout the MAQS worksheet, all seven (7) cost element categories (material, labor, burden, scrap, SG&A, profit, and ED&T) are maintained in the analysis. ***Section C***, MAQS breakout calculator, which resides between the quote summary and manufacturing assumption sections, exists primarily for this function.

The last major section of the MAQS worksheet is the packaging calculation, ***Section E***. In this section of the MAQS worksheet a packaging cost contribution is calculated for each part based on considerations such as packaging requirements, pack densities, volume assumptions, stock, and/or transit lead times.

The sample packaging calculation (**Figure H-H-3**) is taken from the high voltage traction battery subsystem (140301 Battery Module MAQS worksheet, EPA Case Study #N0502). In this example, a minimum of two (2) weeks of packaging are required to support inventory and transit lead times. This equates to packaging for 19,149 parts over the two (2) weeks, based off the weekly capacity planning rates. There are 15 pieces per pallet at a packaging hardware cost of $575 per pallet (container and internal dunnage costs are from the Packaging Database). From this information, 1,277 pallet sets are required at $575/set, totaling $734,275 in packaging costs. Packaging is estimated to last thirty-six (36) months. Thus applying the amortization formula based on thirty-six (36) months, 5% interest, and 1.35 million parts/36 months yields $0.585/part. This cost is added to the subtotal unit cost (TMC + mark-up) to obtain the Total Unit Cost.

Note that in this case both the container and dunnage are assumed returnable. Thus, the bottom section of the packaging calculator is not used.

PACKAGING CALCULATIONS: Packaging Type: Option#2; Part Size: 1000x 300 x 140; Parts/Layer: 3; Number of Layers: 5 	Packaging Cost per Piece	Total Amount	Lump Sum Payment (%)	Total # of Pieces	Number of Months	Interest Rate		Cost per Pallet /Rack	Total Number of Pallets/ Racks Required	Number of Parts per Pallet/ Rack	Supplier, Customer and In-transit Inventory Requirements (Weeks)	Supplier, Customer and In-transit Inventory Requirements (Parts)
Rack/Pallet Investment Amortization:	$0.585	$734,275	0.00%	1,350,000	36	5.00%		$575	1277	15	2	19149
	Packaging Cost per Piece	Tier Pad Price Per	Tier Pads Pallet/Rack	Divider Pads, Price Per	Divider Pads Pallet/Rack	Other #1 Packaging Price Per	Other #1 Pads Pallet/Rack	Other #2 Packaging Price Per	Other #2 Pads Pallet/Rack	Other #3 Packaging, Price Per	Other #3 Pads Pallet/Rack	
Expendable Packaging in Piece Cost:	$0.00	$0.00	0	$0.00	0	$0.00	0	$0.00	0	$0.00	0	
Packaging Cost Total:	$0.585											

Figure H-H-3: Example of Packaging Cost Calculation for Base Battery Module

H.2 Executive Summary for Lotus Engineering Phase 1 Report

Following is the Executive Summary for the Phase 1 report, "An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Program," submitted to the Internal Council on Clean Transportation, by Lotus Engineering (March 2010).

1. Executive Summary

Introduction

The Energy Foundation funded Lotus Engineering to generate a technical paper which would identify potential mass reduction opportunities for a selected baseline vehicle representing the crossover utility segment. Lotus Engineering prepared this document in collaboration with a number of automotive and regulatory experts and submitted it to the ICCT. The 2009 Toyota Venza was selected as the baseline vehicle for evaluation although the materials, concepts and methodologies are applicable to other vehicle segments such as passenger cars and trucks. They could be further developed in separate studies for other applications. This study encompassed all vehicle systems, sub-systems and components. This study was divided into two categories, allowing two distinct vehicle architectures to be analyzed. The first vehicle architecture, titled the "Low Development" vehicle, targeted a 20% vehicle mass reduction (less powertrain), utilizing technologies feasible for a 2014 program start and 2017 production, was based on competitive benchmarking applying industry leading mass reducing technologies, improved materials, component integration and assembled using existing facilities. The second vehicle architecture, titled the "High Development" vehicle targeted a 40% vehicle mass reduction (less powertrain), targeted for 2017 technology readiness and 2020 production, utilized primarily non-ferrous materials, a high degree of component integration with advanced joining and assembly methodologies. Comparative piece costs were developed; indirect costs, including tooling and assembly plant architecture, were beyond the scope of this study. Both studies showed potential to meet their mass targets with minimal piece cost impact. Structural and impact analyses were beyond the scope of this study; these results could impact the mass and cost estimates. All powertrain related hardware studies were subject to a separate paper referenced herein.

Lotus Background
Lotus's guiding design philosophy for more than sixty years has been "Performance through Lightweight". Lotus design principles can be clearly demonstrated by a legacy of iconic product. The Lotus design approach facilitates highly efficient solutions by utilizing well integrated vehicle sub-systems and components, innovative use of materials and process and advanced analytical techniques. Lotus has significant experience in designing low and high volume wheeled transport for a global client base in addition to the engineering and manufacture of high performance Lotus products.

Methodology
A Toyota Venza was torn down and benchmarked to develop a comprehensive list of all components and their respective mass. A baseline Bill of Materials (BOM) was developed around nine major vehicle systems. The powertrain investigation and analysis were performed separately by the U.S. Environmental Protection Agency. This report analyzed the non-powertrain systems. These were divided into the following eight categories:

- Body structure
- Closures
- Front and rear bumpers
- Glazing
- Interior
- Chassis
- Air conditioning
- Electrical

The mass analysis considered engineering methodologies, materials, forming, joining, and assembly. Domestic and international trends in the automotive industry were analyzed, including motorsports. Emerging technologies in numerous non-automotive areas were also investigated, including aerospace, appliance, bicycle, watercraft, motorcycle, electrical and electronics, food container, consumer soft goods, office furniture as well as other sectors traditionally unrelated to the transportation industry. This synergistic approach provided a high level of flexibility in selecting feasible materials, processes, manufacturing and assembly methods.

The mass reductions were accomplished through increased modularization, replacing mild steel with lower mass materials including high strength steel (HSS), advanced high strength steel (AHSS), aluminum, magnesium along with increased utilization of composite materials and the application of emerging design concepts. In many cases, individual parts were eliminated through design integration. The overall approach for both the Low Development and the High Development vehicles was to be conservative relative to a production program, i.e., minimize the technical risk and the component costs for the targeted introduction dates.

Bill of Materials
Target Bill of Materials (BOMs) were created for tracking the mass and cost relative to the Venza.

The BOMs were separated into two categories:

- Low Development, which targeted technologies, manufacturing processes and assembly techniques estimated to be feasible in the 2014 time frame for 2017 MY production; and
- High Development, which targeted technologies, manufacturing processes and assembly techniques estimated to be feasible in the 2017 time frame for 2020 MY production.

Functional Objectives
The functional objectives were to maintain the 2009 Toyota Venza's utility/performance including interior room, storage volume, seating, NVH (Noise, Vibration, Harshness), weight/horsepower ratio, and driving range as well as compliance to current and near term federal regulations. The overall vehicle length was fixed. It was decided that the lightweight vehicle "footprint" (defined by the National Highway Traffic Safety Administration as wheelbase and track) be identical to the 2009 Toyota Venza for the 2017–2020 Low Development design. The wheelbase and track were increased for the High Development model for additional mass reduction and cost savings opportunities. Structural analysis, Federal Motor Vehicle Safety Standards and NCAP compliance verification of both architectures were beyond the scope of this study but may be accomplished in a future phase.

Results
Mass
The total vehicle mass savings (less powertrain) estimates are 21% (277 kg) for the 2017 production target Low Development vehicle and 38% (496 kg) for the 2020 production target High Development vehicle.

Cost
The Low Development vehicle piece cost (less powertrain) is projected to range from 92% to 104% with a nominal estimated value of 98%. The High Development vehicle piece cost (less powertrain) is projected to range from 97% to 109% with a nominal estimated value of 103%.

Both the baseline Venza component costs and the Low and High Development piece costs were estimated using supplier input, material costs and projected manufacturing costs. Metal prices were obtained from Intellicosting, a Detroit area based cost estimating firm experienced in pricing automotive components. Composite material prices were obtained from suppliers. The Venza estimated part costs served as the reference values to establish cost deltas. Current prices as of November, 2009 were used; no material cost projections were made for the 2017-2020 timeframe. The primary areas of focus, the body structure, closures, chassis/suspension and interior, represent approximately 84% of the vehicle non-powertrain cost for a front wheel drive, four cylinder crossover utility class vehicle (with an estimated cost range of +/- 6%). ER&D (Engineering, Research and Development) costs and assembly plant costs were defined to be the same as the current Venza costs although tooling and assembly plant costs could vary significantly depending on the manufacture.

Conclusion

This study indicates that a total vehicle, synergistic approach to mass reduction is feasible and could result in substantial mass savings with minimal piece cost impact.

Recommendations

Lotus recommends additional follow-up and independent studies to validate the materials, technologies and methods referenced in this report for the High and Low Development vehicles or possibly a combination. Many of the Low Development technologies are already used in production vehicle although not in a substantial manner. Additional studies regarding holistic vehicle mass reduction materials, methods and technologies in collaboration with automotive industry, component suppliers, manufacturing specialists, material experts, government agencies and other professional groups would support efforts of further understanding the feasibility, costs (both piece and manufacturing), limitations of this report.

1. A High and/or Low Development body in white (BIW) should be designed and analyzed for body stiffness, modal characteristics and for impact performance referencing the appropriate safety regulations (FMVSS and NCAP) for the time frame. This study should include mass and cost analysis, including tooling and piece cost.

2. High Development closures should be designed and analyzed further. This additional study should include front, rear and side impact performance as well as mass and cost analysis, including tooling and piece cost.

3. High and Low Development models of the chassis/suspension should be designed and analyzed. This study should include suspension geometry analysis, suspension loads, as well as a mass and cost analysis, including tooling and piece cost.

4. A High and Low Development interior model should be designed and analyzed for occupant packaging and head impact performance. This study should include a mass and cost analysis, including tooling and piece cost.

H.3 Light-Duty Vehicle Mass-Reduction Published Articles, Papers, and Journals Used as Information Sources in the Analysis

Applicable Model	Document Name	Publisher	Synopsis	Report Number	Publication Date	Hyperlink to Document
All	How do you reduce a vehicle's weight by 35%? The answer may be in the steel!	Auto123.com	Provides outlook in automotive industry that AHSS can provide weight reduction of up to 35% and that AHSS produces less greenhouse gases in manufacturing than aluminum.		August 2008	http://www.auto123.com/en/news/car-news/how-do-you-reduce-a-vehicles-weight-by-35-the-answer-may-be-in-the-steel?artid=100271
All	In bubble-filled plastic, Ford sees vehicle weight reduction	SmartPlanet	Describes Mucell, an overview of how the process works, who developed it, and what company owns it.		April 2011	http://www.smartplanet.com/blog/smart-takes/in-bubble-filled-plastic-ford-sees-vehicle-weight-reduction/15303
All	Dynamic Vehicle Weight Reduction and Safety Enhancement	SAE International	Describes *Ultra Brake Rotors* which are a steel/aluminum composite that can reduce 40% of the rotor weight compared to traditional cast iron rotors.		April 2009	http://saepcmech.saejournals.org/content/1/1/1202.short
All	Mass Decompounding and Vehicle Lightweighting	Materials Science Forum	Provides description of ideas concerning reducing the mass of vehicles. Discusses the strategic use of lightweight materials and sheds light on the topic from a societal and industrial perspective.	Vols. 618-619	April 2009	http://www.scientific.net/MSF.618-619.411
All	EPA Optimization Model for Reducing Emissions of Greenhouse Gases from Automobiles (OMEGA)	EPA	EPA's OMEGA model is a free desktop computer application which estimates the technology cost for automobile manufacturers to achieve variable fleet-wide levels of vehicle greenhouse gas (GHG) emissions.	EPA-420-B-10-042	October 2010	http://www.epa.gov/oms/climate/models/420b10042.pdf
VW Golf V	Stiffness Relevance and Strength Relevance in Crash of Car Body Components	Aachen University & European Aluminium Association - ika	Higher material strength increases the specific energy absorption capability and the allowable strength. Hence, the application of materials with higher strength allows the reduction of the wall thickness of parts or components without decreasing the crash performance or the safety against plastic failure.	83440	May 2010	http://aluminumintransportation.org/downloads/Ika-Stiffness&CrashRelevance2010.pdf
All	Vehicle weight reduction	U.S. Congress	A series of letters written to Senators by professors and technical professionals regarding the affect that reducing vehicle weight has on driver safety.		June 2000	http://books.google.com/books?id=cT1BOgQ2Ys8C&pg=PA10944&lpg=PA10944&dq=vehicle+weight+reductions+studies&source=bl&ots=GM8UnpXcOl&sig=bZH2Fhvd-xrIGE1CV1CCl2fJbDc&hl=en&ei=eE_BTf3pIcj40gHYgqW3Cg&sa=X&oi=book_result&ct=result&resnum=8&ved=0CEAQ6AEwBzgy#v=o
All	An Assessment of Mass Reduction Opportunities for a 2017 – 2020 Model Year Vehicle Program	Lotus Engineering Inc.	This study was divided into two categories, allowing two distinct vehicle architectures to be analyzed. The first vehicle architecture, titled the "Low Development" vehicle, targeted a 20% vehicle mass reduction (less powertrain), utilizing technologies feasible for a 2014 program start and 2017 production, was based on competitive benchmarking applying industry leading mass reducing technologies, improved materials, component integration and assembled using existing facilities.	Rev 006A	March 2010	http://www.theicct.org/pubs/Mass_reduction_final_2010.pdf
All	Energy Materials Coordinating Committee (EMaCC)	U.S. Department of Energy Office of Science Office of Basic Energy Sciences Division of Materials Sciences and Engineering	Summary of DOE projects	Annual Technical Report	October 2004	http://www.er.doe.gov/bes/dms/publications/EMaCC/EMACC_Annual_Technical_Report_FY2003.pdf
All	Energy Materials Coordinating Committee (EMaCC)	U.S. Department of Energy Office of Science Office of Basic Energy Sciences Division of Materials Sciences and Engineering	Summary of DOE projects	Annual Technical Report	September 2006	http://www.er.doe.gov/bes/dms/publications/EMaCC/EMACC_Annual_Technical_Report_FY2005.pdf
All	2010 Annual Merit Review	U.S. Department of Energy	Peer Review of DOE technological ideas	Annual Technical Report	September 2010	http://www1.eere.energy.gov/vehiclesandfuels/pdfs/merit_review_2010/2010_amr.pdf
All	High Strength Weight Reduction Materials	Energy Efficiency and Renewable Energy Office of FreedomCAR and Vehicle Technologies Advanced Materials Technologies	Work has been focused on developing advanced materials and materials processing technologies that can be applied to a wide array of heavy vehicle body, chassis, and suspension components to achieve weight reduction.	FY2006	March 2006	http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/2006_hswr_report.pdf
All	The Invisible Difference™: Saflex Advanced Acoustic Glazing Technology Reduces Vehicle Weight	Solutia	Acoustic Glazing Technology Reduces Vehicle Weight	US Glass Magazine	2010	http://www.saflex.com/en/AutoReduceVehicleWeight.aspx
Mid-size cars	Can Aluminum Be an Economical Alternative to Steel?	JOM	Cost compareisions between Al and steel	53 (8)	2001	http://www.tms.org/pubs/journals/JOM/0108/Kelkar-0108.html
All	Alternative Materials Reinvent Car Manufacturing	Megan Dobransky	EcoPaXX, a bio-based, heat-resistant, high-performance engineering plastic that is both carbon-neutral and made from 70 percent renewable resources, was introduced by DSM, a Dutch chemical company, and will be on the market early next year. The hope is to use this plastic in the engine compartment, which is too hot for most bio-based plastics.	Article	December 2010	http://earth911.com/news/2010/12/08/alternative-materials-reinvent-car-manufacturing/
All	Economic Opportunities for Polymer Composite Design	Massachusetts Institute of Technology	study finds steel to no longer overwhelmingly dominate as the most cost-effective body material when considering potential advances in the polymer composite body-in-white design against the mild-grade steel body currently on the road.	MIT	2006	http://msl.mit.edu/pubs/working_papers/StratMatlsSelect.pdf
All	3M Weight Reduction ideas	3M	Weight reduction ideas in the headliner, BIW & Bumpers			http://solutions.3m.com/wps/portal/3M/en_EU/EU-Auto/Home/ExploreOur/Solutions/WeightReduction/
All	Specialized polyurethane foams	Energy Efficiency - issue of the Bridge	Reviews the use of polyurethane foam for filling the pillars	Vol. 39 Number 2	2009	http://www.nae.edu/Publications/Bridge/EnergyEfficiency14874/ImprovingEnergyEfficiencyintheChemicalIndustry.aspx
All	UltraLight Steel Auto Body Programme	Worldautosteel	An UltraLight Steel Auto Body (ULSAB) structure has been assembled, weighed and tested validating results from the concept phase of a global steel industry study. ULSAB has proven to be lightweight, structurally sound, safe, executable and affordable.	ULSAB		http://www.worldautosteel.org/Projects/ULSAB/Programme-engineering-report.aspx

