Peer Review of Lotus Engineering Vehicle Mass Reduction Study

Work Assignment 3-04
(RTI 004)

Technical Memorandum

Prepared for

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EPA Contract Number EP-C-08-008

RTI Project Number 0211577.004.004

November 2010

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RTI INTERNATIONAL | Memorandum

TO: Hugh Harris and Michael Olechiw, U.S. Environmental Protection Agency, Office of Transportation and Air Quality (OTAQ)

FROM: Dileep K. Birur, RTI International.

DATE: November 24, 2010.

SUBJECT: Peer Review of Lotus Engineering's Study "An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Vehicle Program."

1. Background

As EPA's Office of Transportation and Air Quality develops regulations to control greenhouse gas (GHG) emissions from light-duty highway vehicles, there is a need to evaluate the feasibility of technologies likely to be used to meet these standards. EPA has worked in conjunction with the California Air Resources Board (CA-ARB), Lotus Engineering, and the International Council on Clean Transportation (ICCT) to perform a detailed analysis of the potential to reduce light-duty vehicle mass through the application of low density or high strength materials, component consolidation, and changes to vehicle architecture. EPA believes this holistic vehicle approach establishes a potential path for future feasible vehicle mass reduction in light duty vehicles to meet more stringent GHG and Fuel Economy standards.

Lotus Engineering has completed its analysis of a typical Cross-over Utility Vehicle (CUV), as outlined in the Lotus Engineering document, "An Assessment of Mass Reduction Opportunities for a 2017 – 2020 Model Year Vehicle Program.", and has presented two levels of mass reduction. The first is termed a "Low Development" vehicle and is presented under the premise that the mass reduction solutions are readily available in 2014 and can be implemented for production in 2017 upon a current redesign schedule for manufacturers. The second is a "High Development" vehicle based on mass reduction solutions targeted for 2017 technology readiness and 2020 production. EPA had sought the reviewers' expert opinion on the methodologies being used in this mass reduction work, whether they are likely to yield accurate results, the feasibility of the proposed solutions to meet all vehicle and manufacturing requirements, cost conclusions, and other key factors such as the customer acceptance and technology maturity. RTI International facilitated this peer review and this technical memorandum contains documentation of the peer review process of the vehicle mars reduction study.

2. Description of Review Process

EPA's Office of Transportation and Air Quality contacted RTI international in August 2010 to facilitate the peer review of the Lotus Engineering's study entitled "An Assessment of Mass Reduction Opportunities for a 2017 – 2020 Model Year Vehicle Program." EPA provided a non-comprehensive list of subject matter experts from academia and public sector (Appendix A of the performance work statement, WA 2-04) to RTI, and this served as a "starting point" from which we assembled the list of subject matter experts. To ensure that the review process was performed in a timely manner, RTI contacted the potential reviewers within ten days of submitting the work plan and determined that each expert would be able to review the study during the period of performance. RTI selected four independent (as defined in Sections 1.2.6 and 1.2.7 of EPA's Peer Review Handbook) subject matter experts based on their expertise and their interest to perform the review in the stipulated time frame. In order to make the review process as credible as possible, RTI did not consult the EPA in the final selection of the reviewers. The subject matter experts consist of a range of expertise in holistic vehicle, system and sub-system mass reduction methodologies and costing. Appendix-A of this technical memorandum provides the resumes obtained from the selected reviewers. The selected experts have (i) sufficient knowledge to judge the merits of both metallic and composite based material substitutions in addition to the design changes required to support said substitutions, (ii) experience in manufacturing, both in body and overall vehicle assembly, and (iii) expertise in vehicle development such as vehicle safety, durability, vehicle dynamics, and noise, vibration, and harshness (NVH).

RTI provided the panel reviewers with the Lotus Engineering report on "An Assessment of Mass Reduction Opportunities for a 2017 – 2020 Model Year Vehicle Program" submitted to the International Council on Clean Transportation[1]. In addition, the panel reviewers were also given a set of charge questions prepared by the EPA. The note from RTI sent to the reviewers with the charge questions is included in Appendix-B of this memorandum.

After two weeks of the review process, a teleconference call was organized between EPA, the panel reviewers and RTI to provide an opportunity to the panel to discuss any questions or concerns they may have regarding the review material provided and the expected deliverables. Some of the questions addressed in this process and the answers provided are included in Appendix-C of this memorandum.

RTI received the completed reviews from the panel reviewers and sent to EPA by the requested date. The review reports included the response to charge questions and any additional

[1] The Lotus report is available at: http://www.theicct.org/2010/03/lightweight-future/

comments or recommendations the reviewers may have had. From each panel participant, RTI obtained a cover letter that stating the reviewer's name, the name and address of their organization if applicable, which model review documents/media were received by the reviewer and which were actually reviewed and a statement of any real or perceived conflict(s) of interest. These cover letters and the review reports are included in Appendices – D and E, respectively, of this memorandum.

3. Summary of Review Comments

Lotus Engineering studied the potential mass reduction opportunities for a selected baseline vehicle (2009 Toyota Venza) representing the crossover utility segment, although the materials, concepts and methodologies are applicable to other vehicle segments such as passenger cars and trucks. This study encompassed all vehicle systems, sub-systems and components. The study analyzed two categories, allowing two distinct vehicle architectures appropriate for production in 2017 and 2020. The first vehicle architecture, titled the "Low Development (LD)" vehicle, utilized technologies feasible for a 2014 program start and 2017 production, involved competitive industry leading mass reducing technologies, improved materials, component integration, and assembled using existing facilities. The mass reduction estimated for the low development vehicle was 21% (excluding powertrain) with a nominal estimated cost saving of 2%. The second vehicle architecture, titled the "High Development (HD)" vehicle estimated a 38% reduction in vehicle mass (excluding powertrain) with a nominal estimated 3% increase in component costs. The high development vehicle technology utilized engineering technologies viable for 2020 mainstream production, and a mix of primarily non-ferrous materials, high degree component integration with advanced joining and assembly methodologies. The study concluded that both the vehicle scenarios showed potential to meet their mass reduction targets with minimal piece cost impact. The Lotus report recommends further follow-up and independent studies to validate the materials, technologies, and methods referenced for the LD and HD vehicles scenarios.

The rest of this section gives a summary of the review comments received from the four panel reviewers: Mercedes Benz Technology team (MB-tech team lead by Ms. Christie Coplen), Mr. Sujit Das (Oak Ridge National Laboratory – UT-Battelle, Knoxville, TN), Mr. John E. Fillion (the Energy Society of Detroit, Troy, MI), and Dr. Donald E. Malen (University of Michigan, Ann Arbor, MI).

3.1 An Overview of the Reviews

MB-tech team reports that the Lotus study has merit, however, they qualified their assessment in saying the Lotus study was specific to only the Toyota Venza model, as feasibility of various technologies presented in the report is not proven for series production implementation. The MB-tech reviewer team disagrees with the Lotus Engineering report that 21% and 38% total vehicle mass reduction will be achievable by 2017 and 2020 for LD and HD technologies, respectively. MB-tech states that this is because most of the high-tech or luxury vehicles OEMs (Original Equipment Manufacturer) such as Mercedes Benz, have already adapted many of the technology concepts presented in the LD and HD sections of the report, however, MB-tech includes a contradictory statement that "… many High Development solutions … will exceed the deadlines for implementation". MB-tech recommends a review of these technologies and also an analysis of the resulting impacts due to overall proposed mass reduction. Mr. John Fillion comments that the methodology used in the LD and HD vehicle scenarios is sound and the bill of materials (BOMs) suggested by Lotus study is viable. But Mr. Fillion recommended to examine if the advanced technologies for the 2020 BOMs commercially viable with conventional powertrain and chassis system using a high technology demonstration vehicle such as GM Volt.

The other two reviewers: Mr. Sujit Das and Dr. Donald Malen, report that the Lotus mass reduction opportunities are reasonable and likely to meet the stated objectives. However, those reviewers identified some of the caveats in the current approach and recommended further work for improvement in the study. Mr. Das suggested estimating cost using a consistent methodology for all vehicle non-powertrain subsystems. Dr. Malen provided a detailed set of recommendations specific to improvements in several subsystems. Overall, Dr. Malen has also recommended for a more transparent, data-driven methodology that can be examined at each step of the analysis.

3.2 Methodology

This section highlights some of the key issues raised by the review panel regarding the methodology employed in the Lotus study. On selection of technology and weight calculations, MB-tech team recommended a regression based approach in determining optimal solution set, instead of scaled-weight approach used for selecting benchmarked components. The factors recommended for a regression based study are: price gap drivers, technology-product concept drivers, and performance-gap drivers. This reviewer team also pointed out that the Lotus report did not analyze the vehicle packaging issues, and the impact of weight reduction on other vehicle requirements such as safety, noise-vibration- and-harshness (NVH), fatigue strength and corrosion.

