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# Mass Reduction for Light-Duty Vehicles for Model Years 2017–2025: Peer Review Summary Report

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# PEER REVIEW OF "MASS REDUCTION FOR LIGHT-DUTY VEHICLES FOR MODEL YEARS 2017-2025"

## PEER REVIEW SUMMARY REPORT
## August 8, 2016

*Submitted to:*
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# CONTENTS

# 1.0 INTRODUCTION

This report documents the results of an independent external peer review of the draft report, *Mass Reduction for Light-Duty Vehicles for Model Years 2017-2025*, developed by EDAG, Inc. for the National Highway Traffic Safety Administration (NHTSA).

Eastern Research Group, Inc. (ERG, a contractor to NHTSA) organized this review and developed this report. The report provides background about the review (Section 1.1), describes the review process (Section 1.2), and provides an executive summary of reviewer comments (Section 1.3). Section 2 presents reviewer comments organized by charge question. Appendices A, B, and C, respectively, provide the charge to reviewers, the individual comments submitted by each of the four reviewers, and reviewer curriculum vitae. Reviewer comments in Section 2 and Appendix B are presented exactly as submitted, without editing or correction of typographical errors (if any).

## 1.1 Background

In response to the 1973 oil crisis, the U.S. Congress passed the Energy Policy and Conservation Act (EPCA) in 1975, establishing the federal Corporate Average Fuel Economy (CAFE) program. In its original form, EPCA directed the National Highway Traffic Safety Administration (NHTSA) to set standards "at a level which the Secretary [of the U.S. Department of Transportation] determines is the maximum feasible average fuel economy level which such manufacturers are able to achieve in each model year." In determining the "maximum feasible" level, EPCA required NHTSA to consider technological feasibility; economic practicability; the effect of other motor vehicle standards on fuel economy; and the need of the United States to conserve energy. As a safety agency, NHTSA has also historically considered the potential safety effects of CAFE standards.

After more than 30 years in effect, EPCA was amended by the Energy Independence and Security Act (EISA) of 2007 to further stipulate that CAFE standards be increased such that model year (MY) 2020 fleetwide fuel economy standards reach at least 35 miles per gallon (mpg). Implementation of the EISA provisions involves multiple phases, and is being carried out in coordination with the U.S. Environmental Protection Agency (EPA) and the California Air Resources Board. The first phase applied to MY 2017-2021 vehicles. The second phase will set CAFE standards for MY 2022-2025 vehicles following a midterm review of the program.

As fleet-average standards that have the capability to require near-total redesigns of new vehicles, CAFE standards have the potential to significantly affect a major industrial sector in a variety of ways. They influence auto manufacturers' choice of technologies, and may also affect fuel prices; refueling infrastructure (gasoline, electric, and other alternative fuels); driving habits; energy security; climate change and air pollution; on-road safety; and many other factors that NHTSA must consider in determining the maximum feasible CAFE levels. It is therefore critical that NHTSA's assessment of potential standards be supported by accurate and comprehensive technical and economic analyses.

One of the key strategies automakers are expected to use to meet increasingly stringent fuel economy standards under EPCA/EISA is mass reduction, or lightweighting. Therefore, NHTSA is very interested in analyzing the potential benefits and consequences of mass reduction as part of their assessment of the maximum feasible fuel economy levels.

In support of this goal, NHTSA tasked Eastern Research Group, Inc. (ERG), a contractor to NHTSA, with organizing an independent peer review of a report entitled *Mass Reduction for Light-Duty Vehicles for Model*

*Years 2017-2025*, with a focus on light-duty pickup trucks. This report summarizes the results of that peer review.

The peer reviewed report included the following components:

**Baseline Vehicle Tear-Down and Finite Element Analysis Modeling**. The report details the selection of a baseline vehicle to represent the light-duty pickup truck fleet and the performance of a teardown study used to establish baselines for the engineering analyses and cost analyses of a lightweighted design.

**Design and Optimization for the Lightweighted Pickup Truck.** The report demonstrates the application of advanced design, materials, and manufacturing processes that will likely be available for high volume production of MY 2020-2030 light-duty pickup trucks. A computer-aided engineering analysis to demonstrate crashworthiness and an incremental cost estimate for the lightweighted vehicle relative to the baseline vehicle are also included.

**Mass Reduction for Other Light-Duty Vehicles.** The report also provides information on the application of mass reduction technologies identified for the pickup truck project to other classes of light-duty passenger vehicles.

## 1.2 Peer Review Process

NHTSA tasked ERG with identifying four reviewers who had no conflict of interest (COI) in performing the review and who, collectively, met the following selection criteria:

- At least 10 years of direct automotive industry experience in the field of crashworthiness, body engineering, and material selection for light weighting (at least two reviewers).
- Expertise in automotive light weighting concepts and strategies in material selection and technology assessment of advanced vehicle designs (at least two reviewers).
- Expertise in cost assessment of lightweight automotive materials and advanced vehicle design (at least one reviewer).
- Experience analyzing results from computer modeling (at least one reviewer to validate the model methods and results).
- Thorough knowledge of federal motor vehicle standards and other performance requirements from the Insurance Institute of Highway Safety (at least two reviewers).

ERG initiated a search process, asking interested candidates to describe their qualifications and respond to a series of "Conflict of Interest" (COI) analysis questions. ERG carefully screened submissions to identify a pool of qualified, COI-free candidates. From this pool, ERG selected the four experts (listed below) who collectively best met the selection criteria. ERG contracted with the reviewers after NHTSA verified that they were appropriately qualified.

Two general reviewers reviewed the entire report, one reviewer focused on the cost assessment, and the fourth reviewer focused on the crash model sections of the report:

- **Sujit Das, M.B.A**., Senior Research Staff Member, Energy and Transportation Science Division, Oak Ridge National Laboratory (cost assessment reviewer).
- **Prakash Krishnaswamy, M.S**., CEO of Xitadel LLC (general reviewer).
- **Dhafer Marzougui, D.Sc.**, Research Director, Center for Collision Safety and Analysis (CCSA), George Mason University (crash model reviewer).
- **Priyaranjan Prasad, Ph.D.**, Prasad Consulting, LLC (general reviewer).

See Appendix C for reviewer curriculum vitae.

ERG provided reviewers with the review document, the charge to reviewers (Appendix A), cost model files, crash model files, and additional background materials. Reviewers worked individually (i.e., without contact with other reviewers or NHTSA) to prepare written comments in response to the charge questions. During this time, one reviewer sent additional questions of clarification to ERG. ERG forwarded these questions to NHTSA and provided NHTSA's responses to all four reviewers. Reviewers completed their individual reviews and submitted their written comments to ERG. ERG forwarded reviewers' original responses to NHTSA and then prepared this report.

### 1.3 Executive Summary of Reviewer Comments

The four reviewers – Sujit Das, Prakash Krishnaswamy, Dhafer Marzougui, and Priyaranjan Prasad – responded to questions within their areas of expertise (with Krishnaswamy and Prasad provided general expertise, Das focusing on the cost assessment, and Marzougui focusing on the modeling components). All reviewers found the report to be well-organized and readable, and generally praised its clarity and thoroughness. Overall, the reviewers gave the report's methodology and conclusions a favorable review, while also suggesting potential areas for improvement and further study.

All four reviewers commented on whether the study's conclusions were adequately backed up by the methods and analytical rigor employed. Krishnaswamy found the work to be competent, comprehensive, and thorough. Prasad stated that, at a high level, the study's conclusions were backed up by their thoroughness in identifying materials that are cost effective and that provide opportunities for mass reduction. Marzougui said that the methods used in the study were adequate. Das thought that the study's conclusions, based on the methods and analytical rigor, were very well documented, in an impressive, well-written, and large report.

The reviewers also identified facets of the report that they felt were especially strong. Prasad highlighted the good use of computer-aided engineering tools. Krishnaswamy was particularly impressed with the topology optimization techniques, and commended the use of state-of-the-art computer simulation and optimization. Das stated that the final lightweight component technology selection for the lightweighted truck (LWT) vehicle design was based on strong, technically rigorous analyses of the mass saving potential and cost of implementation of technologies currently being considered in the industry.

In addition to the overall assessment, the charge questions solicited detailed comments from the reviewers on all components of the study, including the selection and analysis of the baseline vehicle, the design and analysis of the LWT, and the application of mass reduction technologies to other classes of light-duty passenger vehicles.

Reviewers generally felt that the selection of the 2014 Chevrolet Silverado as a baseline vehicle and the methodology used to determine its baseline functionality were appropriate.

The design of the LWT, including material selection, was also generally seen to be appropriate. The fact that the study adopted a strategy that is almost the same as the approach already used by Ford for its F-150, i.e., an aluminum-intensive body on a steel frame, was seen by multiple reviewers as a positive indicator of the feasibility of the proposed LWT design. Regarding the validity of the material choices used to reduce vehicle mass, Prasad thought that the data sources and assumptions were as good as they could be given the study's scope. Given the significant growth in the adoption of aluminum for lightweighting, the widespread use of advanced high-strength steel (AHSS), and the continued development of new AHSS alloys with even greater strength, Krishnaswamy thought that the choice of these materials for the LWT design was reasonable and well justified. Prasad and Krishnaswamy concurred that the joining techniques described in the report were appropriate and proven technologies. In general, Krishnaswamy, Prasad, and Das thought that no different lightweight vehicle design technologies were likely to be more common in the relevant model years than the ones assessed in the study.

The crashworthiness modeling was reviewed in detail by Marzougui, both in response to the charge questions and in a detailed model evaluation. Other reviewers provided input where appropriate. Overall, Marzougui stated that the conclusions of this study regarding the feasibility of designing a LWT that has the same crashworthiness functionality as the baseline design were supported by the computer simulation results. Marzougui noted that the study assumptions and approach used for the LWT crashworthiness assessment were similar to the ones used in a recent study of mid-size vehicle mass reduction, and also stated that the methodology used to assess the safety performance of the LWT design was similar to what all automotive manufacturers and other researchers in the field of vehicle crashworthiness use, including Finite Element Analysis tools that have been employed for over 25 years. Prasad and Marzougui both indicated that the study employed state-of-the-art methods and tools, including finite element structural simulations (LS-DYNA). Prasad, Das, and Marzougui all concluded that an adequate approach was used to ensure that baseline vehicle functionalities were maintained.

Das judged both of the cost modeling methods used in the report, technical cost modeling and supplier assessments, to be appropriate for the incremental cost estimate of the LWT design, and said that the conclusions about the design, development, validation, and cost of the LWT design were valid.

Two of the reviewers (Prasad and Das) who responded regarding the methodology used to estimate the feasible mass reduction in other light-duty vehicle classes found the approach to be generally reasonable. However, Krishnaswamy and Das cautioned that different vehicle classes may present different potentials for mass reduction given differences in vehicle price, performance requirements, and functionality requirements.

The reviewers also had a number of suggestions for improving the study's underlying assumptions and documentation. One key recommendation was that the LWT design push the envelope more, particularly in the later model years considered in this study. Although the study did help demonstrate the feasibility of the proposed design, the fact that the LWT design closely resembled the design of the 2015 Ford F-150 was seen as evidence that probable future advances in materials and manufacturing technology were not fully exploited. For example, two reviewers mentioned that the frame design was not substantially modified to take advantage of the properties of modern aluminum alloys.

A caveat reviewers highlighted was that the LWT design had not yet been validated using hardware prototypes, generating some uncertainty about whether the predicted mass reductions could actually be realized. Krishnaswamy indicated that this uncertainty should also be considered in the extrapolation of results from the LWT study to other light-duty vehicles.

Other major recommendations were to perform simulations with failure defined for all high-strength materials to verify that this does not affect the predicted results (Marzougui); consider the coupling of manufacturing processes and crashworthiness (Krishnaswamy); and include more analytical detail to facilitate independent reproduction of the study's results (Prasad).

In their overall recommendations, three reviewers found the report to be acceptable with minor revisions. The fourth reviewer, Krishnaswamy, found the report acceptable with major revisions to address the large gap between the LWT weight reduction and the reduction achieved by the 2015 Ford F-150; add more context to the section on the mass reduction for other light-duty vehicles; and more completely demonstrate that the technical objectives of the project had been met.

# 2.0 REVIEWER COMMENTS ORGANIZED BY CHARGE QUESTION

This section presents reviewer comments organized by charge question. Sections 2.1 to 2.8 correspond to the eight sections of the charge (Appendix A). Section 2.9 presents additional comments provided by two reviewers.

## 2.1 Assumptions and Data Sources

### a) Please comment on the validity of data sources and assumptions embedded in the study's material choices, vehicle design and optimization, crash validation testing, and cost assessment that may affect the report's findings.

| Reviewer | Comments |
|---|---|
| **Das** | The detailed teardown data of a baseline 2014 Chevrolet Silverado was used for the LWT design. It is appropriate that Silverado was selected as the baseline because of its 5-star rating and latest design used in comparison with the largest sales volume F-150 pickup truck in the market today. The suitability and maturity of each five major lightweight materials manufacturing and assembly technologies considered for major vehicle systems, body structure, closures, and chassis frame were initially classified as mature, mid-term, and long term. The lightweight materials considered for the LWT design were mostly limited to AHSS and aluminum, already being used in some of the high-volume vehicles in the market today which have been classified for various vehicle subsystems as either mature or mid-term. It is interesting to note that the carbon fiber reinforced plastic (CFRC) material option in 2014 was considered as mid-term compared to resin transfer molding (RTM) as long-term, the latter being one of the manufacturing options for CFRC used in the industry today. Sheet molding compound technology commonly used for fiber glass reinforced plastics today was considered as two distinct options, and as a long term technology option today. This lightweight material option has only been considered for the leaf springs of rear suspension. A consistent set of program and general process input data were used for the vehicle part and cost assessment. |
| **Krishnaswamy** | There is no specific section in the report that identifies data sources for material choices, nor of specific material grades. |
| **Marzougui** | The methodology used in this study to assess the safety performance of the LWT design is similar to what all automotive manufacturers and other researchers in the field of vehicle crashworthiness use. The method makes use of Finite Element Analysis (FEA) tools that have been employed for over twenty-five years and have been proven to be effective and efficient in the vehicle design and evaluation process. The method however has its limitations and special care should be taken in the model creation and simulation analyses to ensure accurate simulation predictions are achieved. |
| **Prasad** | The data sources and assumptions in the material choices to reduce vehicle mass are as good as they can get at this stage of the study. The teardown of the base design is exhaustive and the team has done a great job. The choices of material and design |

| Reviewer | Comments |
|---|---|
| | strategy adopted make sense. The fact that the study adopted a strategy almost the same as what has already been adopted by Ford in its F150, i.e. Aluminum intensive body on a steel frame, show the feasibility of the proposal. However, the study does not come up with more innovative solutions for weight reduction as they are already in production on a mass scale. I would have expected a detailed study of what it would take to replace the steel frame with an aluminum frame in a cost effective manner by redesigning the frame structure to take advantage of the properties of Aluminum.<br><br>The baseline frontal crash simulations are acceptable for comparisons with responses of the optimized design, although some other data readily available from their simulations would be more illuminating. For example, the crash pulses in the IIHS moderate and small offset crashes are not reported leaving one to assume that the authors believe that intrusions are more important than the crash pulse. The intrusions reported for the baseline simulation are higher than those observed in the NCAP tests. The door velocity and intrusion time histories are important to determine gap closure times for airbag firing times in side impacts (FMVSS 214 pole, NHTSA NCAP and IIHS side tests). Similar lack of reporting of the occupant compartment acceleration levels leaves one to wonder about the severity of rear end crashes. |

**b) If you find issues with data sources and assumptions, please explain what you believe the issues are and why they are problematic, and provide suggestions for available data that would improve the study.**

| Reviewer | Comments |
|---|---|
| **Das** | Data sources and underlying assumptions are mostly valid with an appropriate reference list of information sources provided. Specific problematic issues requiring attention are listed below under “Additional Comments.” |
| **Krishnaswamy** | No comments provided. This is outside the bounds of my expertise. |
| **Marzougui** | Overall, the study assumptions and approach used for the LWT crashworthiness assessment seem valid. The methods are similar to the ones used in a recent study of mid-size vehicle mass reduction. Based on the review of the model and simulation results, one key factor that may need to be re-examined is material and connection failure parameters defined in the models. This is especially critical for high-strength steels where the material is more likely to rupture rather than buckle. This is also important for the IIHS small-overall impact evaluation (i.e., test) where failures of tire/suspension components have significant effects on the vehicle response. Some high-strength parts and connections in the models were not assigned failure parameters. This applies to both the LWT and Baseline models. |
| **Prasad** | See question 2.1 a. above. |

## 2.2 Vehicle Design and Optimization Methodology and its Rigorousness

### a) Please comment on the material selection and usage, joining technologies, vehicle structure design and optimization methodology, and the resulting final vehicle design.

<table>
<tr><th>Reviewer</th><th>Comments</th></tr>
<tr><td>Das</td><td>The options for lightweighting technologies and solutions applied to the LWT were based on a detailed assessment of several baseline vehicle systems. AHSS, aluminum, and to a limited extent, magnesium, were generally considered for the most vehicle components, being the most mature and suitable for cost-effective high volume production in today's vehicles. It is confusing in the report when mentioning the model year(s) beyond the MY 2017-2025 time frame (e.g., MY 2020-2030 for high volume production on p. 23, 253 & 254) for the selection basis of available lightweight material manufacturing technologies the specific lightweight material selection is mostly based on today's technology maturity level and not the future. Although the desired vehicle mass savings potential and cost penalty were achieved using the available high-volume production lightweight materials available today, but considering a different mix of lightweight materials would have been more appropriate at least for the latter vehicle design generations, i.e., MY 2025 and MY 2030. A consideration of the vehicle design analysis at the four distinct level design generations, MY 2017, MY 2020, MY 2025, and MY 2030 would be more logical for the longer design time-frame as noted several times throughout the report.<br><br>Conventional lightweight materials such as AHSS, aluminum, magnesium, and plastics, manufacturing processes (stamping, hot stamping, die casting, extrusions, and roll forming) and assembly methods (stamping, hot stamping, die casting, extrusions, and roll forming) currently in use were only considered. The process parameters for manufacturing with advanced materials have been validated by computer simulation. The latest weight saving optimization tools such as body structure CAE optimization for material gage-grade-geometry selection has been used. In addition, the final specific technology selection was based on the rating for its mass saving potential and cost of implementation in terms of $ per kg mass saving besides the consideration of multi-material joining issues of several options for similar applications in use in the industry today. However, it is unclear whether any iterative lightweighting vehicle mass optimization procedure was used to meet the final vehicle retail price premium goal.</td></tr>
<tr><td>Krishnaswamy</td><td>1. The lightweight materials options considered for the LWT are Advanced High Strength Steels (AHSS), Aluminum, Magnesium and Plastics/carbon fiber.<br><br>These are common lightweighting materials options in the automobile industry. The LWT is a body-on-frame vehicle concept and the two key subsystems are chassis frame and body, the latter including closures, frond-end sheet metal and box. For these two subsystems, the materials chosen were AHSS and Aluminum respectively. These are sensible choices for the LWT. Both of these materials are widely used in the industry and are also suited for high volume manufacturing.</td></tr>
</table>

| Reviewer | Comments |
|---|---|
| | **AHSS** is widely used and continues to evolve with new alloys offering greater strength although these new alloys present challenges to manufacturers with regard to their formability.<br><br>In the 2025-2030 time frame, High Alloy 2nd Gen AHSS, Low Alloy 3rd Gen AHSS, Low Density High Manganese and Thick Core Laminates will enable a second generation of redesign of the current LMT vehicle.<br><br>**Aluminum** is seeing significant growth as a lightweight material alternative for automobile body applications. At a third of the weight of steel, it is a good lightweighting choice. One point to note is that the rapid rise in demand for Aluminum can present challenges to the supply base. Some of the OEMs presently are signing long term contracts to ensure uninterrupted supply. Given the 2025-2030 time frame, the availability of the metal should not be a concern.<br><br>Currently, 5xxx alloys (Al-Mg) Sheet, 6xxx series (Al-Mg-Si) Extrusions & Sheet and 7xxx Alloys are available for lightweight applications. By the 2025-2030 time frame, more options will be available as HS extrusion and sheet in 5XXX, 6xxx and HS extrusion and Stamping in 7xxx series. These new offerings will help enable a second generation of redesign of the current LWT vehicle.<br><br>**Magnesium** is suitable for smaller parts but the manufacturers of the high volume Light Duty segment may be deterred by the fact that over 85% of the material is imported from China. **Carbon-fiber** has great lightweighting potential, given its high strength to weight ratio. The cost of carbon fiber however is high and it tracks the price of petroleum. Moreover, concerns of repairability, production volume, etc. make carbon fiber unsuitable in the 2020-2030 time frame.<br><br>**Summarily, the choice of AHSS and Aluminum for most of the lightweighting needs of the LWT is reasonable and well justified.**<br><br>2. The joining technologies considered in the study for the LWT frame are acceptable; they are proven and suited for high volume production.<br><br>The joining technique considered for the Aluminum body is a combination of Adhesive bonding and self-piercing rivets (SPR). This technology, originally pioneered by European automotive manufacturers, is now widely used in high volume Aluminum body structures. |
| **Marzougui** | *This reviewer was not charged with responding to this question.* |
| **Prasad** | I do not see any issues with material selection or its usage in production in the time frame of interest. I believe that joining techniques described in the report are already well known and will evolve in the future to further reduce cost and improve reliability in mass scale production. |

### b) Describe the extent to which state-of-the art design methods have been employed, as well as the extent to which the associated analysis exhibits strong technical rigor.

<table>
<tr><th>Reviewer</th><th>Comments</th></tr>
<tr><td>Das</td><td> The final specific lightweight component technology selection for a LWT vehicle design has been based on a strong technical rigorous mass saving potential and cost of implementation analyses of potential technology options being considered in the industry today. Although the latest weight saving optimization tools for the LWT design validation, but the selection of lightweight materials and joining methods particularly when the analysis time frame considered extends beyond 10 years, were mostly materials and manufacturing technologies widely used in the industry today. The effect of mass compounding at the component level due to the overall LWT overall mass has been considered, but the methodology used to derive at the downsized component masses hasn't been discussed. The effect of the lower LWT vehicle mass and smaller engine/transmission on the lighter fuel system, engine cooling system, and exhaust were also considered in the analysis. For those cases, a net cost savings in the LWT design looks reasonable, unlike in FESM and radiator support structure. The specific component technology was primarily driven by the minimum risk in the technology readiness within the time frame of 2020-2030 considered in the study although the report title indicates MYs 2017-2025. </td></tr>
<tr><td>Krishnaswamy</td><td><ol><li>The CAE software used in the study are well known. LS-DYNA, the software used for the crash simulations, NASTRAN, ADAMS, etc. are all industry standard tools and can be relied upon to provide credible simulation solutions. The topology optimization techniques used in the study are impressive. Of particular interest is the modeling of the adhesive/self-piercing riveted joints between Aluminum panels. The report provides good references and sources for the data required. Summarily, the contractor has used state-of-the-art computer simulation and optimization, this is commendable.</li><li>However, modeling the new class of Steels and Aluminum is complex and requires established validated simulation techniques and methodologies. The extent of technical rigor is not entirely clear to me from a reading of the report.</li><li>In the case of both the new generation of Steels and Aluminum, manufacturing and crashworthiness simulations are inherently coupled. The simulations conducted do not appear to have taken this into account. Further, complexities posed by these new materials in simulation include: For Steels, <ol type="i"><li>Manufacturing process will cause the steels to work-harden; change Phase (e.g., TRIP and Hot Formed)</li><li>Material will accumulate property changes during the manufacturing process</li></ol></li></ol></td></tr>
</table>

| Reviewer | Comments |
|---|---|
| | iii. Appropriate data and CAE modeling procedure are needed to predict final geometry of the part, and to capture appropriate physical properties throughout the manufacturing of final design.<br>iv. Process needed for passing these properties to the crash simulation - Mapping of property changes is currently the most challenging aspect of this process.<br><br>For Aluminum (compared to Steel):<br><br>i. Anisotropic yield (different yield stress in different directions)<br>ii. Anisotropic flow (different R-values in different directions)<br>iii. Tensile-compressive asymmetry<br>iv. PLC effects and other plastic instabilities<br>v. Higher order shape of the yield surface and related influence on shear strength and biaxial strength.<br>vi. Many complex material models are available in state-of-the-art software for manufacturing simulations, but certain features needed for crash simulations such as rate dependency, failure, damage, and erosion are lacking. |
| **Marzougui** | *This reviewer was not charged with responding to this question.* |
| **Prasad** | At this stage of development and design of a mass reduced vehicle, the authors have done a good job using CAE technology. In my mind, very little analytical data is presented in the report apart from several statements in the body of the report to the effect that the assembled team has expertise in this type of work. It is doubtful if other groups can duplicate the results presented without careful examination of the full body and chassis Finite Element models developed by the authors. This again is beyond the scope of my review. |

### c) If you are aware of other methods employed elsewhere to select and analyze advanced materials and design engineering rigor for 2017-2025 vehicles, please comment on if and how they might improve the study and how they might be used.

| Reviewer | Comments |
|---|---|
| **Das** | Most potential methods used for advanced materials and design engineering design have been adequately considered for 2017-2025 vehicles. A multi-material design approach (commonly known as "Rightweighting" – a specific lightweight material is detrimental to its final application) has been considered for various potential vehicle component designs, which has been used to the extent possible in this LWT design study with a due consideration of multi-material joining issues. |
| **Krishnaswamy** | No comments provided. This is outside the bounds of my expertise. |

| Reviewer | Comments |
|---|---|
| **Marzougui** | *This reviewer was not charged with responding to this question.* |
| **Prasad** | I agree with the selection of the materials in the report. Based on the report, I believe that the authors have used the methods commonly utilized by OEM's. Stochastic analysis might have led to more accurate answers in terms of actual vehicle responses in crash because such an analysis accounts for variability in material properties, metal gage thickness and weld, rivet or adhesive failures. However, this is beyond the scope of this study. |

## 2.3 Vehicle Functionalities and Crashworthiness Testing Methodological Rigor

### a) Please comment on the approach and effort in maintaining baseline vehicle functionalities while trying to lightweight the vehicle.

| Reviewer | Comments |
|---|---|
| **Das** | Based on LS-DYNA finite element crash analysis simulations, the LWT design structural performance in NHTSA's New Car Assessment Program (NCAP), frontal, side, and side pole test programs equivalent to or better than the baseline vehicle has been demonstrated. The developed LS-DYNA models are anticipated to be useful for conducting future vehicle-to-vehicle crash analysis studies to assess the safety performance of lighter mass vehicles in a future fleet simulation study. LWT design topology optimization and 3G optimization engineering tools were also used to determine optimized structural load paths in a pre-specified three-dimensional space.<br><br>The manufacturability of all proposed body structure panels for the LWT was assessed using suitable simulation tools routinely applied in the industry prior to the design being released for production tooling. FEA models of vehicle performance, crashworthiness, safety, vehicle stiffness and NVH have been developed for both baseline and LWT designs, and the latter models compared with the former to maintain unchanged vehicle functionalities and crashworthiness. |
| **Krishnaswamy** | In concept, the objective of maintaining baseline vehicle functionalities while trying to lighten the vehicle is a reasonable approach. Car companies use this approach all the time as they develop new model variants.<br><br>In the case of the LWT, the study addresses the baseline vehicle functionalities very well with the many load cases that are identified in the study. These load cases span crashworthiness, system stiffness, durability, drivability, ride and handling, NVH and Towing. There additionally are many other subsystem and component loads that are typically considered by car manufacturers in course of engineering the vehicle. For example, many seat load cases, curb impact, door sag, door slam, hood and closure loads, |

| Reviewer | Comments |
|---|---|
| | misuse/craftsmanship loads, rail road tie-down fore-aft and vertical loads, etc. The study represents a "zero prototype" approach.<br><br>Most car companies have evolved their product development processes for more efficiency and shorter duration, progressively relying less on hardware prototypes and more on "analytical prototypes". However, cars are not (yet) designed on "zero prototype" basis.<br><br>In the typical car product development process of a high volume car manufacturer, analytical models are correlated with prototypes at critical junctures. This approach establishes credibility of the simulation models and enables confidence in the prediction of simulation models.<br><br>The load cases identified for the LWT above are typically system level load cases that help establish the preliminary integrity of the vehicle structure. However, vehicle tend to gain weight progressively through the development cycle as a result of various problems not identified in the system load cases. Some of them are NVH problems, some local bending or bucking problems, some stiffness problems that are often treated with local fixes. This results in mass increase and mass "creep". Some of these fixes are engineered away in subsequent models of the vehicle.<br><br>Car companies have developed reliable computer simulation techniques covering traditional materials. A lot of physical testing continues to be reduced or eliminated where conventional vehicle architecture and conventional materials are involved.<br><br>When lightweight materials constitute large and important structural parts of a system, computer modeling does not enjoy the same level of confidence. Lightweight materials often require new and more complex material models and failure models. Joining techniques between lightweight materials, particularly in multimaterial situations need more validation than conventional mild steel/spot weld techniques. Most importantly, the structural performance of lightweight material components is integrally linked to its manufacturing process. During these manufacturing processes, changes in material thicknesses, geometry (spring back), work hardening, etc. alter the post-manufactured component sufficiently enough that post manufacturing properties need to be accounted for as input to structural analysis.<br><br>All of the above highlights the following considerations for generating **confidence** in computer modeling and simulation:<br><br>1. Computer simulation of new designs need a "useful minimum" level of validation with physical tests to establish credibility of the simulation for predictive purposes.<br><br>2. The above is especially true when dealing with unconventional materials.<br><br>3. Computer models of lightweight materials are not reliable for quantitative prediction; they are very useful however for evaluating alternatives A vs. B comparisons, particularly where A and B do not represent extreme changes from the original models. |

| Reviewer | Comments |
|---|---|
| **Marzougui** | With a focus on the crashworthiness aspect, the approach used in this study is adequate. The performance of the LWT was assessed in eight different crash impacts. These included: NCAP frontal, NCAP MDB side, NCAP pole side, IIHS moderate overlap, IIHS MDB side, IIHS small overlap, roof crush, and rear impacts. For each impact, the crashworthiness of the LWT design is assessed and compared to the Baseline design to show that it has similar or improved performance. |
| **Prasad** | There is no obvious reason to believe that the functionality of the base vehicle will be compromised by the proposed mass reduction. |

### b) Comment on the methods used to design and analyze the vehicle body's structural integrity and crashworthiness.

| Reviewer | Comments |
|---|---|
| **Das** | *This reviewer was not charged with responding to this question.* |
| **Krishnaswamy** | No comments provided. This is outside the bounds of my expertise. |
| **Marzougui** | The vehicle design modification aspect is outside the scope of my review. However, simulations showed that some of the replaced components lead to complete rupture of some parts. Introducing components that fail during the crash could be intentional, but I did not see this mentioned in the report. |
| **Prasad** | The methods used for design and analysis of the proposed design are what are used in the Industry for many years and are well established. |

### c) Describe whether, and the extent to which, state-of-the-art crash simulation methodologies have been employedk and the extent to which the associated analysis exhibits strong rigor.

| Reviewer | Comments |
|---|---|
| **Das** | *This reviewer was not charged with responding to this question.* |
| **Krishnaswamy** | No comments provided. This is outside the bounds of my expertise. |
| **Marzougui** | The crash simulations were carried out using the latest FEA methods and tools. The level of detail, element and material formulations, connection types, and contact definitions were adequate and associated analysis was reasonably thorough. |

| | |
|---|---|
| **Prasad** | The state-of-the-art in finite element structural simulations, LS-Dyna, has been utilized. Not much is reported (see comments in section 1) so it is hard to comment on the analysis portion of this report. |

**d) Can the design and LS-DYNA results in this study be validated? If yes, how? If no, why not?**

| Reviewer | Comments |
|---|---|
| **Das** | *This reviewer was not charged with responding to this question.* |
| **Krishnaswamy** | No comments provided. This is outside the bounds of my expertise. |
| **Marzougui** | Validations using tests of the Baseline model have been performed to show the accuracy of the results. Additional coupon and component testing could further improve the simulation predictions and allow more comparisons. These tests would be used to calibrate the material models and allow better capturing of the failure behavior. |
| **Prasad** | The common practice in the Industry is to build a prototype(s) to the specifications in the CAE model and conduct tests, e.g. frontal, side, rear and roof crush. In the process of building production feasible designs using pre-production and production processes many issues relative to fabrication, joining and availability of parts are discovered and further design iterations are pursued. After the prototype builds are complete, crash tests are performed. Comparison of model predicted results with actual crash test results lead to further design changes if necessary and refinement of the model for further studies. At the stage of the writing of the report, the vehicle design shows opportunities for mass reduction of the baseline vehicle, but the prototyping and crash tests might show that all the predicted mass saving may not be realized. |

**e) If you are aware of other methods and tools to help validate advanced materials and design engineering rigor for 2017-25 vehicles, please suggest how they would improve this study.**

| Reviewer | Comments |
|---|---|
| **Das** | *This reviewer was not charged with responding to this question.* |
| **Krishnaswamy** | No comments provided. This is outside the bounds of my expertise. |
| **Marzougui** | As mentioned above, key improvements in the material and connection failure algorithms are being added to the FE programs. These developments are at different stages and |

| Reviewer | Comments |
|---|---|
| | some may be ready for application in this study. Additional testing of coupons and components would be needed to calibrate these failure models. |
| **Prasad** | Validation of components can be carried out as a minimum by fabricating and testing them. It is a good starting point and common practice to assemble the whole vehicle model with validated components. With component modeling and validation, the confidence level in model predictions will be substantially higher. In general, the Industry relies on validated models of components before relying on responses predicted by full-scale crash models. |

### f) Is the crash pulse in full frontal impact acceptable from an air bag sensing point of view? Why or why not?

| Reviewer | Comments |
|---|---|
| **Das** | *This reviewer was not charged with responding to this question.* |
| **Krishnaswamy** | No comments provided. This is outside the bounds of my expertise. |
| **Marzougui** | Yes, the crash pulse seems adequate from an airbag sensing point of view. Manufacturers design the vehicle such that the crash pulse has a 10 g or higher average acceleration value between 5 and 15 milliseconds for this purpose. The vehicle pulse in the full frontal impact configurations meets this "rule of thumb". If the initial vehicle pulse is too "soft", the impact may not be detected in time to trigger the airbag. |
| **Prasad** | Yes, I don't see any reason why the airbag sensing to fire the airbags cannot be done. |

### g) Are durability and NVH values in the acceptable range after mass reduction? If not, what would be an acceptable range?"

| Reviewer | Comments |
|---|---|
| **Das** | *This reviewer was not charged with responding to this question.* |
| **Krishnaswamy** | No comments provided. This is outside the bounds of my expertise. |
| **Marzougui** | These aspects are outside my primary area of expertise. |

| Reviewer | Comments |
|---|---|
| **Prasad** | All indications are that the durability and NHH will be in the acceptable ranges, although some further development may be required during prototype testing that may require additional mass increases. |

### h) Is the high strength steel(s) selected within the plastic strain working range for the part selected?

| Reviewer | Comments |
|---|---|
| **Das** | *This reviewer was not charged with responding to this question.* |
| **Krishnaswamy** | No comments provided. This is outside the bounds of my expertise. |
| **Marzougui** | These aspects are outside my primary area of expertise. |
| **Prasad** | It is hard to tell without further interrogation of the CAE model. This is beyond the scope of my review. |

## 2.4 Vehicle Manufacturing Cost Methodology and its Rigorousness

### a) Comment on the methodology used to estimate the LWV manufacturing costs.

| Reviewer | Comments |
|---|---|
| **Das** | Two cost modeling methods, i.e., technical cost modeling and supplier assessments are appropriate for the incremental cost assessment of the LWT full sized pickup. These methods are consistent with the methodologies used in the earlier LDV cost assessments in support of the forthcoming CAFÉ standards by NHTSA and EPA. The RPE multiplier of 1.45 used for estimating retail price is based on several old published literature and will be appropriate to update given recent changes in the automotive industry. Use of the supplier assessments for future projections and conceptual technologies such as for seats, instrument panel, brakes etc. instead of the detailed technology cost modeling approach is appropriate. OEM purchased component cost estimates were obtained from the leading component suppliers and validated using EDAG/Intellicosting internal cost estimating expertise. The final purchased price of the sub-system was estimated by adding the appropriate SG&A and profit values to manufacturing cost. |
| **Krishnaswamy** | No comments provided. This is outside the bounds of my expertise. |
| **Marzougui** | *This reviewer was not charged with responding to this question.* |

| Reviewer | Comments |
|---|---|
| **Prasad** | I am not an expert in manufacturing cost analysis. |

**b) Please describe whether, and the extent to which, state-of-the-art costing methods have been employed, and the extent to which the associated analysis exhibits strong rigor.**

| Reviewer | Comments |
|---|---|
| **Das** | Technical cost modeling approach used for entire body structure, frame, closures, bumpers, fenders, front suspension, rear suspension, wheels and their corresponding assembly process exhibits the most rigor as the in-depth cost analysis provides sufficient details of the incremental cost elements traceable to the design change. The overall manufacturing cost is estimated as the sum of costs of the sequence of the different operations. Sensitivity of both the technology and economic related costs such as raw material, capital investment, tooling, and labor etc. on the total manufacturing cost can be estimated. |
| **Krishnaswamy** | No comments provided. This is outside the bounds of my expertise. |
| **Marzougui** | *This reviewer was not charged with responding to this question.* |
| **Prasad** | This is beyond the scope of my expertise. |

**c) If you are aware of other methods and tools employed elsewhere that could be used to help estimate costs for advanced materials and design for 2017-25 vehicles, please describe them and suggest why they would improve this study and how they might be used.**

| Reviewer | Comments |
|---|---|
| **Das** | The part manufacturing part cost estimation at the level of major manufacturing steps based on the technical cost modeling approach used is appropriate to facilitate the economic viability of the 2017-2025 vehicle designs. In the cost estimation of future vehicle designs, there remains an uncertainty both in terms of technical design and economic parameters. It is appropriate then to consider the sensitivity analysis of major technical design and economic parameters, based on which a range of part cost be estimated instead of a single value. |
| **Krishnaswamy** | No comments provided. This is outside the bounds of my expertise. |
| **Marzougui** | *This reviewer was not charged with responding to this question.* |

| Reviewer | Comments |
|---|---|
| **Prasad** | This is beyond the scope of my expertise. |

## 2.5 Conclusion and Findings

### a) Are the study's conclusions adequately backed up by the methods and analytical rigors of the study? Any concerns? How can they be addressed?

| Reviewer | Comments |
|---|---|
| **Das** | The study's conclusions based on the methods and analytical rigors used have been very well documented in an impressive and well-written large report. Spreadsheet cost models provide the details for the manufacturing part cost estimates. A better documentation of the spreadsheet cost models in terms of the reference listing of major input variables would be better for the validation purpose. |
| **Krishnaswamy** | Please see comments for each phase of the analytical approach used in this study:<br><br>1. Create Baseline CAE model by reverse engineering the Chevy Silverado.<br><br>This entails tear-down of the vehicle, scanning of the data, finite element modeling of the components and subsequent assembly to generate the full vehicle model.<br><br>**Comments and concerns:** This work is competent, comprehensive and thorough.<br><br>2. The full vehicle model was exercised for a comprehensive set of load cases (regulations and non-regulation). The CAE model was correlated based on results from physical test of the Chevy Silverado model.<br><br>The correlated model was designated as "Baseline" model.<br><br>**Comments and concerns**: This work is competent, comprehensive and thorough. The effort in this phase is conventional in scope and uses current industry practices.<br><br>3. The Baseline model was subsequently modified to incorporate lightweight engineering design concepts to create the LWT model. These design concepts utilized lightweight materials like Aluminum, Magnesium, High strength steels, etc.<br><br>**Comments and Concerns:**<br><br>a. In general this phase constitutes the vulnerable underbelly of lightweight simulation practice and could lead to uncertainty with regard to predictability of the simulations. Some of the factors contributing to this uncertainty are:<br><br>i. Modeling and simulation of joints. The primary joints that need attention are the adhesive bond – self-piercing riveted joints between the Aluminum panels. Such joints have more recently been used in high volume production cars and are simulated by CAE techniques, but as part of the product |

| Reviewer | Comments |
| --- | --- |
| | development process that involves validation with prototypes at critical stages. Validation tests for local joint behavior are also needed to formulate failure models. Tear through the base metal will result in lower threshold crush resistance compared to total integrity idealized in the computer model.<br><br>ii. Post-manufacturing residual stresses, work hardening and geometry (including thickness) changes of Aluminum and HSS components influences prediction of computer models.<br><br>Previous communication (July 6, 2016) relative to this issue (facilitated by NHTSA) is captured below:<br><br>***Question:*** *Were the forming results for the LWT Aluminum body panels accounted for as input to Crash simulation? Specifically, thickness changes, post-forming strain hardening?*<br><br>***Response:*** *The forming results for the LWT Aluminum body panels were not used as input into the crash simulation model. For aluminum panels the reduction in strength due the material thinning during the forming operation, typically stamping, is balanced by the increase in material yield strength due to strain hardening.*<br><br>In my view "balancing" of strength reduction with increase in material yield strength while true in an overall sense, does not necessarily apply to structural performance that is significantly influenced by local effects (such as would be expected in structural crash collapse).<br><br>All of the above factors could lead to non-conservative prediction.<br><br>CAE techniques when applied to lightweight materials, need different levels of validation to build confidence. Such validation is understandably not feasible for the scope of this study; accordingly, quantitative prediction needs to viewed with prudence and caution.<br><br>4. Simulate the LWT model for the same load cases as the Baseline; iterating the design/simulation so that results of the LWT simulation were judged comparable with the Baseline results.<br><br>**Comments and Concerns**: Excellent effort spanning a lot of different cases, commendably comprehensive. |
| **Marzougui** | The methods used in this study are adequate. The main concern, which was mentioned before, is the failure modeling and its potential effects on the accuracy of the simulation results. |
| **Prasad** | At a high level, the study's conclusions are backed up by their thoroughness in identifying the right materials that are cost effective and show opportunities for mass reductions. |

| Reviewer | Comments |
| --- | --- |
| | How much of the opportunities can be realized in production can only be determined at the prototyping stage of vehicle development. |