Applicable Model	Document Name	Publisher	Synopsis	Report Number	Publication Date	Hyperlink to Document
All	CHAPTER V--NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION, DEPARTMENT OF TRANSPORTATION	NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION, DEPARTMENT OF TRANSPORTATION	This site has pdf files of safety standards for various systems.			http://www.access.gpo.gov/nara/cfr/waisidx/49cfr571.html
All	Web Sites for Information and Suppliers	Lear	Lears web site for Enhanced seating comfort using optimal foam chemistry They could be a supplier source for information			http://lear.com/en/seating/foam.aspx
All	Web Sites for Information and Suppliers	Lauren Manufacturing	This is just a reference for Seals and sealing technology, Supplier contact			http://www.lauren.com/Markets/VehicleTransportation
All	Quiet Steel® Body Panel Design with DAMPÒ - A Custom Preprocessor Utilizing MSC-PATRAN/NASTRAN	Material Sciences Corporation, Laminates and Composites	This site has an interesting material that would allow the removal of some of the sound insulation, just an interesting metal laminate that looks like it is being used.			http://www.mscsoftware.com/support/library/conf/auto00/p03700.pdf
All	Reinventing the (Forged) Wheel	Motor Trend	This site has some good numbers on weight reduction with Al Wheels by ALCOA			http://blogs.motortrend.com/reinventing-the-forged-wheel-2287.html
All	Web Sites for Information and Suppliers	Trexel	This is the home web site for the inventor of the Mucell Process and it is worth looking at the entire site.			http://www.trexel.com/injection-molding-solutions/evaluating-mucell.php
All	EPS Electric Power Steering	Vishay	Same as comments Potential source for information the PDF lists the electronic components used in the Electronic Power Steering (EPS) system.			http://www.vishay.com/applications/automotive/eps_electricpowersteering/
All	Web Sites for Information and Suppliers	Automotive Composites Alliance	This is a good source for information and technical documents on Automotive Composites.			http://www.autocomposites.org/resources/downloads.cfm
All	Web Sites for Information and Suppliers	BASF	This is a News Release from BASF- develops innovative structural technology for automotive seating this was referenced in the Lotus report			http://www2.basf.us/corporate/news_2009/news_release_2009_00506.shtml
All	Web Sites for Information and Suppliers	Faurecia	Faurecia was referenced in the Lotus report for seating technology			http://www.faurecia.com/expertise-innovation/Pages/Default.aspx
All	Johnson licenses LEAP to bring Steelcase chair technology to Johnson automotive seating products	Staff -- Interior Design	This is an older bit of information but it shows the progression of technolgy in seating if you look at this compaired to Faurecia today.		January 2003	http://www.interiordesign.net/article/475506-Johnson_licenses_LEAP_to_bring_Steelcase_chair_technology_to_Johnson_automotive_seating_products.php
All	Web Sites for Information and Suppliers	JCI	This is a good look at JCI's latest and new seat technology			http://www.johnsoncontrols.com/publish/us/en/products/automotive_experience/interiors/complete-seats.html
All	With Genus Concept Seat, Johnson Controls Team Delivers an Evolutionary Vision of the Future in Automotive Seating Advanced design from global seating leader sets new benchmarks for comfort, styling, functionality	Automotive Intelligence	More on JCI's composite seats			http://www.autointell.com/supplier/supplier_news/johnson-controls/johnson-controls_news-12-01-05.htm
Upper Class	Johnson Controls re3 Concept Car	MSN	This article talks about seating and some of the new dashboard technology needed to lower mass weight		January 2009	http://autoshow.autos.msn.com/autoshow/detroit2009/Article.aspx?cp-documentid=15947917
All	BASF Develops Innovative Structural Technology for Automotive Seating	ThomasNET	More on thermoplastic seats and some additional link to other seat companies and users. It has a contact name for BASF		October 2010	http://news.thomasnet.com/companystory/BASF-Develops-Innovative-Structural-Technology-for-Automotive-Seating-837829
All	Web Sites for Information and Suppliers	Autronic Plastics	Interesting site this company uses nano-resin plastics, could be a resource for information on advanced plastics			http://www.apisolution.com/plastic-injection-molding-capabilities.html
All	Electric Hydraulic Combi Brake	Continental	Site has a combination hyd-elect. braking system plus other products of interest.			http://www.conti-online.com/generator/www/de/en/continental/automotive/themes/passenger_cars/chassis_safety/ebs/ehc_brake/ehc_bremse_en.html
All	Web Sites for Information and Suppliers	DuPont	Very interesting metal/plastic claded material, I have made contact with the development manager and I hope to have him come and visit.			http://www2.dupont.com/Plastics/en_US/Uses_Applications/advanced_metal_replacement/MetaFuse.html
All	Ford Developing Nano Coatings to Reduce Vehicle Weight	Next Energy News	Article about Fords work on nano coatings for weight reduction		April 2008	http://www.nextenergynews.com/news1/next-energy-news4.18.08a.html
All	Survey of vehicle mass-reduction technology trends and prospects	Nic Lutsey El Monte, California	Great over all info on weight reduction		May 2010	http://www.arb.ca.gov/msprog/levprog/leviii/meetings/051810/lutsey_its_may18_final.pdf
All	Magnesium, Aluminum Will Play Big Role in Auto Weight Reduction	Design News	A good article with numbers on the weight savings of aluminum and magnesium		April 2008	http://www.designnews.com/article/13344-Magnesium_Aluminum_Will_Play_Big_Role_in_Auto_Weight_Reduction.php
All	Making Joints with Structural Adhesives	Welding Design & Fabrication	An older but good article on making joints with structural adhesives		October 2006	http://weldingdesign.com/processes/news/wdf_38771/
All	Technology developments in automotive composites	Reinforced Plastics	A very good read on Composites		November 2010	http://www.reinforcedplastics.com/view/13154/technology-developments-in-automotive-composites/
All	Web Sites for Information and Suppliers	KellySearch	Contact information on Woodbridge			http://automotive.kellysearch.com/profile/the+woodbridge+group/us/mi/troy/48084/900371790
All	Climate and Transportation Solutions: Findings from the 2009 Asilomar Conference on Transportation and Energy Policy	Institute of Transportation Studies University of California, Davis	Has a section on reducing vehicle weight by using alum. and composite materials on body and alternative tire tread design		2010	http://www.its.ucdavis.edu/events/2009book/Chapter11.pdf
All	Modeling Costs and Fuel Economy Benefits of Lightweighting Vehicle Closure Panels	MIT & GM	In-depth report on weight savings and cost analysis of BIW components and compares various solutions	SAE 2008-01-0370	October 2007	http://msl1.mit.edu/msl/pubs/docs/MontalboCostFEofLWSAE2008.pdf
All	Steel and Iron Technologies for Automotive Lightweighting	John M. DeCicco Environmental Defense	Provides info. on weight reducing materials mainly in the steel and iron industry		March 2005	http://www.bvsde.paho.org/bvsacd/cd30/steel.pdf
All	On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions	MIT	A generic report on the future of automotive technology. Ch. 3 has weight reduction information		July 2008	http://web.mit.edu/mitei/research/studies/documents/fueling-transportation/OTRin2035_MIT_July%202008.pdf
Pick-up Trucks	IMPACT Phase II - Study to Remove 25% of the Weight from a Pick-up Truck	SAE	Pick-up truck's weight succesfully reduced by 25%	SAE 2007-01-1727	April 2007	http://papers.sae.org/2007-01-1727
All	Benefit Analysis: Use of Aluminum Structures in Conjunction with Alternative Powertrain Technologies in Automobiles	The Aluminum Association	Study on aluminum vs. steel in automobiles. Mass and cost analysis including BIW and powertrain components		2008	http://aluminumintransportation.org/downloads/IBIS-Powertrain-Study.pdf
All	Multi-Path Transportation Futures Study: Vehicle Characterization and Scenario Analyses	Argonne National Laboratory	Large-scale breakdown of future vehicle technologies and costs	ANL/ESD/09-5	July 2009	http://www.transportation.anl.gov/pdfs/TA/613.PDF

Applicable Model	Document Name	Publisher	Synopsis	Report Number	Publication Date	Hyperlink to Document
All	Materials Crosscutting Research and Development	Oak Ridge National Laboratory	Cost analysis study on using Magneisum and Carbon-Fiber Composite to reduce vehicle weight		August 2008	http://www1.eere.energy.gov/vehiclesandfuels/pdfs/lm_08/12_materials_crosscutting_rd.pdf
All	Study finds aluminum can reduce vehicle body structure weight safely by up to 40%	Aluminum Association's Transportation Group (ATG)	Proposes that aluminum is the future for BIW components and will reduce weight up to 40%		May 2010	http://www.ongreen.com/news/study-finds-aluminum-can-reduce-vehicle-body-structure-weight-safely-40
Compact Car	Honda Insight	Wikipedia	Gives generic breakdown of Honda Insight and notes the contributors to its outstanding fuel economy		April 2011	http://en.wikipedia.org/wiki/Honda_Insight
Luxury Truck/Sedan	Optimizing Designs of Aluminum Suspension Components Using an Integrated Approach	SAE	Alcoa details aluminum alloys used in suspension components and their weight savings	SAE Paper 05M-2		http://www.alcoa.com/car_truck/en/pdf/SAE_paper.pdf
Mazda Miata	Flyin' Miata: Chassis: Suspension Components: Lightweight Lug Nut	Flyin' Miata	Site to buy aluminum conical lug nuts			http://www.flyinmiata.com/index.php?deptid=4537&parentid=0&stocknumber=16-10000
All	U.S. Brake Drag Race Brake Kits	JEGS	U.S. Brake sells drilled/slotted rotors and calipers made out of forged and billet aluminum			http://www.jegs.com/p/AFCO/US-Brake-Drag-Race-Brake-Kits/753026/10002/-1
All	Trelleborg Advances Light-Weight Brake Pedal using Water Injection Technology	Torque News	New process called Water Injection Technology allows brake pedal to be made out of hollow plastic		March 2011	http://www.torquenews.com/119/trelleborg-advances-light-weight-brake-pedal-using-water-injection-technology
BMW 5 series Gran Turismo 550i and 750i	Lightweight Components from ContiTech Win Innovation Prize	Continental ContiTech	Fiber-glass reinforced polyamide Transmission Beam		October 2010	http://www.contitech.de/pages/presse/pressemeldungen/2010/101027_spe/presse_en.html
Micro Cars	ZF carbon fiber damper concept for micro cars	World Car Fans	ZF developed a carbon fiber dampener (suspension) that reduces weight by 50% compared to aluminum		April 2010	http://www.worldcarfans.com/110041225610/zf-carbon-fiber-damper-concept-for-micro-cars
All	AMS/Wilwood EVO IV-IX Lightweight Brake Kit, Rear	AMS Performance	Two-part rear rotors/hats made out of aluminum			http://amsperformance.com/cart/AMS/Wilwood-Mitsubishi-Lancer-Evolution-Evo-4-5-6-7-8-9-Lightweight-Brake-Kit-(Rear).html
Ford Focus and Cadillac CTS	Spare Tire is History	Zimbio	Overviews the trend in the auto industry to not offer spare tires standard, but rather as an option		September 2007	http://www.zimbio.com/Safe+Driving/articles/14/Spare+Tire+Is+History
Luxury & Performance Cars	Wheel Lug Nuts Information	DriveWire	Aftermarket parts supplier that sells Mg & Al lug nuts			http://www.drivewire.com/part/wheels-and-tires/wheel-lug-nuts/
All	Review of technical literature and trends related to automobile mass-reduction technology	California Air Resources Board	Nic Lutsey wrote this extended summary of mass reduction trends	UCD-ITS-RR-10-10	May 2010	
Interior	Faurecia Light Attitude at the L.A. Auto Show	Faurecia	Press Kit that Faurecia released on their innovative Light Attitude line-up		November 2008	
All	InCar: The Innovative Solution Kit for the Automotive Industry	ThyssenKrupp	Literature from ThyseenKrupp with weight reduction ideas		October 2009	
Glazing	Reduce Vehicle Weight without Compromising Passenger Comfort	Solutia	Illustration and data on Safelx laminated glass		2010	