Mr. Fillion comments that the BOMs suggested by the Lotus study in the LD and HD case are entirely viable. He believes that, since the new vehicles designed for 2017 and 2020, will likely replace a vehicle that is already using lighter BOMs than Venza baseline, the mass savings opportunities would be numerically smaller than 21% and 38%, respectively for LD and HD cases. Mr. Fillion cites several studies of Dr. Malen on mass compounding and benchmarking techniques and compares that those studies support the methodology adopted by the Lotus study.

While Mr. Das stated that "Overall, the detailed vehicle teardown approach used for identifying mass reduction opportunities seems like reasonable one" he comments that "the approach used for identifying mass reduction opportunities in the Lotus study seems to be prohibitively expensive and time-consuming for a regular use when other vehicle segments such as passenger cars and trucks need to be considered for similar analysis in the future." He further reports that, though the initial tear-down approach was a good beginning, the ad-hoc approach used for estimation of components' cost lacks repeatability and validity.

Dr. Malen raises several questions that emerge from the methodology adopted by the Lotus study. He recommends for adopting a transparent improved methodology which includes casting a wide net of potential mass reducing technologies, having explicit data driven approach at each step, using a metric to order technologies based on maturity/readiness, etc. Dr. Malen suggested several tools such as statistical mass benchmark models, component function for quantitative material selection, spreadsheet based cost models that allow for volume sensitivity analysis, use of marginal cost, and a mass compounding model. These tools could be used to generate and supplement expert opinion on cost estimation. Dr. Malen's recommendations also included an alternate methodology that supplements and greatly enhances the conclusions of the Lotus study and improves their downstream collaboration. This methodology comprised four major steps: (1) determining mass for the reference vehicle, (2) Identifying mass reduction technologies, (3) sort mass reduction technologies by cost, and (4) estimate the new vehicle mass using mass compounding.

Overall, though one reviewer completely agreed on the precision and viability of the Lotus methodology, the other three members of the review panel had varied opinion. The latter assessed that the Lotus methodology is expensive, prolonged, should use statistical analysis in selecting the benchmarked components, the methodology should be explicit data driven and transparent.

3.3 Feasibility

Feasibility of the Lotus mass reduction technologies has been an important concern of the reviewers. The MB-tech team comments "feasibility of various technologies presented in the report is not proven for series production implementation. These technologies must be reviewed and the impact must be taken into account on the overall proposed weight reduction calculations. As an example, the proposed plastic injection molded fenders versus steel is not realistic as demonstrated based on various MB-tech investigations.", however, MB-tech also offers a contradictory statement that the majority of the mass reduction solutions are already in production.

Mr. Das comments "although the (Lotus) approach is considered to be a synergistic one, providing a high level of flexibility in selecting feasible materials, processes, manufacturing and assembly methods, but the design feasibility yet remains to be proven since the interdependency of designs of vehicle components if at all considered in the analysis was not explicitly discussed in the report."

Dr. Malen provides computed ratios of each subsystem mass to the corresponding vehicle mass. He comments, "this ratio provides a useful rule-of-thumb to see if the proposed subsystem mass is roughly consistent with the vehicle mass which the subsystem is a part of." One of these ratios, the body ratio for the HD vehicle is low compared to the Venza. Dr. Malen expresses his concern if it is the acceptable level of risk for the body proposal. Based on these rations, Dr. Malen has also presented insights on how additional mass reduction opportunities are feasible for with respect to each subsystem such as bumpers and glazing.

On the whole, two of the reviewers reported that the Lotus mass reduction technologies are feasible and are of "low technical risk" and "sound". While one reviewer stated the mass reduction solutions yet to be proven for series production another reviewer suggested further mass reduction opportunities that are feasible in addition to the Lotus technology.

3.4 Cost Conclusions

The MB-tech team comments that the costs in the Lotus study are based entirely on piece cost, rather they recommend including total landed cost and total cost of ownership as these costs would give a different perspective on the overall cost impact on the market. The reviewer suggests that the total landed cost should comprise of cost to design, acquire, manufacture, and manage, and the total cost of ownership should involve the total landed cost as well as cost to assemble into vehicle, cost to maintain, and cost of service. Mr. Das suggests that due to improper derivation of cost factors in the Lotus study, the cost analysis is inconsistent among various vehicle subsystems and therefore the cost analysis need to be revisited.

Dr. Malen has pointed out that the Lotus study has not explicitly included the tooling costs in the cost estimates. He comments "this cost would be a significant one since the lower volume will favor materials and systems which allow integration of several parts into one (the module idea mentioned in the report), and which have a lower tooling cost with a slower cycle time (the emphasis on plastics and non-ferrous alloy metals in the report). So not only is the cost estimate influenced by volume, but the actual configuration design. Given these uncertainties, the cost conclusions need to be clarified and extended."

In general, the three reviewers' comments imply that the cost estimates given in the Lotus study are inconsistent and lack scientific judgment. Those reviewers suggested for alternate cost analysis in the wake of their suggestions and also recommended proper documentation of all the cost assumptions.

3.5 Customer Acceptance

The MB-tech comments that the future vehicle technology demands must be taken into account which are mainly driven by legislation and consumer demand. Since vehicle safety is a crucial issue, MB-tech suggests that the major technology growth in North America will likely be associated with safety. As a result, the safety related technologies will have intrinsic value to both the OEM and the end consumer which results in cost penalty to the vehicle cost as well as to the overall mass reduction efforts.

Mr. Das reports that it is hard to determine the consumer acceptance of LD and HD vehicles until the follow-on validation especially on the vehicle safety performance is completed.

Dr. Malen reports that researchers in general have been very conservative on assessing technology impact on the consumer. He believes that the proposed technologies would be transparent to the customer and positive on the performance aspect. He comments "the conservative bias may be excessive in two areas: The proposed large wheels and tires (heavier) were selected to maintain styling proportions. Given the focus on mass reduction, why not challenge designers to make the smaller wheels visually acceptable? Also, the lighter rear suspension twist axle was rejected as not appropriate for the market. Was this based on functionality, or customer perceptions? If the latter, perhaps perceptions need to be changed."

In the general, the reviewers expressed their difficulty in assessing customer acceptance without surveying customers' opinion. Two of the reviewers suggested that the vehicle safety features would be a major factor determining customer acceptance. However, a panel member suggested that since the Lotus technologies are positive towards vehicle performance, it is also important to visually reflect these improvements so that it helps in changing consumer perceptions.

3.6 Technology Maturity

The MB-tech team comments that the lead time in the given time frame of 2017-2020 would be a limiting factor since the proposed mass reducing technologies require significant development time with often major changes in production technologies and facilities. They report that since the vehicle development life-cycle range from three to seven years, the 2017-2020 time period is much shorter. The MB-tech team further suggests that since many of the LD and HD technologies are already in production or planed for near-term production, an assessment of OEM usages of LD and HD concepts should be undertaken which would statistically validate the technology.

Mr. Fillion comments "the Lotus study relies on the technical readiness of advanced high strength steel (AHHS), aluminum, magnesium, and composites for the year 2020. The automotive industry has been working on these issues since about 1993, through a cooperative agreement between the Department of Energy (DOE), Chrysler, Ford, and GM. This agreement is managed through the United States Automotive Materials Partnership (USAMP). The stated goal of USAMP is to significantly reduce the mass of the vehicle at affordable costs. USAMP envisions that a vehicle in the time frame of 2020, that was significantly lighter than current vehicles, would be a multi-material vehicle consisting of AHSS, high strength steel (HSS), aluminum, magnesium, and composites, similar to the bill of materials proposed by the Lotus study."

Mr. Das comments that some of the lightweighting technology options involve materials such as composites and magnesium are yet to be introduced on commercial scale in the automotive market. He further expresses his concern on technology maturity, since the viability of using magnesium and composites in the HD case requires technology readiness, which is highly optimistic to be available by 2017.

Dr. Malen reports that except for the proposal on body structure of the HD vehicle, the technology maturity of the proposals in the Lotus study is appropriate for the timeframes. He comments, "the High Development body is challenging because of the many and demanding functional requirements (crashworthiness, NVH, durability), because the body is the platform of the vehicle (i.e. presents a high vehicle system failure risk, not just a technology risk for the subsystem), and because so many advanced body technologies are being proposed (alternative materials, joining methods for dissimilar materials, manufacturing strategy, dimensional control, etc." He further suggests for reevaluating the body structure proposal of the HD vehicle as it involves higher level of risk.

Overall, the four reviewers reported that the technology under LD scenario for 2017 production would be matured given the pace of developments in the lightweighting materials used in LD case. However, three reviewers felt that the technology readiness for HD case for 2017 start and 2020 production is optimistic, and challenging. Therefore, those reviewers further recommended for reevaluating the HD vehicle scenario and the stipulated time frame.

3.7 Summary of Reviews on Subsystems

The table below lists some of the key comments made by the review panel on the specific subsystems.