### b) Are the conclusions about the design, development, validation, and cost of the mass-reduced design valid? Any concerns? How can they be addressed?

| Reviewer | Comments |
| --- | --- |
| **Das** | The conclusions about the design, development, validation, and cost of the mass-reduced are valid. Since the most lightweight material technologies considered in the LWT design are currently being used in the high production volume vehicles today, a comparative analysis of mass savings potential achieved and cost premium paid for the vehicles on the road today would be an excellent source of design and cost validations. |
| **Krishnaswamy** | The most significant conclusion of the study is the proposed design concept for the LWT mass-reduced vehicle. At a high level, this design concept consists essentially of an Aluminum alloy body (cab, FESM and pickup box) on a High Strength Steel frame.<br><br>The proposed design, intended for production in the 2025-2030 time frame, is very similar in concept to the 2015 Ford F150 vehicle is already out in the market (in 2015). In this sense, in my concern is that the study ***underachieves***.<br><br>**Comments and concerns:**<br><br>The lightweighting approach used by the contractor (Section 7) for the LWT is logical and reasonable, except for the few concerns noted below.<br><br>Prior communication (July 6, 2016) relative to the general strategy employed by the contractor (facilitated by NHTSA) is captured in my question below:<br><br>***Question****: What components / subsystems of the LWT Aluminum structure use manufacturing technologies that are assumed to be developed and mature by 2025 that are deemed currently <u>not</u> mature for production?*<br><br>***Response****: None; all aluminum related applications are regarded as mature technologies suitable for high volume production in 2014. The manufacturing technologies and choice of aluminum grades used on LWT aluminum structure are very similar to the FORD F-150 that is in production since 2015.*<br><br>The implication of the above response by the contractor is that the LWT vehicle planned for the 2025-2030 time frame is not significantly (if at all) more advanced in design than what is already available in the 2015 Ford 150. A further implication is that the Ford F150 in 2025-2030 would be two more generations evolved beyond the currently proposed LWT concept. This would render the LWT vehicle prematurely obsolete.<br><br>a. The design approach taken by the contractor is one of assessing each of the key subsystems of the vehicle for potential weight reduction. A variety of material- |

| Reviewer | Comments |
|---|---|
| | mix options are considered and the most cost effective option is picked. This is certainly a sound approach.<br><br>**Concern:** However, some assumptions made in the report are not acceptable for vehicle lightweighting. For example, the lightweighting options proposed for the frame are:<br><br>Option 1: AHSS<br>Option 2: Aluminum<br>Option 3: AHSS + Carbon Fiber Reinforced Polymer<br><br>The contractor chose to discard the Aluminum Option 2 because, as with Option 1, manufacturing can be performed with the same presses and processing sequences as the baseline frame".<br><br>The above approach to material substitution for structurally critical components is incorrect and will not result in an acceptable, cost effective light weight design alternative. Key structural components that are being substituted with Aluminum need to be completely redesigned; the approach of using existing presses for both Aluminum and Steel components should be reserved for nonstructural panels (fenders, for example). An efficient lightweight Aluminum frame design will need to achieve maximum structural performance i.e. stiffness, strength and crashworthiness by fully capitalizing on the benefits of superior properties of modern Aluminum alloys. Such a frame would be optimized for both structural performance and cost by judicious mix of multiple manufacturing processes. For example, hydroformed structural members, extruded beams and stamped components. Deeper sections with double celled front rails for crash absorption, cast joints for enhanced frame stiffness could well contribute to a feasible all-Aluminum frame with weight reduction potential of 40 to 50% vs. 18% shown in Figure 185, Page 189).<br><br>**Alternatively**, a multi-piece all-Aluminum cast frame could also be considered. Such a frame would be appropriate for crash performance and also versatile in accommodating the different lengths of the LWT models. A multi-piece cast Aluminum frame may be more weight efficient and possibly more cost-effective. A multi-piece frame would be versatile in accommodating different chassis dimensions for the different models at the same time ideal from repair standpoint perspective.<br><br>The alternative design concepts proposed above could result in much lighter designs than what was considered. The additional manufacturing cost might potentially be offset with lower cost of material used in the frames, although this is not certain until further structural/cost analyses are conducted.<br><br>b. Given the 2025-2030 time horizon, the study should consider more aggressive design options that might yield lighter weight designs. For example, an attractive although disruptive option would be to engineer a frameless (unitized) vehicle architecture. This would seriously challenge the status-quo for this class of |

| Reviewer | Comments |
|---|---|
| | lightweight trucks, but could be structurally feasible and viable with regard to greater weight reduction and consequential potential cost reduction. The availability of 7000 series Aluminum and the new class of AHSS steels could meet the heavy demands such as performance towing capacity, and crashworthiness. |
| **Marzougui** | The conclusions of this study about the feasibility of designing a LWT that has the same crashworthiness functionality as the Baseline design are supported by the computer simulation results. The simulation tools used are well suited for this type of analysis. |
| **Prasad** | As mentioned earlier, validation of the design has not been carried out in the report. Only prototyping and testing can tell if all the identified mass reduction opportunities can be realized in the final design. |

**c) Are you aware of other available research that evaluates and validates the technical potential for mass-reduced vehicles in the 2017-25 time frames that could be helpful for this study? Include sources and additional information for such research.**

| Reviewer | Comments |
|---|---|
| **Das** | 1. "Light-Duty Vehicle Mass Reduction and Cost Analysis – Midsize Crossover Utility Vehicle," EPA-420-R-12-026, Aug. 2012<br>2. Baron, J. (2016) "Identifying Real World Barriers to Implementing Lightweighting Technologies and Challenges in Estimating the Increase in Costs," Center for Automotive Research, Jan. |
| **Krishnaswamy** | None. |
| **Marzougui** | All relevant studies that I am aware of are referenced in the footnotes of the draft report. |
| **Prasad** | Obviously the F150 mass reduced design already in high volume production shows that mass reduction of the body and frame as outlined in this report is possible. The exact amount predicted in the report may not be accurate, but opportunities exist. Further reduction from that already achieved in the F150 as mentioned in the report in the "other light-duty vehicle classes" need to be proven out and validated. |

### 2.6 Other Potential Areas for Comment

#### a) Is the methodology used to estimate the feasible mass reduction in other light-duty vehicle classes reasonable? Please explain.

| Reviewer | Comments |
|---|---|
| **Das** | The general approach used to estimate the first-cut feasible mass reduction in other light-duty vehicle classes using the detailed A2Mac1 North American benchmark database seems reasonable. Honda Accord would have been a more appropriate representative for the mid-sized passenger cars which could have served as the validation of the prior EDAG study data. Mass compounding based on gross vehicle weight vs. gross combined weight rating depending on the light-duty vehicle was taken into consideration for the resizing of engine, powertrain, and fuel system, but the methodology used for estimating the component masses was not discussed as in the case of the light-duty pickup truck Chevrolet Silverado 1500. However, using the same mix of lightweight materials in other light-duty vehicles as considered in the pickup truck may not be appropriate. Besides the differences in the consumer willingness- to-pay for vehicle lightweighting, vehicle performance and functionality requirements vary by the vehicle class. It is unclear whether at a similar extent as the full size pickup truck, vehicle performance and functionality requirements have also been evaluated for other light-duty vehicle classes.<br><br>It'd be good to extend the mass reduction analysis to the incremental cost analysis for other light-duty vehicle classes. |
| **Krishnaswamy** | The proposed methodology appears to impose science on chaos as extrapolates from a specific architecture and weight class to multiple vehicle architecture and weight classes. To my knowledge, such a proposed approach has not been validated at this time.<br><br>Also, weight reduction strategies are distinctly different for different vehicles at different price points. Cars that are even in the same weight class (say 3,000 pound to 4,000 pounds) can be priced quite differently, based on how they are positioned in the market. A car priced at $20,000 will merit entirely different weight reduction strategy than one that is priced at $50,000 which again would be very different for a car priced at $100,000. So the mix of vehicles and their associated price is an important consideration.<br><br>Cars that are already compact have less potential for weight reduction than heavier cars. Likewise, cars that are bare boned and at the low price end cannot justify lightweight materials. For such cars, the economics of conventional materials i.e. mild steel may be more meaningful when accompanied by lower cost solutions such as turbocharging and other powertrain and transmission related enhancements.<br><br>Taking the above into account, the linear segmentation by weight would be better replaced by a grid that includes specific vehicle architecture categories along with price as additional parameters.<br><br>Additionally, the achievable LWT weight reduction projected by the study needs validation before it can be used as a basis for other vehicle classes. |

| Reviewer | Comments |
|---|---|
| **Marzougui** | Outside my primary area of focus. |
| **Prasad** | Yes, the methodology is acceptable for identifying the opportunities for mass reduction utilizing AHSS, Aluminum and Magnesium. |

### b) Is the study valuable to understand the feasibility of 2017-2025 mass reduction technology? Please explain.

| Reviewer | Comments |
|---|---|
| **Das** | The study is extremely valuable in understanding the feasibility of 2017-2025 mass reduction technology. Most LWT design materials considered have been based on the materials and manufacturing technologies being used in high-volume light-duty vehicle production today. |
| **Krishnaswamy** | Many of the comments provided in a) above probably apply here as well.<br><br>In my view, the study does not generate any generic knowledge of vehicle mass reduction technology. Rather it applies well known and understood lightweighting principles to a specific vehicle type. Given the plethora of vehicle architecture, multiple price points, weight classes and design approaches, industry has not as yet converged on common or best practices for mass reduction technology. |
| **Marzougui** | *This reviewer was not charged with responding to this question.* |
| **Prasad** | This in conjunction of an earlier study of mass reduction opportunities for the Honda Accord is valuable to establish feasibility of mass reduction in 2017-2025 time frame. |

### c) Do the study design concepts have any critical deficiencies in their applicability for 2017-2025 mass reduction feasibility that require revision by NHTSA prior to finalizing the report? If yes, please describe.

| Reviewer | Comments |
|---|---|
| **Das** | The study design concepts considered do not have any critical deficiencies that require any NHTSA revisions. Most design concepts considered are lightweight materials such AHSS and aluminum being used in vehicles of today. |
| **Krishnaswamy** | The design concepts proposed in the study are implementable with current technologies and do not appear to have any critical deficiencies. |

| Reviewer | Comments |
|---|---|
| **Marzougui** | *This reviewer was not charged with responding to this question.* |
| **Prasad** | Whether the amount of mass reduction in all the segments of the fleet is advisable can be argued. The reductions in all segments pointed out in the report will not be safety neutral. Although, such a study was beyond the scope of this undertaking by EDAG, NHTSA should conduct such a study. |

### d) Are there any fundamentally different lightweight vehicle design technologies that are likely to be more common than the ones assessed in this study?

| Reviewer | Comments |
|---|---|
| **Das** | Lightweight design technologies other than AHSS and aluminum could be different in some vehicle systems, particularly for the latter MY vehicles. For a single LWT vehicle design scope of the study, they seem to be appropriate. |
| **Krishnaswamy** | I don't think so.<br><br>Light truck design continues to be driven by high volume considerations, so in the time horizon of interest, lightweighting will likely continue to be enabled by AHSS and Aluminum alloys and to a lesser extent Magnesium alloys, and these trends will reflect in the development of associated manufacturing and assembly technologies.<br><br>New grades of Aluminum alloys (7000 series) and the 1300 MPA AHSS steels will likely have greater proportion of usage for lightweighting than is assessed in this study.<br><br>There is emerging interest in Aluminum foam for crash applications that may mature in the years to come.<br><br>Carbon fiber technology is evolving although even at lower prices, may not be a high volume technology such as would be needed for light trucks. Further, CAE technologies still are not developed for use in this respect.<br><br>CAE technology is advancing and keeping in pace with the new materials technology as well as the manufacturing and assembly technologies. There still is a lot of validation that will need to be done, and this will improve CAE predictability beyond what is used in the study. ICME techniques has the potential to revolutionize CAE value. |
| **Marzougui** | *This reviewer was not charged with responding to this question.* |
| **Prasad** | The general trend of mass reduction utilizing materials like AHSS and Aluminum will continue with gradual introduction of Magnesium and composite materials. |

### e) Is the cost from the study reasonable and backed up by sufficiently detailed data? What would you expect the cost to be for the design in this study? Please explain the reasons if your estimate is different than this study.

| Reviewer | Comments |
|---|---|
| **Das** | Cost estimates from the study are reasonable and backed up by sufficiently detailed data. An estimate of 16.7% mass savings at a cost premium of $3.57/kg for the aluminum-AHSS option with powertrain sizing seems reasonable and consistent with earlier published cost estimates of other light-duty vehicle considered in support of the EPA and NHTSA rule making. |
| **Krishnaswamy** | No comments. |
| **Marzougui** | Outside my primary area of focus. |
| **Prasad** | Intensive use of Aluminum for mass reduction will tax the supply of the material that will in turn also increase the cost in the future. I am not sure if the supplier base will stabilize the cost of Aluminum. Steel may have some advantage over other materials. |

## 2.7 General Comments

### a) Describe your overall assessment of the organization, readability, and clarity of this report, including any changes needed.

| Reviewer | Comments |
|---|---|
| **Das** | Overall organization of the report is excellent in terms of both readability and clarity. Appropriate references have been included throughout the document. It'd be appropriate to relabel all the Tables as Table and not Figure and addressing the specific comments as listed under "Additional Comments". |
| **Krishnaswamy** | 1. Much of the Report is generally competent, comprehensive and credible. It also is very well organized and readable.<br>2. The report is clear in presenting concepts and facts; it generally provides useful contextual information. Key points are reinforced with supporting details and visuals that clarify the essential messages. |
| **Marzougui** | The report is thorough and well organized. All aspects of the study, including the methods, data sources, assumptions, results, and conclusion, are included in detail. |

| Reviewer | Comments |
|---|---|
| **Prasad** | The report is very well organized and is easy to read albeit too long. I believe that some of the self-serving messages should be eliminated as they sound more like advertisement for the performing organization and indictment of the OEM's. |

### b) Is the information provided in the report and appendices sufficiently detailed to thoroughly document all essential elements of the study? If not, what additional information is needed?

| Reviewer | Comments |
|---|---|
| **Das** | Information provided in the large report and appendices contain sufficient details to thoroughly document all essential elements of the study. In additional, cost models used to derive the final cost estimates discussed in the report provide further details. |
| **Krishnaswamy** | 1. The quality of documentation is excellent.<br>2. However, it would be helpful if the study were to consolidate all key assumptions relevant to the CAE analysis.<br>3. A breakdown of components with materials before and after redesign. Identification of the Material alloy would be helpful. |
| **Marzougui** | Yes, all relevant information was included in the report and references were provided to the sources of the data or methods used. Any missing information can be obtained from the available models. |
| **Prasad** | Overall, the report in conjunction with the CAE model is sufficiently detailed to document their effort. It will take the report and the model together to understand the details of the design and its validity. |

### c) What are the strongest and weakest parts of this report? How can the weakest parts of the report can be strengthened?

| Reviewer | Comments |
|---|---|
| **Das** | It'd be useful to include a new section on the effect of mass compounding effect on the LWT components. It is hard to validate these implicit estimates used in cost savings estimates and so a table listing of a reduction in mass at the component level is necessary. Total component mass savings is shown but not disaggregated by lightweighting vs. mass compounding. |

<table>
<tr><th>Reviewer</th><th>Comments</th></tr>
<tr><td>Krishnaswamy</td><td>
1. Strong parts of the report:<br>
a. Comprehensive and thorough documentation of the key processes involved in the project, including Tear down and Reengineering the 2014 Chevy Silverado with CAE simulation.<br>
b. Competent computer modeling and simulation (qualified by some comments noted earlier). CAE simulation and optimization studies are state-of-the-art as claimed.<br>
c. Load cases considered are quite comprehensive.<br>
d. The study establishes a general methodology for weight reduction that with a few changes could be of great value to the industry. Various material substitution options are nicely detailed with cost consequences.<br>
2. Weak parts of the Report<br>
a. A key weakness of this study is the extension of a validated computer model to predictive use on evaluating new designs with new materials without any further validation with physical prototypes. This can be expected to yield unconservative results.<br>
Recommendation: A few physical prototypes will be a necessary investment.<br>
b. The lightweighting designs created do not sufficiently stretch the envelope of possibilities and in fact remain close to the original design. Sometimes material substitution has been employed instead of lightweight engineering; while this works for panels, it does not for structural members.<br>
Recommendation: The LWT frame could be redesigned around the strengths of Aluminum rather than substituting Aluminum for steel as was considered.<br>
c. The designs presented appear to have not advanced the engineering of the LWT beyond that of the current production vehicle i.e. 2015 Ford F150.<br>
Recommendation: The LWT innovations beyond the 2015 Ford F150 production vehicle need to be captured.<br>
d. Chapter 11 “Mass Reduction for Other Light-duty Vehicles (Optional Task 1) is hard to understand without more contextual background.<br>
Recommendation: It would benefit from rewriting the introductory paragraphs, clarifying the general objective so that the degree of accuracy (or approximation) needed is better understood.<br>
e. The targeted time frame is referred to as 2025-2030 (Executive summary, P.23, Chapter 7, P. 251) but as 2020-2030 in several places elsewhere (for example, Chapter 3, P. 43).
</td></tr>
</table>

| Reviewer | Comments |
|---|---|
| **Marzougui** | The strongest part of the report is the number of impact cases (eight cases) analyzed to study the crashworthiness of the LWT. The weakest part is the fact that failure models were not included for some high-strength steel components used, these parts were assumed not to fail in the model. Testing may be needed to ascertain material properties used, develop new material properties, and/or determine whether failures would occur. |
| **Prasad** | The strongest part of the report is in stating the various material alternatives for weight reduction of the various components of the vehicle and the reasons for selecting the most effective solutions. The weakest part is the lack of information regarding the design changes in the construction of several elements. A technical discussion of the baseline design and the final design would be helpful rather than stating "optimization and design changes" were used to reduce mass, e.g. "The final optimized cab assembly incorporated the chosen design options previously discussed for the Cab, FESM and Radiator Support, but also took advantage of additional design changes to make the structure lighter, stronger and easier to manufacture and assemble. The nature of those design changes is neither discussed nor is readily obvious. |

### d) Please provide any other comments you may have on this report.

| Reviewer | Comments |
|---|---|
| **Das** | Additional comments by specific page nos. of the report are provided below. |
| **Krishnaswamy** | ***Summary of comments and recommendations:***<br>1. Weight reduction estimates from the LWT computer model are likely to be unconservative.<br>The LWT project starts with a correlated model, but substantially alters the model by incorporating lightweight materials. This extends the simulation into areas of uncertainty where CAE is no longer reliably predictable and quantifiable.<br>The projected LWT 19.9% weight reduction compares with 10.5% for a similar design concept and comparable weight – the 2015 Ford F150 production vehicle. Why this difference? A few possible answers:<br>a. The idealizations assumed in the computer model overestimate weight savings.<br>b. Mass creep that occurs in production vehicles.<br>c. The 2014 Chevy Silverado was less weight efficient and therefore more weight could be reduced. |

| Reviewer | Comments |
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| | 2. Further weight reduction strategies can be explored (as always, subject to cost considerations).<br><br>The LWT Design concepts are rather evolutionary. LWT needs to consider the 2025 time horizon (per original objective) and push the design envelope beyond what is already implemented in current production vehicle (like 2015 Ford F150). Some recommendations:<br><br>a. Between 2016 and 2025, there are ongoing advances in both AHSS and Aluminum alloys. Consider a second generation evolution of the LWT design that incorporated 1300 MPA nanosteels in the frame and 7000 series Aluminum alloys for the Body for further weight reduction.<br><br>b. Reconsider the Option 2 all-Aluminum frame concept – recreate and assess the frame concept to deliver an efficient, lightweight frame. Suggest exploring Option 2a: All-Aluminum cast frame or Option 2b: judicious mix of hydroformed / extruded / stamped / cast components (target 40 to 50% weight savings).<br><br>c. The 2025-2030 time horizon provides adequate time for engineering a new, complete unitized body concept that could be much lighter as it would eliminate the traditional heavy frame. Several engineering problems will need to be addressed, including NVH, crash and other structural problems. Stronger AHSS and Aluminum alloys that will be ready for production manufacturing by 2030 could provide the enhanced strength required for towing and other heavy duty applications. |
| **Marzougui** | Additional comments about the models and simulations are provided in other sections of this review summary report. |
| **Prasad** | The mass reductions predicted in the final design for the body, closures and the frames have high potential of being realized, although may not be exactly what is predicted. Some of the secondary mass reductions due to the lower masses of the body and the frames need further validations. For example, the engine is already "light" and is a 5.3L engine. Due to mass reduction the engine can be downsized to 5L. Any reduction in the mass of the engine and other powertrain and exhaust system will require a redesign of the engine to gain any mass savings unless one with the same displacement, Horse Power and Torque already exists. Similarly, to achieve mass reduction of the exhaust system a new design would be required. It is not clear whether mass of the exhaust system in todays vehicles are linearly related to just the displacement of the engine, i.e. a 6% reduction in displacement of a V-8 engine will result in 6% reduction in mas of all powertrain related components. Similarly, whether a 6% reduction in engine displacement will result in a similar reduction of transmission mass? If such relationships exist, it should be disclosed in the report.<br><br>It is not clear from the report as to the crash responses of the other variants of the Silverado. For example, have the authors considered the large weight variations between the lightest mass baseline vehicle and the heaviest mass vehicle, especially with a |

| Reviewer | Comments |
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| | common frame structure in the front-end and the rear-end of the vehicle. The heaviest variant will have more crush and intrusion than the lightest variant. The lightest variant will have the least crush and the highest acceleration levels. |

### 2.8 Overall Recommendation

a) **Based upon your review, indicate whether you find the report: (1) acceptable as is, (2) acceptable with minor revisions, (3) acceptable with major revisions, or (4) not acceptable. Please justify your recommendation. If you find the report acceptable with minor or major revisions, be sure to describe the revisions needed.**

| Reviewer | Comments |
|---|---|
| **Das** | Overall, it is an excellent and well-written report and is acceptable with minor revisions to address comments listed below under "Additional Comments". |
| **Krishnaswamy** | **The Report is acceptable with major revisions:**<br><br>My review of the Report indicates that a lot of competent and thorough work has gone into this project. However, the proposed design falls short of achieving the objective established for this project, contained in this excerpt from the Executive summary:<br><br>"The light weighted version of full size pickup truck (LWT) will use manufacturing processes available in model year 2025-2030 and capable of high volume production. The team's goal was to determine the maximum feasible weight reduction while maintaining the same vehicle functionalities, such as performance, safety, and crash rating, as the baseline vehicle. Furthermore, the retail price of the LWT must be within +10% of the original baseline vehicle."<br><br>**My comments:**<br><br>1. The design proposed uses technologies that are currently available and productionized as exemplified in the 2015 Ford F150 production vehicle. The design does not stretch either the design or the materials/manufacturing technology envelope that would be consistent with the 2025-2030 time frame.<br><br>2. The weight reduction of 19.9% for the LWT projected through computer simulation is quite a bit higher than the ~ 10.5% achieved by a comparable weight 2015 Ford F150 production vehicle that is fully validated in the field (based on the weight information I have consolidated for the 2015 Ford F150).<br><br>I find the **report acceptable with major revisions**. The revisions to the report would include addressing the following:<br><br>1. Contractor's review and analysis as to what factors might contribute to the rather large gap between the projected 19.9% LWT weight reduction and the corresponding |

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| | 10.5% weight reduction for the 2015 Ford F150 production vehicle. This amounts to about 500 pounds discrepancy per vehicle. Short of a convincing response to this central issue, the veracity of the simulation used for the LWT design can be established conclusively only with expensive and time consuming validation effort with physical prototype.<br><br>In the contractor's review, analysis and judgment,<br><br>a. What design, material choices, manufacturing options contributed to this difference?<br><br>b. What assumptions made in the computer simulation might lead to conservative predictions? What assumptions made in the computer simulation might lead to unconservative predictions?<br><br>c. In the Contractor's review and judgment, was the 2014 Chevy Silverado less mass-optimal than the 2014 Ford F150, lending itself therefore to higher weight reduction potential?<br><br>(Note that there often is "mass creep" in early versions of production models. Such mass creep is a result of local fixes to solve NVH and other structural problems. Such problems are not addressed by CAE simulations that account mostly for system /subsystem loads).<br><br>d. Please reconfirm or comment further on the following communication, which seems to suggest that no additional advantage would be gained in the 15 years between now and the time frame 2025-2030:<br><br>***Question:*** *What components / subsystems of the LWT Aluminum structure use manufacturing technologies that are assumed to be developed and mature by 2025 that are deemed currently <u>not</u> mature for production?*<br><br>***Response:*** *None; all aluminum related applications are regarded as mature technologies suitable for high volume production in 2014. The manufacturing technologies and choice of aluminum grades used on LWT aluminum structure are very similar to the FORD F-150 that is in production since 2015.*<br><br>e. Please respond to the above question as it would relate to other key subsystems including the chassis frame.<br><br>f. The proposed LWT design often takes a conservative approach to lightweighting i.e. material substitution. In addition to the final proposed design, what aggressive new alternate design concepts were considered by the Contractor that would leverage lightweighting technologies appropriate for the 2025-2030 time frame? Were these designs assessed for performance and cost?<br><br>g. Chapter 11 - "Mass Reduction for Other Light-duty Vehicles (Optional Task 1) could be improved with more contextual background. It would benefit from |

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| | revising the introductory paragraphs, clarifying the general objective so that the degree of accuracy (or approximation) needed is better understood. |
| **Marzougui** | The report is found acceptable with minor revisions. The approach that was followed in this study is valid and the conclusions are well supported, however, simulations with failure defined for all high-strength materials in both the Baseline and LWT models should be performed to verify that these do not affect the predicted results. The crashworthiness simulation predictions could be further enhanced by incorporating more advanced material and connection failure models. This would require additional coupon and component testing which may be outside the scope of the study. |
| **Prasad** | I believe that the report is acceptable with minor revisions to address the issues raised in the preceding sections. |

## 2.9 Additional Comments Provided

| Reviewer | Comments |
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| **Das** | 1. p. 54: Any constraints why not more recent than MY2012 full-size pickup trucks sales data were considered for the baseline vehicle selection?<br>2. p. 79, p. 82 (Fig. 47): “alloy” needs to be replaced by “Aluminum Alloy”. It’d be good to address this throughout the document, particularly consistently in all figures.<br>3. p. 80 (line 3-4): one of the values in the statement “2 percent (56.3 kg) of the vehicle weight” doesn’t seem to be right? Figure 43 indicates 18%.<br>4. p. 130: Not clear about the basis for the second least cost option selection for the LWT cab design, although the least cost hybrid structure option has already been implemented in 2015 Cadillac CT6. What criteria were used to determine the most cost-effective option, is it only least $/kg of mass saved? (on pg. 152 says – problem with hybrid is the joining of dissimilar metals).<br>5. p. 133 (Figure 113): listed price data for which year? Manufacturing scrap should be sensitive not only to the material type, but also by the manufacturing process. Assumed manufacturing process scrap rate of 0.20 for carbon fiber seems to be low, at least in the range of 0.30-0.40, depending on the form used for a given application. Not sure about the logic behind a higher manufacturing difficulty value for fiber glass compared to SMC, although the latter is a composite material of glass fiber and polymer resin matrix material.<br>6. p. 156 For FESM Left & Right, cost increase premium in terms of $/kg is significantly lower than Body structure for a similar level of mass reduction potential considered for aluminum and aluminum+AHSS? |

| Reviewer | Comments |
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| | 7. p. 158 It is surprising that cost increase premium for the aluminum radiator support is more than >$10/kg.<br>8. p. 159: Not a convincing argument for the magnesium+aluminum selection for the LWT radiator support design in spite of the multi-material joining issues mentioned in earlier cases.<br>9. p. 161 It is surprising that the use of aluminum and magnesium can result in a more than 60% mass savings in the final LWT cab assembly design of FESM and radiator support.<br>10. p. 163: The lightweight glass fiber reinforced composite should have been considered as one of the LWT options which has already been demonstrated more than a decade ago.<br>11. p. 182 Not convincing how such a low mass savings value of 20% was achieved for a CFRP Hood option 2 considered?<br>12. p. 183: A final paragraph on the optimal selection of hood is missing.<br>13. p. 190: Mass savings cost premium for Frame Option 4 (AHSS+CFRP) should be significantly higher than the aluminum Frame Option 3, including mass savings potential?<br>14. p. 196 (last para): Why LWT bumper designs mass savings cost premium for the front are 1/3$^{rd}$ of rear, although resultant mass savings are similar?<br>15. p. 213: Not sure what methodology used for the downsized 2.7L EcoBoost engine of the LWT design?<br>16. p. 219: The reference needed for “10% reduction in vehicle weight leads to a gain of 3.5-6.5% in fuel economy. The most common range of the fuel economy gain 6-8% used by the industry with the consideration of energy downsizing.<br>17. p. 251 (line 4): The original cast/forged iron is 444 kg and not 32 kg as noted.<br>18. p. 262 (Figure 275): Unlike for Composites, both types of composites and manufacturing technology have been considered. In other lightweight material cases, the appropriate manufacturing technologies have only been made. This figure should focus on manufacturing technology by different lightweight material types.<br>19. p. 363: Mentions that the technical cost modeling methodology is explained in detail in Section 9.4, but instead that section on p. 339 discussed “Ride and Handling Performance.”<br>20. p. 363 (second last line): Shouldn’t this be baseline Chevrolet Silverado and not Accord as indicated?<br>21. p. 365: (Figure 406): It is more appropriate to consider “Energy” for Component Manufacturing Costs under “Process” instead of “Plant.” |

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| | 22. p. 370: Any reason why the interest rate for Program (i.e., 7%) is different from the one (i.e., 7.03%) used for tooling and equipment investment?<br><br>23. p. 381: BLS data source used to estimate the average markup value of 41% is based on old data, i.e., 2010.<br><br>24. p. 383: Self Piercing Rivets (SPR) is considered as one of the joining technologies for assembly, but is not mentioned on p. 374.<br><br>25. p. 394: It is surprising to note that LWT fender structure is about ~80% (quite an unrealistic mass savings potential for aluminum structure).<br><br>26. p. 406: Mass savings cost premium for the LWT AHSS design of >$5.00/kg saved seems too high for the lightweight material AHSS assumed.<br><br>27. p. 407: No mention of baseline and LWT design Bumper masses provided?<br><br>28. p. 410: It is surprising that the LWT control arm was changed to AHSS from baseline aluminum use and resulted in mass savings.<br><br>29. p. 425: Why did using the MuCell technology for HVAC system result in cost savings unlike in other applications as a cost premium?<br><br>30. p. 430 (Figure 503): How were the intermediate values of the manufacturing cost increase curves for various lightweight materials estimated? Any overall system optimization considered by each specific vehicle mass reduction value, particularly when lightweight structural components were considered?<br><br>31. p. 449 (Figure 524): 2014 sales data of Ford F150 is missing.<br><br>32. p. 450 (figure 527). Some data for Large SUV/LT in the last table row are missing.<br><br>33. p. 453: For the vehicle body structure, aluminum+AHSS option used for light-duty pickup truck was not used for all vehicle subclasses.<br><br>34. p. 478: Why is the mass savings potential of minivans the highest among the vehicle subclasses considered, although it is not the heaviest vehicle considered in the analysis?<br><br>35. Cab assembly baseline spreadsheet model (Assembly Inputs: cell o6): Double-counting of total tooling investment. |
| **Marzougui** | **Introduction**<br><br>This document provides a review of a draft report entitled "Mass Reduction for Light-Duty Vehicles for Model Years 2017-2025." The report documents a study that investigated the feasibility of developing a light-weighted pickup truck (LWT) design that would have similar performance functionality as the original design and within cost and manufacturing methods constraints. To assess the crashworthiness of the LWT design, the study made use of computer simulation. A detailed finite-element computer model of |

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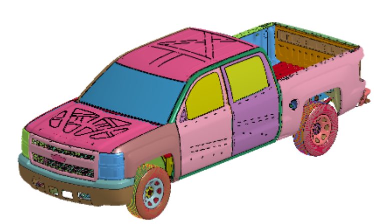
the original (i.e., Baseline) vehicle was created using reverse engineering techniques and validations were conducted to demonstrate that the model can accurately reflect the crash responses for different impact conditions. The Baseline model was then modified to incorporate LWT elements that replaced certain parts. The modified model was used to evaluate the crashworthiness of the LWT design. Simulation results from the LWT model were compared to the Baseline model results to determine if the new design had performance similar to, or better than the original design.

This review focuses on the modeling and simulation aspects of the study. It involved three main tasks. The first task consisted of answering questions listed in the peer review guidelines. In the second task, the two models that were created under the study were evaluated. The third task consisted of review of the simulation results. The findings of the three tasks are presented in the following sections.

**II - Model Evaluations**

In the first phase of the review, the LWT and Baseline models that were created under this Vehicle Mass Reduction study were evaluated. Table 1 includes general information with a summary of the different entities from the two models. The numbers shown in Table 1 are for the vehicle and instrumentations only (without the barriers, occupants, and cargo entities). The two models are very similar in geometry with few components in the LWT altered to reflect the design updates. The mesh size used in both models is also similar and consequently the two models have similar total number of elements. The part names in the LWT and Baseline models are also similar except for the few added parts. This made it convenient to compare the differences in mass between the two models by component.

Table 1: Model General Information

| | | |
|---|---|---|
| |  |  |
| Entities | Baseline Model | LWT Model |
| | | |
| Total Number of Parts | 1519 | 1556 |
| Shells Parts | 1311 | 1377 |
| Solid Parts | 181 | 153 |
| Beam Parts | 17 | 16 |
| Discrete Parts | 10 | 10 |
| | | |

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| | | |
|---|---|---|
| Total Number of Elements | 2960904 | 3046433 |
| Shell Elements | 2654137 | 2699819 |
| Solid Elements | 284342 | 324189 |
| Beam Elements | 22397 | 22397 |
| Discrete Elements | 36 | 28 |
| | | |
| Total Number of Nodes | 2810258 | 2968115 |
| Total Mass Elements | 1666242 | 1305859 |

The total mass, center of gravity location, and moments of inertia were extracted from the two vehicle models and listed in Table 2. The total mass from the Baseline was 2433 kg and the total mass from LWT model was 2013 kg. These numbers are similar to those listed in the report. Masses of different components of the vehicle were also extracted from the models and compared to those listed in the report. The comparisons indicated that the component masses from the Baseline and LWT models matched those listed in the report.

Table 2: Vehicle Model Mass and Inertia Properties

| | Baseline Model (No Occupant or Cargo) | LWT Model (No Occupant or Cargo) |
|---|---|---|
| Mass (kg) Total | 2433 | 2013 |
| CG - X (mm) From Front Axle | 1577 | 1572 |
| CG - Y (mm) From Center Line | 8 | 13 |
| CG - Z (mm) From Ground | 898 | 875 |
| Roll Inertia Ixx (kg-m^2) | 1044 | 817 |
| Pitch Inertia Iyy (kg-m^2) | 6264 | 5266 |
| Yaw Inertia Izz (kg-m^2) | 6710 | 5613 |

The quality of the elements used to represent the different parts of the vehicle models were checked using software tools. Table 3 shows the results from the element quality

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| | checks. The results indicated that the elements used in both models were rated to have good quality. The models were also checks for errors and warnings using different pre-processors. No errors or significant warnings were found in the models. |

Table 3: Mesh Quality Check

**Baseline Model**

| | | | Failed Elements: | Percent Failed: |
| --- | --- | --- | --- | --- |
| Warpage:(HyperMesh) | > | 15.0 | 260 | 0 |
| Aspect ratio:(HyperMesh) | > | 4.0 | 33 | 0 |
| Skew angle:(HyperMesh) | > | 60.0 | 26 | 0 |
| Length:(Minimal normalized height) | < | 4.0 | 3096 | 0 |
| Length:(Minimal normalized height) | > | 15.0 | 51576 | 2 |
| Jacobian:(At integration points) | < | 0.7 | 22073 | 1 |
| Min angle for quads: | < | 40.0 | 6 | 0 |
| Max angle for quads: | > | 135.0 | 114 | 0 |
| Min angle for trias: | < | 15.0 | 9 | 0 |
| Max angle for trias: | > | 140.0 | 0 | 0 |
| Percentage of trias | < | 13 | | 5 |
| | | | | Result: |
| Total number of duplicate elements: | | | | 17124 |
| Total number of quads checked: | | | | 2521877 |
| Total number of trias checked: | | | | 132287 |
| Total number of trias and quads checked: | | | | 2654164 |

**LWT Model**

| | | | Failed Elements: | Percent Failed: |
| --- | --- | --- | --- | --- |
| Warpage:(HyperMesh) | > | 15.0 | 997 | 0 |
| Aspect ratio:(HyperMesh) | > | 4.0 | 63 | 0 |
| Skew angle:(HyperMesh) | > | 60.0 | 38 | 0 |
| Length:(Minimal normalized height) | < | 4.0 | 16715 | 1 |
| Length:(Minimal normalized height) | > | 15.0 | 51424 | 2 |
| Jacobian:(At integration points) | < | 0.7 | 17697 | 1 |
| Min angle for quads: | < | 40.0 | 16 | 0 |
| Max angle for quads: | > | 135.0 | 217 | 0 |
| Min angle for trias: | < | 15.0 | 17 | 0 |
| Max angle for trias: | > | 140.0 | 2 | 0 |
| Percentage of trias | < | 13 | | 5 |
| | | | | Result: |
| Total number of duplicate elements: | | | | 21855 |
| Total number of quads checked: | | | | 2571311 |
| Total number of trias checked: | | | | 128515 |
| Total number of trias and quads checked: | | | | 2699826 |

The element formulations used in the model were also examined. Table 4 depicts the different shell element formulations used in the model and the corresponding vehicle parts that are assigned these formulations. Fully-integrated formulation (Type 16) is used for almost all the shell components with very few parts using the default under-integrated Belytschko-Tsay formulation (Type 2). The fully-integrated formulation requires more operations than the under-integrated formulation and consequently requires more computation time (about 2.5 times). These full-integrated elements may lead to better capture of the deformation especially when used for components with high deformations. Their use may however be optimized in the model to reduce the computation time.