H.4 EPA Toyota Venza Cost Analysis Breakdown

Table A-1: Engine System Cost Breakdown

SYSTEM & SUBSYSTEM DESCRIPTION / **NEW TECHNOLOGY GENERAL PART INFORMATION:**

Item	System	Subsystem	Sub-Subsystem Description	Manufacturing: Material	Manufacturing: Labor	Manufacturing: Burden	Total Manufacturing Cost (Component/ Assembly)	Markup: End Item Scrap	Markup: SG&A	Markup: Profit	Markup: ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	01 Engine													
			01 System downsize (2.7L I4 to 2.4L I4)	441.58	-	-	441.58	-	-	-	-	-	-	441.58
1			02 Engine Frames, Mounting, and Brackets Subsystem	2.57	0.70	2.20	5.47	0.19	0.57	0.44	0.09	1.29	0	6.76
2			03 Crank Drive Subsystem	5.35	3.90	16.28	25.53	0.17	2.24	2.06	0.69	5.16	0	30.69
3			04 Counter Balance Subsystem (NA)	-	-	-	-	-	-	-	-	-	-	-
4			05 Cylinder Block Subsystem	85.10	9.40	45.08	139.58	1.43	7.75	5.54	1.27	15.98	0	155.56
5			06 Cylinder Head Subsystem	3.42	0.54	1.09	5.05	0.03	0.44	0.39	0.10	0.95	0	6.00
6			07 Valvetrain Subsystem	15.50	12.72	33.25	61.47	0.54	4.49	4.94	2.25	12.23	0	73.70
7			08 Timing Drive Subsystem	12.43	0.87	0.99	14.29	0.12	1.49	1.26	0.30	3.16	0	17.45
8			09 Accessory Drive Subsystem (NA)	-	-	-	-	-	-	-	-	-	-	-
9			10 Air Intake Subsystem	8.59	0.75	0.84	10.18	0.06	0.97	0.78	0.15	1.96	0	12.14
10			11 Fuel Induction Subsystem	0.66	0.05	0.04	0.74	0.00	0.08	0.05	0.01	0.14	0	0.89
11			12 Exhaust Subsystem	-	-	-	-	-	-	-	-	-	-	-
12			13 Lubrication Subsystem	1.01	0.19	0.14	1.33	0.01	0.15	0.14	0.04	0.35	0	1.69
13			14 Cooling Subsystem	35.12	12.06	22.46	69.64	0.52	4.76	4.02	1.31	10.62	0	80.25
14			15 Induction Air Charging Subsystem (NA)	-	-	-	-	-	-	-	-	-	-	-
15			16 Exhaust Gas Re-circulation Subsystem (NA)	-	-	-	-	-	-	-	-	-	-	-
16			17 Breather Subsystem	0.95	0.17	0.14	1.27	0.01	0.14	0.15	0.06	0.36	0	1.62
17			60 Engine Management, Engine Electronic, Electrical Subsystem	1.15	0.21	0.16	1.51	0.01	0.16	0.15	0.05	0.39	0	1.90
18			70 Accessory Subsystems (Start Motor, Generator, etc.)	1.25	0.38	1.18	2.81	0.10	0.29	0.31	0.12	0.82	0	3.63
			SUBSYSTEM ROLL-UP	614.67	41.94	123.85	780.47	3.21	23.52	20.24	6.43	53.40	0	833.86

SYSTEM & SUBSYSTEM DESCRIPTION / **BASE TECHNOLOGY GENERAL PART INFORMATION:**

Item	System	Subsystem	Sub-Subsystem Description	Manufacturing: Material	Manufacturing: Labor	Manufacturing: Burden	Total Manufacturing Cost (Component/ Assembly)	Markup: End Item Scrap	Markup: SG&A	Markup: Profit	Markup: ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	01 Engine													
			01 System downsize (2.7L I4 to 2.4L I4)	480.00	-	-	480.00	-	-	-	-	-	-	480.00
1			02 Engine Frames, Mounting, and Brackets Subsystem	2.76	0.86	1.91	5.52	0.12	0.58	0.39	0.05	1.15	0	6.67
2			03 Crank Drive Subsystem	7.00	5.38	18.70	31.07	0.21	2.88	2.58	0.82	6.49	0	37.57
3			04 Counter Balance Subsystem (NA)	-	-	-	-	-	-	-	-	-	-	-
4			05 Cylinder Block Subsystem	76.72	6.96	32.58	116.25	1.48	6.90	4.92	1.07	14.37	0	130.62
5			06 Cylinder Head Subsystem	9.57	1.65	4.92	16.15	0.58	1.60	1.36	0.35	3.89	0	20.04
6			07 Valvetrain Subsystem	18.53	7.44	24.00	49.97	1.13	4.59	4.90	1.98	12.60	0	62.57
7			08 Timing Drive Subsystem	7.39	2.55	7.08	17.02	0.83	2.09	1.69	0.60	5.22	0	22.24
8			09 Accessory Drive Subsystem (NA)	-	-	-	-	-	-	-	-	-	-	-
9			10 Air Intake Subsystem	9.04	1.60	2.06	12.70	0.16	1.16	0.95	0.18	2.45	0	15.15
10			11 Fuel Induction Subsystem	0.88	0.49	1.01	2.39	0.10	0.27	0.21	0.04	0.62	0	3.01
11			12 Exhaust Subsystem	-	-	-	-	-	-	-	-	-	-	-
12			13 Lubrication Subsystem	0.74	0.24	0.22	1.21	0.01	0.13	0.11	0.03	0.28	0	1.48
13			14 Cooling Subsystem	36.97	12.90	23.38	73.25	0.70	5.14	4.37	1.41	11.62	0	84.87
14			15 Induction Air Charging Subsystem (NA)	-	-	-	-	-	-	-	-	-	-	-
15			16 Exhaust Gas Re-circulation Subsystem (NA)	-	-	-	-	-	-	-	-	-	-	-
16			17 Breather Subsystem	1.56	0.87	2.51	4.94	0.18	0.59	0.62	0.23	1.62	0	6.56
17			60 Engine Management, Engine Electronic, Electrical Subsystem	1.26	0.74	0.29	2.29	0.02	0.26	0.24	0.08	0.61	0	2.90
18			70 Accessory Subsystems (Start Motor, Generator, etc.)	1.66	0.07	0.89	2.62	0.10	0.30	0.28	0.10	0.78	0	3.40
			SUBSYSTEM ROLL-UP	654.08	41.76	119.55	815.40	5.62	26.50	22.64	6.95	61.70	0	877.10

SYSTEM & SUBSYSTEM DESCRIPTION				INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE										
Item	System	Subsystem	Sub-Subsystem Description	Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D			
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	01 Engine													
		01	System downsize (2.7L I4 to 2.4L I4)	38.42	-	-	38.42	-	-	-	-	-	-	38.42
1		02	Engine Frames, Mounting, and Brackets Subsystem	0.19	0.16	(0.30)	0.05	(0.07)	0.01	(0.05)	(0.03)	(0.14)	0	(0.09)
2		03	Crank Drive Subsystem	1.64	1.48	2.42	5.54	0.04	0.64	0.52	0.13	1.34	0	6.88
3		04	Counter Balance Subsystem (NA)	-	-	-	-	-	-	-	-	-	-	-
4		05	Cylinder Block Subsystem	(8.38)	(2.44)	(12.50)	(23.32)	0.05	(0.85)	(0.62)	(0.19)	(1.61)	0	(24.93)
5		06	Cylinder Head Subsystem	6.16	1.11	3.83	11.10	0.54	1.17	0.98	0.25	2.94	0	14.04
6		07	Valvetrain Subsystem	3.03	(5.28)	(9.25)	(11.50)	0.58	0.09	(0.04)	(0.27)	0.37	0	(11.13)
7		08	Timing Drive Subsystem	(5.04)	1.68	6.09	2.73	0.72	0.61	0.43	0.30	2.06	0	4.79
8		09	Accessory Drive Subsystem (NA)	-	-	-	-	-	-	-	-	-	-	-
9		10	Air Intake Subsystem	0.45	0.85	1.22	2.52	0.10	0.19	0.17	0.03	0.49	0	3.01
10		11	Fuel Induction Subsystem	0.22	0.44	0.98	1.64	0.10	0.19	0.16	0.04	0.48	0	2.13
11		12	Exhaust Subsystem	-	-	-	-	-	-	-	-	-	-	-
12		13	Lubrication Subsystem	(0.26)	0.06	0.08	(0.13)	(0.00)	(0.02)	(0.03)	(0.02)	(0.07)	0	(0.20)
13		14	Cooling Subsystem	1.85	0.84	0.92	3.62	0.18	0.38	0.35	0.09	1.00	0	4.62
14		15	Induction Air Charging Subsystem (NA)	-	-	-	-	-	-	-	-	-	-	-
15		16	Exhaust Gas Re-circulation Subsystem (NA)	-	-	-	-	-	-	-	-	-	-	-
16		17	Breather Subsystem	0.61	0.69	2.37	3.67	0.17	0.45	0.47	0.17	1.26	0	4.93
17		60	Engine Management, Engine Electronic, Electrical Subsystem	0.11	0.53	0.13	0.78	0.01	0.10	0.09	0.03	0.22	0	1.00
18		70	Accessory Subsystems (Start Motor, Generator, etc.)	0.41	(0.31)	(0.30)	(0.19)	(0.00)	0.01	(0.02)	(0.02)	(0.04)	0	(0.23)
			SUBSYSTEM ROLL-UP	39.42	(0.18)	(4.30)	34.93	2.41	2.98	2.40	0.51	8.30	0	43.24

Table A-2: Transmission System Cost Breakdown

SYSTEM & SUBSYSTEM DESCRIPTION				NEW TECHNOLOGY GENERAL PART INFORMATION										
Item	System	Subsystem	Sub-Subsystem Description	Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D			
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	02		Transmission											
1		01	External Components	-	-	-	-	-	-	-	-	-	-	-
2		02	Case Sbsystem	69.87	-	-	69.87	0.18	3.51	2.34	0.59	6.61	0	76.48
3		03	Gear Train Subsystem	140.22	4.66	10.27	155.16	0.81	15.85	10.76	1.52	28.95	0	184.10
4		05	Launch Clutch Subsystem	11.14	2.25	10.49	23.87	0.77	2.76	2.39	0.56	6.48	0	30.35
5		06	OilPump and Filter Subsystem	2.35	-	-	2.35	0.11	0.28	0.25	0.06	0.70	0	3.05
6		07	Mechanical Controls Subsystem	-	-	-	-	-	-	-	-	-	-	-
7		08	Electriacl Controls Subsystem	-	-	-	-	-	-	-	-	-	-	-
8		09	Parking Mechanism Subsystem	-	-	-	-	-	-	-	-	-	-	-
9		20	Driver Operated External Controls Subsystem	37.68	12.56	12.56	62.80	0.33	6.58	4.39	0.57	11.87	0	74.67
			SUBSYSTEM ROLL-UP	261.26	19.48	33.32	314.05	2.20	28.98	20.12	3.30	54.61	0	368.66

SYSTEM & SUBSYSTEM DESCRIPTION				BASE TECHNOLOGY GENERAL PART INFORMATION										
Item	System	Subsystem	Sub-Subsystem Description	Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D			
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	02		Transmission											
1		01	External Components	-	-	-	-	-	-	-	-	-	-	-
2		02	Case Sbsystem	59.80	-	-	59.80	0.15	3.00	2.00	0.50	5.66	0	65.45
3		03	Gear Train Subsystem	42.78	4.02	10.03	56.83	0.22	3.98	2.81	0.59	7.59	0	64.42
4		05	Launch Clutch Subsystem	38.10	12.70	12.70	63.50	0.33	6.66	4.44	0.58	12.01	0	75.51
5		06	OilPump and Filter Subsystem	3.05	-	-	3.05	0.14	0.36	0.32	0.08	0.90	0	3.95
6		07	Mechanical Controls Subsystem	-	-	-	-	-	-	-	-	-	-	-
7		08	Electriacl Controls Subsystem	-	-	-	-	-	-	-	-	-	-	-
8		09	Parking Mechanism Subsystem	-	-	-	-	-	-	-	-	-	-	-
9		20	Driver Operated External Controls Subsystem	22.80	7.60	7.60	38.00	0.20	3.98	2.66	0.35	7.18	0	45.18
			SUBSYSTEM ROLL-UP	166.53	24.32	30.33	221.17	1.03	17.98	12.23	2.09	33.34	0	254.51

SYSTEM & SUBSYSTEM DESCRIPTION				INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE										
Item	System	Subsystem	Sub-Subsystem Description	Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D			
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	02		Transmission											
1		01	External Components	-	-	-	-	-	-	-	-	-	-	-
2		02	Case Sbsystem	(10.08)	-	-	(10.08)	(0.03)	(0.51)	(0.34)	(0.08)	(0.95)	0	(11.03)
3		03	Gear Train Subsystem	(97.44)	(0.65)	(0.24)	(98.33)	(0.60)	(11.88)	(7.95)	(0.93)	(21.35)	0	(119.68)
4		05	Launch Clutch Subsystem	26.96	10.45	2.21	39.63	(0.44)	3.90	2.05	0.02	5.53	0	45.16
5		06	OilPump and Filter Subsystem	0.69	-	-	0.69	0.03	0.08	0.07	0.02	0.21	0	0.90
6		07	Mechanical Controls Subsystem	-	-	-	-	-	-	-	-	-	-	-
7		08	Electriacl Controls Subsystem	-	-	-	-	-	-	-	-	-	-	-
8		09	Parking Mechanism Subsystem	-	-	-	-	-	-	-	-	-	-	-
9		20	Driver Operated External Controls Subsystem	(14.88)	(4.96)	(4.96)	(24.80)	(0.13)	(2.60)	(1.73)	(0.23)	(4.69)	0	(29.49)
			SUBSYSTEM ROLL-UP	(94.73)	4.84	(2.99)	(92.88)	(1.16)	(11.00)	(7.89)	(1.21)	(21.26)	0	(114.15)