Subsystems:	**MB-tech team**	**Mr. Sujit Das**	**Mr. John Fillion**	**Dr. Donald Malen**
Body structure	Total landed cost and cost of ownership should also be considered.	Cost estimation procedure for baseline body is inaccurate as it based solely on material cost.	Lotus approach is reasonable, though technologies proposed face a barrier of cost effectiveness.	HD- at the lower edge of most expert option for technology regardless of date of use.
Closures	Use of normalized weight as baseline is incorrect; rather a regression- based analysis should be employed.	Several cost factors both in LD & HD cases are too optimistic (see review for details)	The mass savings achieved at the respective cost factors in LD & HD cases are credible.	Clarification on the basis for choosing (plastic outer, HSS inner) vs. (plastic outer, HSS inner) is needed.
Front and Rear Bumpers	-	Clarify if the cost factor is 106% or 103%.	Agrees with Lotus findings.	LD & HD - should be scaled down for curb mass.
Glazing (windshield, backlight, doors, sunroof, fixed)	-	Clarify how the cost competitiveness was determined.	Agrees with Lotus findings.	HD- Polycarbonate glazing (at least on side fixed glass) is worth a try.
Interior	The latest trends in control systems benchmarking and instrument panel, console, and insulation are offered (useful for any further analysis)	Interior components seem to have least weight reduction potential. Needs clarifications & references on cost assumptions.	Lotus report has a good summary on interior choices available. The mass savings results are credible.	LD & HD - Low risk subsystem for mass reduction and this large value is very appropriate.
Chassis	-	Overview of cost estimation is excellent. Need	Agrees with the mass savings potential, but the cost factor is too	LD & HD - Scaling used in the report may have lead to greater than

		clarifications & references on using projected costs	generous.	achievable reduction in this mature subsystem.
Air conditioning system	It is possible to realize considerable weight reduction in air conditioning due to advanced energy saving technologies & other factors.	-	Agrees with Lotus findings.	LD & HD: Carry over Venza HVAC module & air distribution systems.
Electrical	Electric conductive polymers with Carbon Nano Tubes (CNT) could be used for light weight casing material.	References are needed for clarifying Copper clad aluminum (CCA) is 40% lighter than copper, and how it is less sensitive to market price.	Lotus assumptions are reasonable. Results on mass savings & cost factors are credible.	LD & HD: CCA for all wiring. HD: - thin wall Noryl cladding. -carry over Venza lighting in LD & HD.
Powertrain	-	Need to address the interdependency between powertrain & non-powertrain masses.	Though selection of hybrid technology is acceptable assumption, the study could have included the conventional powertrain also.	The powertrain scaling for the new vehicle mass should be confirmed.
Engine	-	Clarification is needed for using the Lotus developed engine, SABRE.	Lotus could have showed the effect of using 2020 BOMs with a 4-cylinder engine vs. the baseline 6-cylinder one.	Here is where mass compounding would be useful. Engine is not sized for vehicle mass.

3.8 Reviewers' Recommendations

Though there are several similarities in the comments made by the peer reviewers on the Lotus study, each of the review panel has given different recommendations and follow-on options. The MB-tech team disagrees with the Lotus results on 21% and 38% mass reduction in the LD and HD scenarios, by 2017 and 2020, respectively, and they estimate that only in the case of in-car entertainment (ICE) based vehicles, an additional 10-12% vehicle mass reduction by 2020 would be possible. The MB-tech team also suggested for additional studies to be carried out with respect to body-in-white requirements, specifically on crash, NVH, strength, corrosion, repair costs, manufacturing and associated costs, environment and recycling concerns, and material availability.

Mr. Fillion comments that the holistic system approach adopted by the Lotus study could be an effective mass reduction effort at a reasonable cost. However, he suggests that the mass reduction method by part to part substitution is not significant rather it needs to be an enabler technology for meeting an important vehicle target. He further states that, apart from technical challenges on choosing the BOMs, it is important to understand the financial payback to a customer who pays higher purchase price and receives lower operational costs over the life of ownership. Mr. Fillion offers some insights on supporting the new improved fuel economy technology at various gasoline prices and the pay-back period for the customer. He further raises a question unanswered by the Lotus study, "is the advanced technology approach for HD vehicle BOMs viable with conventional powertrain systems?" Mr. Fillion recommends that since the automotive industry will be deploying the recommended 2017 BOMs for the new vehicles, it is not necessary to undertake the follow-on studies reported in the Lotus study for the LD vehicle segment. However, Mr. Fillion suggests an alternate follow-on study to address a question on how the rest of the market especially the lower cost end of the market would respond to the mass reduction developments. For this purpose, he suggests to select a high technology vehicle such as GH Volt as demonstration vehicle and apply mass compounding (decompounding) concepts to carry out the analysis similar to that of Lotus study.

Mr. Das has recommended follow-on cost estimation for all vehicle non-powertrain subsystems using a consistent and transparent methodology.

Dr. Malen has given detailed recommendations on improvements that could be readily done in the Lotus study as well as the improvement that require more exploratory analysis. Some of the recommendations that could be readily incorporated are: using a transparent and simple cost model to capture tooling and equipment costs, technology selection done based on a suggested first order analysis, revisiting the Lotus decision on using larger wheels and tires than those functionally required which lead to increase in mass by over 4 kg, accounting for the interaction between the selected subsystems, etc. Some of the improvements that are more exploratory as suggested by Dr. Malen include: searching alternative potentially significant mass reducing technologies from non-traditional sources such as patents, lateral technologies, aerospace, universities, etc., performing a similar study but focusing on mass reducing vehicle architecture changes, focusing further work to lower risk in interior components which have greater mass reduction potential, and work on the HD body proposal instead of LD body structure as the latter is already being undertaken by OEMs and steel supplier groups.

3.9 Overall Conclusions

The reviews on Lotus study performed by the four panel members indicate that, in general, the mass reduction methodology is reasonable and has merit. Each reviewer, however, qualified their conclusions agreeing that the methodology should be revisited as it is expensive, and lacks transparency and statistical judgment on selection of benchmarked components. The reviewers' opinion on technology feasibility was mixed. While two of the reviewers felt the Lotus mass reduction technologies are not yet proven for series production, the other reviewer suggested further mass reduction opportunities that are feasible in addition to the Lotus technology. All the reviewers who commented on cost conclusions indicated inconsistency in cost estimation procedure adopted in both LD and HD scenarios. The reviewers also suggested that all the cost assumptions should be properly reported. Since vehicle safety features are the major determining factors for customer acceptance, two of the reviewers suggested including these features in the analysis. A panel member though indicated that the suggested Lotus technology would improve vehicle performance which is a positive indicator for customer acceptance, also recommended certain visual changes that could be made to the vehicle to influence customer perception.

Though all the reviewers reflected that the Lotus technology under LD case would be matured for 2017 production, three of reviewers felt that the technology under HD scenario for 2020 production is optimistic and challenging. As highlighted in the previous section, the four reviewers gave varied recommendations on improvements to Lotus study and follow-on options. In general, all the reviewers supported the structure and presentation of the Lotus study, though they have sought several clarifications and references on some of the assumptions and cost estimations made in the study. The complete reviews from the panel reviewers are included in Appendix-E of this memorandum.

Appendix A: Resumes of Selected Reviewers

DONALD E. MALEN
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Bloomfield, MI 48304
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Teaching/Research Interests

Automotive body structure engineering, vehicle integration and innovation, First Order Analysis modeling of vehicle systems, statistical product benchmarking, translating customer preference into engineering requirements, improving decision making methods in product design, techniques for system innovation by small multidisciplinary teams, designing sets of products, lead time reduction in product design.

Educational Background

University of Michigan September, 1989 to December, 1992

Interdisciplinary Degree Awarded: Ph.D. from Department of Industrial and Operations Engineering & Department of Mechanical Engineering.
Dissertation: *Engineering for the Customer-Decision Methodology for Preliminary Design*
Co-chairs: Dr. Walton Hancock (IOE) and Dr. R. Scott (ME), (David Cole and G. Herrin committee members.)

Massachusetts Institute of Technology January, 1969 to February, 1970

Degree Awarded: Master of Science, Department of Mechanical Engineering
Thesis: *Applied Damping in the Automobile Body*
Advisor: Dr. J. P. Den Hartog.

General Motors Institute January, 1965 to January, 1970

Degree Awarded: Bachelor of Science in Mechanical Engineering
Alpha Tau Omega, academic honor society
Industry Sponsor: Chevrolet Engineering Center, Warren, MI.

Current Activities at the University of Michigan

Auto Body Structures ME513- Developed the original ME599 course in 1998 for delivery to industry and on-campus students in collaboration with N. Kikuchi. The material includes a new book. The course has also been offered as a short course at Pan Asia Technical Automotive Center, Shanghai, 1999; the American Iron and Steel Institute 2000, Toyota, Japan 2002; Nissan, Japan 2003; Mahindra and Mahindra, India, 2011.