Table 4: Shell Element Formulations used in the Models

| | Baseline Model | LWT Model |
| --- | --- | --- |

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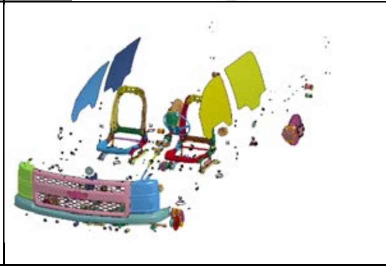
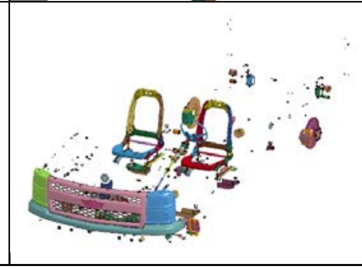
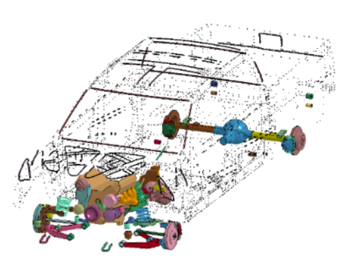
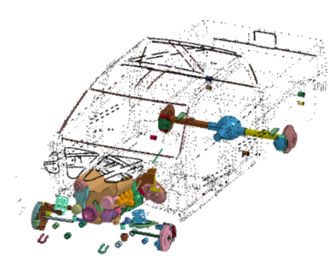
| | | |
|---|---|---|
| Shell element formulation<br>Type 16<br>Fully-Integrated |  |  |
| Shell element formulation<br>Type 2<br>Under-Integrated |  |  |

Table 5 lists the solid element formulations used in the models. The majority of the solid components in both vehicle models use the default under-integrated formulation. A few parts (battery and adhesive parts) use the fully-integrated formulation. It is important to note here, that under-integrated solid elements can lead to inaccuracies in the results. It is often recommended to use appropriate “hourglass control” or use fully-integrated forms for solid elements. Table 6 shows the “hourglass control” types used for the solid elements in the vehicle models. It can be noted from the table that some solid parts in the models use under-integrated formulation and default “hourglass control.” This may not be affecting the simulation results in this study because very few parts are made up of solid elements and the majority of these parts are rigid. It may be worthwhile, however, to change all solid parts in the models to fully-integrated to avoid inaccuracies in the simulations.

Table 5: Solid Element Formulations Used in the Models

| | Baseline Model | LWT Model |
|---|---|---|
| Solid element formulation<br>Type 1<br>Under-Integrated |  |  |

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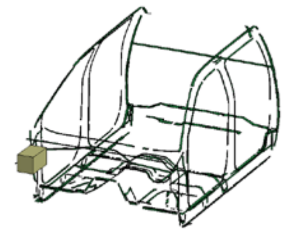
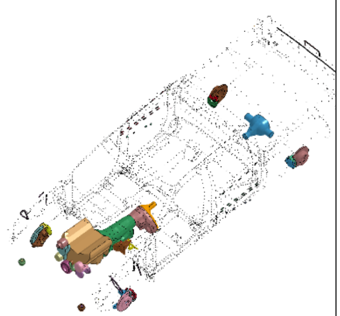
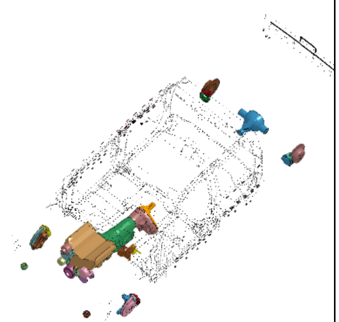
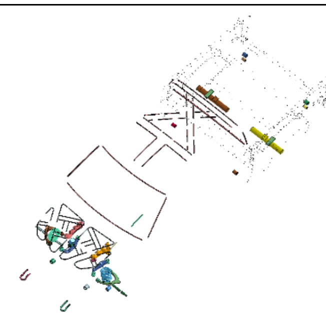
| Solid element formulation Type 2 (for Battery) and 20 (For adhesive) |  |  |

| Table 6: Solid Elements Hourglass Control Used in the Models | | |
|---|---|---|
| | Baseline Model | LWT Model |
| Parts with default hourglass control |  |  |
| Parts with defined hourglass control |  |  |

The nature of materials used in the models was also checked. Table 7 lists the different material types used in the vehicle models and the associated parts. A few parts use “rigid” material behavior; mainly the engine, transmission, and brake systems. These undergo zero deformation during the impact. A few other parts are assigned elastic material behavior; namely the tires and adhesives. These parts are assumed to experience small linear deformations during the impact.

The majority of the parts in the models were assigned elasto-plastic materials. Two types of elasto-plastic materials are used, the Piecewise_Linear_Plasticity (Type 24) and the Modified_Piecewise_Linear_Plasticity (Type 123). These two material types have similar responses except for the failure behavior. The failure behavior in the Piecewise_Linear_

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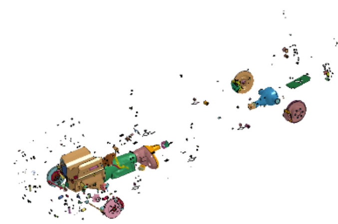
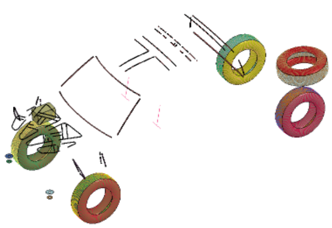
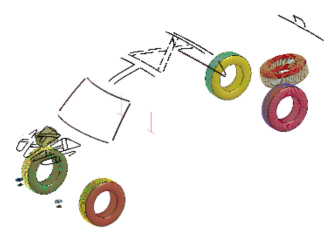
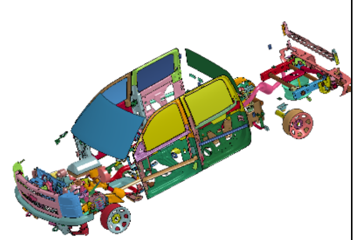
| | Plasticity material model is treated the same whether the element is in compression or tension. The Modified_Piecewise_Linear_Plasticity material model allows for different failure behavior in tension and compression. Typically, metals do not fail in compression, so the Modified_Piecewise_Linear_Plasticity material model is more suitable to simulate the failure response of these materials.<br><br>Table 8 lists the elasto-plastic parts with and without failure defined in the vehicle models. It can be seen that several parts are not assigned a failure strain, consequently these parts are assumed not to fail. This assumption is acceptable for mild steels and aluminums where the part is more likely to buckle during the impact. This assumption, however, may not be valid for high-strength steels where the material is more susceptible to fracture. It can be seen in the last row of Table 8 that some of the high-strength components are not assigned failure in the models which may lead to inaccurate simulation predictions. |

Table 7: Constitutive Formulation (Material Types) Used in the Models

| | Baseline Model | LWT Model |
|---|---|---|
| Rigid Parts |  |  |
| Elastic Parts |  |  |
| Elasto-Plastic Parts – Piecewise_Linear_ Plasticity (Material Type 24) |  |  |

| Reviewer | Comments |
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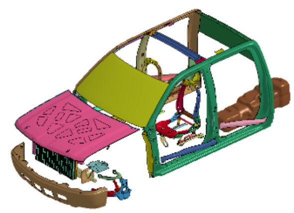
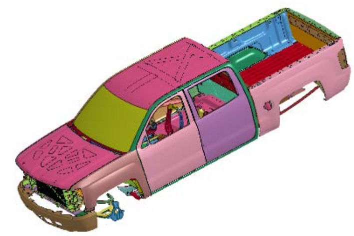
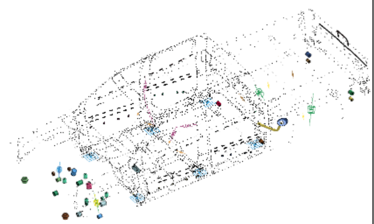
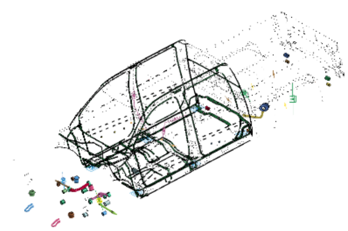
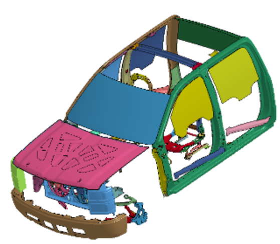
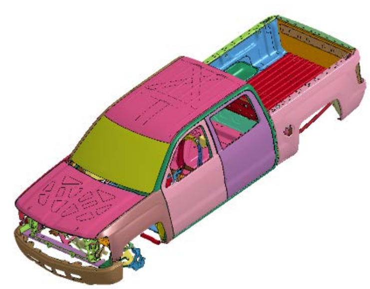
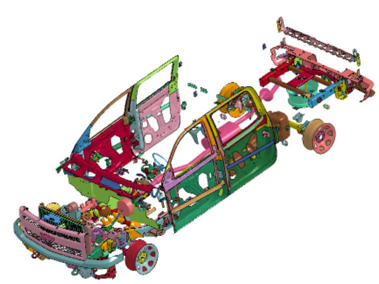
|---|---|---|
| Elasto-Plastic Parts – Modified_Piecewise_ Linear_Plasticity (Material Type 123) |  |  |
| Other Parts |  |  |

Table 8: Failure Implementation in the Elasto-Plastic Parts

| | Baseline Model | LWT Model |
|---|---|---|
| Elasto-Plastic Parts with Failure Strain Defined |  |  |
| Elasto-Plastic Parts with No-Failure Strain Defined |  |  |

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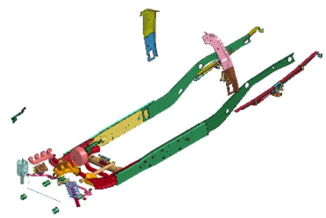
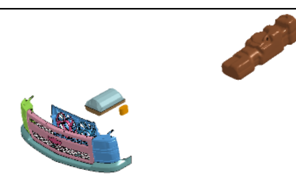
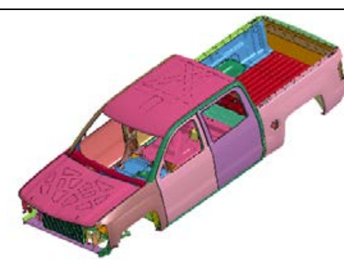
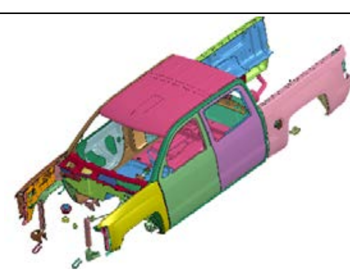
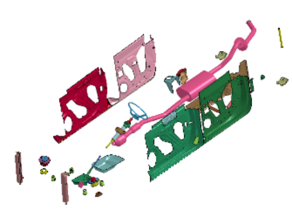
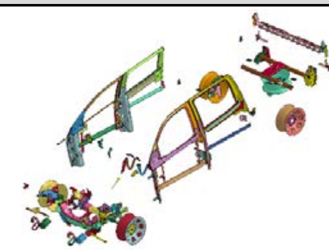
|---|---|---|
| High-Strength Steel Parts (Yield Strength > 500 MPa) with No Failure Strain Defined |  |  |

The defined material properties in the models were also examined to identify the different materials used in the two vehicle designs. Table 9 lists the different materials used in the model and the associated parts that use these materials. It can be seen from the table that the majority of the components of the Baseline model are made-up of steel while the majority of the components in the LWT are made-up of aluminum. This is consistent with descriptions provided in the report.

Table 9: Different Materials Used in the Models

| | Baseline Model | LWT Model |
|---|---|---|
| Parts with Plastics Properties |  |  |
| Parts with Aluminum Properties |  |  |
| Parts with Steel Properties<br>Yield Strength < 300 MPa |  |  |

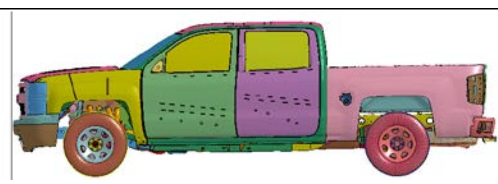
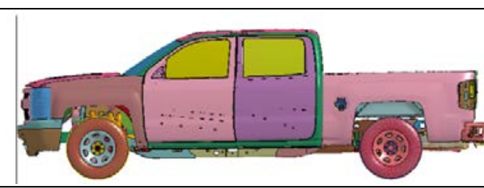
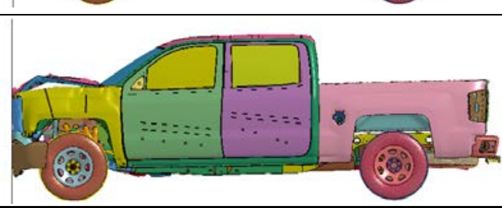
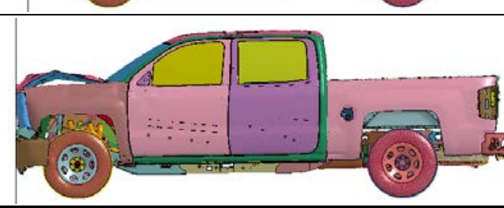
| Reviewer | Comments |
|---|---|

| | | |
|---|---|---|
| Parts with Steel Properties<br>300 < Yield Strength < 500 MPa |  |  |
| Parts with Steel Properties<br>Yield Strength > 500 MPa |  |  |

**III - Simulation Evaluations**

The simulations were run and analyzed to assess the validity of the results. Simulations were run for four of the eight impacts: NCAP frontal, IIHS moderate overlap, NCAP MDB side and IIHS moderate overlap. Two simulations, one with the Baseline model and one with LWT model, were performed for each of the four impact cases. Hence, a total of eight simulations were run. All eight simulations ran to completion with normal termination. Examination of the vehicle deformation at different stages of simulation showed expected crush behavior. A check of the computed global energies indicated no discrepancies in the results. Review of the top ten energy absorbing parts revealed expected findings. Examples of these plots from one of the impact cases, NCAP frontal, are shown in Tables 10-12.

Table 10: NCAP Frontal Deformation Plots

| Baseline Model | LWT Model |
|---|---|
|  |  |
|  |  |

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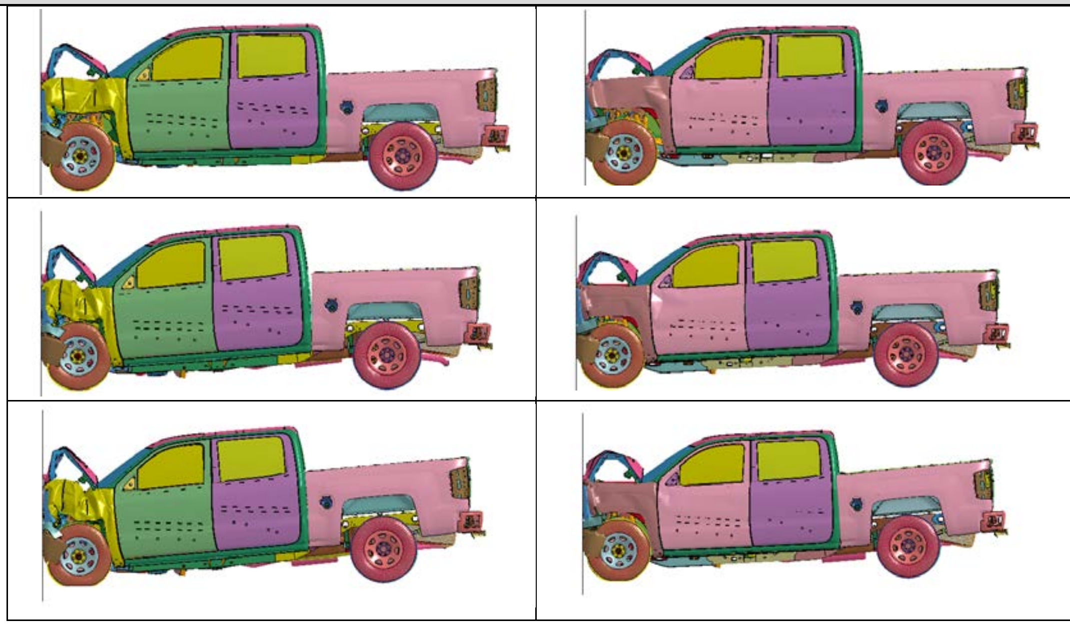
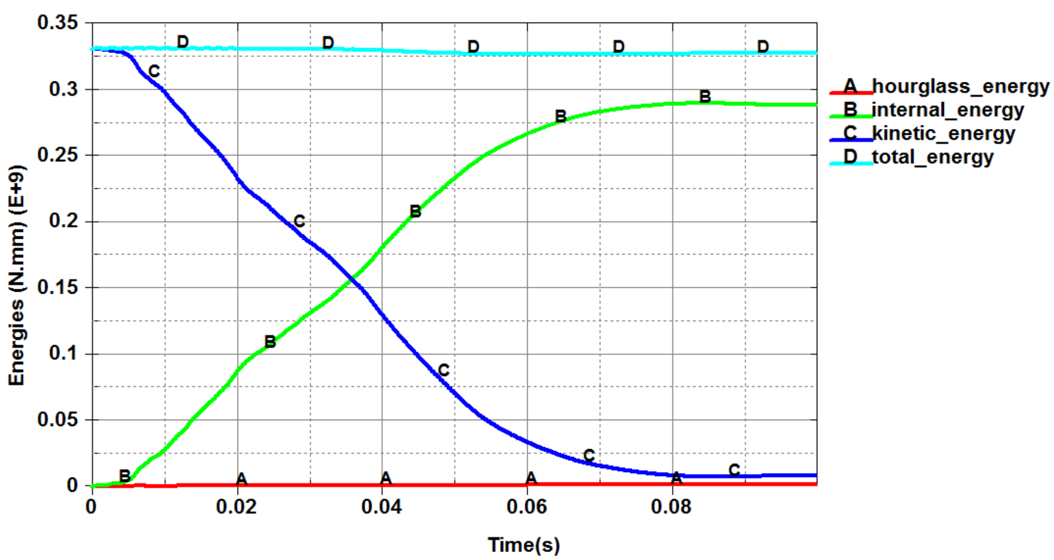
| |  |
| | Table 11: NCAP Frontal Global Energies |
| |   |

| Reviewer | Comments |
| --- | --- |

LWT Model

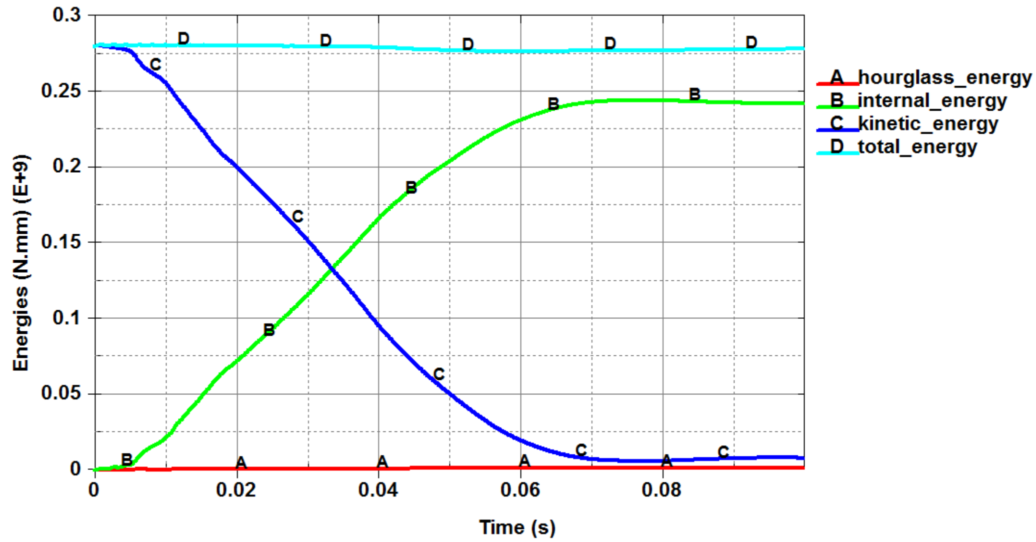
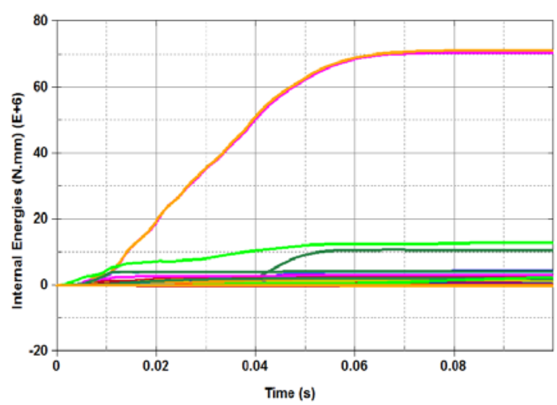
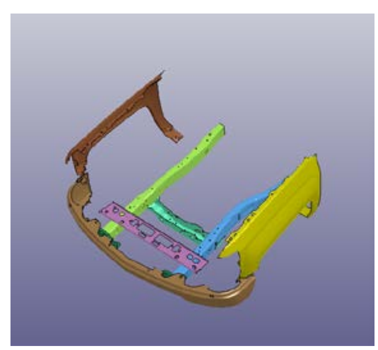



Table 12: Top Ten Energy Absorbing Parts

Baseline Model



<table>
<tr><th>Reviewer</th><th>Comments</th></tr>
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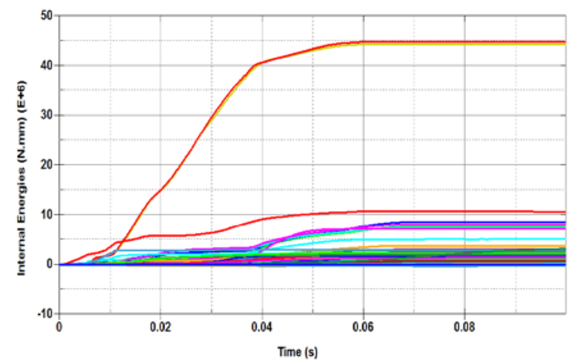
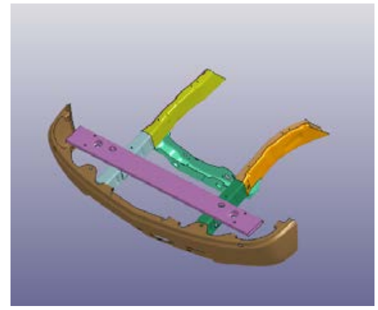
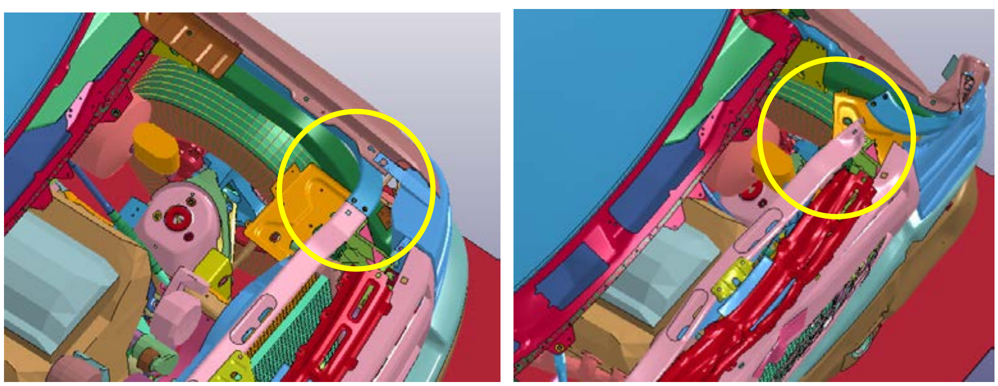
<table>
<tr><td>LWT Model</td><td>
</td><td></td></tr>
</table>
It was noted that some components of the LWT model failed in the simulations as shown in Figure 1. These could have been designed to intentionally fail to achieve better crashworthiness performance, but the reasons are not documented.<br>
<br>
Figure 1: Example of Component Failure in LWT
</td></tr>
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# Appendix A:

## Charge to Reviewers

**PEER REVIEW CHARGE**

DTNH22-13-D-00298

Task Order 0004

***External Peer Review of NHTSA's Draft Report, "Mass Reduction for Light-Duty Vehicles for Model Years 2017-2025"***

## INTRODUCTION

The National Highway Traffic Safety Administration (NHTSA) is an agency within the U.S. Department of Transportation (DOT). NHTSA's mission is to save lives, prevent injuries, and reduce traffic-related health care and other economic costs. The agency develops, promotes and implements effective educational, engineering, and enforcement programs with the goal of ending vehicle crash tragedies and reducing economic costs associated with vehicle use and highway travel.

## BACKGROUND

NHTSA has been issuing Corporate Average Fuel Economy (CAFE) standards under the Energy Policy and Conservation Act (EPCA) for the last thirty years. EPCA requires DOT to establish average fuel economy standards for passenger cars and light trucks at "the maximum feasible average fuel economy level that the Secretary [of DOT] decides the manufacturers can achieve in that model year." When setting "maximum feasible" fuel economy standards, DOT is required to "consider technological feasibility, economic practicability, the effect of other motor vehicle standards of the Government on fuel economy, and the need of the United States to conserve energy." The Energy Independence and Security Act (EISA), enacted on December 19, 2007, amended EPCA. In addition to passenger car and light truck standards being set at the maximum feasible level in each model year, EISA mandated that the model year (MY) 2011-2020 CAFE standards be set sufficiently high to ensure that the industry-wide average of all new passenger cars and light trucks, combined, be not less than 35 miles per gallon (mpg) by MY 2020.

In fulfillment of its EPCA and EISA requirements and in response to President Obama's directive to create a coordinated and harmonized National Program for motor vehicle efficiency and emissions standards, NHTSA published a final rule with the Environmental Protection Agency (EPA). This final rule set CAFE standards under EPCA/EISA and greenhouse gas (GHG) standards under the Clean Air Act (CAA) for passenger cars and light trucks manufactured in model years 2017-2025 for GHG and 2017-2021 for CAFE. 1 NHTSA will develop final CAFE standards for MYs 2022-2025 as part of a future new rulemaking, considering the findings of a "mid-term evaluation" to be conducted jointly with EPA and the California Air Resources Board. The CAFE standards increase annually in stringency, and for MY 2021, are currently estimated to require a combined industry-wide fleet fuel economy of 40.3-41.0 mpg.

Based on NHTSA's discussions with manufacturers about how they plan to comply with CAFE standards in those model years, the agency anticipates that the industry will make use of vehicle mass reduction as a means for reducing vehicle fuel consumption in the future. NHTSA's recent rulemaking analyses have employed "mass reduction" as a technology option for compliance modeling purposes. Specifically, in order

[1] The final rule was issued on August 28, 2012, and published in the Federal Register on October 15, 2012, at http://www.gpo.gov/fdsys/pkg/FR-2012-10-15/pdf/2012-21972.pdf . A copy is also available on NHTSA's website at http://www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/2017-25_CAFE_Final_Rule.pdf (last accessed October 19, 2012).

to ensure that a compliance path for industry exists that would be safety neutral at a societal level, NHTSA applied more mass reduction in the CAFE rulemaking analysis to larger vehicles, such as pickup trucks and minivans, and less or even zero mass reduction to smaller vehicles, such as subcompact and compact cars. For example, in the analysis for MYs 2017-2025, the CAFE model (a computer model used by the agency to conduct rulemaking analysis[2]) was configured to allow up to 20 percent mass reduction per large pickup truck relative to MY 2008 fleet as a way for manufacturers to achieve compliance, and limited mass reduction to 5 percent per vehicle for midsize cars. The agency took this approach for consistency with NHTSA's analysis of safety effects for vehicle mass reduction, which found that mass reduction can occur in a safety-neutral, or perhaps even a safety-beneficial, manner if it occurs in the heaviest of vehicles, while the contrary may be true for lighter vehicles.

In support of the recent rulemaking for MYs 2017-2025, NHTSA funded a mass reduction study on mid-size passenger cars based on a MY 2011 Honda Accord. In that project, the vehicle achieved 20 percent mass reduction with a cost increase[3]. Due to the functionality differences between passenger cars and light trucks, the agency is very interested in exploring the potential differences in mass reduction approaches for passenger cars and light trucks, and believes further research would be helpful to this regard.

NHTSA has recently noticed many Original Equipment Manufacturers (OEMs) announcing more and more complicated types of mass reduction, often in the interest of improving fuel economy. As the agency looks ahead to the future rulemaking to develop final standards for MYs 2022-2025, we expect that more and more mass reduction technologies will be applied and that the baseline fleet may migrate to lighter vehicles overall. The mass reduction technologies employed in the fleet representing the on-road vehicles closer to the time when the analysis for the future rulemaking is conducted will use different materials than the ones used as baseline vehicles in the previous light-weighting studies. Some future light-weighted vehicles will also have downsized powertrains, consistent with the design in the mid-size passenger car mass reduction project and the agency's assumptions in the recent rulemaking for MYs 2017-2025.

As the 2012-2016 CAFE rule is phasing in during the next few years and OEMs are preparing to comply with the MYs 2017-2021 CAFE final rule, OEMs already have started applying more mass reduction technologies in the fleet. This might change the material usage and manufacturing technology usage for the baseline for MYs 2022-2025 rule. The agency is interested in updating the baseline mass reduction technologies for on-road vehicle material and manufacturing technology usage and in confirming and validating the mass compounding effect of downsizing a vehicle powertrain as well as the mass reduction potential for the overall vehicle.

**REPORT OVERVIEW**

The report addresses three tasks:

**1) Baseline Vehicle Tear-Down and Finite Element Analysis Modeling.** The report details baseline vehicle selection to evaluate light-duty pickup truck fleet and perform a teardown study to build the baselines for engineering analysis and cost analysis for the light-weighted design.

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[2] The CAFE Compliance and Effects Modeling System is available for download at http://www.nhtsa.gov/Laws+&+Regulations/CAFE+-+Fuel+Economy/CAFE+Compliance+and+Effects+Modeling+System:+The+Volpe+Model.

[3] The report and models for this project can be found at http://www.nhtsa.gov/Laws+&+Regulations/CAFE+-+Fuel+Economy/Research+Supporting+2017-2025+CAFE+Final+Rule.

**2) Design and Optimization of the Light-Weighted Pickup Truck.** The report demonstrates the use of advanced design, material, and manufacturing processes that will likely be available during model years 2020-2030 to develop a light-weighted pickup truck capable of high volume production. The report also provides an engineering design, computer-aided engineering analysis to demonstrate crashworthiness, and incremental cost estimate for the light-weighted vehicle relative to the baseline vehicle.

**3) Mass Reduction for Other Light-Duty Vehicles.** This report also provides information on application of light-weighted technology identified for the pickup truck project to other classes of passenger cars and pickup trucks.

**BACKGROUND MATERIALS (for your reference as needed)**

1-SAE 2016 - NHTSA Presentation EDAG - Singh1-19-2016.pdf

Also as background, NHTSA has provided these links to a previous mass reduction project on a 2011 Honda Accord:

Honda Accord mass reduction project report:
ftp://ftp.nhtsa.dot.gov/CAFE/2017-25_Final/811666.pdf

Peer Review Report of Honda Accord mass reduction project report:
https://www.regulations.gov/#!documentDetail;D=NHTSA-2010-0131-0329

Updated report and models in response to comments and for IIHS small overlap test:
http://www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/812237_LightWeightVehicleReport.pdf

Honda Accord CAE models:
ftp://ftp.nhtsa.dot.gov/CAFE/2017-25_Final/Accord_LW8b.zip

Honda Accord cost models:
ftp://ftp.nhtsa.dot.gov/CAFE/2017-25_Final/CostModelsAug2012.zip

**CHARGE QUESTIONS**

In your written comments, please provide a detailed response to the following questions, based on your primary area of focus for this review:

- **General Reviewer:** All questions within your area of expertise in Sections 1-4 and all questions in Sections 5-8.
- **Cost Focus:** 1a-b, 2a-c, 3a, 4a-c, 5a-c, 6a-e, 7a-d, 8a (and, as time allows, any additional questions within your area of expertise).
- **Modelling/Simulation Focus:** 1a-b, 3a-h, 5a-c, 6a, 6e, 7a-d, 8a (and, as time allows, any additional questions within your area of expertise).

Please identify additional topics and depart from these examples as necessary to best apply your particular area(s) of expertise. Your comments should be sufficiently clear and detailed to allow readers to thoroughly understand their relevance to this study. Comments should be limited to evaluation of the report as a stand-alone technical document and should not include unrelated commentary.

**To request additional supporting data files, engine maps/models, images, or other materials, please contact Laurie Waite at laurie.waite@erg.com. She will work with NHTSA to make those materials available to all reviewers as soon as possible.**

**1. Assumptions and Data Sources**

a) Please comment on the validity of data sources and assumptions embedded in the study's material choices, vehicle design and optimization, crash validation testing, and cost assessment that may affect the report's findings.

b) If you find issues with data sources and assumptions, please explain what you believe the issues are and why they are problematic and provide suggestions for available data that would improve the study.

**2. Vehicle Design and Optimization Methodology and its Rigorousness**

a) Please comment on the material selection and usage, joining technologies, vehicle structure design and optimization methodology, and the resulting final vehicle design.

b) Describe the extent to which state-of-the art design methods have been employed, as well as the extent to which the associated analysis exhibits strong technical rigor.

c) If you are aware of other methods employed elsewhere to select and analyze advanced materials and design engineering rigor for 2017-2025 vehicles, please comment on if and how they might improve the study and how they might be used.

**3. Vehicle Functionalities and Crashworthiness Testing Methodological Rigor**

a) Please comment on the approach and effort in maintaining baseline vehicle functionalities while trying to lightweight the vehicle.

b) Comment on the methods used to design and analyze the vehicle body's structural integrity and crashworthiness.

c) Describe whether, and the extent to which, state-of-the-art crash simulation methodologies have been employed and the extent to which the associated analysis exhibits strong rigor.

d) Can the design and LS-DYNA results in this study be validated? If yes, how? If no, why not?

e) If you are aware of other methods and tools to help validate advanced materials and design engineering rigor for 2017-25 vehicles, please suggest how they would improve this study.

f) Is the crash pulse in full frontal impact acceptable from an air bag sensing point of view? Why or why not?

g) Are durability and NVH values in the acceptable range after mass reduction? If not, what would be an acceptable range?"

h) Is the high strength steel(s) selected within the plastic strain working range for the part selected?

**4. Vehicle Manufacturing Cost Methodology and its Rigorousness**

a) Comment on the methodology used to estimate the LWV manufacturing costs.

b) Please describe whether, and the extent to which, state-of-the-art costing methods have been employed, and the extent to which the associated analysis exhibits strong rigor.

c) If you are aware of other methods and tools employed elsewhere that could be used to help estimate costs for advanced materials and design for 2017-25 vehicles, please describe them and suggest why they would improve this study and how they might be used.

**5. Conclusion and Findings**

a) Are the study's conclusions adequately backed up by the methods and analytical rigors of the study? Any concerns? How can they be addressed?

b) Are the conclusions about the design, development, validation, and cost of the mass-reduced design valid? Any concerns? How can they be addressed?

c) Are you aware of other available research that evaluates and validates the technical potential for mass-reduced vehicle in the 2017-25 time frames that could be helpful for this study? Include sources and additional information for such research.

**6. Other Potential Areas for Comment**

a) Is the methodology used to estimate the feasible mass reduction in other light-duty vehicle classes reasonable? Please explain.

b) Is the study valuable to understand the feasibility of 2017-2025 mass reduction technology? Please explain.

c) Do the study design concepts have any critical deficiencies in their applicability for 2017-2025 mass reduction feasibility that require revision by NHTSA prior to finalizing the report? If yes, please describe.

d) Are there any fundamentally different lightweight vehicle design technologies that are likely to be more common than the ones assessed in this study?

e) Is the cost from the study reasonable and backed up by sufficiently detailed data? What would you expect the cost to be for the design in this study? Please explain the reasons if your estimate is different than this study.

**7. General Comments**

a) Describe your overall assessment of the organization, readability, and clarity of this report, including any changes needed.

b) Is the information provided in the report and appendices sufficiently detailed to thoroughly document all essential elements of the study? If not, what additional information is needed?

c) What are the strongest and weakest parts of this report? How can the weakest parts of the report can be strengthened?

d) Please provide any other comments you may have on this report.

**8. Overall Recommendation**

a) Based upon your review, indicate whether you find the report: (1) acceptable as is, (2) acceptable with minor revisions, (3) acceptable with major revisions, or (4) not acceptable. Please justify your recommendation. If you find the report acceptable with minor or major revisions, be sure to describe the revisions needed.

# Appendix B:

## INDIVIDUAL REVIEWER COMMENTS

**COMMENTS SUBMITTED BY**

Sujit Das, M.B.A.
Senior Research Staff Member
Energy and Transportation Science Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee

## *External Peer Review of NHTSA's Draft Report,* "Mass Reduction for Light-Duty Vehicles for Model Years 2017-2025"

**1. Assumptions and Data Sources**

**a) Please comment on the validity of data sources and assumptions embedded in the study's material choices and cost assessment that may affect the report's findings.**

The detailed teardown data of a baseline 2014 Chevrolet Silverado was used for the LWT design. It is appropriate that Silverado was selected as the baseline because of its 5-star rating and latest design used in comparison with the largest sales volume F-150 pickup truck in the market today. The suitability and maturity of each five major lightweight materials manufacturing and assembly technologies considered for major vehicle systems, body structure, closures, and chassis frame were initially classified as mature, mid-term, and long term. The lightweight materials considered for the LWT design were mostly limited to AHSS and aluminum, already being used in some of the high-volume vehicles in the market today which have been classified for various vehicle subsystems as either mature or mid-term. It is interesting to note that the carbon fiber reinforced plastic (CFRC) material option in 2014 was considered as mid-term compared to resin transfer molding (RTM) as long-term, the latter being one of the manufacturing options for CFRC used in the industry today. Sheet molding compound technology commonly used for fiber glass reinforced plastics today was considered as two distinct options, and as a long term technology option today. This lightweight material option has only been considered for the leaf springs of rear suspension. A consistent set of program and general process input data were used for the vehicle part and cost assessment.

**b) If you find issues with data sources and assumptions, please explain what you believe the issues are and why they are problematic and provide suggestions for available data that would improve the study.**

Data sources and underlying assumptions are mostly valid with an appropriate reference list of information sources provided. Specific problematic issues requiring attention are listed below under "Additional Comments."

**2. Vehicle Design and Optimization Methodology and its Rigorousness**

**a) Please comment on the material selection and usage, joining technologies, vehicle structure design and optimization methodology and the resulting final vehicle design.**

The options for lightweighting technologies and solutions applied to the LWT were based on a detailed assessment of several baseline vehicle systems. AHSS, aluminum, and to a limited extent, magnesium, were generally considered for the most vehicle components, being the most mature and suitable for cost-effective high volume production in today's vehicles. It is confusing in the report when mentioning the model year(s) beyond the MY 2017-2025 time frame (e.g., MY 2020-2030 for high volume production on p. 23, 253 & 254) for the selection basis of available lightweight material manufacturing technologies and the specific lightweight material selection is mostly based on today's technology maturity level and not the future. Although the desired vehicle mass savings potential and cost penalty were achieved using the available high-volume production lightweight materials available today, considering a different mix of lightweight materials would have been more appropriate at least for the latter vehicle design generations, i.e., MY 2025 and MY 2030. A consideration of the vehicle design analysis at the four distinct level design generations, MY 2017, MY 2020, MY 2025, and MY 2030 would be more logical for the longer design time-frame as noted several times throughout the report.

Conventional lightweight materials such as AHSS, aluminum, magnesium, and plastics, manufacturing processes (stamping, hot stamping, die casting, extrusions, and roll forming) and assembly methods (stamping, hot stamping, die casting, extrusions, and roll forming) currently in use were only considered. The process parameters for manufacturing with advanced materials have been validated by computer simulation. The latest weight saving optimization tools such as body structure CAE optimization for material gage-grade-geometry selection has been used. In addition, the final specific technology selection was based on the rating for its mass saving potential and cost of implementation in terms of $ per kg mass saving besides the consideration of multi-material joining issues of several options for similar applications in use in the industry today. However, it is unclear whether any iterative lightweighting vehicle mass optimization procedure was used to meet the final vehicle retail price premium goal.

**b) Describe the extent to which state-of-the art design methods have been employed, as well as the extent to which the associated analysis exhibits strong technical rigor.**

The final specific lightweight component technology selection for a LWT vehicle design has been based on a strong technical rigorous mass saving potential and cost of implementation analyses of potential technology options being considered in the industry today. Although the latest weight saving optimization tools for the LWT design validation, but the selection of lightweight materials and joining methods particularly when the analysis time frame considered extends beyond 10 years, were mostly materials and manufacturing technologies widely used in the industry today. The effect of mass compounding at the component level due to the overall LWT overall mass has been considered, but the methodology used to derive at the downsized component masses hasn't been discussed.