Table A-3: Body System A Cost Breakdown

SYSTEM & SUBSYSTEM DESCRIPTION			NEW TECHNOLOGY GENERAL PART INFORMATION										
			Manufacturing				Markup						
Item	Subsystem	Sub-Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
			USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
		03 Body Subsystem											
3		01 Body Structure Subsystem	-	-	-	-	-	-	-	-	-	-	-
4		01 Front Floor	29.90	1.65	13.58	45.13	-	-	-	-	-	-	45.13
6		02 Body Dash and Cowl	-	-	-	-	-	-	-	-	-	-	-
6		03 Roof and Cross-Member	39.59	4.07	14.99	58.65	-	-	-	-	-	-	58.65
7		04 Body Side	289.37	33.81	154.64	477.82	-	-	-	-	-	-	477.82
8		05 Parcel Shelf and Cross-Vehicle Framing Parts	-	-	-	-	-	-	-	-	-	-	-
9		06 Cab Back & Ring Frame	-	-	-	-	-	-	-	-	-	-	-
10		07 Rear Wheel Arch Liners	2.32	0.11	0.72	3.15	0.02	0.35	0.28	0.06	0.70	-	3.85
11		08 One Piece Body Structure	-	-	-	-	-	-	-	-	-	-	-
12		10 Rear Floor	24.93	3.00	16.37	44.30	-	-	-	-	-	-	44.30
13		11 Fuel Filler and Flap	-	-	-	-	-	-	-	-	-	-	-
14		99 Misc. Under Ladder Assembly	143.75	28.20	137.32	309.27	-	-	-	-	-	-	309.27
15		02 Front End Subsystem	-	-	-	-	-	-	-	-	-	-	-
16		01 Front Structure	45.98	11.08	59.28	116.34	-	-	-	-	-	-	116.34
18		03 Front Fenders	31.76	0.44	5.35	37.55	-	-	-	-	-	-	37.55
19		04 Front Wheel Arch Liners	3.23	0.12	1.10	4.45	0.03	0.49	0.39	0.08	0.99	-	5.44
20		05 Hood BIW Panel	64.84	1.58	12.26	78.68	-	-	-	-	-	-	78.68
21		10 Under Engine Closures/Air Dams	4.76	0.18	0.34	5.28	0.04	0.58	0.46	0.09	1.17	-	6.45
22		08 Front End Module Carrier	10.28	3.31	17.03	30.62	-	-	-	-	-	-	30.62
23		99 Misc. - Compartment Extras (Al)	19.98	2.55	12.17	34.70	-	-	-	-	-	-	34.70
15		03 Body Closures Subsystem	-	-	-	-	-	-	-	-	-	-	-
16	x	03 Rear Closure BIW Panel	49.73	2.83	17.10	69.66	-	-	-	-	-	-	69.66
15		19 Bumpers Subsystem	-	-	-	-	-	-	-	-	-	-	-
16	x	01 Front Bumper Skin and Foams	19.71	0.63	4.35	24.69	-	-	-	-	-	-	24.69
		SUBSYSTEM ROLL-UP	780.13	93.56	466.60	1,340.29	0.02	0.35	0.28	0.06	0.70	-	1,343.15

SYSTEM & SUBSYSTEM DESCRIPTION			BASE TECHNOLOGY GENERAL PART INFORMATION										
			Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
Item	Subsystem	Sub-Subsystem Description	Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D			
			USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
		03 Body Subsystem											
3		01 Body Structure Subsystem	-	-	-	-	-	-	-	-	-	-	-
4		01 Front Floor	26.21	1.50	12.42	40.13	-	-	-	-	-	-	40.13
6		02 Body Dash and Cowl	-	-	-	-	-	-	-	-	-	-	-
6		03 Roof and Cross-Member	45.07	3.29	15.05	63.41	-	-	-	-	-	-	63.41
7		04 Body Side	223.27	26.81	139.84	389.92	-	-	-	-	-	-	389.92
8		05 Parcel Shelf and Cross-Vehicle Framing Parts	-	-	-	-	-	-	-	-	-	-	-
9		06 Cab Back & Ring Frame	-	-	-	-	-	-	-	-	-	-	-
10		07 Rear Wheel Arch Liners	2.37	0.13	0.82	3.32	0.02	0.37	0.29	0.06	0.74	-	4.06
11		08 One Piece Body Structure	-	-	-	-	-	-	-	-	-	-	-
12		10 Rear Floor	25.33	2.24	15.03	42.60	-	-	-	-	-	-	42.60
13		11 Fuel Filler and Flap	-	-	-	-	-	-	-	-	-	-	-
14		99 Misc. Under Ladder Assembly	145.15	24.70	119.48	289.33	-	-	-	-	-	-	289.33
15		02 Front End Subsystem	-	-	-	-	-	-	-	-	-	-	-
16		01 Front Structure	44.93	10.57	56.72	112.22	-	-	-	-	-	-	112.22
18		03 Front Fenders	9.91	0.44	5.35	15.70	-	-	-	-	-	-	15.70
19		04 Front Wheel Arch Liners	3.29	0.14	1.26	4.69	0.03	0.52	0.41	0.08	1.04	-	5.73
20		05 Hood BIW Panel	25.49	1.61	12.47	39.57	-	-	-	-	-	-	39.57
21		10 Under Engine Closures/Air Dams	4.92	0.20	0.37	5.50	0.04	0.61	0.48	0.10	1.23	-	6.73
22		08 Front End Module Carrier	8.89	3.06	15.76	27.71	-	-	-	-	-	-	27.71
23		99 Misc. - Compartment Extras (Al)	6.35	2.68	12.67	21.70	-	-	-	-	-	-	21.70
15		03 Body Closures Subsystem	-	-	-	-	-	-	-	-	-	-	-
16	x	03 Rear Closure BIW Panel	19.76	2.83	17.11	39.70	-	-	-	-	-	-	39.70
15		19 Bumpers Subsystem	-	-	-	-	-	-	-	-	-	-	-
16	x	01 Front Bumper Skin and Foams	9.00	0.63	4.35	13.98	-	-	-	-	-	-	13.98
		SUBSYSTEM ROLL-UP	599.94	80.83	428.71	1,109.47	0.02	0.37	0.29	0.06	0.74	-	1,112.48

SYSTEM & SUBSYSTEM DESCRIPTION			INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE										
Item	Subsystem	Sub-Subsystem Description	Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
			Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D			
			USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	03 Body Subsystem												
3		01 Body Structure Subsystem	-	-	-	-	-	-	-	-	-	-	-
4		01 Front Floor	(3.69)	(0.15)	(1.16)	(5.00)	-	-	-	-	-	-	(5.00)
6		02 Body Dash and Cowl	-	-	-	-	-	-	-	-	-	-	-
6		03 Roof and Cross-Member	5.48	(0.78)	0.06	4.76	-	-	-	-	-	-	4.76
7		04 Body Side	(66.10)	(7.00)	(14.80)	(87.90)	-	-	-	-	-	-	(87.90)
8		05 Parcel Shelf and Cross-Vehicle Framing Parts	-	-	-	-	-	-	-	-	-	-	-
9		06 Cab Back & Ring Frame	-	-	-	-	-	-	-	-	-	-	-
10		07 Rear Wheel Arch Liners	0.05	0.02	0.11	0.17	0.00	0.02	0.02	0.00	0.04	-	0.21
11		08 One Piece Body Structure	-	-	-	-	-	-	-	-	-	-	-
12		10 Rear Floor	0.40	(0.76)	(1.34)	(1.70)	-	-	-	-	-	-	(1.70)
13		11 Fuel Filler and Flap	-	-	-	-	-	-	-	-	-	-	-
14		99 Misc. Under Ladder Assembly	1.40	(3.50)	(17.84)	(19.94)	-	-	-	-	-	-	(19.94)
15		02 Front End Subsystem	-	-	-	-	-	-	-	-	-	-	-
16		01 Front Structure	(1.05)	(0.51)	(2.56)	(4.12)	-	-	-	-	-	-	(4.12)
18		03 Front Fenders	(21.85)	-	-	(21.85)	-	-	-	-	-	-	(21.85)
19		04 Front Wheel Arch Liners	0.06	0.02	0.16	0.24	-	0.03	0.02	-	0.05	-	0.29
20		05 Hood BIW Panel	(39.35)	0.03	0.21	(39.11)	-	-	-	-	-	-	(39.11)
21		10 Under Engine Closures/Air Dams	0.16	0.02	0.03	0.21	-	0.03	0.02	0.01	0.06	-	0.27
22		08 Front End Module Carrier	(1.39)	(0.25)	(1.27)	(2.91)	-	-	-	-	-	-	(2.91)
23		99 Misc. - Compartment Extras (AI)	(13.63)	0.13	0.50	(13.00)	-	-	-	-	-	-	(13.00)
15		03 Body Closures Subsystem	-	-	-	-	-	-	-	-	-	-	-
16	x	03 Rear Closure BIW Panel	(29.97)	-	0.01	(29.96)	-	-	-	-	-	-	(29.96)
15		19 Bumpers Subsystem	-	-	-	-	-	-	-	-	-	-	-
16	x	01 Front Bumper Skin and Foams	(10.71)	-	-	(10.71)	-	-	-	-	-	-	(10.71)
		SUBSYSTEM ROLL-UP	(180.18)	(12.74)	(37.89)	(230.81)	0.00	0.02	0.02	0.00	0.04	-	(230.66)

Table A-4: Body System B Cost Breakdown

SYSTEM & SUBSYSTEM DESCRIPTION				NEW TECHNOLOGY GENERAL PART INFORMATION:										
				Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
Item	System	Subsystem	Sub-Subsystem Description	Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D			
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	03 Body System B													
1		05	Interior Trim and Ornamentation Subsystem	86.72	11.47	27.90	126.09	0.31	6.16	4.10	1.03	11.59	0	137.68
2		06	Sound and Heat Control Subsystem	3.63	0.27	0.33	4.23	0.01	0.21	0.14	0.04	0.40	0	4.63
3		07	Sealing Subsystem	43.95	9.42	9.42	62.79	-	-	-	-	-	-	62.79
4		10	Seating Subsystem	112.14	18.40	51.55	182.08	1.16	17.58	14.38	4.08	37.20	0	219.28
5		12	Instrument Panel and Console Subsystem	73.61	4.18	15.58	93.36	0.23	4.69	3.13	0.78	8.84	0	102.20
6		20	Occupant Restraining Device Subsystem	16.31	4.07	6.33	26.70	0.07	1.34	0.89	0.22	2.53	0	29.23
			SUBSYSTEM ROLL-UP	336.36	47.79	111.10	495.26	1.78	29.98	22.65	6.15	60.55	0	555.81

SYSTEM & SUBSYSTEM DESCRIPTION				BASE TECHNOLOGY GENERAL PART INFORMATION:										
				Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
Item	System	Subsystem	Sub-Subsystem Description	Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D			
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	03 Body System B													
1		05	Interior Trim and Ornamentation Subsystem	106.39	17.02	36.21	159.62	0.44	7.88	5.73	1.72	15.78	0	175.40
2		06	Sound and Heat Control Subsystem	4.03	0.28	0.26	4.57	0.01	0.23	0.15	0.04	0.43	0	5.01
3		07	Sealing Subsystem	47.09	15.70	15.70	78.49	-	-	-	-	-	-	78.49
4		10	Seating Subsystem	119.32	57.61	75.85	252.79	1.57	22.39	19.26	6.51	49.73	0	302.51
5		12	Instrument Panel and Console Subsystem	64.30	3.98	13.68	81.95	0.21	4.12	2.75	0.69	7.76	0	89.71
6		20	Occupant Restraining Device Subsystem	14.87	4.45	4.75	24.07	0.06	1.21	0.81	0.20	2.28	0	26.35
			SUBSYSTEM ROLL-UP	356.01	99.03	146.46	601.50	2.30	35.83	28.69	9.15	75.97	0	677.47

SYSTEM & SUBSYSTEM DESCRIPTION				INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE										
				Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
Item	System	Subsystem	Sub-Subsystem Description	Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D			
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	03 Body System B													
1		05	Interior Trim and Ornamentation Subsystem	19.68	5.55	8.31	33.54	0.14	1.73	1.63	0.69	4.18	0	37.72
2		06	Sound and Heat Control Subsystem	0.40	0.01	(0.07)	0.34	0.00	0.02	0.01	0.00	0.03	0	0.38
3		07	Sealing Subsystem	3.14	6.28	6.28	15.70	-	-	-	-	-	-	15.70
4		10	Seating Subsystem	7.18	39.22	24.30	70.70	0.42	4.82	4.88	2.42	12.53	0	83.23
5		12	Instrument Panel and Console Subsystem	(9.32)	(0.20)	(1.90)	(11.41)	(0.03)	(0.57)	(0.38)	(0.10)	(1.08)	0	(12.49)
6		20	Occupant Restraining Device Subsystem	(1.44)	0.38	(1.57)	(2.63)	(0.01)	(0.13)	(0.09)	(0.02)	(0.25)	0	(2.88)
			SUBSYSTEM ROLL-UP	19.65	51.24	35.35	106.24	0.52	5.85	6.05	3.00	15.42	0	121.66