Design for Manufacture ME452- Project based course in which students redesign a consumer product to improve functionality and manufacturability. Collaborated with S. Kota to add value for off-campus student projects and developed new material for translating customer needs to engineering requirements, quantifying customer preference, product platform architecture, and robust design.

Design for Manufacture MFG599-Developed and teach a graduate level module addressing analytical customer preference modeling and optimization; offered Fall 2007 to present.

Integrated Vehicle Systems Design, **AUTO501**, Invited lecturer for the *Body Structure* session (each year since 2003).

Global Product Development ME 581- Concurrent course at Seoul National University and Berlin Technical Institute, UM where cross-university teams develop a global product. Developed distance learning logistics for the first offering to industry students, Fall 2004.

Sponsored research- Mass benchmarking; mass compounding; first-order analysis models for body structure design; use of overlapping activities to reduce product lead time.

AISI Summer Internship-Recurring project with UM engineering students working in collaboration with Industrial Design interns from the *College for Creative Studies* to create innovative steel vehicle structures. (First offered in 2006).

Capstone Auto Program Advisor- Capstone Project advisor for over 40 students since 2002.

Work History

Present: **University of Michigan— Department of Interdisciplinary and Professional Engineering**, Adjunct Associate Research Scientist.

2001: Retired from General Motors, joined University of Michigan, Department of Interdisciplinary and Professional Engineering, College of Engineering as Adjunct Assistant Professor.

1997-2001: **Innovation Zone—General Motors**

Creator and Executive Director of a unique organization for multidisciplinary collaborative innovation on key product needs. The activity identifies technical gaps in future products and creates innovative solutions to close those gaps.

Summary of earlier GM work

1970-1997: **Portfolio Development Center -** Systems engineering executive for future product planning activity.

Advance Body Design Leader - Identified, developed, and transferred to production new vehicle body technology. e.g. Ultra-light composite vehicle, Impact electric vehicle, scale plastic structural modeling.

Saturn Car Program - Body design team leader for the original vehicle. This project pioneered simultaneous product/process engineering, team decision making, CAD, and numerical controlled machining at GM.

Underbody structure for Cadillac C body - analysis and design of structure for integral body vehicle.

Project 300: Designed an innovative three wheel cambering vehicle.

Integrated Vehicle Line: Pioneering effort on high fuel economy using integral body construction and transverse power trains.

GM Special Product Development Group—Body design on a vehicle program exploring a rotary engine power-train and the first proposed Federal Motor Vehicle Safety Standards.

Selected Accomplishments

- Registered Professional Engineer in the State of Michigan, Registration No. 20945.
- *Outstanding Distance Learning Faculty Award,* 2006 and 2007.
- *General Motors Chairman's Honors Award* for creating a Product Innovation Process and department, 1999.
- *Engineering Achievement Award*, General Motors, 1985. For the work done on a method to shape automobile panels resulting in highly efficient structural performance.

Patents

- Method for Determining the Shape of a Vehicle Body Panel- 4,581,192. (European Patent 85303349.6)
- Vehicle Body Floor Pan Assembly- 4,572,571. (European Patent 85303350.4).
- Vehicle Front End Structure- Patent 4,428,447.
- Low Force Transmissibility Mount- Patent 4,403,762. (Co-inventor J. Cogswell, II).

Selected Publications

Fundamentals of Automobile Body Structure Design, SAE International. A text book to be published January, 2011.

Automotive Mass Benchmarking, American Iron and Steel Technical Publication, May, 2010.

Crush Performance of Thin Walled Spot-Welded and Weld-Bonded Sections, American Iron and Steel Technical Publication, January, 2009. (with P. Davidson).

Mass Compounding – Phase 2, American Iron and Steel Technical Publication, December, 2008. (A. bin Md Saad).

Preliminary Vehicle Mass Estimation Using Empirical Subsystem Influence Coefficients, American Iron and Steel Technical Publication, May, 2008. (with K. Reddy).

Decision Making in Preliminary Product Design: Combining Economic and Quality Considerations, *The Engineering Economist*, V. 41, No. 2, Winter, 1996, pp105-122.

<u>E. L. Grant Award for best paper in Volume 41 by the ASEE</u>

Engineering for the Customer: Part I Theory, *Journal of Engineering Design*, V. 6, No. 4, December, 1995, pp315-328. (with W. Hancock).

Engineering for the Customer: Part II Application, *Journal of Engineering Design*, V. 6, No. 4, December, 1995, pp329-341. (with W. Hancock).

Improving Automobile Door-Closing Sound for Customer Preference, *Noise Control Engineering Journal*, V. 41, No. 1, July-August, 1993, pp261-271. (with R. Scott).

Others in the areas of body structure design, analytic design tools, crashworthiness, vibration, and scale.

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Current

Leadership position at the Engineering Society of Detroit (ESD) with the following roles:

- Chairman of the member benefits committee
- Program coordinator for member conferences
- Director for student engineer internships programs
- Mentor in the public schools, grade 6 through 8, for programs promoting engineering as a career

Perform as a consultant regarding the use of materials in automotive applications.

Education

1978 Bachelor of Science in Chemical Engineering University of Toledo
1980 Master of Arts in Management Central Michigan University
1985 Master of Science in Materials Engineering University of Dayton.

Career Experience (Retired December 31, 2007)

Chrysler, LLC
2001 -2007 Senior Manager of Chassis and Powertrain Materials Engineering
The position was responsible for 55 engineers and technicians with an operation budget of $7 million per year and a capital budget of $2 million per year. The Department specified and developed metallic materials for components used in engines, transmissions, and chassis systems. The primary technical challenge for the Department was to balance the material performance for the competing component requirements of low cost, quality, manufacturing capability, and long term durability. The materials of choice were usually in the domain of aluminum, iron, or magnesium castings and steel bar products ranging from commodity grades to specialty alloys. In addition, the Department was responsible for the failure analysis of current product parts, and the recommendation for corrective actions. The laboratory was fully equipped for micro and macro testing of both metallic and organic materials.

Department Highlights

- The Department met its budget each and every year
- The Department routinely saved the company $20 million per year
- Completed over 2000 tests per year at best in class cost and quality
- Provided same day turn around for plant production issues
- Maintained a staff of highly competent experts at a high retention rate
- The Department strongly supported external technical organizations
- The Department was viewed by senior management as a vital asset to the company

Senior Manager Highlights

- Chairman of United States Automotive Materials Partnership (USAMP) -a consortium of Ford, GM, and Chrysler with Department of Energy (DOE) funding
  - Oversaw a technical portfolio of $15 million annually
  - Drove USAMP to a balanced portfolio that included steel, aluminum, magnesium and composites
- In addition to the duties above, oversaw the development of a web based network system that tracked and predicted testing costs for the entire Scientific Laboratory and Proving Grounds Organization (SL&PG)
  - Tracked $300 million in tests per year for all vehicle programs
  - Predicted vehicle testing cost for new programs.
  - Established the SL&PG budget based on the product plan (approximately $325 million per year)
  - Used the data to establish productivity improvement metrics that were tracked on Scoreboards throughout the SL&PG organization
  - Directed a dedicated staff of 3 people, in addition to the main department, to execute the tracking system along with 30 additional people within SL&PG through a matrix organization
  - The program proved to senior management, through hard data, that over 70% of the SL&PG testing organization was best in class for cost, productivity, and quality.

1997 -2001 Senior Manager of Body Materials Engineering

This Department functioned similarly to the above department focusing body materials such as sheet metal, welding, corrosion, composites, adhesives, and paint.

Highlights

- Key member of a process redesign team that completely reshaped the organization and internal processes used to paint vehicles resulting in significant improvements in quality and costs
- Key member of the auto steel partnership team that redefined the strategic vision for the organization which led to significantly increased technical funding from DOE
- Performed the same USAMP functions as the above department

1992-1997 Senior Manager of Organic Materials Engineering

This department was responsible for the Materials, Process, and Performance Standards for elastomers, fluids, glass and plastics applied to Chrysler vehicles. In addition the position was responsible for leading Chrysler composite activities associated with the Automotive Composite Consortium (ACC) – a consortium of Ford, GM, and Chrysler. Also, was one of the founding directors of USAMP in 1993, and an active participant in the Partnership for a New Generation of Vehicles (PNGV) sponsored by the Clinton Administration.

1989-1992 Supervisor Interior Plastics and Soft Trim

This position was responsible for the Material, Process, and Performance Standards of all interior decorative materials used for Chrysler products.

1985-1989 Senior Materials Development Engineer
The position was responsible for the development of plastics used for interior trim, instrument panels, and seats

1980-1985 The Duriron Company - Materials Development Engineer
The position was responsible for the development of plastic liners for corrosion resistant pumps and valves.

1978-1980 Chrysler Corporation - Materials Development Engineer
The position was responsible for the development of elastomeric materials for seals in transmission applications.