The effect of the lower LWT vehicle mass and smaller engine/transmission on the lighter fuel system, engine cooling system, and exhaust were also considered in the analysis. For those cases, a net cost savings in the LWT design looks reasonable, unlike in FESM and radiator support structure. The specific component technology was primarily driven by the minimum risk in the technology readiness within the time frame of 2020-2030 considered in the study although the report title indicates MYs 2017-2025.

**c) If you are aware of other methods employed elsewhere to select and analyze advanced materials and design engineering rigor for 2017-2025 vehicles, please comment on if and how they might improve the study and how they might be used.**

Most potential methods used for advanced materials and design engineering design have been adequately considered for 2017-2025 vehicles. A multi-material design approach (commonly known as "Rightweighting" – a specific lightweight material is detrimental to its final application) has been considered for various potential vehicle component designs, which has been used to the extent possible in this LWT design study with a due consideration of multi-material joining issues.

### 3. Vehicle Functionalities and Crashworthiness Testing Methodological Rigor

**a) Please comment on the approach and effort in maintaining baseline vehicle functionalities while trying to lightweight the vehicle.**

Based on LS-DYNA finite element crash analysis simulations, the LWT design structural performance in NHTSA's New Car Assessment Program (NCAP), frontal, side, and side pole test programs equivalent to or better than the baseline vehicle has been demonstrated. The developed LS-DYNA models are anticipated to be useful for conducting future vehicle-to-vehicle crash analysis studies to assess the safety performance of lighter mass vehicles in a future fleet simulation study. LWT design topology optimization and 3G optimization engineering tools were also used to determine optimized structural load paths in a pre-specified three-dimensional space.

The manufacturability of all proposed body structure panels for the LWT was assessed using suitable simulation tools routinely applied in the industry prior to the design being released for production tooling. FEA models of vehicle performance, crashworthiness, safety, vehicle stiffness and NVH have been developed for both baseline and LWT designs, and the latter models compared with the former to maintain unchanged vehicle functionalities and crashworthiness.

### 4. Vehicle Manufacturing Cost Methodology and its Rigorousness

**a) Comment on the methodology used to estimate the LWV manufacturing costs.**

Two cost modeling methods, i.e., technical cost modeling and supplier assessments are appropriate for the incremental cost assessment of the LWT full sized pickup. These methods are consistent with the methodologies used in the earlier LDV cost assessments in support of the forthcoming CAFÉ standards by NHTSA and EPA. The RPE multiplier of 1.45 used for estimating retail price is based on several old published literature and will be appropriate to update given recent changes in the automotive industry. Use of the supplier assessments for future projections and conceptual technologies such as for seats, instrument panel, brakes etc. instead of the detailed technology cost modeling approach is appropriate. OEM purchased component cost estimates were obtained from the leading component suppliers and validated using EDAG/Intellicosting internal cost estimating expertise. The final purchased price of the sub-system was estimated by adding the appropriate SG&A and profit values to manufacturing cost.

**b) Please describe whether and the extent to which state-of-the-art costing methods have been employed and the extent to which the associated analysis exhibits strong rigor.**

Technical cost modeling approach used for entire body structure, frame, closures, bumpers, fenders, front suspension, rear suspension, wheels and their corresponding assembly process exhibits the most rigor as the in-depth cost analysis provides sufficient details of the incremental cost elements traceable to the design change. The overall manufacturing cost is estimated as the sum of costs of the sequence of the different operations. Sensitivity of both the technology and economic related costs such as raw material, capital investment, tooling, and labor etc. on the total manufacturing cost can be estimated.

c) **If you are aware of other methods and tools employed elsewhere that could be used to help estimate costs for advanced materials and design for 2017-25 vehicles, please describe them and suggest why they would improve this study and how they might be used.**

The manufacturing part cost estimation at the level of major manufacturing steps based on the technical cost modeling approach used is appropriate to facilitate the economic viability of the 2017-2025 vehicle designs. In the cost estimation of future vehicle designs, there remains an uncertainty both in terms of technical design and economic parameters. It is appropriate then to consider the sensitivity analysis of major technical design and economic parameters, based on which a range of part cost be estimated instead of a single value.

**5. Conclusion and Findings**

a) **Are the study's conclusions adequately backed up by the methods and analytical rigors of the study? Any concerns? How can they be addressed?**

The study's conclusions based on the methods and analytical rigors used have been very well documented in an impressive and well-written large report. Spreadsheet cost models provide the details for the manufacturing part cost estimates. A better documentation of the spreadsheet cost models in terms of the reference listing of major input variables would be better for the validation purpose.

b) **Are the conclusions about the design, development, validation, and cost of the mass-reduced design valid? Any concerns? How can they be addressed?**

The conclusions about the design, development, validation, and cost of the mass-reduced are valid. Since the most lightweight material technologies considered in the LWT design are currently being used in the high production volume vehicles today, a comparative analysis of mass savings potential achieved and cost premium paid for the vehicles on the road today would be an excellent source of design and cost validations.

c) **Are you aware of other available research that evaluates and validates the technical potential for mass-reduced vehicle in the 2017-25 time frames that could be helpful for this study? Include sources and additional information for such research.**

1. "Light-Duty Vehicle Mass Reduction and Cost Analysis – Midsize Crossover Utility Vehicle," EPA-420-R-12-026, Aug. 2012

2. Baron, J. (2016) "Identifying Real World Barriers to Implementing Lightweighting Technologies and Challenges in Estimating the Increase in Costs," Center for Automotive Research, Jan.

**6. Other Potential Areas for Comment**

a) **Is the methodology used to estimate the feasible mass reduction in other light-duty vehicle classes reasonable? Please explain.**

The general approach used to estimate the first-cut feasible mass reduction in other light-duty vehicle classes using the detailed A2Mac1 North American benchmark database seems reasonable. Honda Accord would have been a more appropriate representative for the mid-sized passenger cars which could have served as the validation of the prior EDAG study data. Mass compounding based on gross vehicle weight vs. gross combined weight rating depending on the light-duty vehicle was taken into consideration for the resizing of engine, powertrain, and fuel system, but the methodology used for estimating the component masses was not discussed as in the case of the light-duty pickup truck Chevrolet Silverado 1500. However, using the same mix of lightweight materials in other light-duty vehicles as considered in the pickup truck may not be appropriate. Besides the differences in the consumer willingness- to-pay for vehicle lightweighting, vehicle performance and functionality requirements vary by the vehicle class. It is unclear whether at a similar extent as the full size pickup truck, vehicle performance and functionality requirements have also been evaluated for other light-duty vehicle classes.

It'd be good to extend the mass reduction analysis to the incremental cost analysis for other light-duty vehicle classes.

**b) Is the study valuable to understand the feasibility of 2017-2025 mass reduction technology? Please explain.**

The study is extremely valuable in understanding the feasibility of 2017-2025 mass reduction technology. Most LWT design materials considered have been based on the materials and manufacturing technologies being used in high-volume light-duty vehicle production today.

**c) Do the study design concepts have any critical deficiencies in their applicability for 2017-2025 mass reduction feasibility that require revision by NHTSA prior to finalizing the report? If yes, please describe.**

The study design concepts considered do not have any critical deficiencies that require any NHTSA revisions. Most design concepts considered are lightweight materials such AHSS and aluminum being used in vehicles of today.

**d) Are there any fundamentally different lightweight vehicle design technologies that are likely to be more common than the ones assessed in this study?**

Lightweight design technologies other than AHSS and aluminum could be different in some vehicle systems, particularly for towards the latter MY vehicles. For a single LWT vehicle design scope of the study, they seem to be appropriate.

**e) Is the cost from the study reasonable and backed up by sufficiently detailed data? What would you expect the cost to be for the design in this study? Please explain the reasons if your estimate is different than this study.**

Cost estimates from the study are reasonable and backed up by sufficiently detailed data. An estimate of 16.7% mass savings at a cost premium of $3.57/kg for the aluminum-AHSS option with powertrain sizing seems reasonable and consistent with earlier published cost estimates of other light-duty vehicle considered in support of the EPA and NHTSA rule making.

**7. General Comments**

**a) Describe your overall assessment of the organization, readability, and clarity of this report, including any changes needed.**

Overall organization of the report is excellent in terms of both readability and clarity. Appropriate references have been included throughout the document. It'd be appropriate to relabel all the Tables as Table and not Figure and addressing the specific comments as listed under "Additional Comments.".

**b) Is the information provided in the report and appendices sufficiently detailed to thoroughly document all essential elements of the study? If not, what additional information is needed?**

Information provided in the large report and appendices contain sufficient details to thoroughly document all essential elements of the study. In addition, cost models used to derive the final cost estimates discussed in the report provide further details.

**c) What are the strongest and weakest parts of this report? How can the weakest parts of the report can be strengthened?**

It'd be useful to include a new section on the effect of mass compounding effect on the LWT components. It is hard to validate these implicit estimates used in cost savings estimates and so a table listing of a reduction in mass at the component level is necessary. Total component mass savings is shown but not disaggregated by lightweighting vs. mass compounding.

**d) Please provide any other comments you may have on this report.**

Additional comments by specific page nos. of the report are provided below.

**8. Overall Recommendation**

**a) Based upon your review, indicate whether you find the report: (1) acceptable as is, (2) acceptable with minor revisions, (3) acceptable with major revisions, or (4) not acceptable. Please justify your recommendation. If you find the report acceptable with minor or major revisions, be sure to describe the revisions needed.**

Overall, it is an excellent and well-written report and is acceptable with minor revisions to address comments listed below under "Additional Comments".

**ADDITIONAL COMMENTS**

1. p. 54: Why weren't more recent than MY2012 full-size pickup trucks sales data considered for the baseline vehicle selection?

2. p. 79, p. 82 (Fig. 47): "alloy" needs to be replaced by "Aluminum Alloy". It'd be good to address this throughout the document, particularly consistently in all figures.

3. p. 80 (line 3-4): one of the values in the statement "2 percent (56.3 kg) of the vehicle weight" doesn't seem to be right? Figure 43 indicates 18%.

4. p. 130: Not clear about the basis for the second least cost option selection for the LWT cab design, although the least cost hybrid structure option has already been implemented in 2015 Cadillac CT6. What criteria were used to determine the most cost-effective option, is it only least $/kg of mass saved? (on pg. 152 says – problem with hybrid is the joining of dissimilar metals).
5. p. 133 (Figure 113): listed price data for which year? Manufacturing scrap should be sensitive not only to the material type, but also by the manufacturing process. Assumed manufacturing process scrap rate of 0.20 for carbon fiber seems to be low, at least in the range of 0.30-0.40, depending on the form used for a given application. Not sure about the logic behind a higher manufacturing difficulty value for fiber glass compared to SMC, although the latter is a composite material of glass fiber and polymer resin matrix material.
6. p. 156 For FESM Left & Right, cost increase premium in terms of $/kg is significantly lower than Body structure for a similar level of mass reduction potential considered for aluminum and aluminum+AHSS?
7. p. 158 It is surprising that cost increase premium for the aluminum radiator support is more than >$10/kg.
8. p. 159: Not a convincing argument for the magnesium+aluminum selection for the LWT radiator support design in spite of the multi-material joining issues mentioned in earlier cases.
9. p. 161 It is surprising that the use of aluminum and magnesium can result in a more than 60% mass savings in the final LWT cab assembly design of FESM and radiator support.
10. p. 163: The lightweight glass fiber reinforced composite should have considered as one of the LWT options which has already been demonstrated more than a decade ago.
11. p. 182 Not convincing how such a low mass savings value of 20% was achieved for a CFRP Hood option 2 considered?
12. p. 183: A final paragraph on the optimal selection of hood is missing.
13. p. 190: Mass savings cost premium for Frame Option 4 (AHSS+CFRP) should be significantly higher than the aluminum Frame Option 3, including mass savings potential?
14. p. 196 (last para): Why LWT bumper designs mass savings cost premium for the front are 1/3rd of rear, although resultant mass savings are similar?
15. p. 213: Not sure what methodology used for the downsized 2.7L EcoBoost engine of the LWT design?
16. p. 219: The reference needed for “10% reduction in vehicle weight leads to a gain of 3.5-6.5% in fuel economy. The most common range of the fuel economy gain 6-8% used by the industry with the consideration of energy downsizing.
17. p. 251 (line 4): The original cast/forged iron is 444 kg and not 32 kg as noted.

18. p. 262 (Figure 275): Unlike for Composites, both types of composites and manufacturing technology have been considered. In other lightweight material cases, the appropriate manufacturing technologies have only been made. This figure should focus on manufacturing technology by different lightweight material types.

19. p. 363: Mentions that the technical cost modeling methodology is explained in detail in Section 9.4, but instead that section on p. 339 discussed "Ride and Handling Performance."

20. p. 363 (second last line): Shouldn't this be baseline Chevrolet Silverado and not Accord as indicated?

21. p. 365: (Figure 406): It is more appropriate to consider "Energy" for Component Manufacturing Costs under "Process" instead of "Plant."

22. p. 370: Any reason why the interest rate for Program (i.e., 7%) is different from the one (i.e., 7.03%) used for tooling and equipment investment?

23. p. 381: BLS data source used to estimate the average markup value of 41% is based on old data, i.e., 2010.

24. p. 383: Self Piercing Rivets (SPR) considered as one of the joining technologies for assembly, but not mentioned on p. 374.

25. p. 394: It is surprising to note that LWT fender structure is about ~80% (quite an unrealistic mass savings potential for aluminum structure).

26. p. 406: Mass savings cost premium for the LWT AHSS design of >$5.00/kg saved seems too high for the lightweight material AHSS assumed.

27. p. 407: No mention of baseline and LWT design Bumper masses provided?

28. p. 410: It is surprising that the LWT control arm was changed to AHSS from baseline aluminum use and resulted in mass savings.

29. p. 425: Why did using the MuCell technology for the HVAC system result in cost savings unlike in other applications as a cost premium?

30. p. 430 (Figure 503): How were the intermediate values of the manufacturing cost increase curves for various lightweight materials were estimated? Any overall system optimization considered by each specific vehicle mass reduction value, particularly when lightweight structural components considered?

31. p. 449 (Figure 524): 2014 sales data of Ford F150 is missing.

32. p. 450 (figure 527). Some data for Large SUV/LT in the last table row are missing.

33. p. 453: For the vehicle body structure, aluminum+AHSS option used for light-duty pickup truck was not used for all vehicle subclasses.

34. p. 478: Why is the mass savings potential of minivans the highest among the vehicle subclasses considered, although it is not the heaviest vehicle considered in the analysis?

35. Cab assembly baseline spreadsheet model (Assembly Inputs: cell o6): Double-counting of total tooling investment.

**COMMENTS SUBMITTED BY**

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## External Peer Review of NHTSA's Draft Report, "Mass Reduction for Light-Duty Vehicles for Model Years 2017-2025"

**1. Assumptions and Data Sources**

a) **Please comment on the validity of data sources and assumptions embedded in the study's material choices, vehicle design and optimization, crash validation testing, and cost assessment that may affect the report's findings.**

There is no specific section in the report that identifies data sources for material choices, nor of specific material grades.

b) **If you find issues with data sources and assumptions, please explain what you believe the issues are and why they are problematic and provide suggestions for available data that would improve the study.**

No comments provided. This is outside the bounds of my expertise.

**2. Vehicle Design and Optimization Methodology and its Rigorousness**

a) **Please comment on the material selection and usage, joining technologies, vehicle structure design and optimization methodology and the resulting final vehicle design.**

1. The lightweight materials options considered for the LWT are Advanced High Strength Steels (AHSS), Aluminum, Magnesium and Plastics/carbon fiber.

   These are common lightweighting materials options in the automobile industry. The LWT is a body-on-frame vehicle concept and the two key subsystems are chassis frame and body, the latter including closures, frond-end sheet metal and box. For these two subsystems, the materials chosen were AHSS and Aluminum respectively. These are sensible choices for the LWT. Both of these materials are widely used in the industry and are also suited for high volume manufacturing.

   **AHSS** is widely used and continues to evolve with new alloys offering greater strength although these new alloys present challenges to manufacturers with regard to their formability.

   In the 2025-2030 time frame, High Alloy 2nd Gen AHSS, Low Alloy 3rd Gen AHSS, Low Density High Manganese and Thick Core Laminates will enable a second generation of redesign of the current LMT vehicle.

   **Aluminum** is seeing significant growth as a lightweight material alternative for automobile body applications. At a third of the weight of steel, it is a good lightweighting choice. One point to note is that the rapid rise in demand for Aluminum can present challenges to the supply base. Some of the OEMs presently are signing long term contracts to ensure uninterrupted supply. Given the 2025-2030 time frame, the availability of the metal should not be a concern.

Currently, 5xxx alloys (Al-Mg) Sheet, 6xxx series (Al-Mg-Si) Extrusions & Sheet and 7xxx Alloys are available for lightweight applications. By the 2025-2030 time frame, more options will be available as HS extrusion and sheet in 5XXX, 6xxx and HS extrusion and Stamping in 7xxx series. These new offerings will help enable a second generation of redesign of the current LWT vehicle.

**Magnesium** is suitable for smaller parts but the manufacturers of the high volume Light Duty segment may be deterred by the fact that over 85% of the material is imported from China. **Carbon-fiber** has great lightweighting potential, given its high strength to weight ratio. The cost of carbon fiber however is high and it tracks the price of petroleum. Moreover, concerns of repairability, production volume, etc. make carbon fiber unsuitable in the 2020-2030 time frame.

Summarily, the choice of AHSS and Aluminum for most of the lightweighting needs of the LWT is reasonable and well justified.

2. The joining technologies considered in the study for the LWT frame are acceptable; they are proven and suited for high volume production.

   The joining technique considered for the Aluminum body is a combination of Adhesive bonding and self-piercing rivets (SPR). This technology, originally pioneered by European automotive manufacturers, is now widely used in high volume Aluminum body structures.

**b) Describe the extent to which state-of-the art design methods have been employed, as well as the extent to which the associated analysis exhibits strong technical rigor.**

1. The CAE software used in the study are well known. LS-DYNA, the software used for the crash simulations, NASTRAN, ADAMS, etc. are all industry standard tools and can be relied upon to provide credible simulation solutions. The topology optimization techniques used in the study are impressive. Of particular interest is the modeling of the adhesive/self-piercing riveted joints between Aluminum panels. The report provides good references and sources for the data required. Summarily, the contractor has used state-of-the-art computer simulation and optimization, this is commendable.

2. However, modeling the new class of Steels and Aluminum is complex and requires established validated simulation techniques and methodologies. The extent of technical rigor is not entirely clear to me from a reading of the report.

3. In the case of both the new generation of Steels and Aluminum, manufacturing and crashworthiness simulations are inherently coupled. **The simulations conducted do not appear to have taken this into account.** Further, complexities posed by these new materials in simulation include:

   For Steels,

   i. Manufacturing process will cause the steels to work-harden; change Phase (e.g., TRIP and Hot Formed)
   ii. Material will accumulate property changes during the manufacturing process

iii. Appropriate data and CAE modeling procedure are needed to predict final geometry of the part, and to capture appropriate physical properties throughout the manufacturing of final design.
iv. Process needed for passing these properties to the crash simulation - Mapping of property changes is currently the most challenging aspect of this process.

For Aluminum (compared to Steel):

i. Anisotropic yield (different yield stress in different directions)
ii. Anisotropic flow (different R-values in different directions)
iii. Tensile-compressive asymmetry
iv. PLC effects and other plastic instabilities
v. Higher order shape of the yield surface and related influence on shear strength and biaxial strength.
vi. Many complex material models are available in state-of-the-art software for manufacturing simulations, but certain features needed for crash simulations such as rate dependency, failure, damage, and erosion are lacking.

**c) If you are aware of other methods employed elsewhere to select and analyze advanced materials and design engineering rigor for 2017-2025 vehicles, please comment on if and how they might improve the study and how they might be used.**

No comments provided. This is outside the bounds of my expertise.

**3. Vehicle Functionalities and Crashworthiness Testing Methodological Rigor**

**a) Please comment on the approach and effort in maintaining baseline vehicle functionalities while trying to lightweight the vehicle.**

In concept, the objective of maintaining baseline vehicle functionalities while trying to lighten the vehicle is a reasonable approach. Car companies use this approach all the time as they develop new model variants.

In the case of the LWT, the study addresses the baseline vehicle functionalities very well with the many load cases that are identified in the study. These load cases span crashworthiness, system stiffness, durability, drivability, ride and handling, NVH and Towing. There additionally are many other subsystem and component loads that are typically considered by car manufacturers in course of engineering the vehicle. For example, many seat load cases, curb impact, door sag, door slam, hood and closure loads, misuse/craftsmanship loads, rail road tie-down fore-aft and vertical loads, etc. The study represents a “zero prototype” approach.

Most car companies have evolved their product development processes for more efficiency and shorter duration, progressively relying less on hardware prototypes and more on “analytical prototypes”. However, cars are not (yet) designed on “zero prototype” basis.

In the typical car product development process of a high volume car manufacturer, analytical models are correlated with prototypes at critical junctures. This approach establishes credibility of the simulation models and enables confidence in the prediction of simulation models.

The load cases identified for the LWT above are typically system level load cases that help establish the preliminary integrity of the vehicle structure. However, vehicle tend to gain weight progressively through the development cycle as a result of various problems not identified in the system load cases. Some of them are NVH problems, some local bending or bucking problems, some stiffness problems that are often treated with local fixes. This results in mass increase and mass “creep”. Some of these fixes are engineered away in subsequent models of the vehicle.

Car companies have developed reliable computer simulation techniques covering traditional materials. A lot of physical testing continues to be reduced or eliminated where conventional vehicle architecture and conventional materials are involved.

When lightweight materials constitute large and important structural parts of a system, computer modeling does not enjoy the same level of confidence. Lightweight materials often require new and more complex material models and failure models. Joining techniques between lightweight materials, particularly in multimaterial situations need more validation than conventional mild steel/spot weld techniques. Most importantly, the structural performance of lightweight material components is integrally linked to its manufacturing process. During these manufacturing processes, changes in material thicknesses, geometry (spring back), work hardening, etc. alter the post-manufactured component sufficiently enough that post manufacturing properties need to be accounted for as input to structural analysis.

All of the above highlights the following considerations for generating **confidence** in computer modeling and simulation:

1. Computer simulation of new designs need a ”useful minimum” level of validation with physical tests to establish credibility of the simulation for predictive purposes.

2. The above is especially true when dealing with unconventional materials.

3. Computer models of lightweight materials are not reliable for quantitative prediction; they are very useful however for evaluating alternatives A vs. B comparisons, particularly where A and B do not represent extreme changes from the original models.

**b) Comment on the methods used to design and analyze the vehicle body’s structural integrity and crashworthiness.**

No comments provided. This is outside the bounds of my expertise.

**c) Describe whether and the extent to which state-of-the-art crash simulation methodologies have been employed and the extent to which the associated analysis exhibits strong rigor.**

No comments provided. This is outside the bounds of my expertise.

**d) Can the design and LS-DYNA results in this study be validated? If yes, how? If no, why not?**

No comments provided. This is outside the bounds of my expertise.

e) **If you are aware of other methods and tools to help validate advanced materials and design engineering rigor for 2017-25 vehicles, please suggest how they would improve this study.**

No comments provided. This is outside the bounds of my expertise.

f) **Is the crash pulse in full frontal impact acceptable from an air bag sensing point of view? Why or why not?**

No comments provided. This is outside the bounds of my expertise.

g) **Are durability and NVH values in the acceptable range after mass reduction? If not, what would be an acceptable range?"**

No comments provided. This is outside the bounds of my expertise.

h) **Is the high strength steel(s) selected within the plastic strain working range for the part selected?**

No comments provided. This is outside the bounds of my expertise.

**4. Vehicle Manufacturing Cost Methodology and its Rigorousness**

a) **Comment on the methodology used to estimate the LWV manufacturing costs.**

b) **Please describe whether and the extent to which state-of-the-art costing methods have been employed and the extent to which the associated analysis exhibits strong rigor.**

c) **If you are aware of other methods and tools employed elsewhere that could be used to help estimate costs for advanced materials and design for 2017-25 vehicles, please describe them and suggest why they would improve this study and how they might be used.**

No comments provided. This is outside the bounds of my expertise.

**5. Conclusion and Findings**

a) **Are the study's conclusions adequately backed up by the methods and analytical rigors of the study? Any concerns? How can they be addressed?**

Please see comments for each phase of the analytical approach used in this study:

1. Create Baseline CAE model by reverse engineering the Chevy Silverado.

   This entails tear-down of the vehicle, scanning of the data, finite element modeling of the components and subsequent assembly to generate the full vehicle model.

   **Comments and concerns:** This work is competent, comprehensive and thorough.

2. The full vehicle model was exercised for a comprehensive set of load cases (regulations and non-regulation). The CAE model was correlated based on results from physical test of the Chevy Silverado model.

The correlated model was designated as "Baseline" model.

**Comments and concerns:** This work is competent, comprehensive and thorough. The effort in this phase is conventional in scope and uses current industry practices.

3. The Baseline model was subsequently modified to incorporate lightweight engineering design concepts to create the LWT model. These design concepts utilized lightweight materials like Aluminum, Magnesium, High strength steels, etc.

**Comments and concerns:**

a) In general this phase constitutes the vulnerable underbelly of lightweight simulation practice and could lead to uncertainty with regard to predictability of the simulations. Some of the factors contributing to this uncertainty are:

   i. Modeling and simulation of joints. The primary joints that need attention are the adhesive bond – self-piercing riveted joints between the Aluminum panels. Such joints have more recently been used in high volume production cars and are simulated by CAE techniques, but as part of the product development process that involves validation with prototypes at critical stages. Validation tests for local joint behavior are also needed to formulate failure models. Tear through the base metal will result in lower threshold crush resistance compared to total integrity idealized in the computer model.

   ii. Post-manufacturing residual stresses, work hardening and geometry (including thickness) changes of Aluminum and HSS components influences prediction of computer models.

   Previous communication (July 6, 2016) relative to this issue (facilitated by NHTSA) is captured below:

   ***Question:*** *Were the forming results for the LWT Aluminum body panels accounted for as input to Crash simulation? Specifically, thickness changes, post-forming strain hardening?*

   ***Response:*** *The forming results for the LWT Aluminum body panels were not used as input into the crash simulation model. For aluminum panels the reduction in strength due the material thinning during the forming operation, typically stamping, is balanced by the increase in material yield strength due to strain hardening.*

   In my view "balancing" of strength reduction with increase in material yield strength while true in an overall sense, does not necessarily apply to structural performance that is significantly influenced by local effects (such as would be expected in structural crash collapse).

   All of the above factors could lead to non-conservative prediction.

   CAE techniques when applied to lightweight materials, need different levels of validation to build confidence. Such validation is understandably not feasible for the scope of this study; accordingly, quantitative prediction needs to viewed with prudence and caution.

4. Simulate the LWT model for the same load cases as the Baseline; iterating the design/simulation so that results of the LWT simulation were judged comparable with the Baseline results.

   **Comments and Concerns:** Excellent effort spanning a lot of different cases, commendably comprehensive.

**b) Are the conclusions about the design, development, validation, and cost of the mass-reduced design valid? Any concerns? How can they be addressed?**

The most significant conclusion of the study is the proposed design concept for the LWT mass-reduced vehicle. At a high level, this design concept consists essentially of an Aluminum alloy body (cab, FESM and pickup box) on a High Strength Steel frame.

The proposed design, intended for production in the 2025-2030 time frame, is very similar in concept to the 2015 Ford F150 vehicle is already out in the market (in 2015). In this sense, in my concern is that the study ***underachieves***.

**Comments and concerns:**

The lightweighting approach used by the contractor (Section 7) for the LWT is logical and reasonable, except for the few concerns noted below.

Prior communication (July 6, 2016) relative to the general strategy employed by the contractor (facilitated by NHTSA) is captured in my question below:

> ***Question:*** *What components / subsystems of the LWT Aluminum structure use manufacturing technologies that are assumed to be developed and mature by 2025 that are deemed currently <u>not</u> mature for production?*
>
> ***Response:*** *None; all aluminum related applications are regarded as mature technologies suitable for high volume production in 2014. The manufacturing technologies and choice of aluminum grades used on LWT aluminum structure are very similar to the FORD F-150 that is in production since 2015.*

The implication of the above response by the contractor is that the LWT vehicle planned for 2025-2030 time frame is not significantly (if at all) more advanced in design than what is already available in the 2015 Ford 150. A further implication is that the Ford F150 in 2025-2030 would be two more generations evolved beyond the currently proposed LWT concept. This would render the LWT vehicle prematurely obsolete.

a) The design approach taken by the contractor is one of assessing each of the key subsystems of the vehicle for potential weight reduction. A variety of material-mix options are considered and the most cost effective option is picked. This is certainly a sound approach.

**Concern:** However, some assumptions made in the report are not acceptable for vehicle lightweighting. For example, the lightweighting options proposed for the frame are:

Option 1: AHSS
Option 2: Aluminum
Option 3: AHSS + Carbon Fiber Reinforced Polymer

The contractor chose to discard the Aluminum Option 2 because, as with Option 1, manufacturing can be performed with the same presses and processing sequences as the baseline frame".

The above approach to material substitution for structurally critical components is incorrect and will not result in an acceptable, cost effective light weight design alternative. Key structural components that are being substituted with Aluminum need to be completely redesigned; the approach of using existing presses for both Aluminum and Steel components should be reserved for nonstructural panels (fenders, for example). An efficient lightweight Aluminum frame design will need to achieve maximum structural performance i.e. stiffness, strength and crashworthiness by fully capitalizing on the benefits of superior properties of modern Aluminum alloys. Such a frame would be optimized for both structural performance and cost by judicious mix of multiple manufacturing processes. For example, hydroformed structural members, extruded beams and stamped components. Deeper sections with double celled front rails for crash absorption, cast joints for enhanced frame stiffness could well contribute to a feasible all-Aluminum frame with weight reduction potential of 40 to 50% vs. 18% shown in Figure 185, Page 189).

**Alternatively**, a multi-piece all-Aluminum cast frame could also be considered. Such a frame would be appropriate for crash performance and also versatile in accommodating the different lengths of the LWT models. A multi-piece cast Aluminum frame may be more weight efficient and possibly more cost-effective. A multi-piece frame would be versatile in accommodating different chassis dimensions for the different models at the same time ideal from repair standpoint perspective.

The alternative design concepts proposed above could result in much lighter designs than what was considered. The additional manufacturing cost might potentially be offset with lower cost of material used in the frames, although this is not certain until further structural/cost analyses are conducted.

b) Given the 2025-2030 time horizon, the study should consider more aggressive design options that might yield lighter weight designs. For example, an attractive although disruptive option would be to engineer a frameless (unitized) vehicle architecture. This would seriously challenge the status-quo for this class of lightweight trucks, but could be structurally feasible and viable with regard to greater weight reduction and consequential potential cost reduction. The availability of 7000 series Aluminum and the new class of AHSS steels could meet the heavy demands such as performance towing capacity, crashworthiness.

**c) Are you aware of other available research that evaluates and validates the technical potential for mass-reduced vehicle in the 2017-25 time frames that could be helpful for this study? Include sources and additional information for such research.**

None

**6. Other Potential Areas for Comment**

a) **Is the methodology used to estimate the feasible mass reduction in other light-duty vehicle classes reasonable? Please explain.**

The proposed methodology appears to impose science on chaos as extrapolates from a specific architecture and weight class to multiple vehicle architecture and weight classes. To my knowledge, such a proposed approach has not been validated at this time.

Also, weight reduction strategies are distinctly different for different vehicles at different price points. Cars that are even in the same weight class (say 3,000 pound to 4,000 pounds) can be priced quite differently, based on how they are positioned in the market. A car priced at $20,000 will merit entirely different weight reduction strategy than one that is priced at $50,000 which again would be very different for a car priced at $100,000. So the mix of vehicles and their associated price is an important consideration.

Cars that are already compact have less potential for weight reduction than heavier cars. Likewise, cars that are bare boned and at the low price end cannot justify lightweight materials. For such cars, the economics of conventional materials i.e. mild steel may be more meaningful when accompanied by lower cost solutions such as turbocharging and other powertrain and transmission related enhancements.

Taking the above into account, the linear segmentation by weight would be better replaced by a grid that includes specific vehicle architecture categories along with price as additional parameters.

Additionally, the achievable LWT weight reduction projected by the study needs validation before it can be used as a basis for other vehicle classes.

b) **Is the study valuable to understand the feasibility of 2017-2025 mass reduction technology? Please explain.**

Many of the comments provided in a) above probably apply here as well.

In my view, the study does not generate any generic knowledge of vehicle mass reduction technology. Rather it applies well known and understood lightweighting principles to a specific vehicle type. Given the plethora of vehicle architecture, multiple price points, weight classes and design approaches, industry has not as yet converged on common or best practices for mass reduction technology.

c) **Do the study design concepts have any critical deficiencies in their applicability for 2017-2025 mass reduction feasibility that require revision by NHTSA prior to finalizing the report? If yes, please describe.**

The design concepts proposed in the study are implementable with current technologies and do not appear to have any critical deficiencies.

d) **Are there any fundamentally different lightweight vehicle design technologies that are likely to be more common than the ones assessed in this study?**

I don't think so.

Light truck design continues to be driven by high volume considerations, so in the time horizon of interest, lightweighting will likely continue to be enabled by AHSS and Aluminum alloys and to a lesser extent Magnesium alloys, and these trends will reflect in the development of associated manufacturing and assembly technologies.

New grades of Aluminum alloys (7000 series) and the 1300 MPA AHSS steels will likely have greater proportion of usage for lightweighting than is assessed in this study.

There is emerging interest in Aluminum foam for crash applications that may mature in the years to come.

Carbon fiber technology is evolving although even at lower prices, may not be a high volume technology such as would be needed for light trucks. Further, CAE technologies still are not developed for use in this respect.

CAE technology is advancing and keeping in pace with the new materials technology as well as the manufacturing and assembly technologies. There still is a lot of validation that will need to be done, and this will improve CAE predictability beyond what is used in the study. ICME techniques has the potential to revolutionize CAE value.

e) **Is the cost from the study reasonable and backed up by sufficiently detailed data? What would you expect the cost to be for the design in this study? Please explain the reasons if your estimate is different than this study.**

No comments.

**7. General Comments**

a) **Describe your overall assessment of the organization, readability, and clarity of this report, including any changes needed.**

1. Much of the Report is generally competent, comprehensive and credible. It also is very well organized and readable.

2. The report is clear in presenting concepts and facts; it generally provides useful contextual information. Key points are reinforced with supporting details and visuals that clarify the essential messages.

b) **Is the information provided in the report and appendices sufficiently detailed to thoroughly document all essential elements of the study? If not, what additional information is needed?**

1. The quality of documentation is excellent.

2. However, it would be helpful if the study were to consolidate all key assumptions relevant to the CAE analysis.

3. A breakdown of components with materials before and after redesign. Identification of the Material alloy would be helpful.

**c) What are the strongest and weakest parts of this report? How can the weakest parts of the report can be strengthened?**

1. Strong parts of the report:

   a. Comprehensive and thorough documentation of the key processes involved in the project, including Tear down and Reengineering the 2014 Chevy Silverado with CAE simulation.

   b. Competent computer modeling and simulation (qualified by some comments noted earlier). CAE simulation and optimization studies are state-of-the-art as claimed.

   c. Load cases considered are quite comprehensive.

   d. The study establishes a general methodology for weight reduction that with a few changes could be of great value to the industry. Various material substitution options are nicely detailed with cost consequences.

2. Weak parts of the Report

   a. A key weakness of this study is the extension of a validated computer model to predictive use on evaluating new designs with new materials without any further validation with physical prototypes. This can be expected to yield unconservative results.

   **Recommendation:** A few physical prototypes will be a necessary investment.

   b. The lightweighting designs created do not sufficiently stretch the envelope of possibilities and in fact remain close to the original design. Sometimes material substitution has been employed instead of lightweight engineering; while this works for panels, it does not for structural members.

   **Recommendation:** The LWT frame could be redesigned around the strengths of Aluminum rather than substituting Aluminum for steel as was considered.

   c. The designs presented appear to have not advanced the engineering of the LWT beyond that of the current production vehicle i.e. 2015 Ford F150.

   **Recommendation:** The LWT innovations beyond the 2015 Ford F150 production vehicle need to be captured.

   d. Chapter 11 "Mass Reduction for Other Light-duty Vehicles (Optional Task 1) is hard to understand without more contextual background.

**Recommendation:** It would benefit from rewriting the introductory paragraphs, clarifying the general objective so that the degree of accuracy (or approximation) needed is better understood.

e) The targeted time frame is referred to as 2025-2030 (Executive summary, P.23, Chapter 7, P. 251) but as 2020-2030 in several places elsewhere (for example, Chapter 3, P. 43).

**d) Please provide any other comments you may have on this report.**

**Summary of comments and recommendations:**

1. Weight reduction estimates from the LWT computer model are likely to be unconservative.

   The LWT project starts with a correlated model, but substantially alters the model by incorporating lightweight materials. This extends the simulation into areas of uncertainty where CAE is no longer reliably predictable and quantifiable.

   The projected LWT 19.9% weight reduction compares with 10.5% for a similar design concept and comparable weight – the 2015 Ford F150 production vehicle. Why this difference? A few possible answers:

   a. The idealizations assumed in the computer model overestimate weight savings.
   b. Mass creep that occurs in production vehicles.
   c. The 2014 Chevy Silverado was less weight efficient and therefore more weight could be reduced.

2. Further weight reduction strategies can be explored (as always, subject to cost considerations).

   The LWT Design concepts are rather evolutionary. LWT needs to consider the 2025 time horizon (per original objective) and push the design envelope beyond what is already implemented in current production vehicle (like 2015 Ford F150). Some recommendations:

   a. Between 2016 and 2025, there are ongoing advances in both AHSS and Aluminum alloys. Consider a second generation evolution of the LWT design that incorporated 1300 MPA nanosteels in the frame and 7000 series Aluminum alloys for the Body for further weight reduction.

   b. Reconsider the Option 2 all-Aluminum frame concept – recreate and assess the frame concept to deliver an efficient, lightweight frame. Suggest exploring Option 2a: All-Aluminum cast frame or Option 2b: judicious mix of hydroformed / extruded / stamped / cast components (target 40 to 50% weight savings).

   c. The 2025-2030 time horizon provides adequate time for engineering a new, complete unitized body concept that could be much lighter as it would eliminate the traditional heavy frame. Several engineering problems will need to be addressed, including NVH, crash and other structural problems. Stronger AHSS and Aluminum alloys that will be ready for production manufacturing by 2030 could provide the enhanced strength required for towing and other heavy duty applications.

**8. Overall Recommendation**

a) **Based upon your review, indicate whether you find the report: (1) acceptable as is, (2) acceptable with minor revisions, (3) acceptable with major revisions, or (4) not acceptable. Please justify your recommendation. If you find the report acceptable with minor or major revisions, be sure to describe the revisions needed.**

**The Report is acceptable with major revisions:**

My review of the Report indicates that a lot of competent and thorough work has gone into this project. However, the proposed design falls short of achieving the objective established for this project, contained in this excerpt from the Executive summary:

"The light weighted version of full size pickup truck (LWT) will use manufacturing processes available in model year 2025-2030 and capable of high volume production. The team's goal was to determine the maximum feasible weight reduction while maintaining the same vehicle functionalities, such as performance, safety, and crash rating, as the baseline vehicle. Furthermore, the retail price of the LWT must be within +10% of the original baseline vehicle."

**My comments:**

1. The design proposed uses technologies that are currently available and productionized as exemplified in the 2015 Ford F150 production vehicle. The design does not stretch either the design or the materials/manufacturing technology envelope that would be consistent with the 2025-2030 time frame.
2. The weight reduction of 19.9% for the LWT projected through computer simulation is quite a bit higher than the ~ 10.5% achieved by a comparable weight 2015 Ford F150 production vehicle that is fully validated in the field (based on the weight information I have consolidated for the 2015 Ford F150).

I find the **report acceptable with major revisions**. The revisions to the report would include addressing the following:

1. Contractor's review and analysis as to what factors might contribute to the rather large gap between the projected 19.9% LWT weight reduction and the corresponding 10.5% weight reduction for the 2015 Ford F150 production vehicle. This amounts to about 500 pounds discrepancy per vehicle. Short of a convincing response to this central issue, the veracity of the simulation used for the LWT design can be established conclusively only with expensive and time consuming validation effort with physical prototype.

   In the contractor's review, analysis and judgment,

   a. What design, material choices, manufacturing options contributed to this difference?

   b. What assumptions made in the computer simulation might lead to conservative predictions? What assumptions made in the computer simulation might lead to unconservative predictions?

c. In the Contractor's review and judgment, was the 2014 Chevy Silverado less mass-optimal than the 2014 Ford F150, lending itself therefore to higher weight reduction potential?