Table A-5: Body System C Cost Breakdown

SYSTEM & SUBSYSTEM DESCRIPTION			NEW TECHNOLOGY GENERAL PART INFORMATION										
Item	Subsystem	Sub-Subsystem Description	Manufacturing: Material	Manufacturing: Labor	Manufacturing: Burden	Total Manufacturing Cost (Component/ Assembly)	Markup: End Item Scrap	Markup: SG&A	Markup: Profit	Markup: ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
			USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
		03 Body System C											
3		08 Exterior Trim & Ornamentation Subsystem	-	-	-	-	-	-	-	-	-	-	-
4		Radiator Grill	3.47	0.05	0.21	3.73	0.03	0.41	0.33	0.07	0.84	-	4.57
5		Lower Exterior Finishers	10.96	0.53	1.05	12.54	0.09	1.39	1.10	0.22	2.80	-	15.34
6		Upper Exterior & Roof Finish	1.82	0.07	0.33	2.22	0.02	0.25	0.19	0.04	0.50	-	2.72
7		Rear Closure Finishers	3.29	0.04	0.39	3.72	0.03	0.41	0.33	0.07	0.84	-	4.56
8		Rear Spoiler Assembly	4.37	0.10	0.71	5.18	0.04	0.57	0.45	0.09	1.15	-	6.33
9		Grill - Cowl Vent	2.07	0.14	0.96	3.17	0.02	0.35	0.28	0.06	0.71	-	3.88
10		09 Rear View Mirrors Subsystem	-	-	-	-	-	-	-	-	-	-	-
11		Exterior Mirror - Driver Side	2.25	0.25	0.19	2.69	0.02	0.30	0.24	0.05	0.61	-	3.30
12		Exterior Mirror - Passenger Side	2.25	0.25	0.19	2.69	0.02	0.30	0.24	0.05	0.61	-	3.30
13		23 Front End Module	-	-	-	-	-	-	-	-	-	-	-
14		Module - Front Bumper & Fascia	10.49	0.29	2.10	12.88	0.09	1.42	1.13	0.23	2.87	-	15.75
15		24 Rear End Module Subsystem	-	-	-	-	-	-	-	-	-	-	-
16		Module - Rear Bumper and Fascia	11.10	0.31	2.11	13.52	0.09	1.50	1.19	0.24	3.02	-	16.54
		SUBSYSTEM ROLL-UP	52.07	2.04	8.24	62.35	0.45	6.90	5.47	1.12	13.95	-	76.30

SYSTEM & SUBSYSTEM DESCRIPTION			BASE TECHNOLOGY GENERAL PART INFORMATION										
Item	Subsystem	Sub-Subsystem Description	Manufacturing: Material	Manufacturing: Labor	Manufacturing: Burden	Total Manufacturing Cost (Component/ Assembly)	Markup: End Item Scrap	Markup: SG&A	Markup: Profit	Markup: ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
			USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
		03 Body System C											
3		08 Exterior Trim & Ornamentation Subsystem	-	-	-	-	-	-	-	-	-	-	-
4		Radiator Grill	3.63	0.06	0.24	3.93	0.03	0.43	0.34	0.07	0.87	-	4.80
5		Lower Exterior Finishers	11.43	0.61	1.19	13.23	0.09	1.46	1.16	0.23	2.94	-	16.17
6		Upper Exterior & Roof Finish	2.02	0.08	0.38	2.48	0.02	0.27	0.22	0.04	0.55	-	3.03
7		Rear Closure Finishers	3.44	0.05	0.43	3.92	0.03	0.43	0.34	0.07	0.87	-	4.79
8		Rear Spoiler Assembly	4.56	0.12	0.84	5.52	0.04	0.61	0.48	0.10	1.23	-	6.75
9		Grill - Cowl Vent	2.12	0.16	1.13	3.41	0.02	0.38	0.30	0.06	0.76	-	4.17
10		09 Rear View Mirrors Subsystem	-	-	-	-	-	-	-	-	-	-	-
11		Exterior Mirror - Driver Side	2.54	0.26	0.20	3.00	0.02	0.33	0.26	0.06	0.67	-	3.67
12		Exterior Mirror - Passenger Side	2.54	0.26	0.20	3.00	0.02	0.33	0.27	0.05	0.67	-	3.67
13		23 Front End Module	-	-	-	-	-	-	-	-	-	-	-
14		Module - Front Bumper & Fascia	12.04	0.32	2.35	14.71	0.10	1.63	1.29	0.26	3.28	-	17.99
15		24 Rear End Module Subsystem	-	-	-	-	-	-	-	-	-	-	-
16		Module - Rear Bumper and Fascia	12.72	0.35	2.35	15.42	0.11	1.71	1.35	0.27	3.44	-	18.86
		SUBSYSTEM ROLL-UP	57.04	2.28	9.30	68.61	0.48	7.57	6.01	1.21	15.28	-	83.89

SYSTEM & SUBSYSTEM DESCRIPTION			INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE										
Item	Subsystem	Sub-Subsystem Description	Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
			Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D			
			USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	03 Body System C												
3		08 Exterior Trim & Ornamentation Subsystem	-	-	-	-	-	-	-	-	-	-	-
4		Radiator Grill	0.16	0.01	0.03	0.20	-	0.02	0.01	-	0.03	-	0.23
5		Lower Exterior Finishers	0.47	0.08	0.14	0.69	-	0.07	0.06	0.01	0.14	-	0.83
6		Upper Exterior & Roof Finish	0.20	0.01	0.05	0.26	-	0.02	0.03	-	0.05	-	0.31
7		Rear Closure Finishers	0.15	0.01	0.04	0.20	-	0.02	0.01	-	0.03	-	0.23
8		Rear Spoiler Assembly	0.19	0.02	0.13	0.34	-	0.04	0.03	0.01	0.08	-	0.42
9		Grill - Cowl Vent	0.05	0.02	0.17	0.24	-	0.03	0.02	-	0.05	-	0.29
10		09 Rear View Mirrors Subsystem	-	-	-	-	-	-	-	-	-	-	-
11		Exterior Mirror - Driver Side	0.28	0.01	0.01	0.30	-	0.03	0.02	0.01	0.06	-	0.36
12		Exterior Mirror - Passenger Side	0.28	0.01	0.01	0.30	-	0.03	0.03	-	0.06	-	0.36
13		23 Front End Module	-	-	-	-	-	-	-	-	-	-	-
14		Module - Front Bumper & Fascia	1.55	0.03	0.24	1.83	0.01	0.20	0.16	0.03	0.41	-	2.24
15		24 Rear End Module Subsystem	-	-	-	-	-	-	-	-	-	-	-
16		Module - Rear Bumper and Fascia	1.62	0.04	0.24	1.90	0.01	0.21	0.17	0.03	0.42	-	2.32
		SUBSYSTEM ROLL-UP	4.96	0.24	1.06	6.26	0.03	0.67	0.54	0.10	1.33	-	7.59

Table A-6: Body System D Cost Breakdown

SYSTEM & SUBSYSTEM DESCRIPTION — NEW TECHNOLOGY GENERAL PART INFORMATION

Item	System	Subsystem	Sub-Subsystem Description	Manufacturing: Material	Manufacturing: Labor	Manufacturing: Burden	Total Manufacturing Cost (Component/ Assembly)	Markup: End Item Scrap	Markup: SG&A	Markup: Profit	Markup: ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	03 Body System D													
		11	Glass (Glazing), Frame, and Mechanism Subsystem											
1			01 Windshield and Front Quarter Window (Fixed)	3.33	1.19	17.30	21.82	0.05	1.10	0.73	0.18	2.06	-	23.88
2			03 First Row Door Window Lift Assy	7.87	0.40	1.32	9.59	0.02	0.48	0.32	0.08	0.91	-	10.49
3			04 Rear Quarter Window Assembly (Moveable)	-	-	-	-	-	-	-	-	-	-	-
4			05 Back and Rear Quarter Windows (Fixed)	0.99	0.33	8.32	9.63	0.02	0.48	0.32	0.08	0.91	-	10.54
5			09 Power Window Electronics	-	-	-	-	-	-	-	-	-	-	-
6			11 Second Row Door, Qtr & Rear Closure Window Lift Assy	7.87	0.40	1.32	9.59	0.02	0.48	0.32	0.08	0.91	-	10.49
7			12 Back Window Assy	3.47	1.72	43.97	49.17	0.12	2.47	1.65	0.41	4.65	-	53.82
8			13 Front Side Door Glass	-	-	-	-	-	-	-	-	-	-	-
9			14 Rear Side Door Glass	2.39	1.66	42.47	46.52	0.12	2.34	1.56	0.39	4.40	-	50.93
15			99 Solvent Bottle	1.99	0.08	0.10	2.17	0.02	0.24	0.19	0.04	0.48	-	2.66
			SUBSYSTEM ROLL-UP	27.90	5.78	114.79	148.48	0.38	7.59	5.09	1.26	14.33	-	162.81

SYSTEM & SUBSYSTEM DESCRIPTION — BASE TECHNOLOGY GENERAL PART INFORMATION

Item	System	Subsystem	Sub-Subsystem Description	Manufacturing: Material	Manufacturing: Labor	Manufacturing: Burden	Total Manufacturing Cost (Component/ Assembly)	Markup: End Item Scrap	Markup: SG&A	Markup: Profit	Markup: ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	03 Body System D													
		11	Glass (Glazing), Frame, and Mechanism Subsystem											
1			01 Windshield and Front Quarter Window (Fixed)	4.02	1.43	14.83	20.28	0.05	1.02	0.68	0.17	1.92	-	22.20
2			03 First Row Door Window Lift Assy	5.70	0.40	1.32	7.42	0.02	0.37	0.25	0.06	0.70	-	8.13
3			04 Rear Quarter Window Assembly (Moveable)	-	-	-	-	-	-	-	-	-	-	-
4			05 Back and Rear Quarter Windows (Fixed)	1.09	0.36	7.43	8.89	0.02	0.45	0.30	0.07	0.84	-	9.73
5			09 Power Window Electronics	-	-	-	-	-	-	-	-	-	-	-
6			11 Second Row Door, Qtr & Rear Closure Window Lift Assy	5.70	0.40	1.32	7.42	0.02	0.37	0.25	0.06	0.70	-	8.13
7			12 Back Window Assy	4.02	1.91	39.32	45.24	0.11	2.27	1.52	0.38	4.28	-	49.53
8			13 Front Side Door Glass	-	-	-	-	-	-	-	-	-	-	-
9			14 Rear Side Door Glass	2.91	1.85	37.97	42.73	0.11	2.15	1.43	0.36	4.04	-	46.78
15			99 Solvent Bottle	2.31	0.09	0.12	2.51	0.02	0.28	0.22	0.04	0.56	-	3.07
			SUBSYSTEM ROLL-UP	25.76	6.44	102.31	134.50	0.35	6.91	4.64	1.15	13.05	-	147.56

SYSTEM & SUBSYSTEM DESCRIPTION — INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE

Item	System	Subsystem	Sub-Subsystem Description	Manufacturing: Material	Manufacturing: Labor	Manufacturing: Burden	Total Manufacturing Cost (Component/ Assembly)	Markup: End Item Scrap	Markup: SG&A	Markup: Profit	Markup: ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	03 Body System D													
		11	Glass (Glazing), Frame, and Mechanism Subsystem											
1			01 Windshield and Front Quarter Window (Fixed)	0.69	0.24	(2.47)	(1.54)	(0.00)	(0.08)	(0.05)	(0.01)	(0.15)	-	(1.68)
2			03 First Row Door Window Lift Assy	(2.16)	-	-	(2.16)	(0.01)	(0.11)	(0.07)	(0.02)	(0.20)	-	(2.37)
3			04 Rear Quarter Window Assembly (Moveable)	-	-	-	-	-	-	-	-	-	-	-
4			05 Back and Rear Quarter Windows (Fixed)	0.10	0.04	(0.88)	(0.74)	(0.00)	(0.04)	(0.02)	(0.01)	(0.07)	-	(0.81)
5			09 Power Window Electronics	-	-	-	-	-	-	-	-	-	-	-
6			11 Second Row Door, Qtr & Rear Closure Window Lift Assy	(2.16)	-	-	(2.16)	(0.01)	(0.11)	(0.07)	(0.02)	(0.20)	-	(2.37)
7			12 Back Window Assy	0.54	0.19	(4.65)	(3.92)	(0.01)	(0.20)	(0.13)	(0.03)	(0.37)	-	(4.29)
8			13 Front Side Door Glass	-	-	-	-	-	-	-	-	-	-	-
9			14 Rear Side Door Glass	0.52	0.18	(4.49)	(3.79)	(0.01)	(0.19)	(0.13)	(0.03)	(0.36)	-	(4.15)
15			99 Solvent Bottle	0.32	0.01	0.01	0.34	0.00	0.04	0.03	0.01	0.08	-	0.42
			SUBSYSTEM ROLL-UP	(2.15)	0.66	(12.48)	(13.97)	(0.03)	(0.68)	(0.45)	(0.11)	(1.28)	-	(15.25)

Table A-7: Suspension System Cost Breakdown

SYSTEM & SUBSYSTEM DESCRIPTION / NEW TECHNOLOGY GENERAL PART INFORMATION

Item	System	Subsystem Description	Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
			Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D			
			USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
		04 Suspension System											
1		01 Front Suspension Subsystem	69.80	13.67	28.91	112.38	1.84	10.86	9.33	2.78	24.81	-	137.20
2		02 Rear Suspension Subsystem	62.26	14.67	28.34	105.26	1.73	10.59	9.03	2.62	23.97	-	129.23
3		03 Shock Absorber Subsystem	56.71	17.17	17.81	91.69	0.65	10.01	8.06	2.08	20.81	-	112.50
4		04 Wheels and Tires Subsystem	173.83	35.66	35.66	245.16	0.62	12.32	8.21	2.05	23.20	-	268.36
		SYSTEM ROLL-UP	362.60	81.18	110.72	554.49	4.83	43.78	34.64	9.54	92.79	-	647.29

SYSTEM & SUBSYSTEM DESCRIPTION / BASE TECHNOLOGY GENERAL PART INFORMATION

Item	System	Subsystem Description	Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
			Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D			
			USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
		04 Suspension System											
1		01 Front Suspension Subsystem	60.25	13.87	32.15	106.27	2.12	10.92	9.41	2.74	25.19	-	131.46
2		02 Rear Suspension Subsystem	58.85	16.49	32.97	108.30	2.07	11.32	9.68	2.77	25.84	-	134.14
3		03 Shock Absorber Subsystem	86.57	26.40	25.96	138.94	0.98	15.18	12.23	3.16	31.55	-	170.48
4		04 Wheels and Tires Subsystem	223.42	46.85	46.85	317.12	0.80	15.93	10.62	2.66	30.01	-	347.13
		SYSTEM ROLL-UP	429.10	103.60	137.94	670.63	5.96	53.36	41.94	11.32	112.58	-	783.22