SUJIT DAS
Oak Ridge National Laboratory
National Transportation Research Center
2360 Cherahala Blvd.
Knoxville, Tennessee 37932-6472
Phone: (865) 946-1222
Fax: (865) 946-1314
Email: dass@ornl.gov

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 II 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 biomass energy analysis programs for the U.S. Department of Energy. Develop, manage and lead projects for the DOE Office of FreedomCAR and Vehicle Technologies. Responsible for a total annual budget of more than $750K consistently over the past several years. 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:

- 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)
- 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 Published

"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 Refereed Articles (Out of 50+ articles)

"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)

"Determination Analysis of Energy Conservation Standards for Distribution Transformers. ORNL-6847, Oak Ridge National Laboratory, Oak Ridge, TN, July 1996.

CHRISTIE COPLEN
Director
MB-technology NA LLC
400 E. Big Beaver Road
Suite 300
Troy, MI 48083
Phone: 248-434-5697/ 248-703-2576
Fax: 248 312-0279
Email: christie.coplen@mbtech-group-na.com
Languages: English, Spanish (intermediate), German (cursory)

Education

Michigan State University:	Master of Business Administration
University of Michigan:	Master of Science Major: Mechanical Engineering
Auburn University:	Bachelor of Science Major: Mechanical Engineering Minor: Spanish

Professional Experience

Since 2008	Director - Engineering Services, Mercedes-Benz Technology
2002-2008	CEO / President - Design & Consulting, AlterUrban, LLC.
2007-2008	Supervisor - Advanced Engineering Systems, Chrysler.
2006-2007	Manager - Advanced Safety Systems, Mercedes-Benz Research & Development.
2005-2007	Senior Engineer - Manufacturing, DaimlerChrysler.
1999-2005	Senior Engineer - Product Development, DaimlerChrysler.

Industry Expertise

- Automotive
- Design
- Start-ups
- Manufacturing
- Military

Methods & Skills

- Technology Assessments
- Process Improvement Mapping
- Program Management
- Design Optimization
- Black Belt Problem Solving

Key projects

- Defined strategic business direction, market position and the financial operating model.
  - Managed supplier contract negotiation and small business loans.
  - Led start-up activities including: business plan completion, state/federal licenses and permits, and financing.
- Managed OEM supplier bid process for a multimillion dollar award of advanced safety system technologies including technical analysis, project presentation and acted as the main contact for business segment.
- Led cost/benefit analysis of potential new advanced safety technology systems; balancing profit opportunities, safety improvements, market segment demand and related risks.
- Led product strategy to define business case for new technologies selection and funding approval resulting in a profit opportunity of $26.7 million within 3 years.
- Coordinated engineering, manufacturing, assembly, & quality departments within an OEM plant to an issue free launch directed the launch effort which included quality resolution meetings, the warranty/customer complaints meetings, and engineering design change management.

Dr.- Ing. PETER KLOSE
Principal
MBtech (Mercedes Benz Technology)
Division 5 (Germany)
Email: peter.p.klose@mbtech-group.com
Languages: German (native language), English

Education

1978-1984	Study of Material Science and Engineering, Univ. of (FAU) Erlangen-Nuernberg, masters degree
1984-1987	Doctorate Degree
2004	Lead Auditor (TÜV) Industrial Processes & Services

Professional Experience

1987-1993	AUDI AG Proj. mgt. Light Weight Design, New Materials & Technology
1993-2001	AUDI AG, Head of QM , Materials Technology
2001-2004	ThyssenKrupp Steel, Director R&D
Since 2004	TKS, Senior VP Dep. of Strategy & Business Excellence MBtech Consulting GmbH Technology & Innovation Management

Industry Expertise

- Automotive/truck industry OEM, OES
- Steel/Aluminum/Glass industry
- Rail industry, Aerospace
- Automotive suppliers (steel sheets, Mg. Al, plastics, fiber reinforced polymers, glass/ceramics, surface technology)
- Materials for nuclear power and gas turbines

Method Expertise

- Quality management, -methods and tools, Audit
- Value stream-, functional-, failure- analysis
- Launch Management Purchased parts
- Change-Management competence
- Intercultural competence (India, China)
- International technical assessments

Key projects

- Project management: Launch of innovative materials and production processes in car manufacturing (e.g. AL-Space frame Audi A8,A2, A6, E and S-Class)
- International supplier management (auditing, qualification and development of suppliers) e.g. in Europe, China, USA, India
- Validation of internal production processes of series production and global launch of innovative technologies
- Audit, qualification and change management of global suppliers
- Initializing and introduction of continuous improvement processes (TPS, FMEA, module strategy, standardization)
- Organization and development of technology and innovation management at MBtech.

EHSAAN TAQBEEM
Senior Associate
MBtech (Mercedes Benz Technology)

Summary of Experience: Strong in product development & program management. Twenty years of experiences in technology strategy, trends & diversification of advance energy technology, engineering, new investment portfolio, entrepreneurship, governmental relations and five years of public service.

Education

1994 MBA - International Business, Wayne State University.

1987 BSEE - Bachelor of Science Electrical Engineering, Wayne State University.

Professional Experience

2008-present: Senior Associate, Mercedes-Benz Technology.

2006-2008: *Executive,* Mercedes-Benz RDNA.

2001-2006: *Portfolio Manager,* Product Strategy, Chrysler.

Industry Expertise

- Automotive OEM and Suppliers
- Plug-in Hybrid / Alternative Propulsion Technology, Active Safety Tech, etc
- Center for Automotive Research (CAR)
- USCAR Industry Collaboration

Other Experience

- President, BAPAC (Bangladeshi American Public affairs Committee)
- Member , Michigan Governor Council on Asia Pacific Affairs Commission
- Chamber of Commerce / Board of Investment
- NAFTA (Trade Agreement)
- Tech Town Selection Committee (Technology Incubator)

Methods & Skills

- Develop & Deploy New Technology
- Technology Trends, Roadmap, Diversify & Strategy Development
- Funding Disbursement
- Effective Profit and Loss (P&L) Mgmt
- Personnel recruitment and training
- Systems Engineering Methodology
- Design for Six Sigma (DFSS), QFD and Voice of the Customer Analysis
- Vehicle Program Management (from Market Research to Launch)

Key projects

- Plug In Hybrid Technology, Product Development & Program Management, Investor Package for Venture Capitals
- Worked with TARDEC/ TACOM, DOE, DARPA for Hybrid technology, DHS
- Developed Strategies and Managed Personnel for the development of E/E, Active Safety, HMI, Chassis Electronics and Diagnostics
- $16.9M Annual Net Profit from Active Safety and $7.05 M from RSE
- Led a team to transfer Tools and Technologies between Mercedes-Benz and Chrysler
- Strategized commercial eletronics for automotive application
- Patent Pending – Collaborative Product Creation
- Led a NRB Business Team to Bangladesh for Trade & Investment
- Mobilized a Nationwide campaign for support of New Trade Bill H.R. 3905

MICHAEL J. VITEK
Vice President
MBtech (Mercedes Benz Technology)

Education

Bachelor of Science, General Motors Institute.
Major: Manufacturing Systems
Minor: Electrical Engineering

Professional Experience

2008-present: Vice President, Consulting Services, Mercedes-Benz Technology

2005-2007: Director – Consulting Services, Mercedes-Benz Technology

2002-2004: CEO/President, Burk, Vitek & Associates

1999-2002: Senior Manager/Account Manager, The North Highland Company.

1994-1999: Operations Manager/Account Manager, Sandalwood.

1992-1994: Associate, Lucas Engineering & Systems, Ltd.

Industry Expertise

- Automotive
- Internet Start-ups
- Venture Capital
- Retail/Consumer Products
- Manufacturing
- Military

Methods & Skills

- Organizational Assessment
- Technical Due Diligence
- Value Stream Mapping
- Supply Chain Optimization
- Value Analysis/Value Engineering

Key projects

- Led Organizational Development, Program Management, and Technical Assessment Activities with several Automotive Hybrid and Electric vehicle ventures:
  - Chrysler NSEV
  - Mercedes-Benz M-Class
  - Fisker Karma
- Led Lean projects driving significant improvements in cycle time, inventory and cost in the fabrication of automotive convertible tops, instrument panels, diesel engines, flat screen DVDs, and gearboxes.
- Led effort to deliver an incremental $42 million profit improvement at a Automotive OEM through Complexity Reduction and Consumer Option pricing
- Developed Collaboration Methodology to allow Engineers, Procurement Specialists, Marketing, and Suppliers to review Product, Process and Testing Specifications for impact to Product Costs.