   (Note that there often is "mass creep" in early versions of production models. Such mass creep is a result of local fixes to solve NVH and other structural problems. Such problems are not addressed by CAE simulations that account mostly for system /subsystem loads).

d. Please reconfirm or comment further on the following communication, which seems to suggest that no additional advantage would be gained in the 15 years between now and the time frame 2025-2030:

   ***Question:*** *What components / subsystems of the LWT Aluminum structure use manufacturing technologies that are assumed to be developed and mature by 2025 that are deemed currently not mature for production?*

   ***Response:*** *None; all aluminum related applications are regarded as mature technologies suitable for high volume production in 2014. The manufacturing technologies and choice of aluminum grades used on LWT aluminum structure are very similar to the FORD F-150 that is in production since 2015.*

e. Please respond to the above question as it would relate to other key subsystems including the chassis frame.

f. The proposed LWT design often takes a conservative approach to lightweighting i.e. material substitution. In addition to the final proposed design, what aggressive new alternate design concepts were considered by the Contractor that would leverage lightweighting technologies appropriate for the 2025-2030 time frame? Were these designs assessed for performance and cost?

g. Chapter 11 - "Mass Reduction for Other Light-duty Vehicles (Optional Task 1) could be improved with more contextual background. It would benefit from revising the introductory paragraphs, clarifying the general objective so that the degree of accuracy (or approximation) needed is better understood.

**COMMENTS SUBMITTED BY**

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## External Peer Review of NHTSA's Draft Report, "Mass Reduction for Light-Duty Vehicles for Model Years 2017-2025"

### Introduction

This document provides a review of a draft report entitled "Mass Reduction for Light-Duty Vehicles for Model Years 2017-2025." The report documents a study that investigated the feasibility of developing a light-weighted pickup truck (LWT) design that would have similar performance functionality as the original design and within cost and manufacturing methods constraints. To assess the crashworthiness of the LWT design, the study made use of computer simulation. A detailed finite-element computer model of the original (i.e., Baseline) vehicle was created using reverse engineering techniques and validations were conducted to demonstrate that the model can accurately reflect the crash responses for different impact conditions. The Baseline model was then modified to incorporate LWT elements that replaced certain parts. The modified model was used to evaluate the crashworthiness of the LWT design. Simulation results from the LWT model were compared to the Baseline model results to determine if the new design had performance similar to, or better than the original design.

This review focuses on the modeling and simulation aspects of the study. It involved three main tasks. The first task consisted of answering questions listed in the peer review guidelines. In the second task, the two models that were created under the study were evaluated. The third task consisted of review of the simulation results. The findings of the three tasks are presented in the following sections.

### I - Response to Review Questions

The focus of this review is the "Modeling/Simulation" aspects of the study. Answers to the questions related to this topic are included below. The questions are listed (with the same numbers as in the "Peer Review Guidelines" document) followed by the response in italic font.

### 1. Assumptions and Data Sources

a) **Please comment on the validity of data sources and assumptions embedded in the study's material choices, vehicle design and optimization, crash validation testing, and cost assessment that may affect the report's findings.**

*Response: The methodology used in this study to assess the safety performance of the LWT design is similar to what all automotive manufacturers and other researchers in the field of vehicle crashworthiness use. The method makes use of Finite Element Analysis (FEA) tools that have been employed for over twenty-five years and have been proven to be effective and efficient in the vehicle design and evaluation process. The method however has its limitations and special care should be taken in the model creation and simulation analyses to ensure accurate simulation predictions are achieved.*

**b) If you find issues with data sources and assumptions, please explain what you believe the issues are and why they are problematic and provide suggestions for available data that would improve the study.**

*Response: Overall, the study assumptions and approach used for the LWT crashworthiness assessment seem valid. The methods are similar to the ones used is a recent study of mid-size vehicle mass reduction. Based on the review of the model and simulation results, one key factor that may need to be re-examined is material and connection failure parameters defined in the models. This is especially critical for high-strength steels where the material is more likely to rupture rather than buckle. This is also important for the IIHS small-overall impact evaluation (i.e., test) where failures of tire/suspension components have significant effects on the vehicle response. Some high-strength parts and connections in the models were not assigned failure parameters. This applies to both the LWT and Baseline models.*

**3. Vehicle Functionalities and Crashworthiness Testing Methodological Rigor**

**a) Please comment on the approach and effort in maintaining baseline vehicle functionalities while trying to lightweight the vehicle.**

*Response: With a focus on the crashworthiness aspect, the approach used in this study is adequate. The performance of the LWT was assessed in eight different crash impacts. These included: NCAP frontal, NCAP MDB side, NCAP pole side, IIHS moderate overlap, IIHS MDB side, IIHS small overlap, roof crush, and rear impacts. For each impact, the crashworthiness of the LWT design is assessed and compared to the Baseline design to show that it has similar or improved performance.*

**b) Comment on the methods used to design and analyze the vehicle body's structural integrity and crashworthiness.**

*Response: The vehicle design modification aspect is outside the scope of my review. However, simulations showed that some of the replaced components lead to complete rupture of some parts. Introducing components that fail during the crash could be intentional, but I did not see this mentioned in the report.*

**c) Describe whether and the extent to which state-of-the-art crash simulation methodologies have been employed and the extent to which the associated analysis exhibits strong rigor.**

*Response: The crash simulations were carried out using the latest FEA methods and tools. The level of detail, element and material formulations, connection types, and contact definitions were adequate and associated analysis was reasonably thorough.*

**d) Can the design and LS-DYNA results in this study be validated? If yes, how? If no, why not?**

*Response: Validations using tests of the Baseline model have been performed to show the accuracy of the results. Additional coupon and component testing could further improve the simulation predictions and allow more comparisons. These tests would be used to calibrate the material models and allow better capturing of the failure behavior.*

e) **If you are aware of other methods and tools to help validate advanced materials and design engineering rigor for 2017-25 vehicles, please suggest how they would improve this study.**

*Response: As mentioned above, key improvements in the material and connection failure algorithms are being added to the FE programs. These developments are at different stages and some may be ready for application in this study. Additional testing of coupons and components would be needed to calibrate these failure models.*

f) **Is the crash pulse in full frontal impact acceptable from an air bag sensing point of view? Why or why not?**

*Response: Yes, the crash pulse seems adequate from an airbag sensing point of view. Manufacturers design the vehicle such that the crash pulse has a 10 g or higher average acceleration value between 5 and 15 milliseconds for this purpose. The vehicle pulse in the full frontal impact configurations meets this "rule of thumb". If the initial vehicle pulse is too "soft", the impact may not be detected in time to trigger the airbag.*

g) **Are durability and NVH values in the acceptable range after mass reduction? If not, what would be an acceptable range?"**

*Response: These aspects are outside my primary area of expertise.*

h) **Is the high strength steel(s) selected within the plastic strain working range for the part selected?**

*Response: These aspects are outside my primary area of expertise.*

**5. Conclusions and Findings**

a) **Are the study's conclusions adequately backed up by the methods and analytical rigors of the study? Any concerns? How can they be addressed?**

*Response: The methods used in this study are adequate. The main concern, which was mentioned before, is the failure modeling and its potential effects on the accuracy of the simulation results.*

b) **Are the conclusions about the design, development, validation, and cost of the mass-reduced design valid? Any concerns? How can they be addressed?**

*Response: The conclusions of this study about the feasibility of designing a LWT that has the same crashworthiness functionality as the Baseline design are supported by the computer simulation results. The simulation tools used are well suited for this type of analysis.*

c) **Are you aware of other available research that evaluates and validates the technical potential for mass-reduced vehicle in the 2017-25 time frames that could be helpful for this study? Include sources and additional information for such research.**

*Response: All relevant studies that I am aware of are referenced in the footnotes of the draft report.*

**6. Other Potential Areas for Comment**

**a) Is the methodology used to estimate the feasible mass reduction in other light-duty vehicle classes reasonable? Please explain.**

*Response: Outside my primary area of focus.*

**b) Is the cost from the study reasonable and backed up by sufficiently detailed data? What would you expect the cost to be for the design in this study? Please explain the reasons if your estimate is different than this study.**

*Response: Outside my primary area of focus.*

**7. General Comments**

**a) Describe your overall assessment of the organization, readability, and clarity of this report, including any changes needed.**

*Response: The report is thorough and well organized. All aspects of the study, including the methods, data sources, assumptions, results, and conclusion, are included in detail.*

**b) Is the information provided in the report and appendices sufficiently detailed to thoroughly document all essential elements of the study? If not, what additional information is needed?**

*Response: Yes, all relevant information was included in the report and references were provided to the sources of the data or methods used. Any missing information can be obtained from the available models.*

**c) What are the strongest and weakest parts of this report? How can the weakest parts of the report can be strengthened?**

*Response: The strongest part of the report is the number of impact cases (eight cases) analyzed to study the crashworthiness of the LWT. The weakest part is the fact that failure models were not included for some high-strength steel components used, these parts were assumed not to fail in the model. Testing may be needed to ascertain material properties used, develop new material properties, and/or determine whether failures would occur.*

**d) Please provide any other comments you may have on this report.**

*Response: Additional comments about the models and simulations are provided in other sections of this review summary report.*

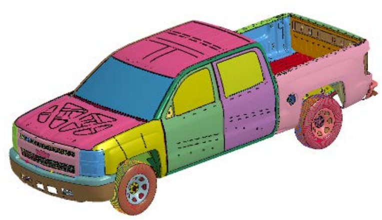
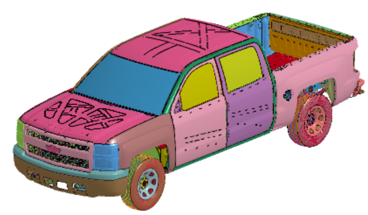
**8. Overall Recommendation**

**a) Based upon your review, indicate whether you find the report: (1) acceptable as is, (2) acceptable with minor revisions, (3) acceptable with major revisions, or (4) not acceptable. Please justify your recommendation. If you find the report acceptable with minor or major revisions, be sure to describe the revisions needed.**

*Response: The report is found acceptable with minor revisions. The approach that was followed in this study is valid and the conclusions are well supported, however, simulations with failure defined for all high-strength* *materials in both the Baseline and LWT models should be performed to verify that these do not affect the predicted results. The crashworthiness simulation predictions could be further enhanced by incorporating more advanced material and connection failure models. This would require additional coupon and component testing which may be outside the scope of the study.*

## II - Model Evaluations

In the first phase of the review, the LWT and Baseline models that were created under this Vehicle Mass Reduction study were evaluated. Table 1 includes general information with a summary of the different entities from the two models. The numbers shown in Table 1 are for the vehicle and instrumentations only (without the barriers, occupants, and cargo entities). The two models are very similar in geometry with few components in the LWT altered to reflect the design updates. The mesh size used in both models is also similar and consequently the two models have similar total number of elements. The part names in the LWT and Baseline models are also similar except for the few added parts. This made it convenient to compare the differences in mass between the two models by component.

| Table 1: Model General Information | | |
|---|---|---|
| |  |  |
| Entities | Baseline Model | LWT Model |
| | | |
| Total Number of Parts | 1519 | 1556 |
| Shells Parts | 1311 | 1377 |
| Solid Parts | 181 | 153 |
| Beam Parts | 17 | 16 |
| Discrete Parts | 10 | 10 |
| | | |
| Total Number of Elements | 2960904 | 3046433 |
| Shell Elements | 2654137 | 2699819 |
| Solid Elements | 284342 | 324189 |
| Beam Elements | 22397 | 22397 |
| Discrete Elements | 36 | 28 |
| | | |
| Total Number of Nodes | 2810258 | 2968115 |
| Total Mass Elements | 1666242 | 1305859 |

The total mass, center of gravity location, and moments of inertia were extracted from the two vehicle models and listed in Table 2. The total mass from the Baseline was 2433 kg and the total mass from LWT model was 2013 kg. These numbers are similar to those listed in the report. Masses of different components of the vehicle were also extracted from the models and compared to those listed in the report. The comparisons indicated that the component masses from the Baseline and LWT models matched those listed in the report.

Table 2: Vehicle Model Mass and Inertia Properties

| | Baseline Model (No Occupant or Cargo) | LWT Model (No Occupant or Cargo) |
|---|---|---|
| Mass (kg) Total | 2433 | 2013 |
| CG - X (mm) From Front Axle | 1577 | 1572 |
| CG - Y (mm) From Center Line | 8 | 13 |
| CG - Z (mm) From Ground | 898 | 875 |
| Roll Inertia Ixx (kg-m^2) | 1044 | 817 |
| Pitch Inertia Iyy (kg-m^2) | 6264 | 5266 |
| Yaw Inertia Izz (kg-m^2) | 6710 | 5613 |

The quality of the elements used to represent the different parts of the vehicle models were checked using software tools. Table 3 shows the results from the element quality checks. The results indicated that the elements used in both models were rated to have good quality. The models were also checks for errors and warnings using different pre-processors. No errors or significant warnings were found in the models.

Table 3: Mesh Quality Check

**Baseline Model**

| | | | Failed Elements: | Percent Failed: |
|---|---|---|---|---|
| Warpage:(HyperMesh) | > | 15.0 | 260 | 0 |
| Aspect ratio:(HyperMesh) | > | 4.0 | 33 | 0 |
| Skew angle:(HyperMesh) | > | 60.0 | 26 | 0 |
| Length:(Minimal normalized height) | < | 4.0 | 3096 | 0 |
| Length:(Minimal normalized height) | > | 15.0 | 51576 | 2 |
| Jacobian:(At integration points) | < | 0.7 | 22073 | 1 |
| Min angle for quads: | < | 40.0 | 6 | 0 |
| Max angle for quads: | > | 135.0 | 114 | 0 |
| Min angle for trias: | < | 15.0 | 9 | 0 |
| Max angle for trias: | > | 140.0 | 0 | 0 |
| Percentage of trias | < | 13 | | 5 |
| | | | | Result: |
| | | | Total number of duplicate elements: | 17124 |
| | | | Total number of quads checked: | 2521877 |
| | | | Total number of trias checked: | 132287 |
| | | | Total number of trias and quads checked: | 2654164 |

**LWT Model**

| | | | Failed Elements: | Percent Failed: |
|---|---|---|---|---|
| Warpage:(HyperMesh) | > | 15.0 | 997 | 0 |
| Aspect ratio:(HyperMesh) | > | 4.0 | 63 | 0 |
| Skew angle:(HyperMesh) | > | 60.0 | 38 | 0 |
| Length:(Minimal normalized height) | < | 4.0 | 16715 | 1 |
| Length:(Minimal normalized height) | > | 15.0 | 51424 | 2 |
| Jacobian:(At integration points) | < | 0.7 | 17697 | 1 |
| Min angle for quads: | < | 40.0 | 16 | 0 |
| Max angle for quads: | > | 135.0 | 217 | 0 |
| Min angle for trias: | < | 15.0 | 17 | 0 |
| Max angle for trias: | > | 140.0 | 2 | 0 |
| Percentage of trias | < | 13 | | 5 |
| | | | | Result: |
| | | | Total number of duplicate elements: | 21855 |
| | | | Total number of quads checked: | 2571311 |
| | | | Total number of trias checked: | 128515 |
| | | | Total number of trias and quads checked: | 2699826 |

The element formulations used in the model were also examined. Table 4 depicts the different shell element formulations used in the model and the corresponding vehicle parts that are assigned these formulations. Fully-integrated formulation (Type 16) is used for almost all the shell components with very few parts using the default under-integrated Belytschko-Tsay formulation (Type 2). The fully-integrated formulation requires more operations than the under-integrated formulation and consequently requires more computation time (about 2.5 times). These full-integrated elements may lead to better capture of the deformation especially when used for components with high deformations. Their use may however be optimized in the model to reduce the computation time.

| Table 4: Shell Element Formulations used in the Models | | |
|---|---|---|
| | Baseline Model | LWT Model |
| Shell element formulation<br>Type 16<br>Fully-Integrated |  |  |
| Shell element formulation<br>Type 2<br>Under-Integrated |  |  |

Table 5 lists the solid element formulations used in the models. The majority of the solid components in both vehicle models use the default under-integrated formulation. A few parts (battery and adhesive parts) use the fully-integrated formulation. It is important to note here, that under-integrated solid elements can lead to inaccuracies in the results. It is often recommended to use appropriate “hourglass control” or use fully-integrated forms for solid elements. Table 6 shows the “hourglass control” types used for the solid elements in the vehicle models. It can be noted from the table that some solid parts in the models use under-integrated formulation and default “hourglass control.” This may not be affecting the simulation results in this study because very few parts are made up of solid elements and the majority of these parts are rigid. It may be worthwhile, however, to change all solid parts in the models to fully-integrated to avoid inaccuracies in the simulations.

Table 5: Solid Element Formulations Used in the Models

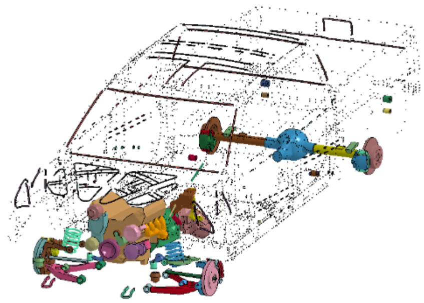
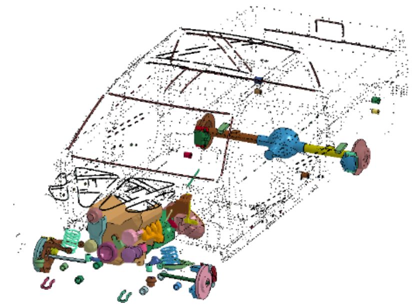
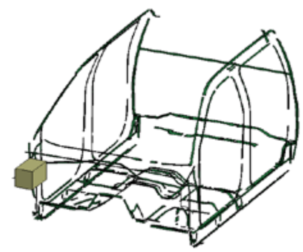
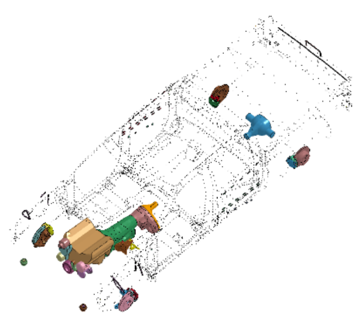
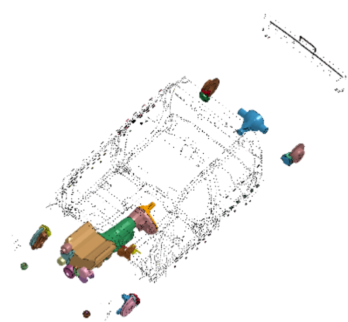
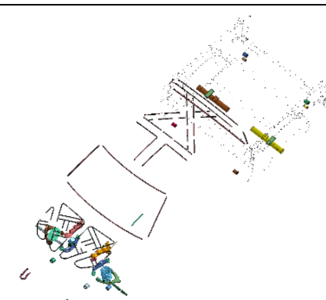
| | Baseline Model | LWT Model |
|---|---|---|
| Solid element formulation<br>Type 1<br>Under-Integrated |  |  |
| Solid element formulation<br>Type 2 (for Battery) and 20 (For adhesive) |  |  |

Table 6: Solid Elements Hourglass Control Used in the Models

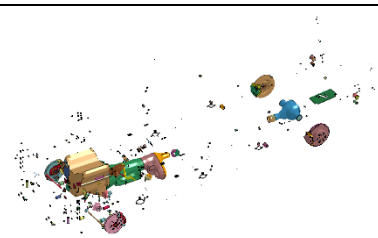
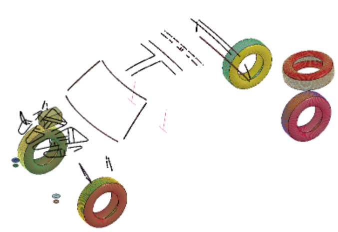
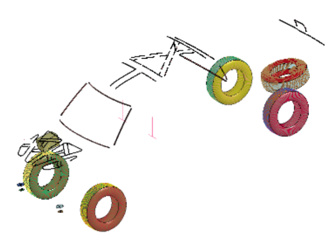
| | Baseline Model | LWT Model |
|---|---|---|
| Parts with default hourglass control |  |  |
| Parts with defined hourglass control |  |  |

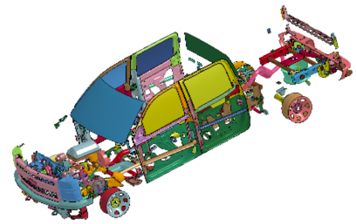
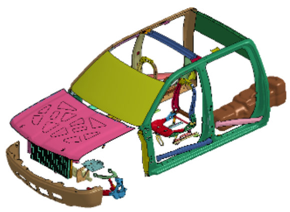
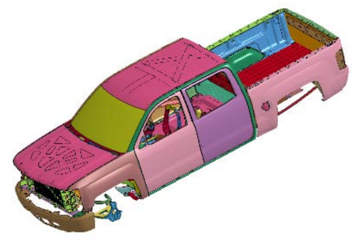
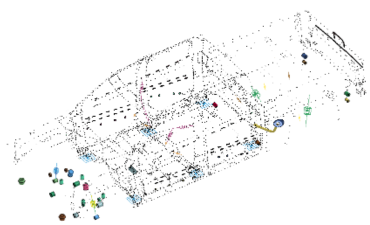
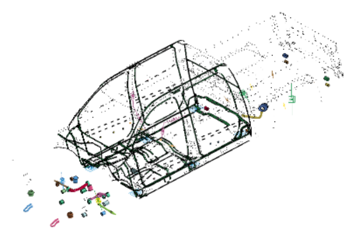
The nature of materials used in the models was also checked. Table 7 lists the different material types used in the vehicle models and the associated parts. A few parts use “rigid” material behavior; mainly the engine, transmission, and brake systems. These undergo zero deformation during the impact. A few other parts are assigned elastic material behavior; namely the tires and adhesives. These parts are assumed to experience small linear deformations during the impact.

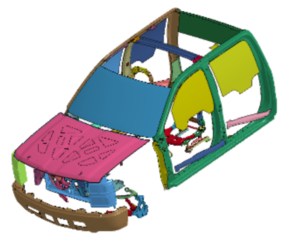
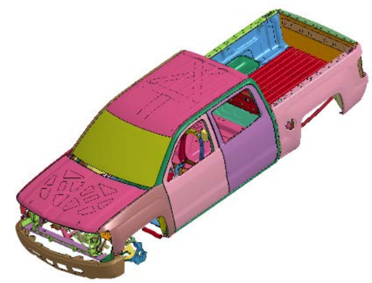
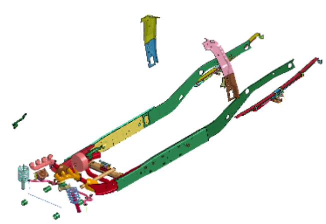
The majority of the parts in the models were assigned elasto-plastic materials. Two types of elasto-plastic materials are used, the Piecewise_Linear_Plasticity (Type 24) and the Modified_Piecewise_Linear_Plasticity (Type 123). These two material types have similar responses except for the failure behavior. The failure behavior in the Piecewise_Linear_Plasticity material model is treated the same whether the element is in compression or tension. The Modified_Piecewise_Linear_Plasticity material model allows for different failure behavior in tension and compression. Typically, metals do not fail in compression, so the Modified_Piecewise_Linear_Plasticity material model is more suitable to simulate the failure response of these materials.

Table 8 lists the elasto-plastic parts with and without failure defined in the vehicle models. It can be seen that several parts are not assigned a failure strain, consequently these parts are assumed not to fail. This assumption is acceptable for mild steels and aluminums where the part is more likely to buckle during the impact. This assumption, however, may not be valid for high-strength steels where the material is more susceptible to fracture. It can be seen in the last row of Table 8 that some of the high-strength components are not assigned failure in the models which may lead to inaccurate simulation predictions.

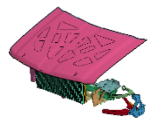
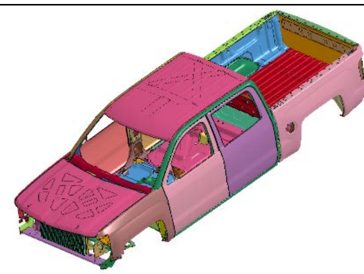
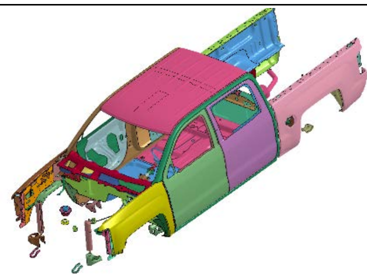
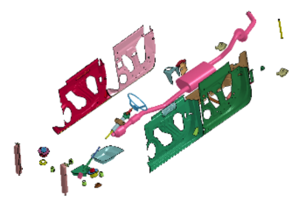
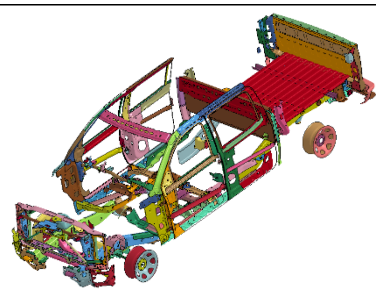
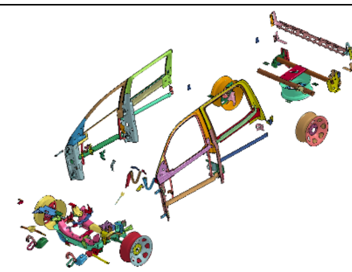
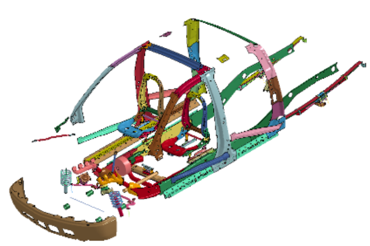
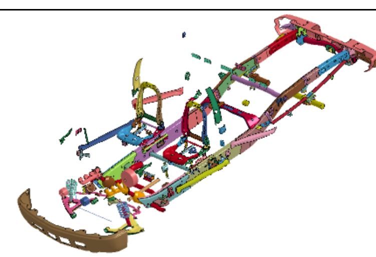
Table 7: Constitutive Formulation (Material Types) Used in the Models

| | Baseline Model | LWT Model |
|---|---|---|
| Rigid Parts |  |  |
| Elastic Parts |  |  |

| | | |
|---|---|---|
| Elasto-Plastic Parts – Piecewise_Linear_Plasticity (Material Type 24) |  |  |
| Elasto-Plastic Parts – Modified_Piecewise_ Linear_Plasticity (Material Type 123) |  |  |
| Other Parts |  |  |

| Table 8: Failure Implementation in the Elasto-Plastic Parts | | |
|---|---|---|
| | Baseline Model | LWT Model |
| Elasto-Plastic Parts with Failure Strain Defined |  |  |
| Elasto-Plastic Parts with No-Failure Strain Defined |  |  |
| High-Strength Steel Parts (Yield Strength > 500 MPa) with No Failure Strain Defined |  |  |

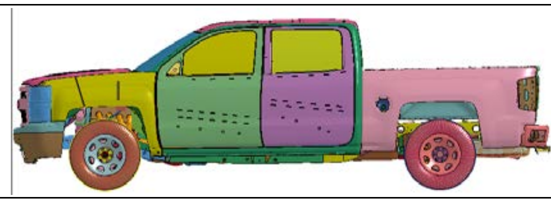
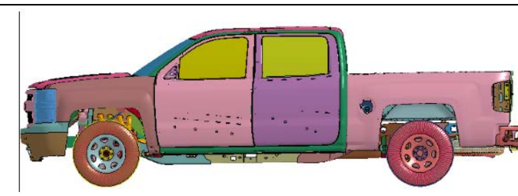
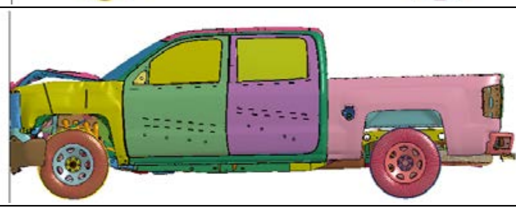
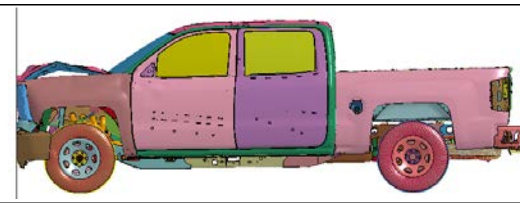
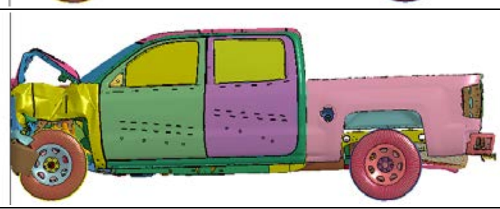
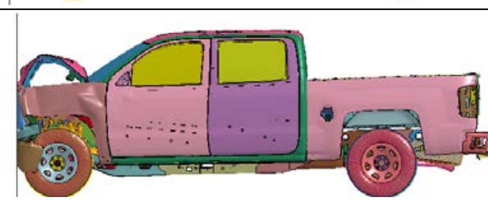
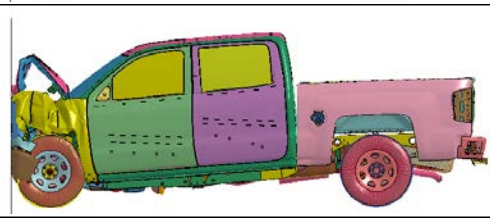
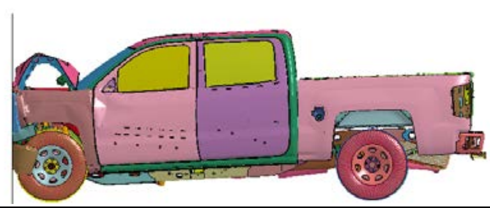
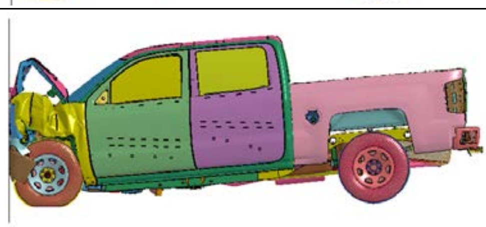
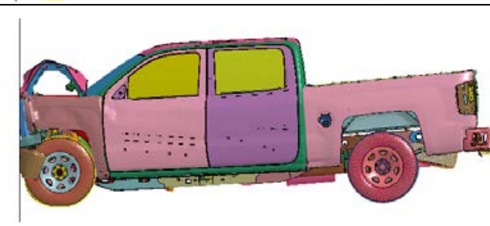
The defined material properties in the models were also examined to identify the different materials used in the two vehicle designs. Table 9 lists the different materials used in the model and the associated parts that use these materials. It can be seen from the table that the majority of the components of the Baseline model are made-up of steel while the majority of the components in the LWT are made-up of aluminum. This is consistent with descriptions provided in the report.

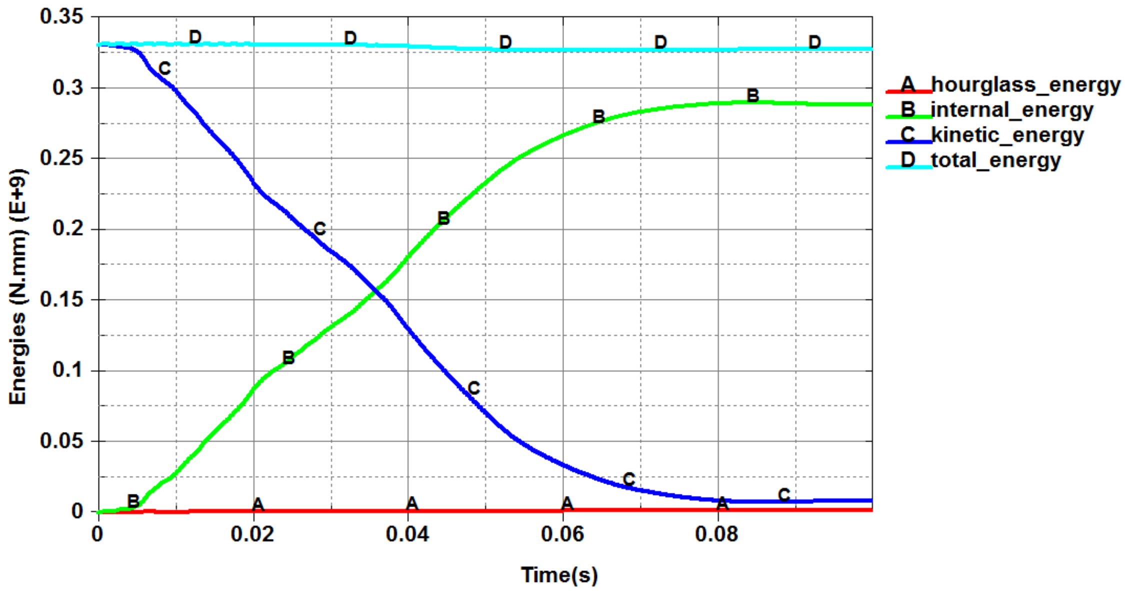
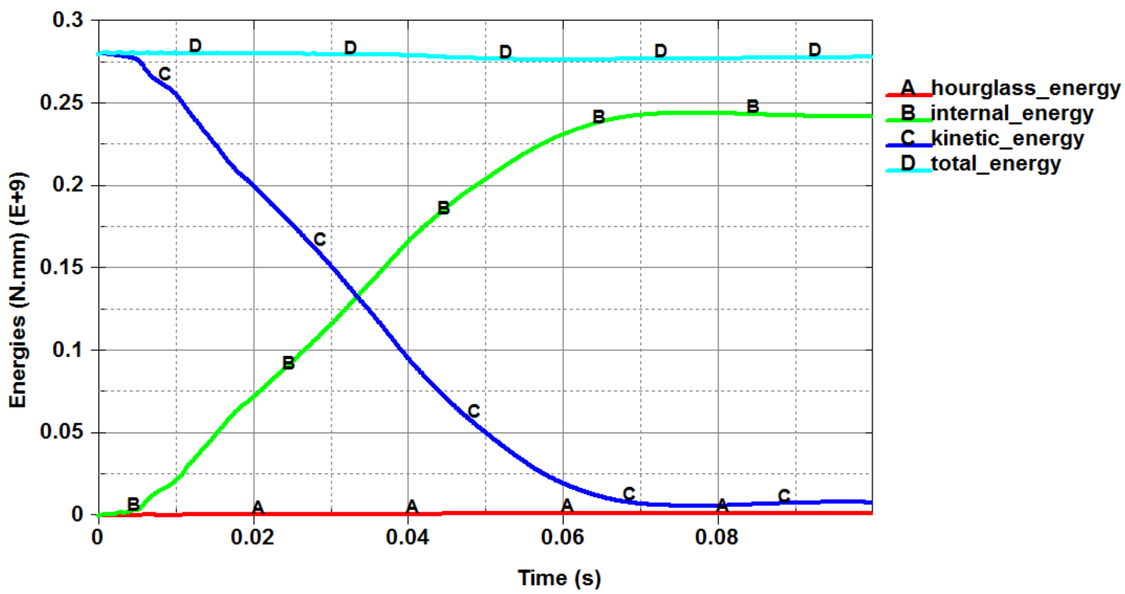
| Table 9: Different Materials Used in the Models | | |
|---|---|---|
| | Baseline Model | LWT Model |
| Parts with Plastics Properties |  |  |
| Parts with Aluminum Properties |  |  |
| Parts with Steel Properties Yield Strength < 300 MPa |  |  |
| Parts with Steel Properties 300 < Yield Strength < 500 MPa |  |  |
| Parts with Steel Properties Yield Strength > 500 MPa |  |  |

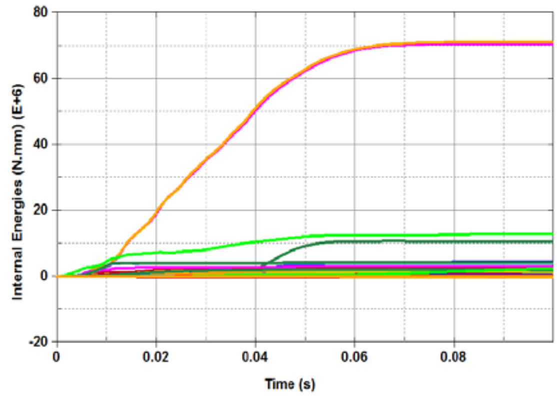
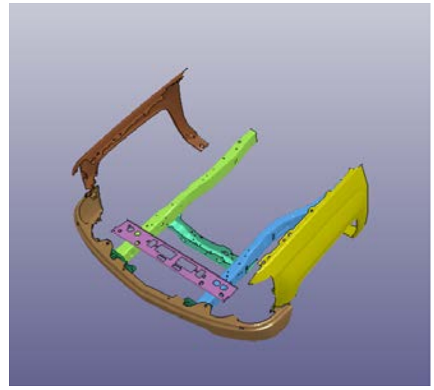
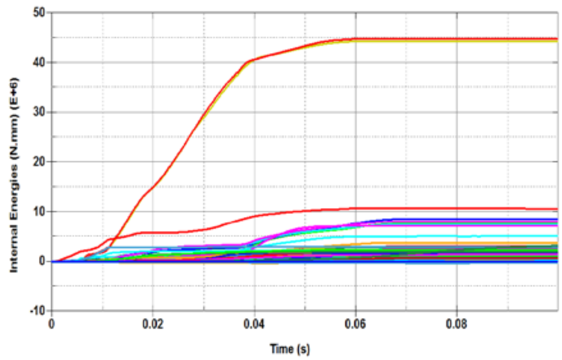
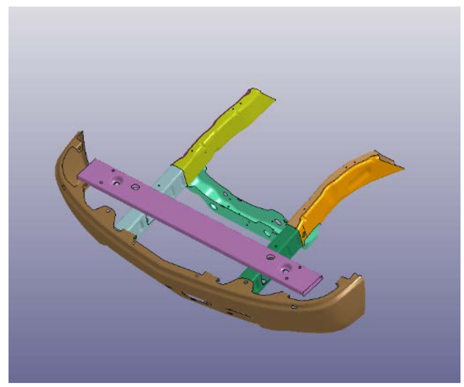
## III - Simulation Evaluations

The simulations were run and analyzed to assess the validity of the results. Simulations were run for four of the eight impacts: NCAP frontal, IIHS moderate overlap, NCAP MDB side and IIHS moderate overlap. Two simulations, one with the Baseline model and one with LWT model, were performed for each of the four impact cases. Hence, a total of eight simulations were run. All eight simulations ran to completion with normal termination. Examination of the vehicle deformation at different stages of simulation showed expected crush behavior. A check of the computed global energies indicated no discrepancies in the results. Review of the top ten energy absorbing parts revealed expected findings. Examples of these plots from one of the impact cases, NCAP frontal, are shown in Tables 10-12.

Table 10: NCAP Frontal Deformation Plots

| Baseline Model | LWT Model |
|---|---|
|  |  |
|  |  |
|  |  |
|  |  |
|  |  |

<table>
<tr><th colspan="2">Table 11: NCAP Frontal Global Energies</th></tr>
<tr><td>Baseline Model</td><td>
</td></tr>
<tr><td>LWT Model</td><td>
</td></tr>
</table>

<table>
<tr><th colspan="3">Table 12: Top Ten Energy Absorbing Parts</th></tr>
<tr><td>Baseline Model</td><td>
</td><td></td></tr>
<tr><td>LWT Model</td><td>
</td><td></td></tr>
</table>

It was noted that some components of the LWT model failed in the simulations as shown in Figure 1. These could have been designed to intentionally fail to achieve better crashworthiness performance, but the reasons are not documented.