SYSTEM & SUBSYSTEM DESCRIPTION / INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE

Item	System	Subsystem Description	Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
			Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D			
			USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
		04 Suspension System											
1		01 Front Suspension Subsystem	(9.55)	0.20	3.24	(6.11)	0.28	0.06	0.07	(0.04)	0.37	-	(5.74)
2		02 Rear Suspension Subsystem	(3.41)	1.82	4.64	3.04	0.33	0.73	0.65	0.15	1.87	-	4.91
3		03 Shock Absorber Subsystem	29.87	9.23	8.16	47.25	0.33	5.17	4.16	1.07	10.74	-	57.99
4		04 Wheels and Tires Subsystem	49.59	11.18	11.18	71.96	0.18	3.62	2.41	0.60	6.81	-	78.77
		SYSTEM ROLL-UP	66.50	22.42	27.22	116.14	1.13	9.58	7.30	1.79	19.79	-	135.93

Table A-8: Driveline System Cost Breakdown

SYSTEM & SUBSYSTEM DESCRIPTION				NEW TECHNOLOGY GENERAL PART INFORMATION										
				Manufacturing				Markup						
Item	System	Subsystem	Sub-Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	05	Driveline System												
1		03	Front Drive Housed Axle Subsystem	5.62	0.00	0.00	5.63	0.03	0.33	0.38	0.19	0.93	0	6.55
2		04	Front Drive Half Shaft Subsystem	10.97	2.84	5.87	19.67	0.31	2.28	2.19	0.77	5.54	0	25.22
		▲	SUBSYSTEM ROLL-UP	16.59	2.84	5.87	25.30	0.34	2.61	2.57	0.95	6.47	0	31.77

SYSTEM & SUBSYSTEM DESCRIPTION				BASE TECHNOLOGY GENERAL PART INFORMATION										
				Manufacturing				Markup						
Item	System	Subsystem	Sub-Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	05	Driveline System												
1		03	Front Drive Housed Axle Subsystem	6.94	0.00	0.00	6.95	0.04	0.41	0.47	0.23	1.15	0	8.09
2		04	Front Drive Half Shaft Subsystem	9.84	2.52	5.95	18.31	0.25	2.13	2.08	0.74	5.20	0	23.51
		▲	SUBSYSTEM ROLL-UP	16.79	2.52	5.96	25.26	0.29	2.54	2.55	0.97	6.34	0	31.60

SYSTEM & SUBSYSTEM DESCRIPTION				INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE										
				Manufacturing				Markup						
Item	System	Subsystem	Sub-Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	05	Driveline System												
1		03	Front Drive Housed Axle Subsystem	1.32	-	-	1.32	0.01	0.08	0.09	0.04	0.22	0	1.54
2		04	Front Drive Half Shaft Subsystem	(1.13)	(0.32)	0.09	(1.36)	(0.06)	(0.15)	(0.11)	(0.03)	(0.35)	0	(1.70)
		▲	SUBSYSTEM ROLL-UP	0.19	(0.32)	0.09	(0.04)	(0.05)	(0.07)	(0.02)	0.01	(0.13)	0	(0.16)

Table A-9: Brake System Cost Breakdown

SYSTEM & SUBSYSTEM DESCRIPTION			NEW TECHNOLOGY GENERAL PART INFORMATION										
Item	System	Subsystem Description	Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
			Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D			
			USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	06 Brake System												
1		01 N / A	-	-	-	-	-	-	-	-	-	-	-
2		02 N / A	-	-	-	-	-	-	-	-	-	-	-
3		03 Front Rotor/Drum and Shield Subsystem	74.53	10.16	29.81	114.50	0.69	7.50	8.02	3.62	19.83	-	134.33
4		04 Rear Rotor/Drum and Shield Subsystem	55.01	11.32	30.51	96.84	0.33	6.23	4.35	0.95	11.87	-	108.71
5		05 Parking Brake and Actuation Subsystem	7.34	3.21	5.47	16.02	0.10	1.66	1.31	0.27	3.34	-	19.36
6		06 Brake Actuation Subsystem	11.19	3.53	5.29	20.00	0.14	2.08	1.68	0.37	4.26	-	24.26
7		07 Power Brake Subsystem (for Hydraulic)	2.94	1.05	2.22	6.21	0.04	0.66	0.48	0.08	1.26	-	7.47
	▲	SYSTEM ROLL-UP	151.00	29.27	73.30	253.57	1.30	18.13	15.85	5.29	40.57	-	294.14

SYSTEM & SUBSYSTEM DESCRIPTION			BASE TECHNOLOGY GENERAL PART INFORMATION										
Item	System	Subsystem Description	Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
			Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D			
			USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	06 Brake System												
1		01 N / A	-	-	-	-	-	-	-	-	-	-	-
2		02 N / A	-	-	-	-	-	-	-	-	-	-	-
3		03 Front Rotor/Drum and Shield Subsystem	49.19	10.39	49.94	109.53	0.65	7.16	7.54	3.39	18.74	-	128.26
4		04 Rear Rotor/Drum and Shield Subsystem	33.71	12.26	56.46	102.43	0.35	6.49	4.53	1.00	12.37	-	114.79
5		05 Parking Brake and Actuation Subsystem	45.88	19.62	22.20	87.69	0.43	7.67	5.52	1.03	14.65	-	102.34
6		06 Brake Actuation Subsystem	26.04	8.26	11.91	46.21	0.31	5.01	3.87	0.75	9.93	-	56.13
7		07 Power Brake Subsystem (for Hydraulic)	2.99	1.56	2.86	7.42	0.04	0.78	0.52	0.07	1.40	-	8.82
	▲	SYSTEM ROLL-UP	157.80	52.09	143.38	353.27	1.77	27.10	21.98	6.23	57.08	-	410.35

SYSTEM & SUBSYSTEM DESCRIPTION			INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE										
Item	System	Subsystem Description	Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
			Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D			
			USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	06 Brake System												
1		01 N / A	-	-	-	-	-	-	-	-	-	-	-
2		02 N / A	-	-	-	-	-	-	-	-	-	-	-
3		03 Front Rotor/Drum and Shield Subsystem	(25.34)	0.23	20.13	(4.98)	(0.04)	(0.34)	(0.48)	(0.23)	(1.10)	-	(6.07)
4		04 Rear Rotor/Drum and Shield Subsystem	(21.30)	0.94	25.95	5.59	0.01	0.26	0.18	0.05	0.49	-	6.08
5		05 Parking Brake and Actuation Subsystem	38.54	16.40	16.73	71.67	0.32	6.01	4.22	0.76	11.31	-	82.98
6		06 Brake Actuation Subsystem	14.85	4.73	6.63	26.21	0.17	2.93	2.18	0.38	5.66	-	31.87
7		07 Power Brake Subsystem (for Hydraulic)	0.05	0.51	0.65	1.21	0.00	0.12	0.04	(0.02)	0.14	-	1.35
	▲	SYSTEM ROLL-UP	6.80	22.81	70.08	99.70	0.46	8.97	6.13	0.94	16.51	-	116.21

Table A-10: Frame and Mounting System Cost Breakdown

SYSTEM & SUBSYSTEM DESCRIPTION				NEW TECHNOLOGY GENERAL PART INFORMATION										
				Manufacturing				Markup						
Item	System	Subsystem	Sub-Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	07	Frame and Mounting System												
1		01	Frame Subsystem	71.76	10.88	42.55	125.19	0.85	8.95	9.83	4.46	24.09	0	149.28
			SUBSYSTEM ROLL-UP	71.76	10.88	42.55	125.19	0.85	8.95	9.83	4.46	24.09	0	149.28

SYSTEM & SUBSYSTEM DESCRIPTION				BASE TECHNOLOGY GENERAL PART INFORMATION										
				Manufacturing				Markup						
Item	System	Subsystem	Sub-Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	07	Frame and Mounting System												
1		01	Frame Subsystem	77.41	21.22	17.43	116.06	0.99	12.53	11.84	4.19	29.55	0	145.61
			SUBSYSTEM ROLL-UP	77.41	21.22	17.43	116.06	0.99	12.53	11.84	4.19	29.55	0	145.61

SYSTEM & SUBSYSTEM DESCRIPTION				INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE										
				Manufacturing				Markup						
Item	System	Subsystem	Sub-Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	07	Frame and Mounting System												
1		01	Frame Subsystem	5.65	10.34	(25.12)	(9.13)	0.14	3.58	2.02	(0.27)	5.46	0	(3.66)
			SUBSYSTEM ROLL-UP	5.65	10.34	(25.12)	(9.13)	0.14	3.58	2.02	(0.27)	5.46	0	(3.66)

Table A-11: Exhaust System Cost Breakdown

SYSTEM & SUBSYSTEM DESCRIPTION				NEW TECHNOLOGY GENERAL PART INFORMATION:										
				Manufacturing				Markup						
Item	System	Subsystem	Sub-Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	09 Exhaust System													
1		01	Acoustical Control Components Subsystem	17.82	0.32	0.32	18.46	0.07	0.96	0.88	0.37	2.28	0	20.74
2		02	Exhaust Gas Treatment Components Subsystem	19.14	0.63	0.64	20.42	0.05	0.61	0.56	0.23	1.45	0	21.87
	SUBSYSTEM ROLL-UP			36.97	0.95	0.97	38.88	0.12	1.57	1.45	0.60	3.74	0	42.62

SYSTEM & SUBSYSTEM DESCRIPTION				BASE TECHNOLOGY GENERAL PART INFORMATION:										
				Manufacturing				Markup						
Item	System	Subsystem	Sub-Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	09 Exhaust System													
1		01	Acoustical Control Components Subsystem	17.55	0.28	0.35	18.18	0.08	0.99	0.91	0.38	2.36	0	20.54
2		02	Exhaust Gas Treatment Components Subsystem	21.47	0.56	0.70	22.73	0.06	0.76	0.70	0.29	1.82	0	24.55
	SUBSYSTEM ROLL-UP			39.02	0.84	1.05	40.90	0.13	1.75	1.62	0.67	4.18	0	45.08

SYSTEM & SUBSYSTEM DESCRIPTION				INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE										
				Manufacturing				Markup						
Item	System	Subsystem	Sub-Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	09 Exhaust System													
1		01	Acoustical Control Components Subsystem	(0.28)	(0.04)	0.03	(0.28)	0.00	0.03	0.03	0.01	0.08	0	(0.21)
2		02	Exhaust Gas Treatment Components Subsystem	2.33	(0.07)	0.05	2.31	0.01	0.15	0.14	0.06	0.37	0	2.68
	SUBSYSTEM ROLL-UP			2.05	(0.11)	0.08	2.02	0.01	0.19	0.17	0.07	0.44	0	2.47

Table A-12: Fuel System Cost Breakdown

SYSTEM & SUBSYSTEM DESCRIPTION / NEW TECHNOLOGY GENERAL PART INFORMATION

Item	System	Subsystem	Sub-Subsystem Description	Manufacturing: Material	Manufacturing: Labor	Manufacturing: Burden	Total Manufacturing Cost (Component/ Assembly)	Markup: End Item Scrap	Markup: SG&A	Markup: Profit	Markup: ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	10	Fuel System												
1		01	Fuel Tank and Lines SubSystem	42.87	5.37	17.09	65.34	0.44	4.67	5.04	2.28	12.42	0	77.76
2		02	Fuel Vapor Management Subsystem	4.10	0.60	0.65	5.36	0.05	0.61	0.57	0.19	1.42	0	6.78
		▲	SUBSYSTEM ROLL-UP	46.98	5.97	17.74	70.69	0.48	5.28	5.61	2.47	13.84	0	84.54

SYSTEM & SUBSYSTEM DESCRIPTION / BASE TECHNOLOGY GENERAL PART INFORMATION

Item	System	Subsystem	Sub-Subsystem Description	Manufacturing: Material	Manufacturing: Labor	Manufacturing: Burden	Total Manufacturing Cost (Component/ Assembly)	Markup: End Item Scrap	Markup: SG&A	Markup: Profit	Markup: ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	10	Fuel System												
1		01	Fuel Tank and Lines SubSystem	24.51	11.35	31.38	67.24	0.46	5.11	5.34	2.32	13.22	0	80.45
2		02	Fuel Vapor Management Subsystem	4.15	1.00	1.15	6.30	0.06	0.72	0.68	0.23	1.69	0	7.99
		▲	SUBSYSTEM ROLL-UP	28.66	12.35	32.53	73.54	0.51	5.83	6.01	2.55	14.91	0	88.45

SYSTEM & SUBSYSTEM DESCRIPTION / INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE

Item	System	Subsystem	Sub-Subsystem Description	Manufacturing: Material	Manufacturing: Labor	Manufacturing: Burden	Total Manufacturing Cost (Component/ Assembly)	Markup: End Item Scrap	Markup: SG&A	Markup: Profit	Markup: ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	10	Fuel System												
1		01	Fuel Tank and Lines SubSystem	(18.37)	5.98	14.29	1.90	0.02	0.44	0.29	0.04	0.79	0	2.70
2		02	Fuel Vapor Management Subsystem	0.05	0.40	0.50	0.95	0.01	0.11	0.11	0.04	0.27	0	1.21
		▲	SUBSYSTEM ROLL-UP	(18.32)	6.38	14.79	2.85	0.03	0.55	0.40	0.08	1.06	0	3.91

Table A-13: Steering System Cost Breakdown

Item	System	Subsystem	SYSTEM & SUBSYSTEM DESCRIPTION: Sub-Subsystem Description	NEW TECHNOLOGY GENERAL PART INFORMATION: Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D			
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	11		Steering System											
		01	Steering Gear Subsystem	4.79	-	-	4.79	0.02	0.26	0.24	0.10	0.62	0	5.41
		02	Power Steering Subsystem	0.39	0.13	0.07	0.59	0.00	0.03	0.02	-	0.05	0	0.64
		04	Steering Column Subsystem	3.57	2.80	3.75	10.12	0.18	1.04	0.88	0.23	2.34	0	12.45
		05	Steering Column Switches Subsystem	-	-	-	-	-	-	-	-	-	-	-
		06	Steering Wheel Subsystem	8.07	1.72	1.75	11.54	0.00	0.02	0.01	0.00	0.03	0	11.56
			SUBSYSTEM ROLL-UP	16.81	4.64	5.57	27.03	0.20	1.35	1.15	0.34	3.04	0	30.07