ERIC JORK ZEISS
Senior Consultant
MBtech (Mercedes Benz Technology)
Languages: German (native language), English

Education

1954 Primary School Wien 9
1958 Residential school (Grammar school)
1963 Technologisches Gewerbemuseum (Polytechnic), Wien 9, Manufacturing systems and automotive engineering, High school diploma
1968 Military duty, Wien
1970-1974 Technical University Braunschweig, Electro technology; Graduate Engineer

Professional Experience

1974 General Quality Assurance VW AG
1982 Team Leader Product Audit, VW AG
1984 QA Manager VW / TES Berndorf/A
1987 QA Manager VW / BARKAS, Chemnitz
1990 Assistant to Group Manager QA
1992 QA Manager VW Bratislava;
1998 QA Manager Product Team VW Golf
1999 Manager Human Resources, Auel 2001-2004 Project Mgmt (self employed)
since 7/2004 MBtech Consulting

Industry Expertise

- Automotive (OEM and suppliers)
- Polymers and Carbon
- Electrical components
- Steel and iron industry
- Aluminum and magnesium pressure die casting

Methods & Skills

- QM automotive industry (SPC, CIP…)
- Process audit VDA Volume 6 and DPA
- PPAP and initial sample VDA 2
- Lean Manufacturing
- Management Assessment

Key projects

- Manager QM / QA: Planning, configuration and management QA for automobile and gearbox production VW Bratislava
- Support Relocation of a pressure die inventory from Stuttgart to Hof: Optimization process layout and product quality.
- Support Porsche DI-Cylinder-head: Optimization cast system
- Support iron casting VW crankcase: Reduction scrap rate
- Flat Spring Manufacture: Optimization product quality for NCV3
- Paint: Hedging water based innovative corrosion protection System.

Appendix B: Charge Questions

3040 Cornwallis Road ▪ PO Box 12194 ▪ Research Triangle Park, NC 27709-2194 ▪ USA
Telephone 919.541.6000 ▪ Fax 919.541.5985 ▪ www.rti.org

TO:

Christie Coplen (Mercedes-Benz Technology)
Sujit Das (Oak Ridge National Laboratory)
John E. Fillion (The Engineering Society of Detroit)
Donald E. Malen (University of Michigan)

FROM: Dileep K. Birur

CC: Michael P. Gallaher

DATE: September 2, 2010

SUBJECT: Charge Questions for Peer Review of Vehicle Mass Reduction Study.

The U.S. EPA's Office of Transportation and Air Quality is currently analyzing the potential to reduce light-duty vehicle mass through the application of low density or high strength materials, component consolidation, and changes to vehicle architecture. This holistic vehicle approach establishes a potential path for future feasible vehicle mass reduction in light duty vehicles to meet more stringent GHG and Fuel Economy standards. Lotus Engineering has completed a study entitled "An Assessment of Mass Reduction Opportunities for a 2017 – 2020 Model Year Vehicle Program." EPA is seeking the reviewer's expert opinion on the methodologies being used in this mass reduction work, the feasibility of the proposed solutions to meet all vehicle and manufacturing requirements, cost conclusions, customer acceptance and technology maturity, and whether they are likely to yield accurate results.

EPA has provided direction and charge questions for this review and these are included below. A teleconference call will also be arranged so that EPA can respond to questions from individual reviewers on the material that was provided for review.

The review will involve a written report that includes the response to the charge questions and any additional comments you may have, e.g., margin notes on review materials. Comments should be provided in an enclosure to a cover letter that clearly states the reviewer's name, the name and address of their organization if applicable, which model review documents/media were received by the reviewer and which were actually reviewed and a statement of any real or perceived conflict(s) of interest. The completed review reports are to be furnished to RTI by September 27, 2010.

Though the document under review is publicly available, please keep your comments confidential until the initial release of the peer review report by the EPA. If you review the document as a team, please provide the details of your team members as well.

Elements to be addressed in the Charge to the Reviewers of Lotus Engineering's report: "An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Vehicle Program"

Lotus Engineering's report is the result an extensive effort being carried out under contract with the California Air Resources Board to assess the opportunities to reduce light-duty vehicle mass as an enabling vehicle technology to meet future light-duty highway vehicle greenhouse gas (GHG) emissions standards. This report details the methodologies used by Lotus Engineering to determine the feasibility and associated variable cost impact for various mass reduction strategies and reports the results of this assessment. No independent data analysis will be required for this review.

Specifically, EPA is seeking the reviewer's expert opinion on the methodologies being used in this mass reduction work and whether they are likely to yield accurate results. Toward this end, we ask that each subject matter expert comment on all aspects of the report, with particular emphasis on the mass reduction methodology, the feasibility of the proposed solutions to meet all vehicle and manufacturing requirements, cost conclusions, and other key factors, such as the customer acceptance and technology maturity.

In preparing their comments, each reviewer should distinguish between recommendations for clearly defined improvements that can be readily made, based on data or literature reasonably available to EPA, and improvements that are more exploratory or dependent, which would be based on information not readily available to EPA. Comments should be clear and detailed enough to EPA readers or other parties familiar with the report to allow a thorough understanding of the comment's relevance to material provided for review. EPA requests that the reviewers not release the peer review materials or their comments until the Agency makes its report/cost model and supporting documentation public. EPA will notify the reviewers when this occurs.

Any questions about what is required in order to complete this review or request for additional background material from a reviewer shall be directed back to RTI's project manager for this work assignment. If a reviewer has any questions about the EPA peer review process itself, the reviewer may contact Ms. Ruth Schenk in EPA's Quality Office, National Vehicle and Fuel Emissions Laboratory by phone (734-214-4017) or through e-mail (schenk.ruth@epa.gov).

Appendix C: Questions and Answers Provided During the Review Process

Questions from Dr. Donald Malen.

1. Is the intent to show that the mass reductions of 20% and 40% are feasible?

   Ans. from EPA: Yes. The intent of the study is to demonstrate a methodology by which vehicle manufacturers could reduce weight. The report is not meant to replace all of the required validation to demonstrate feasibility, but rather a potential for reducing mass.

2. Is the intent to have a follow-up proof-of-concept by analysis or hardware build based on the recommendations of this report?

   Ans. from EPA: There are on-going proof-of-concept activities that will be informed by the recommendations.

3. Costs are highly volume dependent, was the target yearly volume specified?

   Ans. from EPA: The annual volume target was 60,000 (page-304 of the report).

4. Is the primary audience for the findings policy makers or influencing auto companies?

   Ans. from EPA: Both regulatory entities and vehicle manufacturers will be reviewing the peer review results.

Questions from Mr. John Fillion

1. Is any part of the Lotus report confidential?

   Ans. from EPA: Lotus report is publicly available study.

2. Will my report be public information?

   Ans. from EPA: The review report is confidential until the first release of the report by the EPA. The peer review results will be made public.

3. Can I discuss my work with anyone I choose while I am in the process of preparing the report?

   Ans. from EPA: Yes, if you are reviewing as a team, please provide the details of the other experts involved in the review work.

4. Should I let anyone know in advance if I expect to be critical of the Lotus report and its recommendations?

   Ans. from EPA: There is no need for advance notification. EPA only asks that each peer reviewer have a full understanding of the methodology being presented and associated constraints.

Questions from Mr. Sujit Das

1. How the benchmarking results were used in the final selection of vehicle subsystem components?

   Ans. from Lotus: "They drove the selection of LD components and were used as reference for the HD model." It is EPA's understanding that the concern was based on how the final selection of the benchmarking results were applied. (i.e., cost, weight, complexity, etc.). Hugh Harris to follow up with Lotus.

2. Why were the detailed cost factors at the component level available only for some of the vehicle subsystems, starting with chassis subsystems in the document?

   Ans. from Lotus: "In some cases subsystem only cost estimates were published. A judgment was made that either the background information would overwhelm the reader, e.g., there were several thousand calculations used to optimize the LD body in white cost or that the number of parts had been reduced substantially and that it was clear what parts remained."

3. Was the cost methodology used consistent with various subsystems and quantitative in nature? Any generic cost model used to insure that consistent underlying assumptions have been used across all vehicle subsystems? Any supporting information available in order to verify the underlying assumptions used in the methodology?

   Ans. from Lotus: "Was the cost methodology used consistent with various subsystems and quantitative in nature? Yes; material cost sources referenced as required. Any generic cost model used to insure that consistent underlying assumptions have been used across all vehicle subsystems? Standard industry practices were followed. Any supporting information available in order to verify the underlying assumptions used in the methodology? All supporting information used is referenced in the report; in many cases this was supplier dependent"

4. Was there any consideration of interdependency among vehicle subsystems in the final technology selection of vehicle components?

   Ans. from Lotus: "This was a key driver in parts elimination and consolidation."

5. Since the objective of the report is on non-powertrain mass and cost of two potential mid-term scenarios, what is the objective behind the inclusion of discussion on powertrain in the report?

   Ans. from Lotus: "The powertrain mass was required to develop the chassis system masses such as tire and wheel size. Additionally, fuel economy improvement estimates require total vehicle mass." In addition, the inclusion of a powertrain provided some perspective as to the downsizing and hybridization that could be facilitated through mass reduction.