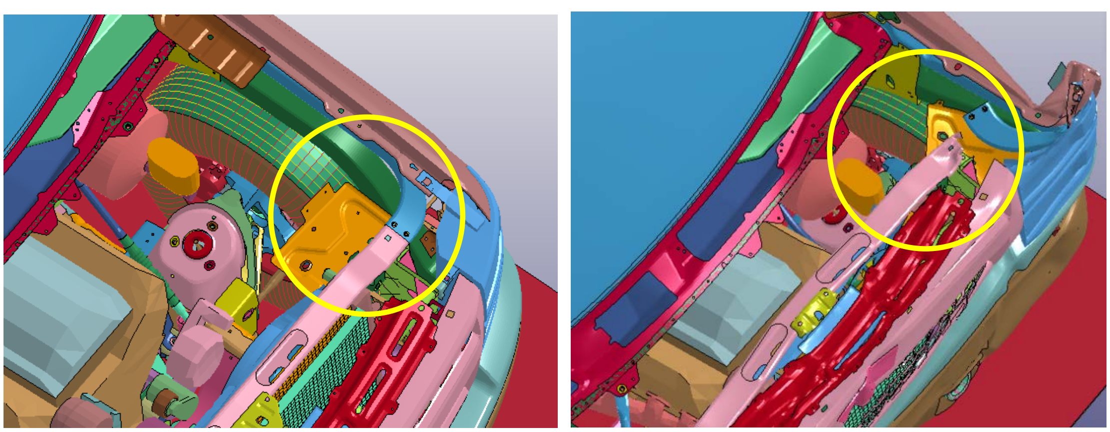


Figure 1: Example of Component Failure in LWT

**COMMENTS SUBMITTED BY**

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## External Peer Review of NHTSA's Draft Report, "Mass Reduction for Light-Duty Vehicles for Model Years 2017-2025"

### 1. Assumptions and Data Sources

**a) Please comment on the validity of data sources and assumptions embedded in the study's material choices, vehicle design and optimization, crash validation testing, and cost assessment that may affect the report's findings.**

**b) If you find issues with data sources and assumptions, please explain what you believe the issues are and why they are problematic and provide suggestions for available data that would improve the study.**

The data sources and assumptions in the material choices to reduce vehicle mass are as good as they can get at this stage of the study. The teardown of the base design is exhaustive and the team has done a great job. The choices of material and design strategy adopted make sense. The fact that the study adopted a strategy almost the same as that already been adopted by Ford in its F150, i.e. Aluminum intensive body on a steel frame, show the feasibility of the proposal. However, the study does not come up with more innovative solutions for weight reduction as they are already in production on a mass scale. I would have expected a detailed study of what it would take to replace the steel frame with an aluminum frame in a cost effective manner by redesigning the frame structure to take advantage of the properties of Aluminum.

The baseline frontal crash simulations are acceptable for comparisons with responses of the optimized design, although some other data readily available from their simulations would be more illuminating. For example, the crash pulses in the IIHS moderate and small offset crashes are not reported leaving one to assume that the authors believe that intrusions are more important than the crash pulse. The intrusions reported for the baseline simulation are higher than those observed in the NCAP tests. The door velocity and intrusion time histories are important to determine gap closure times for airbag firing times in side impacts (FMVSS 214 pole, NHTSA NCAP and IIHS side tests). Similar lack of reporting the occupant compartment acceleration levels leaves one to wonder about the severity of rear end crashes.

### 2. Vehicle Design and Optimization Methodology and its Rigorousness

**a) Please comment on the material selection and usage, joining technologies, vehicle structure design and optimization methodology and the resulting final vehicle design.**

I do not see any issues with material selection or its usage in production in the time frame of interest. I believe that joining techniques described in the report are already well known and will evolve in the future to further reduce cost and improve reliability in mass scale production.

b) **Describe the extent to which state-of-the art design methods have been employed, as well as the extent to which the associated analysis exhibits strong technical rigor. If you are aware of other methods employed elsewhere to select and analyze advanced materials and design engineering rigor for 2017-2025 vehicles, please comment on if and how they might improve the study and how they might be used.**

At this stage of development and design of a mass reduced vehicle, the authors have done a good job using CAE technology. In my mind, very little analytical data is presented in the report apart from several statements in the body of the report to the effect that the assembled team has expertise in this type of work. It is doubtful if other groups can duplicate the results presented without careful examination of the full body and chassis Finite Element models developed by the authors. This again is beyond the scope of my review.

c) **If you are aware of other methods employed elsewhere to select and analyze advanced materials and design engineering rigor for 2017-2025 vehicles, please comment on if and how they might improve the study and how they might be used.**

I agree with the selection of the materials in the report. Based on the report, I believe that the authors have used the methods commonly utilized by OEM's. Stochastic analysis might have led to more accurate answers in terms of actual vehicle responses in crash because such an analysis accounts for variability in material properties, metal gage thickness and weld, rivet or adhesive failures. However, this is beyond the scope of this study.

**3. Vehicle Functionalities and Crashworthiness Testing Methodological Rigor**

a) **Please comment on the approach and effort in maintaining baseline vehicle functionalities while trying to lightweight the vehicle.**

There is no obvious reason to believe that the functionality of the base vehicle will be compromised by the proposed mass reduction.

Comment on the methods used to design and analyze the vehicle body's structural integrity and crashworthiness.

The methods used for design and analysis of the proposed design are what are used in the Industry for many years and are well established.

b) **Describe whether and the extent to which state-of-the-art crash simulation methodologies have been employed and the extent to which the associated analysis exhibits strong rigor.**

The state-of-the-art in finite element structural simulations, LS-Dyna, has been utilized. Not much is reported (see comments in section 1) so it is hard to comment on the analysis portion of this report.

c) **Can the design and LS-DYNA results in this study be validated? If yes, how? If no, why not?**

The common practice in the Industry is to build a prototype(s) to the specifications in the CAE model and conduct tests, e.g. frontal, side, rear and roof crush. In the process of building production feasible designs using pre-production and production processes many issues relative to fabrication, joining and availability of parts are discovered and further design iterations are pursued. After the prototype builds are complete, crash tests are performed. Comparison of model predicted results with actual crash test results lead to further design changes if necessary and refinement of the model for further studies. At the stage of the writing of the report, the vehicle design shows opportunities for mass reduction of the baseline vehicle, but the prototyping and crash tests might show that all the predicted mass saving may not be realized.

**d) If you are aware of other methods and tools to help validate advanced materials and design engineering rigor for 2017-25 vehicles, please suggest how they would improve this study**.

Validation of components can be carried out as a minimum by fabricating and testing them. It is a good starting point and common practice to assemble the whole vehicle model with validated components. With component modeling and validation, the confidence level in model predictions will be substantially higher. In general, the Industry relies on validated models of components before relying on responses predicted by full-scale crash models.

**e) Is the crash pulse in full frontal impact acceptable from an air bag sensing point of view? Why or why not?**

Yes, I don't see any reason why the airbag sensing to fire the airbags cannot be done.

**f) Are durability and NVH values in the acceptable range after mass reduction? If not, what would be an acceptable range?**

All indications are that the durability and NHH will be in the acceptable ranges, although some further development may be required during prototype testing that may require additional mass increases.

**g) Is the high strength steel(s) selected within the plastic strain working range for the part selected?**

It is hard to tell without further interrogation of the CAE model. This is beyond the scope of my review.

**4. Vehicle Manufacturing Cost Methodology and its Rigorousness**

**a) Comment on the methodology used to estimate the LWV manufacturing costs.**

I am not an expert in manufacturing cost analysis.

**b) Please describe whether and the extent to which state-of-the-art costing methods have been employed and the extent to which the associated analysis exhibits strong rigor.**

This is beyond the scope of my expertise.

**c) If you are aware of other methods and tools employed elsewhere that could be used to help estimate costs for advanced materials and design for 2017-25 vehicles, please describe them and suggest why they would improve this study and how they might be used.**

This is beyond the scope of my expertise.

**5. Conclusion and Findings**

**a) Are the study's conclusions adequately backed up by the methods and analytical rigors of the study? Any concerns? How can they be addressed?**

At a high level, the study's conclusions are backed up by their thoroughness in identifying the right materials that are cost effective and show opportunities for mass reductions. How much of the opportunities can be realized in production can only be determined at the prototyping stage of vehicle development.

**b) Are the conclusions about the design, development, validation, and cost of the mass-reduced design valid? Any concerns? How can they be addressed?**

As mentioned earlier, validation of the design has not been carried out in the report. Only prototyping and testing can tell if all the identified mass reduction opportunities can be realized in the final design.

**c) Are you aware of other available research that evaluates and validates the technical potential for mass-reduced vehicle in the 2017-25 time frames that could be helpful for this study? Include sources and additional information for such research.**

Obviously the F150 mass reduced design already in high volume production shows that mass reduction of the body and frame as outlined in this report is possible. The exact amount predicted in the report may not be accurate, but opportunities exist. Further reduction from that already achieved in the F150 as mentioned in the report in the "other light-duty vehicle classes" need to be proven out and validated.

**6. Other Potential Areas for Comment**

**a) Is the methodology used to estimate the feasible mass reduction in other light-duty vehicle classes reasonable? Please explain.**

Yes, the methodology is acceptable for identifying the opportunities for mass reduction utilizing AHSS, Aluminum and Magnesium.

**b) Is the study valuable to understand the feasibility of 2017-2025 mass reduction technology? Please explain.**

This in conjunction of an earlier study of mass reduction opportunities for the Honda Accord is valuable to establish feasibility of mass reduction in 2017-2025 time frame.

**c) Do the study design concepts have any critical deficiencies in their applicability for 2017-2025 mass reduction feasibility that require revision by NHTSA prior to finalizing the report? If yes, please describe.**

Whether the amount of mass reduction in all the segments of the fleet is advisable can be argued. The reductions in all segments pointed out in the report will not be safety neutral. Although, such a study was beyond the scope of this undertaking by EDAG, NHTSA should conduct such a study.

**d) Are there any fundamentally different lightweight vehicle design technologies that are likely to be more common than the ones assessed in this study?**

The general trend of mass reduction utilizing materials like AHSS and Aluminum will continue with gradual introduction of Magnesium and composite materials.

e) **Is the cost from the study reasonable and backed up by sufficiently detailed data? What would you expect the cost to be for the design in this study? Please explain the reasons if your estimate is different than this study.**

Intensive use of Aluminum for mass reduction will tax the supply of the material that will in turn also increase the cost in the future. I am not sure if the supplier base will stabilize the cost of Aluminum. Steel may have some advantage over other materials.

**7. General Comments**

a) **Describe your overall assessment of the organization, readability, and clarity of this report, including any changes needed.**

The report is very well organized and is easy to read albeit too long. I believe that some of the self-serving messages should be eliminated as they sound more like advertisement for the performing organization and indictment of the OEM's.

b) **Is the information provided in the report and appendices sufficiently detailed to thoroughly document all essential elements of the study? If not, what additional information is needed?**

Overall, the report in conjunction with the CAE model is sufficiently detailed to document their effort. It will take the report and the model together to understand the details of the design and its validity.

c) **What are the strongest and weakest parts of this report? How can the weakest parts of the report can be strengthened?**

The strongest part of the report is in stating the various material alternatives for weight reduction of the various components of the vehicle and the reasons for selecting the most effective solutions. The weakest part is the lack of information regarding the design changes in the construction of several elements. A technical discussion of the baseline design and the final design would be helpful rather than stating "optimization and design changes" were used to reduce mass, e.g. "The final optimized cab assembly incorporated the chosen design options previously discussed for the Cab, FESM and Radiator Support, but also took advantage of additional design changes to make the structure lighter, stronger and easier to manufacture and assemble. The nature of those design changes is neither discussed nor is readily obvious.

d) **Please provide any other comments you may have on this report.**

The mass reductions predicted in the final design for the body, closures and the frames have high potential of being realized, although may not be exactly what is predicted. Some of the secondary mass reductions due to the lower masses of the body and the frames need further validations. For example, the engine is already "light" and is a 5.3L engine. Due to mass reduction the engine can be downsized to 5L. Any reduction in the mass of the engine and other powertrain and exhaust system will require a redesign of the engine to gain any mass savings unless one with the same displacement, Horse Power and Torque already exists. Similarly, to achieve mass reduction of the exhaust system a new design would be required. It is not clear whether mass of the exhaust system in todays vehicles are linearly related to just the displacement of the engine, i.e. a 6% reduction in displacement of a V-8 engine will result in 6% reduction in mas of all powertrain related components. Similarly, whether a 6% reduction in engine displacement will result in a similar reduction of transmission mass? If such relationships exist, it should be disclosed in the report.

It is not clear from the report as to the crash responses of the other variants of the Silverado. For example, have the authors considered the large weight variations between the lightest mass baseline vehicle and the heaviest mass vehicle, especially with a common frame structure in the front-end and the rear-end of the vehicle. The heaviest variant will have more crush and intrusion than the lightest variant. The lightest variant will have the least crush and the highest acceleration levels.

**8. Overall Recommendation**

**Based upon your review, indicate whether you find the report: (1) acceptable as is, (2) acceptable with minor revisions, (3) acceptable with major revisions, or (4) not acceptable. Please justify your recommendation. If you find the report acceptable with minor or major revisions, be sure to describe the revisions needed.**

I believe that the report is acceptable with minor revisions to address the issues raised in the preceding sections.

# Appendix C:

## REVIEWER CURRICULUM VITAE

# VITA

## SUJIT DAS

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Knoxville, Tennessee 37934

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## EDUCATION

**MBA** Management Science and Computer Science, University of Tennessee 1984

**MS** Metallurgical Engineering, University of Tennessee, 1982

**B. Tech** Metallurgical Engineering, Indian Institute of Technology, Kharagpur, India, 1979. Ranked 2nd in class with Honors.

### PROFESSIONAL EXPERIENCE

**Sr. Research Staff Member, Energy and Transportation Science Division, Oak Ridge National Laboratory, December 1984-present.**

Program manager of the cost modeling of lightweight materials and clean energy manufacturing programs for the U.S. Department of Energy. Develop, manage and lead projects for the DOE Office of Vehicle Technologies and Advanced Manufacturing Office. Responsible for a total annual budget of more than $750K consistently over the past several years and managing a team of 1-6 people per project depending on the project type. Develop cost models of advanced materials and transportation technologies and decision-making tools for several resource markets. Provide market assessments of energy efficient technologies including environmental implications for both domestic and international markets. Developed expertise in several multi-disciplinary research areas including:

- Life Cycle Assessment of Aluminum Intensive Vehicles for the Aluminum Association
- Next generation materials with energy/emissions reduction potential in the U.S. industry for DOE Advanced Manufacturing Office
- Manufacturing process modeling of high temperature stationary fuel cell systems in the 350-400 kW power range for DOE Fuel Cell Technologies Program
- Life cycle modeling of alternative lightweight engine design options for the DOE Propulsion Materials Program
- Market potential and infrastructure assessment of ethanol and hydrogen as alternative transportation fuels
- Cost modeling and life cycle analysis of advanced vehicles and lightweight materials Technologies for DOE Office of Vehicle Technologies
- Material technology assessments related to Partnership for A New Generation of Vehicles (PNGV)/Freedom Cooperative Automotive Research (FreedomCAR)
- Potential of renewable energy technologies in rural Bangladesh
- Biomass refinery analysis
- Economic analysis of advanced power electronics, electric motors, and intelligent transportation systems

- Energy efficiency of distribution transformers
- Cost of alternative fuels
- Forecasting of petroleum and uranium supplies
- Estimation of flood-stage economic damages
- The economic viability of plastics and automobile recycling
- Environmental implications of privatization of the power sector in India
- Market assessments of energy efficient technologies such as home refrigerators in India
- Inspection and Maintenance of two-wheeler vehicles in India
- Assessment of uranium resources

**Visiting Fellow, Tata Energy Research Institute (TERI), New Delhi, India, October 1992-June 1993.**

Developed a comprehensive, computerized, and PC-based Energy-Economic-Environment database for TERI - the first of its kind in India and provided technical support in their ongoing energy and economic modeling activities.

**Research Assistant, Energy and Economic Analysis Section, Oak Ridge National Laboratory, September 1982-December 1984.**

Documented and evaluated several EIA, DOE maintained computers models, i.e., Headwater Benefit Energy Gains Model and the Petroleum Allocation Model. Developed a computer software "BIOCUT" for Economic Evaluation Model for Wood Energy Plantations.

## LIST OF PUBLICATIONS

### *BOOK/CHAPTERS PUBLISHED*

Two book chapters published in "Advanced Composite Materials for Automotive Applications: Structural Integrity and Crashworthiness," Edited by Ahmed Elmarakbi, Univ. of Sunderland, UK and published by Wiley & Sons (Aug.'13).

Chapter 3: Low Cost Carbon Fibre for Automotive Applications (Part 1: Low Cost Carbon Fibre Development);

Chapter 17: Low Cost Carbon Fibre for Automotive Applications (Part 2: Applications, Performance and Cost Reduction Models)

"Recycling and Life Cycle Issues for Lightweight Vehicles," A Book Chapter in Materials, Design and Manufacturing for L.ightweight Vehicles, edited by P.K. Mallick, Woodhead Publishing Limited, pp. 309-330, 2010

"Material Use in Automobiles." A Book Chapter in Encyclopedia of Energy, published by Elsevier Inc., Vol. 3, pp. 859-869, 2004.

"Plastic Wastes: Management, Control, Recycling, and Disposal." Noyes Data Corporation, NJ (Co-Authored with U.S. Environmental Protection Agency and T. R. Curlee), 1991.

***SELECTED REFERRED ARTICLES/PRESENTATIONS (Out of 60+ articles)***

"Cost of Ownership and Well-to-Wheels Carbon Emissions/Oil Use of Alternative Fuels and Advanced Light-Duty Vehicle Technologies," Energy for Sustainable Development, 17(2013), pp. 626-641.

Served as one of the expert reviewers for the following three recent U.S. DOT/U.S. EPA reports:

- Mass Reduction for Light-Duty Vehicles for Model Years 2017-2025, EDAG/The George Washington University Report, Apr. 2012
- Light-Duty Technology Cost Analysis Pilot Study, FEV Draft Report, Sept. 3, 2009
- An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Vehicle Program, Lotus Engineering Inc., Mar. 2010

"Lightweighting Opportunities in the Global Automotive Industry," invited presentation at the 2011 International Automotive Lightweight Materials Development Forum, held in Chongqing, China, on Mar. 24-25,'11. (Also at the 12th IUMRS International Conference on Advanced Materials, held in Qingdao, China on Sept. 22-28, 2013).

"Importance of Economic Viability Assessment of Automotive Lightweight Materials" invited presentation at the 3rd Annual Advanced Lightweight Materials for Vehicles conference held on Aug. 11-12, '10, Detroit, MI.

"Analysis of Fuel Ethanol Transportation Activity and Potential Distribution Constraints," Transportation Research Record: Journal of the Transportation Research Board, No. 2168, Transportation Research Board of the National Academies, Washington, DC, 2010, pp. 136-145.

"Reducing GHG Emissions in the United States' Transportation Sector" Energy for Sustainable Development, 15 (2011) 117–136, May 11.

"Life Cycle Assessment of Carbon Fiber-Reinforced Polymer Composites," Intl. Journal of Life Cycle Assessment, Volume 16, Issue 3, pp. 268-282, 2011.

"Battle Green," an interview article published in American Metal Market, Oct. 2010, pp. 36-40.

"Shedding Pounds On a Magnesium Diet," Automotive Engg. International, Apr. 6, 2010, pp. 34-36, interview article by Steven Ashley.

"Analysis of Fuel Ethanol Transportation Activity and Potential Distribution Constraints," Transportation Research Record: Journal of the Transportation Research Board, No. 2168, Transportation Research Board of the National Academies, Washington, DC, 2010, pp. 136-145.

"Low-Carbon Fuel Standard – Status and analytic issues," Energy Policy, vol. 38, No.1, Jan. 2010, pp. 580-591.

"Importance of Economic Viability Assessment of Automotive Lightweight Materials," invited presentation at the 3rd Annual Advanced Lightweight Materials for Vehicles," held in Detroit, MI on Aug. 11-12, 2010.

"A Comparative Life Cycle Assessment of Magnesium Front End Parts," SAE Paper No. 2010-01-0275, Society of Automotive Engineers, Warrendale, PA.

"Primary Magnesium Production Costs for Automotive Applications," Journal of Metals, Vol. 60, No. 11, 2008, pp. 51-58.

"A Systems Approach to Life Cycle Truck Cost Estimation," SAE Paper No. 2006-01-3562, Society of Automotive Engineers, Warrendale, PA.

"Automotive Lightweighting Materials Benefit Evaluation," ORNL/TM-2006/545, Oak Ridge National Laboratory, Oak Ridge, TN, Nov. 2006.

"Lightweight Opportunities for Fuel Cell Vehicles," SAE Paper No. 2005-01-0007, Society of Automotive Engineers, Warrendale, PA.

"A Comparative Assessment of Alternative Powertrains and Body-in-White Materials for Advanced Technology Vehicles," SAE Paper No. 2004-01-0573, Society of Automotive Engineers, Warrendale, PA.

"Back To Basics? The Viability of Recycling Plastics by Tertiary Approaches," Working Paper #5, Program on Solid Waste Policy, School of Forestry and Environmental Studies, Yale University, New Haven, CT, September 1996. (with T. R. Curlee)

## AWARDS & PROFESSIONAL ACTIVITIES

Awarded 2004 Journal of Metals Best Paper by the Mineral, Metals, and Materials Society (TMS)

Chair of Society of Automotive Engineering (SAE) Sustainable Program Development Committee (2013-2014)

Member of Transportation Research Board (TRB) Committees (2008- Present)
- Transportation Economics
- Alternative Transportation Fuels and Technologies

Invited Speaker on the Life Cycle Assessment of Materials by Beijing University of Technology, China
Conference Session Organizers for SAE and TRB

Peer Reviewers for Several Energy and Environmental Related Journals

Past peer reviewers for the EPA and NHTSA draft reports on the vehicle mass reduction and cost analysis of light-, medium-, and heavy-duty vehicles including:
(i) 2014 EPA Light-Duty Pickup Truck
(ii) 2015 NHTSA Costs of Medium- and Heavy-Duty Vehicle Fuel Efficiency Emission Reduction Technologies for MY 2019-2022
(iii) 2016 NHTSA Mass Reduction for Light-Duty Vehicles for MY 2017-2025

## Prakash "Krish" Krishnaswamy

Krish is CEO of Xitadel, a CAE company that offers transformative expertise, innovation and technologies. He co-founded EASi Engineering (1981), a leader in CAE technology and pioneered a viable global delivery model EASi India (1992). Krish is passionate about impacting industry by leveraging his three decades of experience as entrepreneur, technology and business leader.

### AREAS OF INTEREST

Next Generation CAE technologies and materials; passive and active safety technologies; low cost product innovation for emerging market and the bottom-of-the-pyramid.

### EDUCATION

- MS Engineering Mechanics from the University of Missouri-Rolla
- BEME University of Bombay
- MS Mechanical Engineering - Honorary Degree
- Executive program Tuck School of Business, Dartmouth 1994, 1995

### CAREER BACKGROUND

#### CEO of Xitadel LLC (www.xitadel.com)

Xitadel Group charter deploys CAE technology and expertise in emerging markets. Its technology partners are Beta CAE, Mechanical Simulation Corp, Dassault Simulia and ThermoAnalytics. Xitadel's CAE expertise spans Materials, Process Automation, Design Space Exploration, etc.

#### CEO and Founder EASi Engineering www.easi.com (Detroit, USA) 1981 –2012

EASi provides high end virtual product engineering and technology solutions to global customers. EASi is a Tier-1 supplier to some of the largest Automotive companies.

### TALKS AND AWARDS

- 2016 "Next Generation CAE" Mahindra Research Valley GuruSpeak Series
- 2015 "Next Generation CAE – can India seize the opportunity?" Guest of Honor, NAFEMS Conference, Chennai
- 2012 "Lightweight Materials', Eminent Speaker Series, ARAI Pune
- 2012 "CAE Predictiveness of Lightweight Materials" Government Industry Conference, Washington DC
- 2012 November "Megabits and Megabytes: Remaking the Auto Industry" Guest Post in Forbes
- 2012 "My Entrepreneurial Journey" IndoAmerican Chamber of Conference (IACC), Detroit Michigan
- 2011 "Entrepreneurship with a Conscience", IACC, Detroit

- 2009 KeyNote Speaker, ESI Conference, Bangalore
- 2009 “Lightweight Materials” Talk at IBM/ESI Conference, Amagi, Japan
- 2008 Business Lecture, AKKA Conference, Chicago, IL
- 2008 “Global Engineering and Entrepreneurship” - Great Lakes Institute of Management, Chennai
- 2002 KeyNote Speaker, AKKA Conference, Detroit, MI
- 1999 “Business Accomplishments” Kiwanis Club
- 1997 “American Dreamers” Crains Detroit Award
- 1995 “Entrepreneur Award” Governor of Missouri
- 1989 “Entrepreneur of the Year” American Society of Engineers from India

## PUBLICATIONS

Umesh Mallikarjunaiah, Murali Balasubramanian, Mrityunjaya Yeli and Prakash (Krish) Krishnaswamy and FCA Fiat Chrysler Automobiles and Xitadel CAE Technologies India Pvt Ltd “Spot Weld Optimization Process”, 2016 BETA CAE Open Meeting and Seminars in Bangalore, February 17 & 18, 2016, Le Méridien, Bangalore

Priya Prasad, Prakash Krishnaswamy, Michael Lee, Ravi Chilukuri, Predictive Capability of CAE Technology for Lightweight Material Applications, SAE Government-Industry Conference, Washington DC 27 January 2012

Megabets And Megarisks: Remaking The Auto Industry Forbes Magazine, Nov 29, 2011

EASi-Process: Technical Whitepaper, Thirumurthy Nallasamy, Prakash Krishnaswamy, Sural V, EASi Inc. (2001)

Mani, A., Srivastava, M., Krishnaswamy, P., Summers, S., Hollowell, T., “Rollover Crashworthiness of Pick-up Trucks”, to be presented at the SAE Stapp Crash Conference, 1995

Shyu, S., Mani, A., Krishnaswamy, P., Conroy, R., Shermetaro, M., and Exner, G. “Designing Energy Absorbing Steering Wheels through Finite Element Impact Simulation”, SAE Technical Paper 931844

Mani, A., Krishnaswamy, P., “Challenges in Crash Simulation Due to Emerging Safety Standards”, SAE Technical Paper 930209

O’Mahony, Patrick., Cronin, Donald., Krishnaswamy, P. “Forced Response Optimization with MSC/NASTRAN”, presented at the MSC Users Conference, 1992

Avanessian, H., Ridella, S., Mani, A., Krishnaswamy, P. “An analytical Model to Study the Infant Seat/Airbag Interaction”, SAE Technical Paper 920126

Mani, A., and Krishnaswamy, P. “Advances in crash simulation technology”, Automotive Engineering, February 1991, Vol. 99, Number 2

Mani, A., and Krishnaswamy, P. “Crash simulation”, Computer-aided engineering, Penton Publication, January 1991

Krishnaswamy, P,. and Mani, A,. “Crash Codes pave the way to Safer Vehicles”, Mechanical Engineering, April 1991, Volume 113/No. 4

Krishnaswamy, P., “Computer Aided Engineering”, Mass Transit, July/August 1990

Krishnaswamy, P., “Designing the material to fit the part”, Mechanical Engineering, August 1989

Krishnaswamy, P. “Coming together with CAE”, Automotive Industries, June 1988

Krishnaswamy, P. and Muhlbauer, K. “Investigation of energy absorbing steering column”, (Master’s degree thesis, 1973)

Krishnaswamy, P. and Mahajan, A. “Design of a collapsible steering column”, (Bachelor’s degree thesis, 1970)

**Dhafer Marzougui, D.Sc.**
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## EDUCATION

D.Sc. Mechanical Engineering, The George Washington University, 1999
Major: Solid Mechanics
Dissertation: Implementation of a Fracture Failure Model to a 3D Nonlinear Dynamic Finite Element Code (DYNA3D)

M.Sc. Engineering Mechanics, The Pennsylvania State University, 1993
Major: Solid Mechanics
Thesis: Effects of a Knee Prosthesis on the Stress Distribution in the Human Tibia

B.Sc. Mechanical Engineering, The Pennsylvania State University, 1988

## WORK EXPERIENCE

July 13 –Present: Associate Professor
College of Science,
*Research Director*
*Center for Collision Safety and Analysis (CCSA)*
George Mason University

Jan 03 – June 13: *Highway Safety and Infrastructure Research, Director*
*National Crash Analysis Center (NCAC),*
*Assistant Research Professor,*
*Civil & Environmental Engineering Department*
*The George Washington University*

- Direct Federal Highway Administration (FHWA) sponsored research projects to identify potential transportation safety problems related to roadside hardware designs and installations. Projects make use the latest tools in computer simulation and modeling coupled with crash testing to predict the crash events. Detailed models of vehicles and roadside devices are developed and validated. Simulations with varied impact conditions are performed and the results are analyzed to identify problems and recommend countermeasures.

- Manage the FHWA Federal Outdoor Impact Laboratory (FOIL). Responsibilities include planning and conducting full-scale and components crash tests for FHWA and other government agencies to assist in improving transportation safety and security

- Direct US Department of State (DOS) sponsored research projects. The research consists of developing the tools needed to simulate impacts into perimeter security barriers. These tools are used to develop accurate computer models of the impacting vehicle and the barriers. The emphasis of the research is to simplify current anti-ram designs, reduce their cost, and improve their esthetics without compromising their protection performance.

- Supervise and assist graduate students in research projects related to transportation safety and perimeter security. Teach undergraduate and graduate classes including courses related to non-linear finite element simulation and modeling

July 96 – Dec 02: *Research Scientist,*
*FHWA/NHTSA National Crash Analysis Center (NCAC),*
*The George Washington University*

- Develop and improve methodology for creating detailed computer models of automotive vehicles. These models are used worldwide by researchers in the field of transportation safety to analyze, evaluate, and improve vehicles and roadside hardware crashworthiness. This project is sponsored by the National Highway Traffic Safety Administration and The Federal Highway Administration.

- Develop high fidelity finite element computer models of roadside hardware devices. The models included: Guardrails, Portable Concrete Barriers, Cable barriers, Transitions, and Sign Supports systems. These models are used to investigate the safety of these devices in cases of crash with automotive vehicles. This work is sponsored by the Federal Highway Administration and State Departments of Transportation. The research was presented in transportation safety related conferences and published in crashworthiness journals.

- Develop models of occupants (dummies) and restraint systems (seatbelts and airbags). These models are necessary to assess injuries incurred by occupants during crashes.

- Use explicit nonlinear finite element simulations to evaluate and improve the design of several anti-ram devices such as bollards, walls, and fences that are used to protect U.S. embassies and building abroad. This project is sponsored by the U.S. Department of State.

- Assist and provide support to other researchers in the field of transportation safety modeling and simulation.

- Teach non-linear finite element simulation and modeling courses

Jan. 93 - Jun. 96: *Graduate Research Assistant,*
*FHWA/NHTSA National Crash Analysis Center (NCAC),*
*The George Washington University*

- Maintained simulation programs used by the FHWA. Used INGRID, LS-INGRID,PATRAN, HYPERMESH, EASi-CRASH, GENERIS, MODEDIT, DYNA3D, LS-DYNA, PAM-CRASH, RADIOSS, TAURUS, LS-TAURUS, LS-POST, PAMVIEW, MODANIM and several other finite element software packages which simulate and analyze vehicles, roadside hardware apparatuses, occupants, and restrain systems during automotive crashes.

## HONORS/AWARDS/AFFILIATIONS

- Transportation Research Board AFB20 Committee Member, 2010
- Guest Speaker, Perimeter Security Design and Testing Symposium, 2004
- Session Chair, International Crashworthiness Conference, 2000 and 2004
- FHWA/NHTSA NCAC Special Recognition, 1995
- FHWA Graduate Research Fellow Award, 1993
- Honors Scholars program (1986-1988), The Pennsylvania State University

## SPONSORED RESEARCH PROJECTS

1. NCHRP Project 03-119: “Application of MASH Test Criteria to Breakaway Sign and Luminaire Supports and Crashworthy Work-Zone Traffic Control Devices”
   Sponsor: National Academy of Sciences, Award: $600,000 (9/28/2015 - Current)
   Dhafer Marzougui (PI)
2. NCHRP Project 15-53: “Roadside Barrier Designs Near Bridge Ends with Restricted Rights of Way”
   Sponsor: National Academy of Sciences, Award: $500,000 (8/25/2014 - Current)
   Dhafer Marzougui (CO-PI) and Richard Powers (PI)
3. NCHRP Project 22-29A: “Evaluating the Performance of Longitudinal Barriers on Curved, Superelevated Roadway Sections”
   Sponsor: National Academy of Sciences, Award: $250,000 (7/28/2014 - Current)
   Dhafer Marzougui (CO-PI) and Cing-Dao (Steve) Kan (PI)
4. Developing Anthromporphic Test Devices-Dummy Model
   Sponsor: Livermore Software Technology, Award: $469,439.00 (3/1/08 - 12/31/11)
   Dhafer Marzougui (CO-PI) and Cing-Dao (Steve) Kan (PI)
5. Timber Guardrail Development
   Sponsor: Department of Transportation, Award: $220,000 (10/01/07 -12/31/09)
   Dhafer Marzougui (CO-PI) and Cing-Dao (Steve) Kan (PI)
6. Brifen Cable Barrier Modeling
   Sponsor: Hill & Smith Limited, Award: $75,208.00 (1/1/2007- 02/29/2008)
   Dhafer Marzougui (CO-PI) and Cing-Dao (Steve) Kan (PI)
7. Development of Cable Barrier Guidelines
   Sponsor: National Academy of Sciences, Award: $399,987.00 (04/28/08 - 07/28/09)
   Dhafer Marzougui (CO-PI) and Cing-Dao (Steve) Kan (PI)

## PUBLICATIONS

### Journal Papers

Marzougui, D., Kan C.D., and Opiela K., "Further Considerations for Effective Median Barrier Lateral Placement for Varying Highway Cross Sections", Journal of the Transportation Research Board, Washington DC, 2014.

Sahraei E., Digges K., Marzougui D., Roddis K., “High Strength Steels, Stiffness of Vehicle Front-end Structure, and Risk of Injury to Rear Seat Occupants, an Study based on Computational Modeling,”, Accident Analysis and Prevention Journal, Vol. 66, pp. 43–54, 2014.

Sahraei E., Digges K., Marzougui D., “Effects of Vehicle Front-End Stiffness on Rear Seat Dummies in NCAP and FMVSS208 Tests,” Traffic Injury Prevention, vol. 14, no. 6, pp. 602-606, 2013.
Marzougui, D., Kan C.D, and Opiela K, "Comparison of Crash Test and Simulation Results for Impact of Silverado Pickup into New Jersey Barrier Under Manual for Assessing Safety Hardware", Journal of the Transportation Research Board, Washington DC, 2012.

Bolarinwa E.O., Mahadevaiah U., Marzougui D., Opiela K.S., “The Development of an Enhanced Finite Element Tire Model for Roadside Safety Hardware Assessment”, Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics, Vol. 226 No. 3, pp 206-219, September 2012.

Sahraei E., Marzougui D., Digges K., Kan C.D, “Effect of Increase in Weight and Stiffness of Vehicles on the Safety of Rear Seat Occupants”, International Journal of Crashworthiness, Vol. 16, No. 3, pp 309-318, June 2011.

Gabauer J.D., Kusano K.D., Marzougui D., Opiela K., Hargrave M., Gabler C.H., “Pendulum testing as a means of assessing the crash performance of longitudinal barrier with minor damage”, International Journal of Impact Engineering, Vol. 37, pp. 1121-1137, Nov. 2010.

Silva, P. F., Mesia, W.D., Marzougui, D., and Badie, S.S., “Performance Evaluation of the Flexure Impact Resistance Capacity of RC Members”, American Concrete Institute (ACI) Structural Journal, Vol. 106, No. 5, pp. 726-736, Sep., 2009.

Buyuk, M., Kurtaran, H., Marzougui, D., and Kan, C.D., “Automated Design of Threats and Shields Under Hypervelocity Impacts by Using Successive Approximate Optimization Methodology”, Int. Journal of Impact Engineering, Vol. 35, No. 12, 1449-1458, June 2008.

Mohan, P., Marzougui, D., and Kan, C. D., “Modified Approach to Accurately Measure Height of Force (HOF),” SAE 2007 Transactions Journal of Passenger Cars, V116-6, August 2008.

Marzougui, D., Mohan P., Kan C.D, and Opiela K, "Performance Evaluation of Low-Tension Three-Strand Cable Median Barriers ", Journal of the Transportation Research Board, pp 34-44, Issue 2025, Washington DC, 2007.

Mohan P., Marzougui D., and Kan C.D., “Validation of a Single Unit Truck Model for Roadside Hardware Impact”, International Journal of Vehicle Systems Modeling and Testing, Vol. 2, No. 1, pp 1-15, 2007.

Tahan F., Marzougui D., Zaouk A. Bedewi N.E., Eskandarian A., and Meczkowski L., “Safety performance evaluation of secure mailboxes using finite element simulations and crash testing”, International Journal of Crashworthiness, Vol. 10, No. 4, pp. 341-349, 2005.

Mohan P., Marzougui D., Meczkowski L., and Bedewi N.E., “Finite Element Modeling and Validation of a 3-Strand Cable Guardrail System”, International Journal of Crashworthiness, Vol. 10, No 3, pp 267-273, 2005.

Yonten K., Manzari M., Marzougui D., and Eskandarian A., “An assessment of constitutive models of concrete in the crashworthiness simulation of roadside safety structures”, International Journal of Crashworthiness, Vol. 10, No. 1, pp. 5-19, 2005.

**Technical Reports**

D. Marzougui, U. Mahadevaiah, F. Tahan, C.D. Kan, R. McGinnis, and R. Powers, “Report 711: Development of Guidance for the Selection, Use, and Maintenance of Cable Barrier Systems”, National Cooperative Highway Research Program (NCHRP), Transportation Research Board of the National Academies, Washington D.C., 2012. (submitted to NCHRP)

D. Marzougui, C.D. Kan, K.S. Opiela, “Analyzing the Potential Interface Effectiveness for Cable Barriers in Elevated Median Cross Sections”, National Crash Analysis Center, The George Washington University, NCAC Report No. 2011-W-002, April 2011. (submitted to FHWA)

D. Marzougui, C.D. Kan, K.S. Opiela, “Analyzing the Potential Interface Effectiveness for Cable Barriers in Asymmetrical Median Cross Sections”, National Crash Analysis Center, The George Washington University, NCAC Report No. 2011-W-001, Feb. 2011. (submitted to FHWA)

D. Marzougui, C.R. Story, and C.D. Kan, “Crash Test Evaluation of the DOS 30 MPH Anti-Ram Wall at the M30 Impact Condition”, National Crash Analysis Center, The George Washington University, NCAC Report No. 2011-R-002, Sep. 2011. (Submitted to FHWA and DOS)

D. Marzougui, C.R. Story, U. Mahadeviah, and C.D. Kan, “Evaluation & Testing of the DOS Fixed Bollard at the M30 Impact Condition”, National Crash Analysis Center, The George Washington University, NCAC Report No. 2011-R-001, Aug. 2010. (Submitted to FHWA and DOS)

D. Marzougui, C.D. Kan, K.S. Opiela, “Comparison of the Crash Test and Simulation of an Angle Impact of a 2007 Chevrolet Silverado Pick-Up Truck into a New Jersey-Shaped Concrete Barrier for MASH Conditions”, National Crash Analysis Center, The George Washington University, NCAC Report No. 2009-R-004, Oct. 2009. (submitted to FHWA)

D. Marzougui, C.D. Kan, K.S. Opiela, “Vehicle Dynamics Investigations to Develop Guidelines for Crash Testing Cable Barriers on Sloped Surfaces”, National Crash Analysis Center, The George Washington University, NCAC Report No. 2010-W-009, Aug. 2010. (submitted to FHWA)

D. Marzougui, C.D. Kan, K.S. Opiela, “Developing Functional (Design) and Evaluation Requirements for Cable Median Barriers”, National Crash Analysis Center, The George Washington University, NCAC Report No. 2010-W-008, Aug. 2010. (submitted to FHWA)

D. Marzougui, C.D. Kan, K.S. Opiela, “Comparing Vehicle Dynamics Analysis Results for Roadside Hardware Evaluations”, National Crash Analysis Center, The George Washington University, NCAC Report No. 2010-W-007, Aug. 2010. (submitted to FHWA)

D. Marzougui, C.D. Kan, K.S. Opiela, “Using Vehicle Dynamics Simulation as a Tool for Analyzing Cable Barrier Effectiveness”, National Crash Analysis Center, The George Washington University, NCAC Report No. 2010-W-006, Aug. 2010. (submitted to FHWA)

D. Marzougui, C. Story, L. Nix, C.D. Kan, and R.D. Powers, "Development of an Energy Absorbing End-Terminal for the Steel Backed Timber Guardrail - Phase IIA: Design of TL 2 SBT End Treatment", National Crash Analysis Center, The George Washington University, NCAC Report No. 2010-R-002, March 2010. (submitted to FHWA)
D. Marzougui, C. Story, L. Nix, C.D. Kan, and R.D. Powers, "Development of an Energy Absorbing End-Terminal for the Steel Backed Timber Guardrail - Phase IIB: Test Level 2 Crash Testing Results", National Crash Analysis Center, The George Washington University, NCAC Report No. 2010-R-003, March 2010. (submitted to FHWA)

D. Marzougui, C. R. Story, L. Nix, and C.D. Kan, "Crash Test Evaluation of the DOS Tubular Steel Fence Barrier at the M50 Impact Condition", National Crash Analysis Center, The George Washington University, NCAC Report 2010-R-001, March 2010. (Submitted to FHWA and DOS)

D. Marzougui, U. Mahadevaiah, C.D. Kan, K.S. Opiela, "Analyzing the Effects of Cable Barriers Behind Curbs Using Computer Simulation", National Crash Analysis Center, The George Washington University, NCAC Report No. 2009-W-008, Nov. 2009. (submitted to FHWA)

D. Marzougui, C. R. Story, L. Nix, and C.D. Kan, "Crash Test Evaluation of the DOS Tubular Steel Fence Barrier at the K4 Impact Condition", National Crash Analysis Center, The George Washington University, NCAC Report 2009-R-001, Jan. 2009. (Submitted to FHWA and DOS)

P. Mohan, D. Marzougui, E. Arispe, C. Story, "Component and Full-Scale Tests of the 2007 Chevrolet Silverado Suspension System", National Crash Analysis Center, The George Washington University, NCAC Report 2009-R-004, Oct. 2009. (submitted to FHWA)

P. Mohan, M. Ritter, D. Marzougui, D. Brown, C.D. Kan, "Modeling, Testing, and Validation of the 2007 Chevy Silverado Finite Element Model", National Crash Analysis Center, The George Washington University, NCAC Report 2009-W-005, Oct. 2009. (submitted to FHWA)

D. Marzougui, U. Mahadevaiah, C.D. Kan, K.S. Opiela, "Analyzing the Effects of Cable Barriers Behind Curbs Using Computer Simulation", National Crash Analysis Center, The George Washington University, NCAC Report 2009-W-008, Nov 2009. (submitted to FHWA)

D. Marzougui, E. Arispe, C. Story, and C.D. Kan, "Crash Testing and Evaluation of Plastic Water Filled Barrier at DOS K4 Impact Condition", National Crash Analysis Center, The George Washington University, NCAC Report 2008-R-005, December 2008. (Submitted to FHWA and DOS)

D. Marzougui, E. Arispe, C. Story, and C.D. Kan, "Crash Testing and Evaluation of Chain Link Fences at the K4 Impact Condition", National Crash Analysis Center, The George Washington University, NCAC Report 2008-R-004, January 2009. (Submitted to FHWA and DOS)

D. Marzougui, C. Story, P. Mohan, and C.D. Kan, "Crash Testing and Evaluation of a Concrete Masonry Unit Barrier at the K4 Impact Condition", National Crash Analysis Center, The George Washington University, NCAC Report 2008-R-006, May 2009. (Submitted to FHWA and DOS)

D. Marzougui, E. Arispe, C. Story, and C.D. Kan, "Crash Testing and Evaluation of Temporary Concrete Barriers at DOS K4 Impact Condition", National Crash Analysis Center, The George Washington University, NCAC Report 2008-R-007, January 2009. (Submitted to FHWA and DOS).