Item	System	Subsystem	SYSTEM & SUBSYSTEM DESCRIPTION: Sub-Subsystem Description	BASE TECHNOLOGY GENERAL PART INFORMATION: Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D			
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	11		Steering System											
		01	Steering Gear Subsystem	5.01	-	-	5.01	0.02	0.27	0.25	0.10	0.65	0	5.66
		02	Power Steering Subsystem	0.55	0.06	0.07	0.67	0.00	0.03	0.02	-	0.06	0	0.73
		04	Steering Column Subsystem	5.42	6.28	7.06	18.76	0.14	1.84	1.64	0.47	4.08	0	22.84
		05	Steering Column Switches Subsystem	-	-	-	-	-	-	-	-	-	-	-
		06	Steering Wheel Subsystem	7.51	1.50	1.73	10.73	0.23	0.54	0.37	0.01	1.15	0	11.88
			SUBSYSTEM ROLL-UP	18.48	7.84	8.86	35.18	0.38	2.69	2.28	0.59	5.94	0	41.11

Item	System	Subsystem	SYSTEM & SUBSYSTEM DESCRIPTION: Sub-Subsystem Description	INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE: Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D			
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	11		Steering System											
		01	Steering Gear Subsystem	0.22	-	-	0.22	0.00	0.01	0.01	0.00	0.03	0	0.24
		02	Power Steering Subsystem	0.16	(0.07)	(0.00)	0.09	0.00	0.00	0.00	-	0.01	0	0.10
		04	Steering Column Subsystem	1.85	3.48	3.31	8.64	(0.04)	0.80	0.75	0.24	1.75	0	10.39
		05	Steering Column Switches Subsystem	-	-	-	-	-	-	-	-	-	-	-
		06	Steering Wheel Subsystem	(0.56)	(0.22)	(0.02)	(0.80)	0.23	0.53	0.36	0.01	1.12	0	0.32
			SUBSYSTEM ROLL-UP	1.67	3.19	3.28	8.15	0.18	1.34	1.13	0.25	2.90	0	11.05

Table A-14: Climate Control System Cost Breakdown

Item	System	Subsystem	Sub-Subsystem Description	NEW TECHNOLOGY GENERAL PART INFORMATION: Manufacturing Material	Manufacturing Labor	Manufacturing Burden	Total Manufacturing Cost (Component/ Assembly)	Markup End Item Scrap	Markup SG&A	Markup Profit	Markup ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
12 Climate Control														
1		01	Air Handling/Body Ventilation Subsystem	16.17	4.74	3.63	24.54	0.06	1.23	0.82	0.21	2.32	0	26.86
2		02	Heating/Defrosting Subsystem	1.43	0.59	0.29	2.31	0.01	0.12	0.08	0.02	0.22	0	2.52
3		03	Refrigeration/Air Conditioning Subsystem	-	-	-	-	-	-	-	-	-	-	-
4		04	Controls Subsystem	0.22	0.06	0.05	0.33	0.00	0.03	0.02	0.01	0.07	0	0.39
			SUBSYSTEM ROLL-UP	17.82	5.39	3.97	27.17	0.07	1.38	0.92	0.23	2.61	0	29.78

Item	System	Subsystem	Sub-Subsystem Description	BASE TECHNOLOGY GENERAL PART INFORMATION: Manufacturing Material	Manufacturing Labor	Manufacturing Burden	Total Manufacturing Cost (Component/ Assembly)	Markup End Item Scrap	Markup SG&A	Markup Profit	Markup ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
12 Climate Control														
1		01	Air Handling/Body Ventilation Subsystem	16.65	3.66	10.87	31.18	0.08	1.57	1.04	0.26	2.95	0	34.13
2		02	Heating/Defrosting Subsystem	1.22	0.65	2.29	4.16	0.01	0.21	0.14	0.03	0.39	0	4.55
3		03	Refrigeration/Air Conditioning Subsystem	-	-	-	-	-	-	-	-	-	-	-
4		04	Controls Subsystem	0.25	0.06	0.05	0.36	0.00	0.04	0.03	0.01	0.07	0	0.43
			SUBSYSTEM ROLL-UP	18.12	4.37	13.20	35.70	0.09	1.81	1.21	0.30	3.42	0	39.11

Item	System	Subsystem	Sub-Subsystem Description	INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE: Manufacturing Material	Manufacturing Labor	Manufacturing Burden	Total Manufacturing Cost (Component/ Assembly)	Markup End Item Scrap	Markup SG&A	Markup Profit	Markup ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
12 Climate Control														
1		01	Air Handling/Body Ventilation Subsystem	0.49	(1.08)	7.24	6.65	0.02	0.33	0.22	0.06	0.63	0	7.27
2		02	Heating/Defrosting Subsystem	(0.21)	0.06	2.00	1.85	0.00	0.09	0.06	0.02	0.18	0	2.03
3		03	Refrigeration/Air Conditioning Subsystem	-	-	-	-	-	-	-	-	-	-	-
4		04	Controls Subsystem	0.02	0.01	0.00	0.03	0.00	0.00	0.00	0.00	0.01	0	0.04
			SUBSYSTEM ROLL-UP	0.30	(1.01)	9.24	8.53	0.02	0.43	0.29	0.07	0.81	0	9.34

Table A-15: Info, Gage and Warning System Cost Breakdown

SYSTEM & SUBSYSTEM DESCRIPTION				NEW TECHNOLOGY GENERAL PART INFORMATION										
				Manufacturing				Markup						
Item	System	Subsystem	Sub-Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	13	Info, Gage and Warning System												
1		01	Instrument Cluster Subsystem	1.70	0.05	0.31	2.07	0.01	0.12	0.14	0.07	0.34	0	2.41
			SUBSYSTEM ROLL-UP	1.70	0.05	0.31	2.07	0.01	0.12	0.14	0.07	0.34	0	2.41

SYSTEM & SUBSYSTEM DESCRIPTION				BASE TECHNOLOGY GENERAL PART INFORMATION										
				Manufacturing				Markup						
Item	System	Subsystem	Sub-Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	13	Info, Gage and Warning System												
1		01	Instrument Cluster Subsystem	1.95	0.06	0.22	2.23	0.01	0.13	0.15	0.07	0.37	0	2.60
			SUBSYSTEM ROLL-UP	1.95	0.06	0.22	2.23	0.01	0.13	0.15	0.07	0.37	0	2.60

SYSTEM & SUBSYSTEM DESCRIPTION				INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE										
				Manufacturing				Markup						
Item	System	Subsystem	Sub-Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	13	Info, Gage and Warning System												
1		01	Instrument Cluster Subsystem	0.25	0.01	(0.09)	0.16	0.00	0.01	0.01	0.01	0.03	0	0.19
			SUBSYSTEM ROLL-UP	0.25	0.01	(0.09)	0.16	0.00	0.01	0.01	0.01	0.03	0	0.19

Table A-16: In-Vehicle Entertainment System Cost Breakdown

SYSTEM & SUBSYSTEM DESCRIPTION				NEW TECHNOLOGY GENERAL PART INFORMATION										
				Manufacturing				Markup						
Item	System	Subsystem	Sub-Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	15		In-Vehicle Entertainment											
1		01	Receiver and Audio Media Subsystem	1.22	0.61	0.76	2.59	0.01	0.26	0.18	0.02	0.48	0	3.07
2		02	Antenna Subsystem	0.03	0.03	0.02	0.08	0.00	0.01	0.01	0.00	0.02	0	0.09
3		03	Speaker Subsystem	-	-	-	-	-	-	-	-	-	-	-
			SUBSYSTEM ROLL-UP	1.26	0.64	0.78	2.67	0.01	0.27	0.18	0.02	0.49	0	3.16

SYSTEM & SUBSYSTEM DESCRIPTION				BASE TECHNOLOGY GENERAL PART INFORMATION										
				Manufacturing				Markup						
Item	System	Subsystem	Sub-Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	15		In-Vehicle Entertainment											
1		01	Receiver and Audio Media Subsystem	1.39	1.31	1.26	3.96	0.04	0.41	0.28	0.04	0.77	0	4.73
2		02	Antenna Subsystem	0.07	0.24	0.36	0.66	0.00	0.07	0.05	0.01	0.13	0	0.79
3		03	Speaker Subsystem	-	-	-	-	-	-	-	-	-	-	-
			SUBSYSTEM ROLL-UP	1.46	1.55	1.62	4.62	0.04	0.48	0.32	0.04	0.89	0	5.52

SYSTEM & SUBSYSTEM DESCRIPTION				INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE										
				Manufacturing				Markup						
Item	System	Subsystem	Sub-Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	15		In-Vehicle Entertainment											
1		01	Receiver and Audio Media Subsystem	0.16	0.70	0.50	1.37	0.03	0.15	0.10	0.01	0.29	0	1.66
2		02	Antenna Subsystem	0.04	0.21	0.34	0.58	0.00	0.06	0.04	0.01	0.11	0	0.69
3		03	Speaker Subsystem	-	-	-	-	-	-	-	-	-	-	-
			SUBSYSTEM ROLL-UP	0.20	0.91	0.84	1.95	0.03	0.21	0.14	0.02	0.40	0	(2.35)

Table A-17: Lighting System Cost Breakdown

SYSTEM & SUBSYSTEM DESCRIPTION				NEW TECHNOLOGY GENERAL PART INFORMATION										
Item	System	Subsystem	Sub-Subsystem Description	Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D			
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	17 Lighting													
1		01	Front Lighting	10.87	1.23	3.31	15.41	0.04	0.77	0.52	0.13	1.46	0	16.87
			SUBSYSTEM ROLL-UP	10.87	1.23	3.31	15.41	0.04	0.77	0.52	0.13	1.46	0	16.87

SYSTEM & SUBSYSTEM DESCRIPTION				BASE TECHNOLOGY GENERAL PART INFORMATION										
Item	System	Subsystem	Sub-Subsystem Description	Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D			
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	17 Lighting													
1		01	Front Lighting	7.91	2.26	4.55	14.72	0.04	0.74	0.49	0.12	1.39	0	16.11
			SUBSYSTEM ROLL-UP	7.91	2.26	4.55	14.72	0.04	0.74	0.49	0.12	1.39	0	16.11

SYSTEM & SUBSYSTEM DESCRIPTION				INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE										
Item	System	Subsystem	Sub-Subsystem Description	Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D			
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	17 Lighting													
1		01	Front Lighting	(2.95)	1.03	1.24	(0.69)	(0.00)	(0.03)	(0.02)	(0.01)	(0.07)	0	(0.76)
			SUBSYSTEM ROLL-UP	(2.95)	1.03	1.24	(0.69)	(0.00)	(0.03)	(0.02)	(0.01)	(0.07)	0	(0.76)

Table A-18: Electrical Distribution and Electronic Control System Cost Breakdown

SYSTEM & SUBSYSTEM DESCRIPTION				NEW TECHNOLOGY GENERAL PART INFORMATION:										
				Manufacturing				Markup						
Item	System	Subsystem	Sub-Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	18		Electrical Distribution and Electronic Control System											
1		01	Electrical Wiring and Circuit Protection Subsystem	7.61	0.62	0.58	8.82	0.03	0.45	0.34	0.05	0.87	-	9.69
			SUBSYSTEM ROLL-UP	7.61	0.62	0.58	8.82	0.03	0.45	0.34	0.05	0.87	-	9.69

SYSTEM & SUBSYSTEM DESCRIPTION				BASE TECHNOLOGY GENERAL PART INFORMATION:										
				Manufacturing				Markup						
Item	System	Subsystem	Sub-Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	18		Electrical Distribution and Electronic Control System											
1		01	Electrical Wiring and Circuit Protection Subsystem	8.92	0.59	0.63	10.14	0.03	0.51	0.34	0.03	0.90	-	11.04
			SUBSYSTEM ROLL-UP	8.92	0.59	0.63	10.14	0.03	0.51	0.34	0.03	0.90	-	11.04

SYSTEM & SUBSYSTEM DESCRIPTION				INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE										
				Manufacturing				Markup						
Item	System	Subsystem	Sub-Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
				USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	18		Electrical Distribution and Electronic Control System											
1		01	Electrical Wiring and Circuit Protection Subsystem	1.31	(0.03)	0.04	1.32	(0.00)	0.06	0.00	(0.03)	0.03	-	1.35
			SUBSYSTEM ROLL-UP	1.31	(0.03)	0.04	1.32	(0.00)	0.06	0.00	(0.03)	0.03	-	1.35

H.5 Suppliers Contributed in Study

System	Subsystem	Sub-Subsystem	Description	Major Supplier Contributed in Ideas	Logos
01	00	00	Engine System	Mubea, Mahle, DSM	Mubea MAHLE DSM
02	00	00	Transmission System	DuPont Alcast Company Aluminum Foundry	DUPONT ALCAST COMPANY
03	00	00	Body System(Group -A-) BIW & Closures	PolyOne	PolyOne
03	00	00	Body System(Group -B-) Interior	Trexel, Polyone, SABIC	TREXEL PolyOne سابك sabic
03	00	00	Body System(Group -C-) Exterior	PolyOne	PolyOne
03	00	00	Body System(Group -D-) Glazing & Body Mechatronics	Pikington, Exatec, Intermac	PILKINGTON EXATEC INTERMAC
04	00	00	Suspension System	Mubea, Delphi	Mubea DELPHI
05	00	00	Driveline System		
06	00	00	Brake System	Delphi	DELPHI
07	00	00	Frame and Mounting System		
09	00	00	Exhaust System	Mubea, SGF	Mubea SGF
10	00	00	Fuel System	Delphi	DELPHI
11	00	00	Steering System		
12	00	00	Climate Control System	Zotefoams, DSM	ZOTEFOAMS DSM
13	00	00	Info, Gage and Warning System	Trexel	TREXEL
14	00	00	Electrical Power Supply System		
15	00	00	In-Vehicle Entertainment System	Parker	Parker
17	00	00	Lighting System	SABIC, Trexel	سابك sabic TREXEL
18	00	00	Electrical Dis. And Electronic Control System		
19	00	00	Electronic Features System		

I. Glossary of Terms

Assembly: a group of interdependent components joined together to perform a defined function (e.g., turbocharger assembly, high pressure fuel pump assembly, high pressure fuel injector assembly).