Appendix D: Cover Letters

To: Messrs. Hugh Harris and Michael Olechiw
U.S. Environmental Protection Agency, Assessment and Standards Division (OTAQ)
2000 Traverwood Drive
Ann Arbor, Michigan 48105-2498 USA

From: Christina E. Coplen
MB-technology NA LLC (Mbtech)
Director - Vehicle Engineering & Government Solutions
christie.coplen@mbtech-group-na.com
400 E Big Beaver Road, Suite 300
Troy, Michigan 48083 USA

September 28, 2010

Re: Peer review of the Lotus Engineering "An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Vehicle Program."

Messrs. Harris and Olechiw,

MBtech received a memo containing charge questions and a link to the Lotus Engineering report from the U.S. Environmental Protection Agency (EPA) via RTI International. MBtech has reviewed all of the noted documents in developing the provided expert opinions. These opinions are contained in the MBtech "Peer Review of the U.S. Environmental Protection Agency / Lotus Engineering: *An Assessment of Mass Reduction Opportunities for a 2017 – 2020 Model Year Vehicle Program*" submitted on September 28, 2010.

MBtech declares that there are no real or perceived conflicts of interest concerning our involvement in this review for the U.S. Environmental Protection Agency.

We appreciate the opportunity, look forward to your feedback and continuing our working relationship.

Thank you,

Christina E. Coplen
MB-technology NA LLC
Director - Vehicle Engineering & Government Solutions
Mobile +1 248 703 2576
christie.coplen@mbtech-group-na.com http://www.mbtech-group.com

To:

Hugh Harris and Michael Olechiw
US EPA, Assessment and Standards Division (OTAQ)
2000 Traverwood Drive
Ann Arbor, Michigan 48105-2498.

From:

Sujit Das
Affiliation: Oak Ridge National Laboratory – UT-Battelle.
Email: dass@ornl.gov
Address: 12305 Fort West Drive
Knoxville, Tennessee 37934

September 28, 2010

Cover Letter to Accompany "Review of Lotus Study, An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Vehicle Program."

Greetings:

The documents that I received from EPA (or RTI International) were a memo containing the charge questions and the study report by Lotus Engineering.
I reviewed all of the documents that I received in developing my expert opinion as contained in the "Review of Lotus Study, *An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Vehicle Program*." submitted on September 28, 2010.

I declare that there are no real or perceived conflicts of interest concerning my involvement in this review for the U.S. Environmental Protection Agency.

Best regards,
Sujit Das

To:

Hugh Harris and Michael Olechiw
US EPA, Assessment and Standards Division (OTAQ)
2000 Traverwood Drive
Ann Arbor, Michigan 48105-2498.

From:

John Fillion
Affiliation: Chrysler (retired), Engineering Society of Detroit.
Email: john.fillion@comcast.net
Address: 6197 Silverstone Dr.
Troy, Michigan 48085
Phone : 248-505-5862

September 26, 2010

Cover Letter to Accompany "Review of Lotus Study, *An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Vehicle Program*."

Greetings:

The documents that I received from EPA (or RTI International) were a memo containing the charge questions and the study report by Lotus Engineering.

I reviewed all of the documents that I received in developing my expert opinion as contained in the "Review of Lotus Study, *An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Vehicle Program*." submitted on September 26, 2010.

I declare that there are no real or perceived conflicts of interest concerning my involvement in this review for the U.S. Environmental Protection Agency.

Best regards,

John Fillion

To:

Hugh Harris and Michael Olechiw
US EPA, Assessment and Standards Division (OTAQ)
2000 Traverwood Drive
Ann Arbor, Michigan 48105-2498.

From:

Dr. Donald Malen
Affiliation: University of Michigan, Ann Arbor.
Email: dmalen@umich.edu
Address: 1051 Rock Spring
Bloomfield Township, Michigan 48304.

September 28, 2010

Cover Letter to Accompany "Review of Lotus Study, *An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Vehicle Program*." Greetings:

The documents that I received from EPA (or RTI International) were a memo containing the charge questions and the study report by Lotus Engineering.

I reviewed all of the documents that I received in developing my expert opinion as contained in the "Review of Lotus Study, *An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Vehicle Program*." submitted on September 28, 2010.

I declare that there are no real or perceived conflicts of interest concerning my involvement in this review for the U.S. Environmental Protection Agency.

Best regards,

Donald Malen

Appendix E: Review Reports

Review-1 by: MB-technology NA LLC.

Review of Lotus Engineering Study "An Assessment of Mass Reduction Opportunities for a 2017 – 2020 Model Year Vehicle Program."

Introduction

The EPA has funded MBtech to act as a peer reviewer of the methodologies and results presented in the Lotus Engineering: "An Assessment of Mass Reduction Opportunities for a 2017 – 2020 Model Year Vehicle Program". Lotus Engineering's report is the result of a contract with the California Air Resources Board to assess mass reduction as a path to meet future light-duty vehicle greenhouse gas (GHG) emissions standards. MBtech has prepared this document independently and commented on the report, with particular focus on the mass reduction methodology, the feasibility of the proposed solutions to meet all vehicle and manufacturing requirements, cost conclusions, and other key factors. In preparing this document they have distinguished between recommendations for improvements and exploratory or dependent improvements. Finally, no independent data analysis was completed nor required for this peer review of the Lotus Engineering report. A link to the Lotus Report can be found at: [http://www.theicct.org/pubs/Mass_reduction_final_2010.pdf].

MBtech Background

MB-technology NA, LLC (MBtech), is a leading international engineering and consulting company for the automotive industry. The company has 2500 employees at locations in Europe, North America and Asia. MBtech is distinguished by the tightly meshed development and consulting services covering the entire automotive value chain. The MBtech brand combines all of its products and services into four segments: Vehicle Engineering, Powertrain Solutions, Electronics Solutions and Consulting. Flexible, inter-disciplinary project teams work in close collaboration with customers, suppliers and cooperation partners for automotive and other industries. MBtech supports manufacturers and suppliers beginning with the detailed specifications, design, modeling and testing to series maturity.

MBtech is a corporate subsidiary of the Daimler group. Business is conducted independently and in open competition to established engineering and consulting companies within the automotive, defense, aerospace and commercial vehicle arena. Their top priorities are customer-oriented services, confidentiality, and independent results.

Methodology

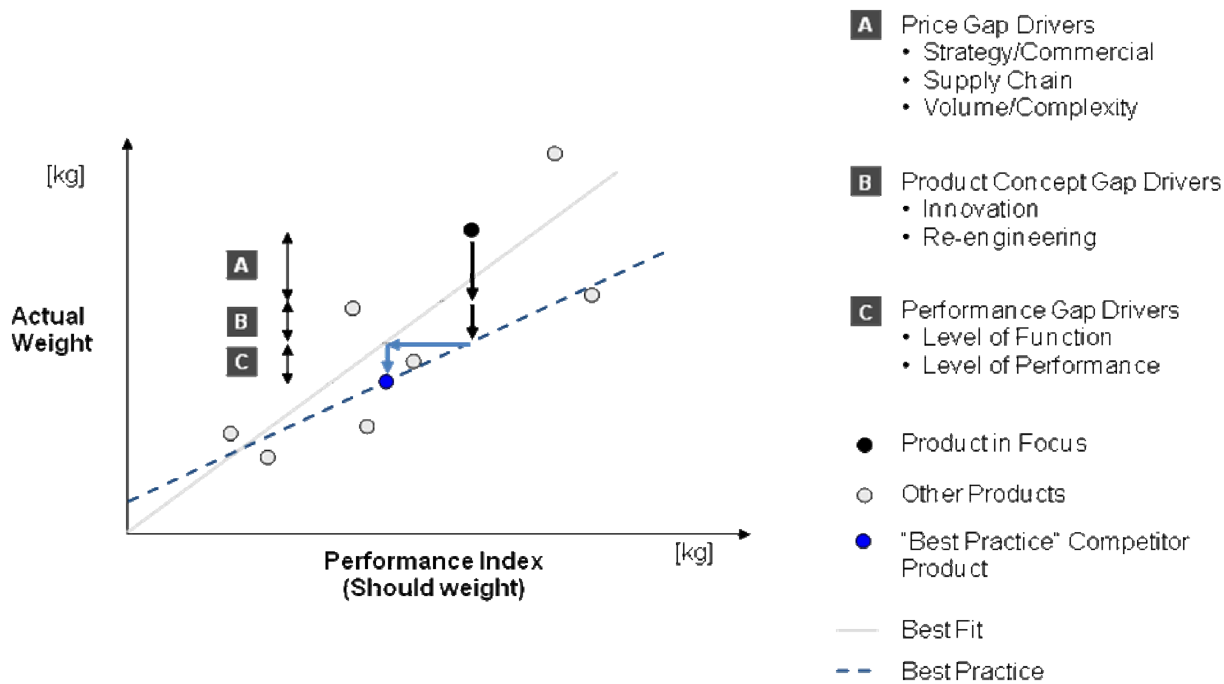
With respect to the methodology utilized in the development of the Lotus study, MBtech has selected four specific areas for potential improvement and further clarification:

- Technology Selection and Weight Calculations
- Piece Price Calculation
- Technology Development Timing
- Future Technology / Legislation

Technology Selection & Weight Calculations:

The report noted weight calculations or technology selection resulting in either normalized or predicted weight reductions, however, it has been the experience of MBtech that any normalization should include consideration for additional or reduced features and functions, rather than the scaled-weight approach that was utilized in the study's selection of benchmarked components. It is the recommendation of MBtech that a regression-based approach be utilized to determine the optimal solution set. Factors that should be considered as part of this regression-based study:

- Price Gap Drivers
- Technology/Product Concept Drivers
- Performance Gap Drivers



As an example, the hood in section 6.0: Closures. The normalized weight of the smallest hood is used as the baseline to determine the weight reduction potential of the overall Toyota Venza's hood. However, a detailed analysis of the selected benchmark hood would highlight a more limited feature and function set than provided by the Venza hood. Therefore, the structure of a smaller hood cannot and should not be linearly scaled to hoods of greater dimensions as noted in Table 6.3.d. Additionally, ancillary components, such as hinges, fasteners, deadening material and support struts will also have a larger contribution as hood dimensions grow. These items were also not included in the overall hood analysis.