D. Marzougui, R.D. Powers, and C.D. Kan, “Development of an End-Treatment for the Steel Backed Timber Guardrail - Phase I: Conceptual Design”, National Crash Analysis Center, The George Washington University, Final Report, February 2008 (Submitted to FHWA)

D. Marzougui, E. Arispe, C.D. Kan, and M. Hargrave, “Crash Testing of a Retrofit Cable Barrier Placed on 6H:1V sloped, V-shaped, Median at a 4 ft Offset”, National Crash Analysis Center, The George Washington University, NCAC Report 2007-R-006, December 2007 (Submitted to FHWA)

D. Marzougui, E. Arispe, P. Mohan, and C.D. Kan, “Crash Testing and Evaluation of the DOS Anti-Ram Surface Planter Barrier at the K12 Impact Condition”, National Crash Analysis Center, The George Washington University, NCAC Report 2007-R-002, June 2007. (Submitted to FHWA and DOS)

D. Marzougui, E. Arispe, P. Mohan, and C.D. Kan, “Crash Testing and Evaluation of the DOS Anti-Ram Surface Planter Barrier at the K4 Impact Condition”, National Crash Analysis Center, The George Washington University, NCAC Report 2007-R-001, June 2007. (Submitted to FHWA and DOS)

D. Marzougui, M. Buyuk, and C.D. Kan, “Performance Evaluation of Roadside Portable Concrete Barriers”, National Crash Analysis Center, The George Washington University, NCAC Report 2007-R-004, Jan. 2007. (submitted to FHWA)

D. Marzougui, P. Mohan, and C.D. Kan, “Evaluation of Rail Height Effects on the Safety Performance of W-Beam Barriers”, National Crash Analysis Center, The George Washington University, NCAC Report 2007-R-003, Nov. 2007. (http://www.ncac.gwu.edu/research/infrastructure.html)

D. Marzougui, P. Mohan, U. Mahadevaiah, and C.D. Kan, “Performance Evaluation of Low-Tension, Three-Strand Cable Median Barriers on Sloped Terrains”, National Crash Analysis Center, The George Washington University, NCAC Report 2007-R-006, April 2007. (submitted to FHWA)

P. Mohan, D. Marzougui, and C.D. Kan, “Finite Element Simulations to Evaluate and Improve Anti-Ram Cable Fence”, National Crash Analysis Center, The George Washington University, Final Report, Jan. 2006. (Submitted to FHWA and USSS)

D. Marzougui, P. Mohan, U. Mahadevaiah, C.D. Kan, “Design and Evaluation of the DOS Anti-Ram Removable Bollard Using Finite Element Anlysis”, National Crash Analysis Center, The George Washington University, NCAC Report 2006-R-002, Jan. 2006. (Submitted to FHWA and US Department of State)

P. Mohan, D. Marzougui, A. Zaouk, N. Bedewi, “Crash Testing and Evaluation of the Anti-Ram 1-Meter Wall with a Single Unit Truck”, National Crash Analysis Center, The George Washington University, NCAC 2006-R-001, March 2006. (Submitted to FHWA and DOS)

P. Mohan, Marzougui D., “Crash Testing and Evaluation of the DOS Anti-Ram Removable Bollard with a Single Unit Truck”, National Crash Analysis Center, The George Washington University, NCAC Report 2005-R-001, Oct. 2005 (Submitted to FHWA and DOS)

P. Mohan, Marzougui D., “Crash Testing and Evaluation of the Pennsylvania Avenue Cable Fence with a Single Unit Truck”, National Crash Analysis Center, The George Washington University, Final Report, July 2005. (Submitted to FHWA and USSS)

P. Mohan, Marzougui D., U. Mahadevaiah, and C.D. Kan, "Finite Element Simulations to Evaluate and Improve Perimeter Security Systems", National Crash Analysis Center, The George Washington University, Final Report, Washington DC, June 2005. (Submitted to Federal Reserve Board)

## Conference Papers

Marzougui D., Opiela K.S., Kan C.D., "Analyses of Vehicle Trajectories when Leaving the Traveled Way on Curved, Superelevated Road Sections", Transportation Research Board Annual Meeting, Washington, D.C., January 2015.

Marzougui D., Opiela K.S., Kan C.D., "Analysis of Sensitivity of Bridge Rail Face Slope on Crashworthiness Performance", Transportation Research Board Annual Meeting, Washington, D.C., January 2015.

Marzougui D., Kan C.D., Opiela K.S., "Crash Test & Simulation Comparisons of a Pickup Truck & a Small Car Oblique Impacts Into a Concrete Barrier", 13$^{th}$ International LS-DYNA Users Conference, Detroit, MI, June 2014.

Marzougui D., Kan C.D., Opiela K.S., "Assessing Options for Improving Roadside Barrier Crashworthiness", 13$^{th}$ International LS-DYNA Users Conference, Detroit, MI, June 2014

Marzougui D., Brown, D., Park C.K., Kan C.D., Opiela K.S., "Development & Validation of a Finite Element Model for a Mid-Sized Passenger Sedan", 13$^{th}$ International LS-DYNA Users Conference, Detroit, MI, June 2014.

Reichert R., Kan C.D., Marzougui D., Mahadevaiah U., Morgan R., Park C.K., Tahan F., "Methodologies and Examples for Efficient Short and Long Duration Integrated Occupant-Vehicle Crash Simulation", 13$^{th}$ International LS-DYNA Users Conference, Detroit, MI, June 2014

Cohen, S., Marzougui, D., Kan, C., and Tahan, F., "Design and Evaluation of a Guided Dynamic Rollover Test Device," SAE Technical Paper 2014-01-0540, 2014, doi:10.4271/2014-01-0540, March 2014.

Marzougui, D.; Kan, C.D.; Samaha, R.; Cui, C.; Nix, L. Extended Validation of the Finite Element Model for the 2007 Chevrolet Silverado Pick-Up Truck (MASH 2270kg Vehicle). Transportation Research Board 92nd Annual Meeting, Transportation Research Board, 2013.

Marzougui, D.; Samaha, .; Nix, L.; Kan, C.D., Extended Validation of the Finite Element Model for the 2010 Toyota Yaris Passenger Sedan (MASH 1100kg Vehicle). Transportation Research Board 92nd Annual Meeting, Transportation Research Board, 2013.

Morgan, R.; Cui, C.; Marzougui, D.; Digges, K.; Cao, L.; Kan, C.D., Frontal Pole Impacts. IRCOBI Conference Proceedings, IRCOBI (International Research Council on the Biomechanics of Injury), pp 155-165, 2012

Marzougui D., Kan C.D., and Opiela K.S., "Slope Rounding Influences on the Trajectories of Vehicles", Transportation Research Board Annual Meeting, Washington, D.C., January 2012.

Marzougui D., Kan C.D., and Opiela K.S., "Comparison of the Crash Test and Simulation of an Angle Impact of a 2007 Chevrolet Silverado Pick-Up Truck into a New Jersey-Shaped Concrete Barrier for MASH Conditions", Transportation Research Board Annual Meeting, Washington, D.C., January 2012.

Marzougui D., Kan C.D., and Opiela K.S., "Safety Performance Evaluation of Concrete Barriers on Curved and Superelevated Roads", Transportation Research Board Annual Meeting, Washington, D.C., January 2012.

Marzougui D., Kan C.D., and Opiela K.S., “Analyzing the Potential Interface Effectiveness for Cable Barriers in Elevated Median Cross Sections”, Transportation Research Board Annual Meeting, Washington, D.C., January 2012.

Marzougui D., Kan C.D., and Opiela K.S., “Vehicle Dynamics Investigations to Develop Guidelines for Crash Testing Cable Barriers on Sloped Surfaces”, Transportation Research Board Annual Meeting, Washington, D.C., January 2011.

Sahraei E., Marzougui D., Digges K., and Kan C.D., “Effect of Increase in Weight and Stiffness of Vehicles on the Safety of Rear Seat Occupants”, International Crashworthiness Conference, Washington DC, September 2010.

Mohan P., Ritter M., Marzougui D., Brown D., Kan C.D., and Opiela K.S., “Modeling, Testing, and Validation of the 2007 Chevy Silverado Finite Element Model”, International Crashworthiness Conference, Washington DC, September 2010.

Sahraei E., Digges K., and Marzougui D., “Reduced Protection for Belted Occupants in Rear Seats Relative to Front Seats of New Model Year Vehicles”, Annals of Advances in Automotive Medicine, Vol. 54, pp 149-158, 2010.

Marzougui D., Kan C.D., Opiela K., and McGinnis R.G., “Effects of End-Anchor Spacing and Initial Tension on Cable Barrier Deflection”, Transportation Research Board 89th Annual Meeting, Washington, D.C., January 2010.

Mohan P., Ritter M., Marzougui D., Brown D., Kan C.D., and Opiela K. “Modeling, Testing, and Validation of 2007 Chevy Silverado Finite Element Model”, Transportation Research Board 89th Annual Meeting, Washington, D.C., January 2010.

Mohan P., Park C.K., Marzougui D., Kan C.D., Guha S., Maurath C., and Bhalsod D., “LSTC/NCAC Dummy Model Development”, 11th International LS-DYNA Users Conference, Detroit, MI, June 2010.

Maurath C., Guha S., Bhalsod D., Burger M., Krebs J., Stahlschmidt S., D'Souza R., Mohan P., and Marzougui D., “Overview of LSTC’s LS-DYNA Anthropomorphic Models”, 11th International LS-DYNA Users Conference, Detroit, MI, June 2010.

Esfahani, E., Marzougui, D., and Opiela K., Society of Automotive Engineers World Congress, Paper Number 09B-0309, Detroit, April 2009.

Mohan, P., Marzougui, D., Kan, C.D., and Opiela, K., “Component and Full Scale Tests for Suspension Model Validation”, 2nd Annual ASME Dynamic Systems and Control Conference, Paper Number 2636, Hollywood, California, Oct 2009.

Mohan, P., Marzougui, D., and Kan, C.D., “Development and Validation oh Hybrid III Crash Test Dummy”, Society of Automotive Engineers World Congress, Paper Number 2009-01-0473, Detroit, April 2009.

Fesich, T., Mohan, P., Marzougui D., and Kan, C.D., “A Study of the Gurson Damage Model and Numerical Simulation of Ductile Failure”, 7th German LS-DYNA Users Conference, Bamberg, Germany, October 2008.

Buyuk M., Marzougui D., Kan C.D., “Safety Performance Evaluation of Portable Concrete Barriers with Different Design Combinations by Using Modular Finite Element Modeling Approach”, International Crashworthiness Conference, Kyoto, Japan, 22-25 July 2008.

Buyuk M., Kurtaran H., Marzougui D., Kan C.D., "A Multi-Objective Discrete Design Optimization Algorithm for Portable Concrete Barriers by Coupling Grey Relational Analysis with Successive Taguchi Method", TRB 87th Annual Meeting, Washington, D.C., 13-17 January 2008.

Marzougui D., Buyuk M., Kan C.D., Opiela K., "Safety Performance Evaluation of Portable Concrete Barriers", TRB 87th Annual Meeting, Washington, D.C., 13-17 January 2008.

Buyuk M., Kurtaran H., Marzougui D., Kan C.D.," Automated Design of Threats and Shields Under Hypervelocity Impacts by Using Successive Approximate Optimization Methodology", Hypervelocity Impact Symposium, Williamsburg, Virginia, 23-27 September 2007.

Marzougui, D., Mohan P., Kan C.D, and Opiela K, "Evaluation of Rail Height Effects on the Safety Performance of W-Beam Barriers", 6th European LS-DYNA Users' Conference, Gothenburg, Sweden, May 2007.

Buyuk, M., Marzougui, D., Kan. S., "On the V&V Procedures of Fullscale Vehicle Crashworthiness and Roadside Hardware Performance Evaluation Simulations", 9th U.S. National Congress on Computational Mechanics, San Francisco, CA, 23-26 July 2007.

Mohan P., Marzougui, D., and Kan C.D., "Modified Approach to Accurately Measure Height of Force (HOF)", Society of Automotive Engineering World Congress, Detroit, MI, April 2007

Marzougui, D., Mohan P., and Kan C.D, and Opiela K, "Performance Evaluation of Low-Tension Three-Strand Cable Median Barriers ", Transportation Research Board Annual Meeting, Washington DC, 2007.

Bhargava A., Roddis K., Mohan P., and Marzougui D., "Analysis of Extended End-Plate Connections Under Cyclic Loading Using the LS-DYNA Implicit Solver", 9th International LS-DYNA Users Conference, Detroit, June 2006.

Buyuk M., Kurtaran H., Kan C.D., Marzougui D., "Approximate Optimization Method as an Efficient Design Methodology for Armors under Ballistic Impacts", 1st AIAA Multidisciplinary Design Optimization Specialist Conference, Austin, Texas, 18-21 Apr 2005.

Durmus A., Buyuk M., Musayev E., Ulku S., Kan C.D., Marzougui D., "Determination of the Ballistic Performance of a Cold-Rolled, Deep-Drawing Sheet Metal", 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, Austin, Texas, 18-21 Apr 2005.

Buyuk M., Kildare S., Kan C.D., Marzougui D., "Moving Beyond the Finite Elements: A Comparison between Finite Element Methods and Meshless Methods for Modeling Honeycomb Materials and Simulating Side Impact Moving Deformable Barriers (MDBs)", 5th European LS-DYNA Users Conference, Birmingham, UK, 25-26 May 2005.

Buyuk M., Kildare S., Kan C.D., Marzougui D., Kurtaran H."A Successive Inverse Approach to Identify the Constitutive Model Parameters and Mesh - Grid Dependency for Crashworthiness Modeling of Aluminum Honeycombs and Moving Deformable Barriers (MDBs)", 5th European LS-DYNA Users Conference, Birmingham, UK, 25-26 May 2005.

Buyuk M., Kan C.D., and Marzougui D., "Moving Beyond the Finite Elements: Applications of Meshfree Methods for Transportation Safety Problems", 8th U.S. National Congress on Computational Mechanics, Austin, Texas, 25-27 July 2005.

Buyuk M., Kan C.D., Marzougui D., "Vulnerability-Survivability and Lethality Assessment of Vehicles and Occupants under Blast Loading", 8th U.S. National Congress on Computational Mechanics, Austin, Texas, 25-27 July 2005.

## Technical Presentations

“Performance of Longitudinal Barriers on Curved, Superelevated Roadway Sections (CSRS) NCHRP Project 22-29”, ASHTOO TF13/TCRS Meeting, Shepherdstown, WV, September 2014.

“Toyota Yaris FE Model Development and Validations”, AFB20 Committee Meeting, Transportation Research Board Annual Meeting, AFB-20 Computational Mechanics sub-Committee Meeting, Washington, DC, January 2012.

“Assessment of Vehicle Dynamics on Sloped Medians for New MASH Cable Barrier Testing ASHTOO TF13/TCRS Meeting, Kansas City, MO, September 2010.

“NCHRP 22-25: Development of Guidance for the Selection, Use, and Maintenance of Cable Barrier Systems”, ASHTOO TF13/TCRS Meeting, Kansas City, MO, September 2010.

“Safety Performance Evaluations of Roadside Hardware Using Finite Element Simulations”, MODSIM World 2009 Conference and Expo, Virginia Beach, VA, October 2009.

“Infrastructure Security Evaluations through Computer Simulations”, MODSIM World 2009 Conference and Expo, Virginia Beach, VA, October 2009.

“Silverado Model Validations using Roadside Hardware Crash Tests”, AFB20 Committee Meeting, Transportation Research Board Annual Meeting, AFB-20 Computational Mechanics Sub-Committee Meeting, Washington, DC, January 2010.

“Development of a New End-Treatment for a Steel-Backed Timber Guardrail”, Transportation Research Board Annual Meeting, AFB-20 Winter Meeting, Washington, DC, January 2010.

“Development of Guidance for the Selection, Use, and Maintenance of Cable Barrier Systems”, Transportation Research Board AFB-20 Committee Mid-Year Meeting, Yountville, CA, June 2010.

“Development of Guidance for the Selection, Use, and Maintenance of Cable Barrier Systems”, AASHTO Task Force 13 Meeting, Yountville, CA, June 2010.

“Comparison of Silverado Crash Test and Simulation Results”, Transportation Research Broad AFB-20 Committee Summer Meeting, San Antonio, TX, June, 2009.

“Testing of Cable Barrier in Medians and on 4:1 Slopes”, Transportation Research Broad AFB-20 Committee Summer Meeting, San Antonio, TX, June, 2009.

“Analyzing the Effects of Cable Barriers Behind Curbs”, Transportation Research Broad AFB-20 Committee Summer Meeting, Jackson, WY, June, 2008.

“Effects of End-anchor Spacing and Initial Tension on Cable Barrier Deflection”, Transportation Research Broad AFB-20 Committee, Summer Meeting, Jackson, WY, June, 2008.

“Optimizing Design of Portable Concrete Barriers”, Transportation Research Broad AFB-20 Committee Summer Meeting, Jackson, WY, June, 2008.
“Cable Barrier Research Efforts at NCAC”, AASHTO TIG Meeting, Raleigh, NC, June 2008.

“Effects of End-anchor Spacing and Initial Tension on Cable Barrier Deflection”, AASHTO Task Force 13 Meeting, Hershey, Pennsylvania, May, 2008.

“Evaluation of Existing Hardware Relative to the Proposed Update of NCHRP Report 350 Using Crash Simulation”, AFB20 Committee Meeting, Transportation Research Board Annual Meeting, Washington, DC, January 2008.

“Development of a New End Treatment for Steel-Backed Timber Guardrails”, AFB20 Committee Meeting, Transportation Research Board Annual Meeting, Washington, DC, January 2008.

“Update on Cable Median Barrier Design and Placement”, AFB20 Committee Meeting, Transportation Research Board Annual Meeting, Washington, DC, January 2008.

“Open Source Models of Digitized Crash Test Dummies”, Society of Automotive Engineering Government/ Industry Meeting, Washington DC, May 2007.

"Cable Barriers Safety Performance Using Computer Simulations, PHASE II", Transportation Research Board Summer Meeting, AFB20 Committee Meeting, Jackson CA, July 2006.

**Personal History**
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**Plymouth, Michigan 48170**
**Phone: 734 404 5217 or 734 414 8243**

*Member: National Academy of Engineering*
*Fellow: Society of Automotive Engineers*
*Fellow: American Institute for Medical and Biological Engineering*

## EDUCATION

| | | |
|---|---|---|
| June, 1973 | Ph.D Bio-Mechanics | Wayne State University |
| June, 1968 | M.S. Mechanical Engineering | Wayne State University |
| June, 1965 | B.S. Mechanical Engineering | Bihar College of Engineering |

## AWARDS & RECOGNITION

National Highway Traffic Safety Administration (NHTSA) **Engineering Excellence Award for Safety**- 1991 and 2009.

US Department of Transportation **National Award for the Advancement of Motor Vehicle Research and Development**, 1994.

**Henry Ford Technology Award** (Side Impact CAE and Bolsters): 1990, 1995.

**Bertil Aldman Award** from the International Research Committee on the Biomechanics of Impact (IRCOBI), 1999.

**John Paul Stapp Award** for the best paper in the 2003 Stapp Car Crash Conference.

**SAE Ralph H. Isbrandt Automotive Safety Engineering Award** – 2005.

**Distinguished Engineering Alumni Award from Wayne State University**- 2005.

**Award of Merit** from the Association for the Advancement of Automotive Medicine- 2006.

**The Path Finder Award from the Automotive Occupant Restraints Council**- 2010.

**IIHS Top Safety Pick Award**- 2010.

**Arnold W. Siegel Transportation Safety Award, SAE**- 2011.

**Soichiro Honda Medal Presented by the American Society of Mechanical Engineers**, 2012.

## LEADERSHIP POSITIONS ON NATIONAL AND INTERNATIONAL FORUMS

- Advised governments such as Canada, Australia and U.S. on the development of relevant crash regulations. **I was also instrumental in the 1998 modification of FMVSS208, which succeeded in** minimizing **unintended side effects of first generation airbags.**

- Past Chairman/Member Biomechanics and Crashworthiness Sub-Committee of the Motor Vehicle Safety Research Advisory Committee of NHTSA
- Chairman of the ISO Working Group 3 (development of test procedures to evaluate the effect of airbag deployments on out-of-position occupants in frontal and side impacts) 1990-2000. The test procedures were incorporated in the FMVSS208 in US and the TWG for side impact test procedures by all manufacturers selling products in the US.
- Chairman of a Technical Working Group established by a consortium of Domestic and International Automotive Manufacturers charged by the Administrator of NHTSA to develop an Industry wide agreement to improvecompatibility between light trucks and cars in US. I successfully developed such an agreement which has been in place since 2005.
- Leader of the U.S. delegation to the International Standards Organization working group charged with developing scientifically-based injury criteria for various body regions that could be used to evaluate vehicular crash worthiness. (1987-1999)

## EXPERIENCE AND MAJOR CONTRIBUTIONS

### Prasad Consulting, LLC: 8/1/2008 to present

Consultant to universities, e.g. George Washington and Wayne State Universities on safety related projects and graduate student committees. Frequently consulted by the automotive OEM's and Consortia on current and future safety trends and issues. Involved in conducting and directing safety research, currently for the Alliance of Automobile Manufacturers.

Provide court testimonies as an expert or fact witness in product defense cases for OEM's and suppliers. Have defended OEM's and suppliers in patent infringement cases.

### Ford Motor Company: 1973 to 7/31/2008

I have worked in various areas of the Company since joining Ford Motor Company in 1973 and conducted basic and applied safety research in the following areas:

- **impact responses** of the skull/brain, cervical/thoracic/lumbar spine, chest and extremities (arm and lower leg and the pelvis)
- **impact tolerance** of the human body
- **application of biomechanical principles in vehicle designs** (vehicle structure designs and restraint systems) to improve real world safety.

I also pioneered the development and application of modeling techniques for:

- human surrogates
- vehicle structures in various impact modes
- restraint systems (i.e., seatbelts, frontal airbags, side airbags and side curtains)

As a Technical Fellow in Automotive Safety (1995 – 2008), I reported directly to the Chief Technical Officer of the Company and the Vice-President of Research and Advanced Engineering. I was responsible for directing the research, development and implementation of active and passive safety technologies worldwide.

My contributions in safety research have been recognized by the U.S. Secretary of Transportation (1994), by NHTSA (1990) and by Europe (I.R.C.O.B.I.) in 1999. I have advised various governments around the world in establishing relevant regulations and research programs which enhance real world safety. I have led working groups and participated in committees of professional organizations such as SAE, International Standards Organization (ISO) and the International Harmonization Research Activity.

Some of my contributions in specific areas are listed below:

- **Biomechanics:**
    - Development of responses and injury criteria for 3-year old child surrogates in airbag testing. This research formed the basis of U.S. regulations (FMVSS208) for neck injury criteria (Nij).
    - Developed an injury risk function (Prasad and Mertz curves) associating Head Injury Criteria (HIC) with risk of skull fracture and serious brain injuries. These HIC functions are now used in regulations worldwide and the injury risk function is used to evaluate effectiveness of restraint systems in the real world.
    - Developed neck injury risk functions for various sized ATD's which are used by NHTSA in current regulations.
    - Developed injury risk functions which associated measured chest deflections of various sized ATD's with real world chest injuries in frontal crashes.
    - Developed Injury risk functions and criteria for tibial injuries in frontal crashes.
    - Developed ankle injury criteria.
    - Developed response and injury criteria for the lumbar spine shear in the A-P and lateral modes.
- **CAE Modeling:**
    - Developed non-linear whole body finite element models of the skull/brain, chest, abdomen, pelvis, femur and the tibia/fibula.
    - Developed lumped mass and finite element models of vehicle structures in frontal and side impact.
    - Developed multi-link and finite element models of various frontal and side impact crash test dummies.
    - Developed vehicle structural rate effects for use in vehicle crash models.
    - Developed models of air bags.
- **Safety Regulations:**
    - Led the analysis of the side effects of unbelted FMVSS208 regulation in U.S.A., and established the need to change the regulation to allow "depowered" airbags.
    - Responsible for Ford's corporate responses to various rulemaking activities worldwide. The current FMVSS208 regulations are based on biomechanical research conducted under my direction.

- **Restraint Systems and Vehicle Design:**
  - Developed performance guidelines for frontal and side air bags and curtains to further improve protection of in-position occupants and reduce injuries to out-of-position occupants.
  - Developed system design guidelines for vehicle structures designed to enhance occupant protection in frontal, side and rear impacts.
  - Developed structural design guidelines to enhance compatibility between heavy and light weight vehicles involved in crashes.
- **Publications and Patents**
  - Published more than one hundred and thirty technical papers (see attached lists) covering various areas of biomechanics and automotive safety. The majority of these papers are in peer reviewed technical journals and conference proceedings and transactions of the SAE.
  - Eight patents awarded covering side impact restraint, external airbags and accident avoidance technologies.
- **Vehicle Platform Designs**

  Led the pre-program efforts for most Ford cars between 1984 to 1999. The pre-programs entailed selecting the best architecture to satisfy existing and near-future crash requirements (both internal and governmental), NVH and Durability. All trade-offs were conducted in Program Steering Teams (PST). I was the leader of the Safety PST for many platforms that were brought into production and achieved high safety ratings in IIHS and NCAP. Some of the high volume platforms included Contour/Mystique, Probes, Escorts, Festiva, Mid-90's Taurus, Lincoln LS/Jaguar S-Type, 2000 Taurus, Ford 500/Freestyle, Lincoln MKZ, MKS, MKX. The Ford 500/Freestyle achieved Quadruple 5* in USNCAP and Best Safety Pick from IIHS. The derivatives from this platform continue even today and have garnered many safety accolades.
- **Safety Design Guidelines**

  Developed enablers for achieving high ratings and real world safety, Safety Design Guidelines for most components of cars and trucks, e.g. steering control system, intrusion into cabs, crash pulse, seat designs, bumpers, interior trims, etc. All Ford Motor Company cars and trucks sold worldwide had to meet these Safety Design Guidelines.

## <u>WSU Department of Biomechanics: 1966 – 1973</u>

- Developed an experimentally verified a 2-D model of the human spine, head and pelvis subjected to +Gz and + Gx accelerations
- Discovered a dual-load path in the spine and the role of articular facets in +Gz acceleration
- Developed and experimentally verified hyperextension devices to substantially increase human tolerance to impact in the vertical direction.
- Predicted and experimentally verified the existence of compressive forces in the spine restrained by military harness systems in purely frontal accelerations. The phenomenon of the straightening of the thoracic spine was predicted by the 2-D model, and later verified by experiments.
- Evaluated the ability of the severity index for predicting head injuries

- Identified the need for biofidelic head forms for testing of helmets
- Developed specialized load cells for measuring in-vivo axial loads developed in the lumbar spine during +Gz acceleration.

## PUBLICATIONS BY TOPICAL AREAS

### Biomechanics of Head Impact:

V.R. Hodgson, L.M. Thomas and P. Prasad: Testing the Validity and Limitations of the Severity Index. Proc. of the 14th Stapp Car Crash Conference, 1970.

P. Prasad and R.P. Daniel: A Biomechanical Analysis of Head, Neck and Torso Injuries to Child Surrogates Due to Sudden Torso Acceleration. Proc. of the 28th Stapp Car Crash Conference, 1984.

P. Prasad and H.S. Mertz: The position of the U.S. Delegation to ISO Working Group 6 on the Use if HIC in the Automotive Environment, SAE Paper No. 851246, 1985

P. Prasad, J.W. Melvin, D.E. Huekle, A.I. King and G.W. Nyquist: Head-Review of Biomechanical Impact Response and Injury in the Automotive Environment. UMTRI Ed. Melvin and Weber, 1985.

J. Ruan and P. Prasad: Head Injury Potential Assessment in Frontal Impact by Mathematical Modeling. Proc. of 38th Stapp Car Crash Conference, SAE Paper No. 942212, 1994.

J. Ruan and P. Prasad: Coupling of a Finite Element Human Head Model with a Lumped Parameter Hybrid III Dummy Model – Preliminary Results, Journal of Neurotrauma, Vol. 12, November 4, 1995.

H.J. Mertz, G. Nusholtz and P. Prasad: Head Injury Risk Assessment for Forehead Impacts. SAE Paper No. 960099, International Congress, March 1996.

J.S. Ruan and P. Prasad: Biomechanical Study of Head Injury through Finite Element Analysis. Invited chapter in Frontiers in Head and Neck Trauma – Clinical and Biomechanical, Editors: N. Yoganandan and F.A. Pintar, in print, 1998.

J. Ruan, P. Prasad: The Effects of Skull Thickness Variations on Human Head Dynamic Impact Responses. 45th Stapp Car Crash Journal, 2001.

J. S. Ruan and P. Prasad: The Influence of Human Head Tissue Properties on Intracranial Pressure Response During Direct Head Impact, Intl. Journal of Vehicle Safety, 1(4):282-291.

### Biomechanics of the Neck:

P. Prasad, A. Kim, D.P.V. Weerappuli: Biofidelity of Anthropomorphic Test Devices for Rear Impact, Proc. of 41st Stapp Crash Conference, SAE Paper No. 973342, 1997.

P. Prasad, A. Kim, D.P.V. Weerappuli, V. Roberts and D. Schneider: Relationships Between Passenger Car Seat Back Strength and Occupant Injury Severity in Rear End Collisions: Field and Laboratory Studies, Proc. of 41st Stapp Car Crash Conference, SAE Paper No. 973343, 1997.

F. Heitzplatz, R. Sferco, P. Fay, J. Rheim, A. Kim and P. Prasad: An Evaluation of Existing and Proposed Injury Criteria with Various Dummies to Determine Their Ability to Predict the Levels of STNI seen in Real Accidents, Proc. 18th ESV Conference, Nagoya, Japan, DOT HS809543, May 2003.

S. Sundararajan, P. Prasad, C.K. Demetropoulos, S. Tashman, P. C. Bergeman, K. H. Yanbg, A. I. King: Effect of Head- Neck Position on Cervical Facet Stretch of Post Mortem Human Subjects During Low Speed, Rear-End Impacts, 48th Stapp Car Crash Journal, 2004.

D. C. Viano, C. Parenteau, P. Prasad and R. Burnett: Stiff versus Yielding Seats: Analysis of Matched Rear Impact Tests, SAE Paper No. 2007-01-0708, International Congress, 2007.

**Spinal Biomechanics:**

C.L. Ewing, A.I. King and P. Prasad: Structural Considerations of the Human Vertebral Column Under +Gz Impact Acceleration. Journal of Aircraft, 1972.

A.I. King, P. Prasad and P.C. Begeman: Spinal Responses to Forward Deceleration. Proc. of the 3rd All-India Symposium on Biomedical Engineering, 1972.

P. Prasad: The Dynamic Response of the Spine During +Gz Acceleration. Ph.D. Dissertation, Wayne State University, Detroit, 1973.

P. Prasad, A.I. King and C.L. Ewing: The Role of Articular Facets during +Gz Acceleration. Journal of Applied Mechanics, 1974.

P. Prasad, A.I. King and C.L. Ewing: An Experimentally Validated Dynamic Model of the Spine. Journal of Applied Mechanics, 1974.

A.I. King, P. Prasad and C.L. Ewing: Mechanism of Spinal Injury Due to Caudocephalad Acceleration. Proc. of the Orthopedic Clinics of North America, 1975.

P. Prasad, N.K. Mital, A.I. King and L.M. Patrick: Dynamic Response of the Spine During +Gx Acceleration. Proc. of the 19th Stapp Car Crash Conference, 1975.

L.P. Nolte, H. Visarius, P.C. Begeman and P. Prasad: Isolated Viscoelastic Shear Properties of the Human Lumbar Spine in Direct Shear. The ASME BED-Vol. 24, June 25-29, 1993.

P.C. Begeman, H. Visarius, L.P. Nolte, P. Prasad: Viscoelastic Shear Responses of the Cadaver and Hybrid III Dummy. Proc. of 37th Stapp Car Crash Conference, 1994.

S. Sundararajan, P. Prasad, S. Rouhana, C. Demetropoulos, , K. Yang, A. King: Characteristics of PMHS Lumbar Motion Segments in Lateral Shear. 49th Stapp Car Crash Conference Journal, November, 2005

**Biomechanics of the Thorax:**

R. Kent, J. Bolton, J. Crandall, P. Prasad, G. Nusholtz, H. Mertz, D. Kallieris: Restrained Hybrid III Dummy-Based Criteria for Thoracic Hard Tissue Injury Prediction. SAE Paper No. 2001-13-0017. IRCOBI Conference, United Kingdom, 2001.

R. Kent, J. Crandall, J. Bolton, P. Prasad, G. Nusholtz, H. Mertz: The Influence of Superficial Soft Tissues and Restraint Condition on Thoracic Skeletal Injury Prediction. 45th Stapp Car Crash Journal, 2001.

T. Laituri, B. Kachnowski, P. Prasad, K. Sullivan, P. Przybylo: Predictions of AIS3+ Thoracic Risks for Belted Occupants in Full Engagement, Real-World Frontal Impacts: Sensitivity to Various Theoretical Risk Curves. SAE Paper No. 2003-01-1355. World Congress, 2003.

T. Laituri, D. Sullivan, K. Sullivan, P. Prasad:  A Theoretical Math Model for Projecting AIS3+ Thoracic Injury for Belted Occupants in frontal Impacts. 48th Stapp Car Crash Conference, Journal, Nov.2004.

T. Laituri, P. Prasad, K. Sullivan, M. Frankstein, R. Thomas:  Derivation and Evaluation of a Provisional, Age-Dependent, AIS3+ Thoracic Risk Curve for Belted Occupants in Frontal Impacts, SAE 2005-01-0297. April, 2005.

J. Ruan, R. El-Jawahri, L. Chai, S. Barbat, P. Prasad:  Prediction and Analysis of Human Thoracic Impact Reponses and Injuries in Cadaver Impacts Using a Full Human Body Finite Element Model. 47th Stapp Car Crash Journal, 2003.

P. Prasad, T. Laituri, K. Sullivan:  Estimation of AIS3+ Thoracic Injury Risks of Belted Drivers in NASS Frontal Crashes, Journal of Automobile Engineering, 2004. Vol. 218, No. D6. IMechE, United Kingdom.

J. Forman, D. Lessley, C. G. Shaw, J. Evans, R. Kent, S. W. Rouhana, P. Prasad: Thoracic Response of Belted PMHS, Hybrid III, and the THOR-NT Mid-Sized Male Surrogates in Low Speed, Frontal Crashes, 50th Stapp Car Crash Conference Journal, November, 2006.

**Abdominal Biomechanics:**

J. Ruan, R. El-Jawahri, S. Barbat, P. Prasad:  Biomechanical Analysis of Human Abdominal Impact Responses and Injuries through Finite Element simulations of a Full Human Body Model. 49th Stapp Car Crash Conference Journal, November, 2005.

J. Ruan, R. El-Jawahri, S. W. Rouhana, S. D. Barbat and P. Prasad: Analysis and Evaluation of the Biofidelity of the Human Body Finite Element Model in Lateral Impact Simulations According to ISO-TR9790 Procedures, 50th Stapp Car Crash Conference Journal, 2006.

**Extremity Biomechanics:**

P.C. Begeman and P. Prasad:  Human Ankle Impact Response in Dorsiflexion. Proc. of the 34th Stapp Conference, 1990.

N. Yoganandan, F. Pintar, M. Boynton, P. Begeman, P. Prasad, S.M. Kuppa, R.M. Morgan and R.H Eppinger:  Dynamic Axial Tolerance of the Human Foot-Ankle Complex. Proc. of 40th Stapp Car Crash Conference SAE Paper No. 962426, 1996.

A. Manoli, R.S. Levine and P. Prasad:  Foot and Ankle Severity Scale, International Journal of the Foot and Ankle Society, 1998.

A. Jibril, P. Prasad, J. Prybylski, I. Parekh, E. S. Grush:  Logistic Regression Analysis of Lower Limb Injuries in Frontal Crashes. 16th International Technical Conference on Experimental Safety Vehicles. Report No. 98-S6-W-43, 1998.

P. C. Begeman, K. Pratima, P. Prasad:  Bending Strength of the Human Cadaveric Forearm Due to Lateral Loads. 43rd Stapp Car Crash Conference. Report No. SAE 99SC24, 1999.

P. J. Schuster, C. C. Chou, P. Prasad, G. Jayaraman:  Development and Validation of a Pedestrian Lower Limb Non-Linear 3-D Finite Element Model. 44th Stapp Car Crash Conference. Paper No. 2000-01-SC21, 2000.

P. Beillas, P. Begeman, K. Yang, A. King, P-J Arnoux, H-S Kang, K. Kayvantash, C. Brunet, C. Cavallero, P. Prasad: Lower Limb: Advanced FE Model and New Experimental Data. 45th Stapp Car Crash Journal, 2001.

J. Ruan, R. El-Jawahri, S. Barbat, P. Prasad: Pelvic Impact Response and Injury Simulation using a Full Human Body Finite Element Model. Proceedings of NAFEMS World Congress. May, 2005

T. R. Laituri, S. Henry, K. Sullivan, P. Prasad: Derivation and Theoretical Assessment of a Set of Biomechanics-based, AIS2+ Risk Equations for the Knee-Thigh-Hip Complex, 50th Stapp Car Crash Conference Journal, November 2006.