Automatic Transmission (AT): is one type of motor vehicle transmission that can automatically change gear ratios as the vehicle moves, freeing the driver from having to shift gears manually.

BAS (Belt Alternator Starter): is a system design to start/re-start an engine using a non-traditional internal combustion engine (ICE) starter motor. In a standard internal ICE the crankshaft drives an alternator, through a belt pulley arrangement, producing electrical power for the vehicle. In the BAS system, the alternator is replaced with a starter motor/generator assembly so that it can perform opposing duties. When the ICE is running, the starter motor/generator functions as a generator producing electricity for the vehicle. When the ICE is off, the starter motor/generator can function as a starter motor, turning the crankshaft to start the engine. In addition to starting the ICE, the starter motor can also provide vehicle launch assist and regenerative braking capabilities.

Buy: the components or assemblies a manufacturer would purchase versus manufacture. All designated "buy" parts, within the analysis, only have a net component cost presented. These types of parts are typically considered commodity purchase parts having industry established pricing.

CBOM (Comparison Bill of Materials): a system bill of materials, identifying all the subsystems, assemblies, and components associated with the technology configurations under evaluation. The CBOM records all the high-level details of the technology configurations under study, identifies those items which have cost implication as a result of the new versus base technology differences, documents the study assumptions, and is the primary document for capturing input from the cross-functional team.

Component: the lowest level part within the cost analysis. An assembly is typically made up of several components acting together to perform a function (e.g., the turbine wheel in a turbocharger assembly). However, in some cases, a component can independently perform a function within a sub-subsystem or subsystem (e.g., exhaust manifold within the exhaust subsystem).

Cost Estimating Models: cost estimating tools, external to the Design Profit® software, used to calculate operation and process parameters for primary manufacturing processes (e.g., injection molding, die casting, metal stamping, forging). Key information calculated from the costing estimating tools (e.g., cycle times, raw material usage, equipment size) is inputted into the Lean Design® process maps supporting the cost analysis. The Excel base cost estimating models are developed and validated by Munro & Associates.

Costing Databases: the five (5) core databases that contain all the cost rates for the analysis. (1) The **material database** lists all the materials used throughout the analysis along with the estimated price/pound for each. (2) The **labor database** captures various automotive, direct labor, manufacturing jobs (supplier and OEM), along with the associated mean hourly labor rates. (3) The **manufacturing overhead rate database** contains the cost/hour for the various pieces of manufacturing equipment assumed in the analysis. (4) A **mark-up database** assigns a percentage of mark-up for each of the four (4) main mark-up categories (i.e., end-item scrap, SG&A, profit, and ED&T), based on the industry, supplier size, and complexity classification. (5) The **packaging database** contains packaging options and costs for each case.

Cross Functional Team (CFT): is a group of people with different functional expertise working toward a common goal.

Direct Labor (DIR): is the mean manufacturing labor wage directly associated with fabricating, finishing, and/or assembling a physical component or assembly.

Dual Clutch Transmission (DCT): is a differing type of semi-automatic or automated manual automotive transmission. It utilizes two separate clutches for odd and even gear sets. It can fundamentally be described as two separate manual transmissions (with their respective clutches) contained within one housing, and working as one unit. They are usually operated in a fully automatic mode, and many also have the ability to allow the driver to manually shift gears, albeit still carried out by the transmission's electro-hydraulics.

ED&T (engineering, design, and testing): is an acronym used in accounting to refer to engineering, design, and testing expenses.

Fringe (FR): all the additional expenses a company must pay for an employee above and beyond base wage.

Fully Variable Valve Actuation (FVVA): is a generalized term used to describe any mechanism or method that can alter the shape or timing of a valve lift event within an internal combustion engine.

Gasoline Direct Inject (GDI): is a variant of fuel injection employed in modern two-stroke and four-stroke gasoline engines. The gasoline is highly pressurized, and injected via a common rail fuel line directly into the combustion chamber of each cylinder, as opposed to conventional multi-point fuel injection that happens in the intake tract, or cylinder port.

Hybrid Electric Vehicle (HEV): is a type of hybrid vehicle and electric vehicle which combines a conventional internal combustion engine (ICE) propulsion system with an electric propulsion system.

Internal Combustion Engine (ICE): is an engine in which the combustion of a fuel occurs with an oxidizer in a combustion chamber.

Indirect Cost Multipliers (ICM): is developed by EPA to address the OEM indirect costs associated with manufacturing new components and assemblies. The indirect costs, costs associated with OEM research and development, corporate operations, dealership support, sales and marketing material, legal, and OEM owned tooling, are calculated by applying an ICM factor to the direct manufacturing cost.

Indirect Labor (IND): is the manufacturing labor indirectly associated with making a physical component or assembly.

Intellectual property (**IP**): is a term referring to a number of distinct types of creations of the mind for which a set of exclusive rights are recognized under the corresponding fields of law.

Lean Design® (a module within the *Design Profit® software):* is used to create detailed process flow charts/process maps. Lean Design® uses a series of standardized symbols, with each base symbol representing a group of similar manufacturing procedures (e.g., fastening, material modifications, inspection). For each group, a Lean Design® library/database exists containing standardized operations along with the associated manufacturing information and specifications for each operation. The information and specifications are used to generate a net operation cycle time. Each operation on a process flow chart is represented by a base symbol, operation description, and operation time, all linked to a Lean Design® library/database.

Maintenance Repair (MRO): aall actions which have the objective of retaining or restoring an item in or to a state in which it can perform its required function. The actions include the combination of all technical and corresponding administrative, managerial, and supervision actions

Make: terminology used to identify those components or assemblies a manufacturer would produce internally versus purchase. All parts designated as a "make" part, within the analysis, are costed in full detail.

MAQS (Manufacturing Assumption and Quote Summary) worksheet: standardized template used in the analysis to calculate the mass production manufacturing cost, including supplier mark-up, for each system, subsystem, and assembly quoted in the analysis. Every component and assembly costed in the analysis will have a MAQS worksheet. The worksheet is based on a standard OEM (original equipment manufacturer) quote sheet modified for improved costing transparency and flexibility in sensitivity studies. The main feeder documents to the MAQS worksheets are **process maps** and the **costing databases**.

MCRs (Material Cost Reductions): a process employed to identify and capture potential design and/or manufacturing optimization ideas with the hardware under evaluation. These savings could potentially reduce or increase the differential costs between the new and base technology configurations, depending on whether an MCR idea is for the new or the base technology.

Metal injection molding (**MIM**): is a metalworking process where finely-powdered metal is mixed with a measured amount of binder material to comprise a 'feedstock' capable of being handled by plastic processing equipment through a process known as injection mold forming

MSRP: Manufacturing Suggested Retail Price

Naturally Aspirated (NA): is one common type of reciprocating piston internal combustion that depends solely on atmospheric pressure to counter the partial vacuum in the induction tract to draw in combustion air.

Net Component/Assembly Cost Impact to OEM: the net manufacturing cost impact per unit to the OEM for a defined component, assembly, subsystem, or system. For components produced by the supplier base, the net manufacturing cost impact to the OEM includes total manufacturing costs (material, labor, and manufacturing overhead), mark-up (end-item scrap costs, selling, general and administrative costs, profit, and engineering design and testing costs) and packaging costs. For OEM internally manufactured components, the net manufacturing cost impact to the OEM includes total manufacturing costs and packaging costs; mark-up costs are addressed through the application of an indirect cost multiplier.

NTAs (New Technology Advances): a process employed to identify and capture alternative advance technology ideas which could be substituted for some of the existing hardware under evaluation. These advanced technologies, through improved function and performance, and/or cost reductions, could help increase the overall value of the technology configuration.

Port Fuel Injected (PFI): is a method for admitting fuel into an internal combustion engine by fuel injector sprays into the port of the intake manifold.

Powertrain Package Proforma: a summary worksheet comparing the key physical and performance attributes of the technology under study with those of the corresponding base configuration.

Power-Split HEV: In a power-split hybrid electric drive train there are two motors: an electric motor and an internal combustion engine. The power from these two motors can be shared to drive the wheels via a power splitter, which is a simple planetary gear set.

Process Maps: detailed process flow charts used to capture the operations and processes and associated key manufacturing variables involved in manufacturing products at any level (e.g., vehicle, system, subsystem, assembly, and component).

P-VCSM (Powertrain–Vehicle Class Summary Matrix): records the technologies being evaluated, the applicable vehicle classes for each technology, and key parameters for vehicles or vehicle systems that have been selected to represent the new technology and baseline configurations in each vehicle class to be costed.

Quote: the analytical process of establishing a cost for a component or assembly.

RPE: Retail Price Equivalent

SG&A (selling general and administrative): is an acronym used in accounting to refer to Selling, General and Administrative Expenses, which is a major non-production costs presented in an Income statement.

Sub-subsystem: a group of interdependent assemblies and/or components, required to create a functioning sub-subsystem. For example, the air induction subsystem contains several sub-subsystems including turbocharging, heat exchangers, pipes, hoses, and ducting.

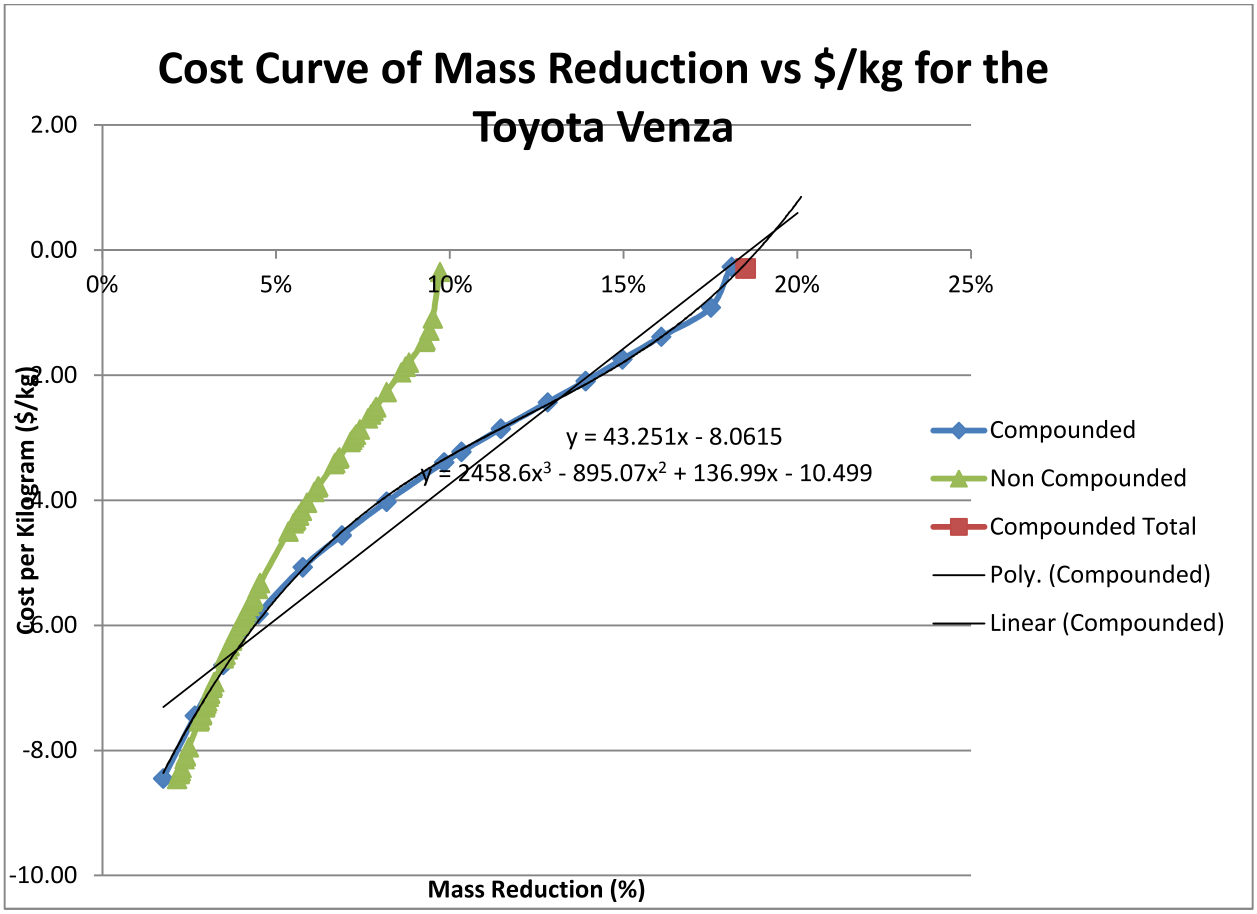
Subsystem: a group of interdependent sub-subsystems, assemblies and/or components, required to create a functioning subsystem. For example, the engine system contains several subsystems including crank drive subsystem, cylinder block subsystem, cylinder head subsystem, fuel induction subsystem, and air induction subsystem.

Subsystem CMAT (Cost Model Analysis Templates): the document used to display and roll up all the sub-subsystem, assembly, and component incremental costs associated with a subsystem (e.g., fuel induction, air induction, exhaust), as defined by the Comparison Bill of Material (CBOM).

Surrogate part: a part similar in fit, form, and function as another part that is required for the cost analysis. Surrogate parts are sometimes used in the cost analysis when actual parts are unavailable. The surrogate part's cost is considered equivalent to the actual part's cost.

System: a group of interdependent subsystems, sub-subsystems, assemblies, and/or components working together to create a vehicle primary function (e.g., engine system, transmission system, brake system, fuel system, suspension system).

System CMAT (Cost Model Analysis Template): the document used to display and roll up all the subsystem incremental costs associated with a system (e.g., engine, transmission, steering) as defined by the CBOMs.



Cost Curve of Mass Reduction vs $/kg for the Toyota Venza
2.00
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
0%
5%
10%
15%
20%
25%
Cost per Kilogram ($/kg)
Mass Reduction (%)
y = 43.251x - 8.0615
y = 2458.6x³ - 895.07x² + 136.99x - 10.499
Compounded
Non Compounded
Compounded Total
Poly. (Compounded)
Linear (Compounded)