J. S. Ruan, R. El-Jawahri, S. D. Barbat, S. W. Rouhana and P. Prasad: Impact Response and Biomechanical Analysis of the Knee-Thigh-Hip Complex in Frontal Impacts With a Full Human Body Finite Element Model, 52nd Stapp Car Crash Conference Journal, 2008.

**Injury Risk Assessment:**

H.J. Mertz, P. Prasad and A. Irwin: Injury Risk Curves for Children and Adults in Frontal and Rear Collisions, 41st Stapp Car Crash Conference, SAE Paper No. 973318 November, 1997.

H. J. Mertz, P. Prasad: Improved Neck Injury Risk Curves for Tension and Extension Moment Measurements of Crash Dummies. Proc. of the 44th Stapp Car Crash Conference. Paper No. 2000-01-SC05, 2000.

H Mertz, A. Irwin, P. Prasad: Biomechanical and Scaling Bases for Frontal and Side Impact Injury Assessment Reference Values. 47th Stapp Car Crash Journal, 2003.

T. Laituri, B. Kachnowski, P. Prasad, K. Sullivan, P. Przybylo: A Theoretical, Risk Assessment Procedure for In-Position Drivers Involved in Full-Engagement Frontal Impacts. SAE Paper No. 2003-01-1354. World Congress, 2003.

L. Wang, R. Banglmaier, P. Prasad: Injury Risk Assessment of Several Crash Data Sets. SAE Paper No. 2003-01-1214. World Congress, 2003.

Dalmotas D.J., P. Prasad, J. S. Augenstein and K. Digges: Assessing the Field Relevance of Testing Protocols and Injury Risk Functions Employed in New Car Assessment Programs, Proc. of the ESAR Conference, Hannover, Germany, 2010.

P. Prasad, H. J. Mertz, D. J. Dalmotas, K. Digges and J. S. Augenstein: Evaluation of the Field Relevance of Several Injury Risk Functions, 54th Stapp Car Crash Conference Journal, 2010

**Airbag and Advanced Restraints:**

P. Prasad, T. R. Laituri: Consideration for Belted FMVSS 208 Testing. The 15th International Technical Conference on Enhanced Safety of Vehicles, Paper No. 96-S3-O-03, 1996.

T. Laituri, N. Sriram, B. Kachnowski, Brian Scheidel, P. Prasad: Theoretical Evaluation of the Requirements of the 1999 Advanced Airbag SNPRM – Part One: Design Space Constraint Analysis, SAE Paper No. 2001-01-0165, International Congress, 2001.

S. Rouhana, P. Bedewi, S. Kankanala, P. Prasad, J. Zwolinski, A. Meduysky, J. Rupp, T. Jeffreys, L Schneider: Biomechanics of 4-Point Seat Belt Systems in Frontal Impacts. 47th Stapp Car Crash Journal, 2003.

S. W. Rouhana, S. V. Kankanala, P. Prasad, J. D. Rupp, T. A. Jeffreys, L. A. Schneider: Biomechanics of 4-point Seat Belt Systems in Farside Impacts, 50th Stapp Car Crash Conference Journal, 2006.

P. Prasad, L. W. Schneider and W. Hardy: Interactions of Out-of-Position Small-female Surrogates with a Depowered Driver Airbag, 52nd Stapp Car Crash Conference Journal, 2008.

Sundararajan, S., Rouhana, S.W., Board, D., DeSmet, E., Prasad, P., Rupp. J.D., Miller, C.S. and Schneider, L.S., Biomechanical Assessment of a Rear-Seat Inflatable Seat Belt, Stapp Car Crash Journal, Vol. 55, 2011.

Mertz, H.J., Prasad, P. and Dalmotas, D. Minimizing the Injury Potential of Deploying Airbag Interactions with Car Occupants, John Paul Stapp Memorial Lecture, Stapp Car Crash Journal, Vol. 57, Nov. 2013.

Rouhana, S.W., Sundararajan, S., Board, D., Prasad, P., Rupp, J.D., Miller, C.S. Jeffreys, T.A. and Schneider, L., Biomechanical Considerations for Assessing Interactions of Children and Small Occupants with Inflatable Seat Belts, Stapp Car Crash Journal, Vol. 57, Nov. 2013.

### Vehicle-to-Vehicle Compatibility:

S. Barbat, X. Li, P. Prasad: Evaluation of Vehicle Compatibility in Various Frontal Impact Configurations. SAE Paper No. 2001-06-0097. International Technical Conference on the Enhanced Safety of Vehicles, Amsterdam, The Netherlands, 2001.

S. Barbat, X. Li, P. Prasad: A Comparative Analysis of Vehicle-to-Vehicle and Vehicle-to-Rigid Fixed Barrier Frontal Impacts. SAE Paper No. 2001-06-0031. International Technical Conference on the Enhanced Safety of Vehicles, Amsterdam, The Netherlands, 2001.

S. D. Barbat, X. Li, P. Przybolo and P. Prasad: Vehicle-to-Vehicle Full Frontal Crash Optimization Using a CAE-Based Methodology, Proc. 18th ESV Conference, Nagoya, Japan. DOT HS809543, May 2003.

S. D. Barbat, X. Li and P. Prasad: Vehicle-to-Vehicle Front-to-Side Crash Analysis Using a CAE-based Methodology, Proc. 20th ESV Conference, Paper no. 07-0347, Lyon, France, June 2007.

S.D. Barbat, X. Li, S. Reagan and P. Prasad: Vehicle Compatibility Assessment Using Test Data of Full Frontal Vehicle-to-Vehicle and Vehicle-to-Full Width Deformable Barrier Impacts, Proc. 20th ESV Conference, paper no. 07-0348, Lyon, France, June 2007.

Barbat, S., Li, Xiaowei and Prasad, P., Bumper and Grille Airbags Concept for Improved Vehicle Compatibility in Side Impact: Phase I, Paper No. 13-0189-O, Enhanced Safety of Vehicles Conference, Seoul, Korea, 2013.

Barbat, S., Li, Xiaowei and Prasad, P., Bumper and Grille Airbags Concept for Improved Vehicle Compatibility in Side Impact: Phase II, Paper No. 13-0189-O, Enhanced Safety of Vehicles Conference, Seoul, Korea, 2013, also in the Traffic Injury Prevention Journal special issue, 2013.

### Vehicle Structure and ATD Modeling:

A.J. Padgaonkar and P. Prasad: Simulation of Side Impact Using the CAL3D Occupant Simulation Model. Proc. of the 23rd Stapp Car Crash Conference, 1979.

P. Prasad, A.J. Padgaonkar: Static-to-Dynamic Amplification Factors for Use in Lumped-Mass Vehicle Crash Models. SAE810475, International Congress, February, 1981.

A.J. Padgaonkar and P. Prasad: A Mathematical Analysis of Side Impact Using the CAL3D Simulation Model. Proc. of the 9th International ESV Conference, 1982.

T.C. Low and P. Prasad: Dynamic Response and Mathematical Model of the Side Impact Dummy. Proc. of 34th Stapp Car Crash Conference, 1990.

P. Prasad, T.C. Low, C.C. Chou, G.G. Lim and S. Sundararajan: Side Impact Modeling Using Quasi-Static Crush Data, SAE Paper, International Congress, 1991.

D.E. Midoun, D.M. Johnson, M.K. Rao and P. Prasad: Hybrid Modeling for Frontal Impact Into a Rigid Barrier. Proc. of International Body Engineering Conference, September 21-23, 1993. Detroit, MI.

S. Barbat and P. Prasad: Finite Element Modeling of Structural Foam and Head Impact Interaction with Vehicle Upper Interior, SAE 950885, International Congress, March 1995.

N.K. Saha, S.M. Calso, P. Prasad and M.U. Asjad: Simulation of Frontal Barrier Offset Impacts and Comparison of Intrusions and Decelerations. SAE 950647, International Congress, March, 1995.

S. D. Barbat, H.Y. Jeong and P. Prasad: Finite Element Modeling and Development of the Deformable Featureless Head form and Its Application to Vehicle Interior Head Impact Tests. SAE Paper No. 960104, International Congress, February 1996.

N. Saha, S. Calso, D. Midoun and P. Prasad: Critical Comparison of U.S. and European Dynamic Side Impacts, SAE Congress and Exposition, SAE Paper No. 970128, 1997.

L. Chai, T. Subbian, A. Khan, S. Barbat, C. O'Conner, R. McCoy, P, Prasad: Finite Element Model Development of SID-IIs. 43rd Stapp Car Crash Conference. Paper No. SAE 99SC06, 1999.

D. P. Weerappuli, L. Chai, S. Barbat, D. Wan, P. Prasad: Development of a MADYMO3D Model of the SID-IIs Dummy. ASME, 1999.

## CHRONOLOGICAL LIST OF PUBLICATIONS

1. V.R. Hodgson, L.M. Thomas and P. Prasad: Testing the Validity and Limitations of the Severity Index. Proc. of the 14th Stapp Car Crash Conference, 1970.

2. C.L. Ewing, A.I. King, P. Prasad and A.P. Vulcan: A Method for Increasing the Threshold Level for Vertebral Fracture Due to +Gz Impact Acceleration. Proc. Of the 9th International Conference on Medical and Biological Engineering, 1971.

3. P. Prasad, A.I. King and C.L. Ewing: The Role of the Articular Facets During +Gz Acceleration. Proc. of the 25th Conference on Engineering in Medicine and Biology, 1972.

4. A.I. King, P. Prasad and P.C. Begeman: Spinal Responses to Forward Deceleration. Proc. of the 3rd All-India Symposium on Biomedical Engineering, 1972.

5. C.L. Ewing, A.I. King and P. Prasad: Structural Considerations of the Human Vertebral Column Under +Gz Impact Acceleration. Journal of Aircraft, 1972.

6. P.C. Bergeman, A.I. King and P. Prasad: Spinal Loads Resulting from –Gx Acceleration. Proc. of the 10th International Conference on Medical and Biological Engineering, 1973.

7. P. Prasad: The Dynamic Response of the Spine During +Gz Acceleration. Ph.D. Dissertation, Wayne State University, Detroit, 1973.

8. P. Prasad, A.I. King, R.A. Denton and P.C. Begeman: Intervertebral Force Transducer. Proc. of the 10th International Conference on Medical and Biological Engineering, 1973.

9. P. Prasad, A.I. King and C.L. Ewing: The Role of Articular Facets during +Gz Acceleration. Journal of Applied Mechanics, 1974.

10. P. Prasad, A.I. King and C.L. Ewing: An Experimentally Validated Dynamic Model of the Spine. Journal of Applied Mechanics, 1974.

11. A.I. King, P. Prasad and C.L. Ewing: Mechanism of Spinal Injury Due to Caudocephalad Acceleration. Proc. of the Orthopedic Clinics of North America, 1975.

12. P. Prasad, N.K. Mital, A.I. King and L.M. Patrick: Dynamic Response of the Spine During +Gx Acceleration. Proc. of the 19th Stapp Car Crash Conference, 1975.

13. A.J. Padgaonkar and P. Prasad: Simulation of Side Impact Using the CAL3D Occupant Simulation Model. Proc. of the 23rd Stapp Car Crash Conference , 1979.

14. P. Prasad, A.J. Padgaonkar: Static-to-Dynamic Amplification Factors for Use in Lumped-Mass Vehicle Crash Models. SAE810475, International Congress, February, 1981.

15. A.J. Padgaonkar and P. Prasad: A Mathematical Analysis of Side Impact Using the CAL3D Simulation Model. Proc. of the 9th International ESV Conference, 1982.

16. R.P. Daniel, M.S. Koga, P. Prasad and C.D. Yost: A Force Measuring Mechanical Device for Estimating and Comparing the Energy Absorbing Characteristics of Vehicle Interior Side Panels. Proc. of the 9th International ESV Conference, 1982.

17. P. Prasad: An Overview of Major Occupant Simulation Models. SAE 840855, SP-146, 1984.

18. R.P. Daniel, P. Prasad and CD. Yost: A Biomechanical Evaluation of the Ford Side Impact Body Block and the SID/APR Side Impact Dummies. SAE 840882, International Congress, 1984.

19. P. Prasad and R.P. Daniel: A Biomechanical Analysis of Head, Neck and Torso Injuries to Child Surrogates Due to Sudden Torso Acceleration. Proc. of the 28th Stapp Car Crash Conference, 1984.

20. P. Prasad and H.S. Mertz: The position of the U.S. Delegation to ISO Working Group 6 on the Use if HIC in the Automotive Environment, SAE Paper No. 851246, 1985.

21. P. Prasad: Comparative Evaluation of the MVMA2D and the MADYMO2D Occupant Simulation Models with MADYMO Test Comparisons. Proc. of the 10th International Conference of the ESV, Oxford, U.K. 1985.

22. P. Prasad, J.W. Melvin, D.E. Huekle, A.I. King and G.W. Nyquist: Head-Review of Biomechanical Impact Response and Injury in the Automotive Environment. UMTRI Ed. Melvin and Weber, 1985.

23. P. Prasad and C.C. Chou: A Review of Mathematical Occupant Simulation Models. Proc. of the ASME Annual Conference, 1989.

24. P. Prasad: Comparative Evaluation of the Dynamic Responses of the Hybrid II and the Hybrid III Dummies. Proc. of the 34th Stapp Car Crash Conference. 1990.

25. T.C. Low and P. Prasad: Dynamic Response and Mathematical Model of the Side Impact Dummy. Proc. of 34th Stapp Car Crash Conference, 1990.

26. P.C. Begeman and P. Prasad: Human Ankle Impact Response in Dorsiflexion. Proc. of the 34th Stapp Conference, 1990.

27. P. Prasad, T.C. Low, C.C. Chou, G.G. Lim and S. Sundararajan: Side Impact Modeling Using Quasi-Static Crush Data, SAE Paper, International Congress, 1991.

28. T.C. Low, P. Prasad, G.G. Lim, C.C. Chou and S. Sundararajan: A MADYMO3D Side Impact Simulation Model. Proc. of the ASME Annual Conference, 1991.

29. L.P. Nolte, H. Visarius, P.C. Begeman and P. Prasad: Isolated Viscoelastic Shear Properties of the Human Lumbar Spine in Direct Shear. The ASME BED-Vol. 24, June 25-29, 1993.

30. L.P. Nolte, H. Visarius, P.C. Begeman and P. Prasad: Isolated Viscoelastic Shear Properties of the Human Lumbar Spine, Proc. of 3rd Injury Prevention Through Biomechanics Symposium, May 20-23, 1993. Sponsored by CDC, Wayne State University Press.

31. P. Prasad and C.C. Chou: A Review of Mathematical Occupant Simulation Models, Chapter 6, Accidental Injury – Biomechanics and Prevention. Edited by A.M. Nahum, A.M. and J.W. Melvin, Springer-Vertag, New York. 1993.

32. C. C. Chou, S. Neriya, T.C. Low and P. Prasad: MADYMO2D/3D Vehicle Structural/Occupant Simulation Models, AMD Volume 169/BED Volume 25, Crashworthiness and Occupant Protection in Transportation Systems, ASME 1993.

33. D.E. Midoun, D.M. Johnson, M.K. Rao and P. Prasad: Hybrid Modeling for Frontal Impact Into a Rigid Barrier. Proc. of International Body Engineering Conference, September 21-23, 1993. Detroit, MI.

34. J. Ruan and P. Prasad: Head Injury Potential Assessment in Frontal Impact by Mathematical Modeling. Proc. of 38th Stapp Car Crash Conference, SAE Paper No. 942212, 1994.

35. C. C. Chou, G G. Li, S. Sundararajan, T. C. Low, P. Prasad, J. O. Mitchell: Experimental Validation of Ellipsoid - To - Foam Contact Model, SAE Paper No. 9408881, SAE World Congress, 1994.

36. P.C. Begeman, H. Visarius, L.P. Nolte, P. Prasad: Viscoelastic Shear Responses of the Cadaver and Hybrid III Dummy. Proc. of 37th Stapp Car Crash Conference, 1994.

37. J. Ruan and P. Prasad: Coupling of a Finite Element Human Head Model with a Lumped Parameter Hybrid III Dummy Odel – Preliminary Results, Journal of Neurotrauma, Vol. 12, November 4, 1995.

38. P. Prasad and L. Smorgonsky: Comparative Evaluation of Various Frontal Impact Test Procedures, SAE 950646, International Congress, March 1995.

39. S. Barbat and P. Prasad: Finite Element Modeling of Structural Foam and Head Impact Interaction with Vehicle Upper Interior, SAE 950885, International Congress, March 1995.

40. N.K. Saha, S.M. Calso, P. Prasad and M.U. Asjad: Simulation of Frontal Barrier Offset Impacts and Comparison of Intrusions and Decelerations. SAE 950647, International Congress, March, 1995.

41. P. Krypton, U. Berleman, H. Vasarius, P.C. Begeman, L.P. Nolte and P. Prasad: Response of the Lumbar Spine Due to Shear Loading. Proc. of the 5th Injury Prevention Through Biomechanics Symposium, Sponsored by CDC, Wayne State University.

42. S. D. Barbat and P. Prasad: Numerical Simulations and Predictions of Spot-Weld/Weld-Bond Separation in Aluminum Closed-Hat Sections in Axial Collapse. Proc. Of the Crashworthiness and Occupant Protection in Transportation Systems. AMD-Vol. 210/BED-Vol. 30, San Francisco, CA, 1995.

43. J. S. Ruan and P. Prasad: Prediction of Skull and Brain Stress (Strain) Utilizing a Human Head Model, ASME/AICH/ASCE Summer Bioengineering Conference, Beaver Creek, Colorado, June 28-July 2, 1995.

44. S. H. Backaitis, M.E. Hicks, P. Prasad, T. Laituri and J. Nadeau: Variability of Hybrid III Clearance Dimensions with FMVSS 208 and NCAP Vehicle Test Fleet and the Effects of Clearance Dimensions on Dummy Impact Responses, Proc. of the 39th Stapp Car Crash Conference, San Diego, California, November 8-10, 1995.

45. P. Prasad, T. R. Laituri: Consideration for Belted FMVSS 208 Testing. The 15th International Technical Conference on Enhanced Safety of Vehicles, Paper No. 96-S3-O-03, 1996.

46. N. Yoganandan, F. Pintar, M. Boynton, P. Begeman, P. Prasad, S.M. Kuppa, R.M. Morgan and R.H Eppinger: Dynamic Axial Tolerance of the Human Foot-Ankle Complex. Proc. of 40th Stapp Car Crash Conference SAE Paper No. 962426, 1996.

47. J. S. Ruan and P. Prasad: Study of the Biodynamic Characteristics of the Human Head, Proc. Of 1996 International IRCOBI Conference, pp. 63-74.

48. S. D. Barbat, H.Y. Jeong and P. Prasad: Finite Element Modeling and Development of the Deformable Featureless Headform and Its Application to Vehicle Interior Head Impact Tests. SAE Paper No. 960104, International Congress, February 1996.

49. H.J. Mertz, G. Nusholtz and P. Prasad: Head Injury Risk Assessment for Forehead Impacts. SAE Paper No. 960099, International Congress, March 1996.

50. G.G. Lim, C.C. Chou, S. Sundararajan, L.A. Walker, G. Fletcher and P. Prasad: Deployable Door Trim System for Side Impact Protection, An Addendum of the Proceedings of Automotive Body Interior and Safety Systems, Vol. 23, International Body Engineering Conference, October 1-3, 1996.

51. S.D. Barbat, H.F. Mahmood and P. Prasad: Aluminum Intensive Vehicle Crashworthiness Design Approach, Proceedings of the Crashworthiness, Occupant Protection and Biomechanics in Transportation Systems, AMD-Vol. 225/BED-Vol. 38, Dallas, Texas, 1997.

52 H.J. Mertz, P. Prasad and A. Irwin: Injury Risk Curves for Children and Adults in Frontal and Rear Collisions, 41st Stapp Car Crash Conference, SAE Paper No. 973318 November, 1997.

53. P. Prasad: Occupant Simulation Models: Experiment and Practice, Proc. Of Crashworthiness of Transportation Systems: Structural Impact and Occupant Protection, NATO ASI Series Vol. 332, 1997.

54. P. Prasad, A. Kim, D.P.V. Weerappuli: Biofidelity of Anthropomorphic Test Devices for Rear Impact, Proc. of 41st Stapp Crash Conference, SAE Paper No. 973342, 1997.

55. P. Prasad, A. Kim, D.P.V. Weerappuli, V. Roberts and D. Schneider: Relationships Between Passenger Car Seat Back Strength and Occupant Injury Severity in Rear End Collisions: Field and Laboratory Studies, Proc. of 41st Stapp Car Crash Conference, SAE Paper No. 973343, 1997.

56. N. Saha, S. Calso, D. Midoun and P. Prasad: Critical Comparison of U.S. and European Dynamic Side Impacts, SAE Congress and Exposition, SAE Paper No. 970128, 1997.

57. J.S. Ruan, P. Prasad and D. Weerappuli: A Study of the Influence of the Neck Restraint on the Human Head Impact Response, ASME/AICHE/ASCE Summer Bioengineering Conference, Sunriver, June 11-15, 1997.

58. J.S. Ruan and P. Prasad: Biomechanical Study of Head Injury through Finite Element Analysis. Invited chapter in Frontiers in Head and Neck Trauma – Clinical and Biomechanical, Editors. N. Yoganandan and F.A. Pintar, in print, 1998.

59. S.D. Barbat and P. Prasad: Design Analysis of Aluminum Exterior Body Panels for Crashworthiness Improvements, ASCE Conference, May 17, 1998.

60. A. Manoli, R.S. Levine and P. Prasad: Foot and Ankle Severity Scale, International Journal of the Foot and Ankle Society, 1998.

61. A. Jibril, P. Prasad, J. Prybylski, I. Parekh, E. S. Grush: Logistic Regression Analysis of Lower Limb Injuries in Frontal Crashes. 16th International Technical Conference on Experimental Safety Vehicles. Report No. 98-S6-W-43, 1998

62. L. Chai, T. Subbian, A. Khan, S. Barbat, C. O'Conner, R. McCoy, P, Prasad: Finite Element Model Development of SID-IIs. 43rd Stapp Car Crash Conference. Paper No. SAE 99SC06, 1999.

63. P. Prasad, Biomechanical Basics for Injury Criteria Used in Crashworthiness Regulations, Bertil Aldman Award Lecture, Proc. of the IRCOBI Conference on the Biomechanics of Impact, 1999.

64. P. C. Begeman, K. Pratima, P. Prasad: Bending Strength of the Human Cadaveric Forearm Due to Lateral Loads. 43rd Stapp Car Crash Conference. Report No. SAE 99SC24, 1999.

65. T. R. Laituri, P. Prasad: Correlation of Drive Inflator Predictor Variables with the Viscous Criterion for the Mid-Sized Male, Instrumented Test Dummy in the Chest-on-Module Condition, SAE Paper No. 1999-01-0763, SAE International Congress, 1999.

66. D. P. Weerappuli, L. Chai, S. Barbat, D. Wan, P. Prasad: Development of a MADYMO3D Model of the SID-IIs Dummy. ASME, 1999.

P. Prasad: Role of Electronics in Automotive Safety. SAE Paper No. SAE 2000-01-C086, 2000.

67. A. Kim, P. Prasad: Hybrid III and Hybrid III with a TRID Neck in Low Speed Rear Impacts, in Frontiers of Whiplash Trauma, Edited by N. Yoganandan and F. A. Pinter, ISO Press, 2000.

68. H. J. Mertz, P. Prasad: Improved Neck Injury Risk Curves for Tension and Extension Moment Measurements of Crash Dummies. Proc. of the 44th Stapp Car Crash Conference. Paper No. 2000-01-SC05, 2000.

69. P. J. Schuster, C. C. Chou, P. Prasad, G. Jayaraman: Development and Validation of a Pedestrian Lower Limb Non-Linear 3-D Finite Element Model. 44th Stapp Car Crash Conference. Report No. 2000-01-SC21, 2000.

70. T. Laituri, N. Sriram, B. Kachnowski, Bron Scheidel, P. Prasad: Theoretical Evaluation of the Requirements of the 1999 Advanced Airbag SNPRM – Part One: Design Space Constraint Analysis, SAE Paper No. 2001-01-0165, International Congress, 2001.

71. S. Barbat, X. Li, P. Prasad: Evaluation of Vehicle Compatibility in Various Frontal Impact Configurations. SAE Paper No. 2001-06-0097. International Technical Conference on the Enhanced Safety of Vehicles, Amsterdam, The Netherlands, 2001.

72. S. Barbat, X. Li, P. Prasad: A Comparative Analysis of Vehicle-to-Vehicle and Vehicle-to-Rigid Fixed Barrier Frontal Impacts. SAE Paper No. 2001-06-0031. International Technical Conference on the Enhanced Safety of Vehicles, Amsterdam, The Netherlands, 2001.

73. R. Kent, J. Bolton, J. Crandall, P. Prasad, G. Nusholtz, H. Mertz, D. Kallieris: Restrained Hybrid III Dummy-Based Criteria for Thoracic Hard Tissue Injury Prediction. SAE Paper No. 2001-13-0017. IRCOBI Conference, United Kingdom, 2001.

74. P. Beillas, P. Begeman, K. Yang, A. King, P-J Arnoux, H-S Kang, K. Kayvantash, C. Brunet, C. Cavallero, P. Prasad: Lower Limb: Advanced FE Model and New Experimental Data. 45th Stapp Car Crash Journal, 2001.

75. J. Ruan, P. Prasad: The Effects of Skull Thickness Variations on Human Head Dynamic Impact Responses. 45th Staff Car Crash Journal, 2001.

76. R. Kent, J. Crandall, J. Bolton, P. Prasad, G. Nusholtz, H. Mertz: The Influence of Superficial Soft Tissues and Restraint Condition on Thoracic Skeletal Injury Prediction. 45th Staff Car Crash Journal, 2001.

77. T. Dhaliwal, P. Beillas, C. Chou, P. Prasad, K. Yang, A. King: Structural Response of Lower Leg Muscles in Compression: A Low Impact Energy Study Employing Volunteers, Cadavers and the Hybrid III. 45th Stapp Car Crash Journal, 2001.

78. S.-H. Lin, J. Pan, T. Tyan, S. R. Wu and P. Prasad: Modeling and Testing of Spot Welds Under Dynamic Impact Loading Conditions, SAE Paper No. 2002-01-0149, SAE World Congress, 2002.

79. S.H. Lin, J. Pan. T. Tyan, P. Prasad: Failure Modeling of Spot Welds Under Complex Combined Loading Conditions for Crash Applications, SAE Paper No. 2002-01-2032. Int'l. Body Engineering Conf. and Exhibition, 2002.

80. S.T. Hong, J. Pan, T. Tyan and P. Prasad: Influence of Shear Loads on Crush of Honeycomb Materials, SAE Paper No. 2002-01-0683. SAE World Congress, 2002.

81. T. S. Dhaliwal, P. Beillas, C. C. Chou, P. Prasad, K. H. Yang, A. I. King: Structural Response of Lower Leg Muscles in Compression: A Low Impact Energy Study Employing Volunteers, Cadavers and the Hybrid III, SAE Paper No. 2002-22-0012. 46th Stapp Car Crash Journal, 2002.

82. T. Laituri, B. Kachnowski, P. Prasad, K. Sullivan, P. Przybylo: Predictions of AIS3+ Thoracic Risks for Belted Occupants in Full Engagement, Real-World Frontal Impacts: Sensitivity to Various Theoretical Risk Curves. SAE Paper No. 2003-01-1355. World Congress, 2003.

83. S.-H. Lin, J. Pan, T. Tyan, P. Prasad: A General Failure Criterion for Spot Welds With Consideration of Plastic Anisotropy and Separation Speed, SAE Paper No. 2003-01-0611. SAE World Congress, 2003.

84. S. T. Hong, J. Pan, T. Tyan, P. Prasad: Crush Strength of Aluminum 5052-H38 Honeycomb Materials Under Combined Compressive and Shear Loads, SAE Paper No. 2003-01-0331. SAE World Congress, 2003.

85. T. Laituri, B. Kachnowski, P. Prasad, K. Sullivan, P. Przybylo: A Theoretical, Risk Assessment Procedure for In-Position Drivers Involved in Full-Engagement Frontal Impacts. SAE Paper No. 2003-01-1354. World Congress, 2003.

86. L. Wang, R. Banglmaier, P. Prasad: Injury Risk Assessment of Several Crash Data Sets. SAE Paper No. 2003-01-1214. World Congress, 2003.

87. S. D. Barbat, X. Li, P. Przybolo and P. Prasad: Vehicle-to-Vehicle Full Frontal Crash Optimization Using a CAE-Based Methodology, Proc. 18th ESV Conference, Nagoya, Japan. DOT HS809543, May 2003.

88. F. Heitzplatz, R. Sferco, P. Fay, J. Rheim, A. Kim and P. Prasad: An Evaluation of Existing and Proposed Injury Criteria with Various Dummies to Determine Their Ability to Predict the Levels of STNI seen in Real Accidents, Proc. 18th ESV Conference, Nagoya, Japan, DOT HS809543, May 2003.

89. S. Rouhana, P. Bedewi, S. Kankanala, P. Prasad, J. Zwolinski, A. Meduysky, J. Rupp, T. Jeffreys, L Schneider: Biomechaics of 4-Point Seat Belt Systems in Frontal Impacts. 47th Stapp Car Crash Journal, 2003.

90. J. Ruan, R. El-Jawahri, L. Chai, S. Barbat, P. Prasad: Prediction and Analysis of Human Thoracic Impact Reponses and Injuries in Cadaver Impacts Using a Full Human Body Finite Element Model. 47th Stapp Car Crash Journal, 2003.

91. H. Mertz, A. Irwin, P. Prasad: Biomechanical and Scaling Bases for Frontal and Side Impact Injury Assessment Reference Values. 47th Stapp Car Crash Journal, 2003.

92. T. Laituri, D. Sullivan, K. Sullivan, P. Prasad: A Theoretical Math Model for Projecting AIS3+ Thoracic Injury for Belted Occupants in frontal Impacts. 48th Stapp Car Crash Conference, Journal, November, 2004.

93. S. Sundararajan, P. Prasad, C.K. Demetropoulos, S. Tashman, P. C. Bergeman, K. H. Yanbg, A. I. King: Effect of Head- Neck Position on Cervical Facet Stretch of Post Mortem Human Subjects During Low Speed, Rear-End Impacts, 48th Stapp Car Crash Journal, 2004.

94. S.T. Hong, J. Pan, T. Tyan, P. Prasad: Effects of Impact Velocity on Crush Behavior of Honeycomb Specimens, SAE Paper No. 2004-01-0245, SAE World Congress, 2004.

95. P. Prasad, T. Laituri, K. Sullivan: Estimation of AIS3+ Thoracic Injury Risks of Belted Drives in NASS Frontal Crashes, Journal of Automobile Engineering, 2004. Vol. 218, No. D6. IMechE, United Kingdom.

96. P. Weerappuli, P. Prasad, S. Barbat: Effectiveness of the Head and Neck Support (HANS©) Device in Frontal Impacts of CART Carts: A CAE Analysis. International Journal of Vehicle Safety. Volume 1, January, 2005.

97. T. Laituri, P. Prasad, K. Sullivan, M. Frankstein, R. Thomas: Derivation and Evaluation of a Provisional, Age-Dependent, AIS3+ Thoracic Risk Curve for Belted Occupants in Frontal Impacts, SAE 2005-01-0297. April, 2005.

98. R. Banglmaier, L. Wang, P. Prasad: Influence of Interval Censoring and Bias on Injury Risk Curve Development. International Journal of Vehicle Design, In Press.

99. J. Ruan, R. El-Jawahri, S. Barbat, P. Prasad: Pelvic Impact Response and Injury Simulation using a Full Human Body Finite Element Model. Proceedings of NAFEMS World Congress. May, 2005.

100. J. Ruan, R. El-Jawahri, S. Barbat, P. Prasad: Biomechanical Analysis of Human Abdominal Impact Responses and Injuries through Finite Element simulations of a Full Human Body Model. 49th Stapp Car Crash Conference Journal, November, 2005.

101. S. Sundararajan, P. Prasad, S. Rouhana, C. Demetropoulos, , K. Yang, A. King: Characteristics of PMHS Lumbar Motion Segments in Lateral Shear. 49th Stapp Car Crash Conference Journal, November, 2005

102. S-T. Hong, J. Pan, T. Tyan, P. Prasad: Honeycomb Specimens Under Combined Compressive and Shear Displacement Conditions, SAE Paper No. 2005-01-0360, International Congress, 2005.

103. T. R. Laituri, S. Henry, K. Sullivan, P. Prasad: Derivation and Theoretical Assessment of a Set of Biomechanics-based, AIS2+ Risk Equations for the Knee-Thigh-Hip Complex, 50th Stapp Car Crash Conference Journal, November 2006.

104. J. Forman, D. Lessley, C. G. Shaw, J. Evans, R. Kent, S. W. Rouhana, P. Prasad: Thoracic Response of Belted PMHS, Hybrid III, nd the THOR-NT Mid-Sized Male Surrogates in Low Speed, Frontal Crashes, 50th Stapp Car Crash Conference Journal, November, 2006.

105. S. W. Rouhana, S. V. Kankanala, P. Prasad, J. D. Rupp, T. A. Jeffreys, L. A. Schneider: Biomechanics of 4-point Seat Belt Systems in Farside Impacts, 50th Stapp Car Crash Conference Journal, 2006.

106. K. H. Yang, J. Hu, N. A. White, A. I. King, C. C. Chou: Development of Numerical Models for Biomechanical Research: A Review of 50 Years of Publication in the Stapp Car Crash Conference, 50th Stapp Car Crash Conference Journal, 2006.

107. J. S. Ruan, R. El-Jawahri, S. W. Rouhana, S. D. Barbat and P. Prasad: Analysis and Evaluation of the Biofidelity of the Human Body Finite Element Model in Lateral Impact Simulations According to ISO-TR9790 Procedures, 50th Stapp Car Crash Conference Journal, 2006.

108. S.-T. Hong, J. Pan, T. Tyan and P. Prasad: Quasi-Static Crush Behavior of Aluminum Honeycomb Specimens under Non-Proportional Compression Dominant Combined Loads. International Journal of Plasticity, Vol. 22, 2006, pp.1062-1088.

109. S.-T. Hong, J. Pan, T. Tyan and P. Prasad: Quasi-Static Crush Behavior of Aluminum Honeycomb Specimens under Compression Dominant Combined Loads. International Journal of Plasticity, Vol. 22, 2006, pp.73-109.

110. V.-X. Tran, S.-T. Hong, J. Pan, T. Tyan and P. Prasad: Crush Behaviors of Aluminum Honeycombs of Different Cell Geometries under Compression Dominant Combined Loads, SAE Transactions, Journal of Materials and Manufacturing, 2007, pp. 163-170.

111. J. S. Ruan and P. Prasad: The Influence of Human Head Tissue Properties on Intracranial Pressure Response During Direct Head Impact, Intl. Journal of Vehicle Safety, 1(4):282-291.

112. D. C. Viano, C. Parenteau, P. Prasad and R. Burnett: Stiff versus Yielding Seats: Analysis of Matched Rear Impact Tests, SAE Paper No. 2007-01-0708, International Congress, 2007.

113. S. D. Barbat, X. Li and P. Prasad: Vehicle-to-Vehicle Front-to-Side Crash Analysis Using a CAE-based Methodology, Proc. 20th ESV Conference, Paper no. 07-0347, Lyon, France, June 2007.

114. S.D. Barbat, X. Li, S. Reagan and P. Prasad: Vehicle Compatibility Assessment Using Test Data of Full Frontal Vehicle-to-Vehicle and Vehicle-to-Full Width Deformable Barrier Impacts, Proc. 20th ESV Conference, paper no. 07-0348, Lyon, France, June 2007.

115. D. C. Viano, C. Parenteau, P. Prasad and R. Burnett: Occupant Responses in High Speed Rear Crashes: Analysis of Government Sponsored Tests, SAE Paper No. 2008-08-1360, International Congress 2008.

116. S.-T. Hong, J. Pan, T. Tyan and P. Prasad: Dynamic Crush Behaviors of Aluminum Honeycomb Specimens under out of plane inclined loads. International Journal of Plasticity, Vol. 24, 2008, pp. 89-117.

117. S.-T. Hong, J. Pan, T. Tyan and P. Prasad: Macroscopic Constitutive Behaviors of Aluminum Honeycombs under Dynamic Inclined Loads, 2007 SAE Transactions, Journal of Material and Manufacturing, 2008.

118. S.-T. Hong, J. Pan, T. Tyan and P. Prasad: A Comparison of Two Crush Test Methods for Honeycombs under Compression and Shear. Journal of Testing and Evaluation, 2008.

119. P. Prasad, L. W. Schneider and W. Hardy: Interactions of Out-of-Position Small-female Surrogates with a Depowered Driver Airbag, 52nd Stapp Car Crash Conference Journal, 2008.

120. J. S. Ruan, R. El-Jawahri, S. D. Barbat, S. W. Rouhana and P. Prasad: Impact Response and Biomechanical Analysis of the Knee-Thigh-Hip Complex in Frontal Impacts With a Full Human Body Finite Element Model, 52nd Stapp Car Crash Conference Journal, 2008.

121. Dalmotas D.J., Prasad, P., Augenstein, J.S. and Digges K. (2010) Assessing the Field Relevance of Testing Protocols and Injury Risk Functions Employed in New Car Assessment Programs, Proc. of the ESAR Conference, Hannover, Germany.

122. P. Prasad, H. J. Mertz, D. J. Dalmotas, K. Digges and J. S. Augenstein, Evaluation of the Field Relevance of Several Injury Risk Functions, 54th Stapp Car Crash Journal, 2010.

123. Sundararajan, S., Rouhana, S.W., Board, D., DeSmet, E., Prasad, P., Rupp. J.D., Miller, C.S. and Schneider, L.S., Biomechanical Assessment of a Rear-Seat Inflatable Seat Belt, Stapp Car Crash Journal, Vol. 55, 2011.

124. Samaha, R. Prasad P. et al., An Integrated Modeling Method to Evaluate Fleet Safety Performance of New Vehicle Designs, IMECE2013-66285, ASME, 2013.

125. Samaha, R. R., Prasad, P. et al., Occupant Modeling for Injury Risk Computation in Vehicle Fleet, IMECE2013-66275, ASME, 2013.

126. Samaha, R.R., Prasad P. and L. Nix, Opportunities for Injury Reduction in US Frontal Crashes: An Overview by Structural Engagement, Vehicle Class, and Occupant Age. Stapp Car Crash Journal Paper No. 13S-38, 2013.

127. Digges, K. et al., An NCAP Star Rating System for Older Occupants, Enhanced Safety of Vehicles Conference, Seoul, Korea, 2013.

128. Barbat, S., Li, Xiaowei and Prasad, P., Bumper and Grille Airbags Concept for Improved Vehicle Compatibility in Side Impact: Phase I, Paper No. 13-0189-O, Enhanced Safety of Vehicles Conference, Seoul, Korea, 2013.

129. Barbat, S., Li, Xiaowei and Prasad, P., Bumper and Grille Airbags Concept for Improved Vehicle Compatibility in Side Impact: Phase II, Paper No. 13-0189-O, Enhanced Safety of Vehicles Conference, Seoul, Korea, 2013, also in the Traffic Injury Prevention Journal Special Issue, 2013.

130. Mertz, H.J., Prasad, P. and Dalmotas, D. Minimizing the Injury Potential of Deploying Airbag Interactions with Car Occupants, John Paul Stapp Memorial Lecture, Stapp Car Crash Journal, Vol. 57, Nov. 2013.

131. Rouhana, S.W., Sundararajan, S., Board, D., Prasad, P., Rupp, J.D., Miller, C.S.. Jeffreys, T.A. and Schneider, L., Biomechanical Considerations for Assessing Interactions of Children and Small Occupants with Inflatable Seat Belts, Stapp Car Crash Journal, Vol. 57, Nov. 2013.

132. Prasad, P., Dalmotas, D.J. and German, A., An Examination of Crash and NASS Data to Evaluate the Field Relevance of IIHS Small Offset Tests, SAE Int. J. Transportation Safety, Vol. 2 No. 2, 2014.

133. Prasad, P., Dalmotas, D.J. and German, A., The Field Relevance of NHTSA's Oblique Research Moving Deformable Barrier Tests, Stapp Car Crash Journal, Vol. 58, Nov. 2014.

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