It is MBtech's recommendation that a systematic tool, such as regression-based analysis, be used to select and normalize the impact of the selected technology. This would result in the desired and repetitive trade off of weight, cost, fit feature and functional requirements noted within the study.

Piece Price Calculation

The Lotus report bases costs entirely on the piece cost differential. The inclusions of the Total Landed Cost (cost to design, acquire, manufacture, and manage) and Total Cost of Ownership (Total Landed Cost + Cost to Assemble into Vehicle + Cost to Maintain + Cost of Service) would provide a much different perspective on overall cost impact to the market.

As an example, the magnesium casting for rear hatch costs should include the Total Landed Cost differential of tooling and Engineering Development & Design (ED&D). The actual tooling cost for a magnesium casting tool would not be significantly greater than that for other material options. However, the abrasiveness of the magnesium material would decrease the number of parts that could be produced by a given tool. It is the experience of MBtech that in higher volume applications, tool life would be 70% of standard tools. Additionally, the Total Cost of Ownership differential would require the investigation of costs for service and the potential replacement costs to the end consumer and the OEM.

It is the recommendation of MBtech that the total delivered cost be computed to understand actual impact on new technology development and implementation. As a secondary measure the following total costs should be reviewed, noted and categorized on overall new technology developments: transportation & logistics (land, sea, air, surcharges, dunnage, add-ons), product/component/system grouping (dunnage, quality controls, size, weight), customs/duties/taxes (international, domestic, C-TPAT), inventory based on supply chain length (effect on capital, inventory efficiencies, safety stock), additionally quality constraints due changes in technology (internal and external), global cash management (cost of cash, exchange rates, terms and conditions), supply chain tracking technology (domestic and international), compliance implications (ITAR, C-TPAT, staff, supply disruption), SG&A associated with supply chain effects (procurement resources, new relationship growth & maintenance, new supplier learning curves).

Transparency: System Level Cost Analysis allows for Risk to be evaluated with every decision

	China to Michigan	Indiana to Michigan
Piece Price	$35	$50
Raw Material Transportation (MI to China) vs. (MI to IN)	$4.00	$.80
Transportation per Piece Ocean/Rail/Truck vs. Truck Only	$9.94	$.79
Packaging per Piece Expendable vs. Returnable	$1.14	$.14
Inventory Carrying Cost	$.58	$.10
Floor Space Cost	$.08	$.02
Total Landed Cost per Piece	$50.74	$51.85
In supply Chain		

Figure 1.0: System Level Cost Analysis

Perhaps some of these fundamentals where considered as percentage of the pieces costs noted in the Lotus report, however, the details needed to come to this conclusion were not disclosed in the report. It is MBtech's conclusion that a holistic review is needed to fully understand the financial impact to the OEMs.

Technology Development Timing

For many High Development solutions, the design, development and testing windows for specific technologies will exceed the deadlines for implementation. As an example, the development time required for the magnesium casting for the rear hatch would be at a significant premium to applications utilizing standard materials. MBtech Program Managers typically plan a 30% development time premium for all magnesium applications. In addition to the design & development timeframe, testing constraints/unknowns would likely exceed the implementation window for the following elements of the vehicle development process: crash, NVH, durability, manufacturability, assembly and service.

Additionally, the majority of the weight saving technologies can only be implemented in conjunction with a completely new vehicle design and development program. Mid-model year face lifts or “top hats” will not be able to realize the majority of these technologies.

The proposed weight reducing technologies not only require significant development time but often major changes in production technologies and facilities. Therefore, lead time is also a limiting factor with respect to the weight reduction potential in the time frame being reviewed, 2017 - 2025. The vehicle development life-cycle can range from three to seven years; this is OEM and market segment dependent. Thus, the time period 2017 - 2025 is only one and a half of the required vehicle development life-cycle. This needs to be considered when assessing the total weight reduction potential in the targeted time period.

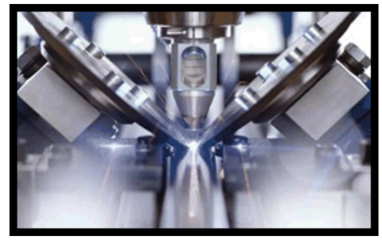
Finally, it is critical to note that many of the Low Development technologies are already in production. To that end, MBtech finds that many of the High Development technologies are in production or planed for near-term mass production. An assessment of OEM usages of the various technologies presented in the LD and HD concepts should be undertaken. This effort would allow for statistically valid review of the industry and would provide an understanding of what is achievable versus a generic extrapolation based on a sample size of one vehicle.

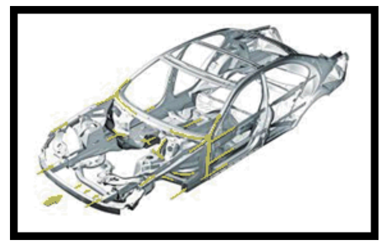
Future Technology / Legislation

Finally, with respect to the vehicle mass, the future vehicle technology demands must be taken into account. These requirements will be driven by legislation and consumer demand. The major growth technologies in North America will likely be associated with safety. This is because of the emphasis that the National Highway Traffic Safety Administration (NHTSA) places on reducing crashes and saving lives associated with vehicle crashes. The safety-related technologies will be adopted at a rate that depends on legislation, which is heavily influenced by NHTSA**.** While the safety features have intrinsic value to both the OEM and the end consumer, this is a cost penalty allocated to the vehicle cost but also to overall weight reduction efforts.

Section 5.0: Body Structure

Low Development (LD) and High Development (HD)





Light weight concepts require a collective consideration by automotive manufactures. An individual approach to each individual component does not result in an overall weight reduction. Additional expenses such as NVH, strength, crash, corrosion, repair, environment, recycling, material availability, manufacturing, thermal management, drive comfort must be considered. In addition to cost, quality and quantity, many approaches are driven by legal requirements, image, corporate strategy and the market place.

MBtech proposes a reduction of 10-12% by 2020 is realistic. Many technologies noted in the Lotus report failed in series production implementation due to the fact most high tech materials and production processes are not globally available (forming technology, joining technology, surface technology) nor are they sufficiently developed for series production (test procedures, repairing methods). Thus, the demand on the global supply-base, incumbent processes and technology advancement will increase greatly in the years to come. This is especially true with globalization and the increasingly diversified manufacturing footprint.

Production locations must be reviewed as the standardization of materials and the need for specific material properties become a more critical issue to the overall body structure. Production location changes combined with various governmental mandates and incentives to increasing local part content will drive inconsistencies in the overall material content. These issues may limit technology implementation.

Trends: High Strength Steel

Steel will continue to be a critical material and the foundation of the LD area.

In the HD arena the challenge will be the availability of suitable forming technologies (ex. warm in-mold hardening), joining technologies (ex. cold joining technologies such as Flow Drill, punch riveting and clinching) and surface technology with multi-material design. With the new technologies, new challenges will appear with respect to corrosion and surface technology in body construction for the OEMs. As an example, OEMs will be faced with leakage currents or hydrogen embitterment. Developments of new materials and constructions are not likely in the near-term as an extended understanding of the material properties (static / dynamic) and the overall context of construction are needed. The current automotive suppliers often lack the basics in high developed alloys (HSS, DP, LIP, TRIP and TWIP steels) for numeric forming, vehicle properties (ex. modal analysis) or crash simulation. Other considerations must be reviewed as well such as packaging, integration, and quality. (Figure 2.0)

The packaging and integration of these parts must be included in the overall cost calculation. This is important as the use of new materials can often be justified by the elimination of components (sandwich base with thermal insulation) or by enhanced quality measures (elimination of additional insulation material or dynamic vibration absorber).

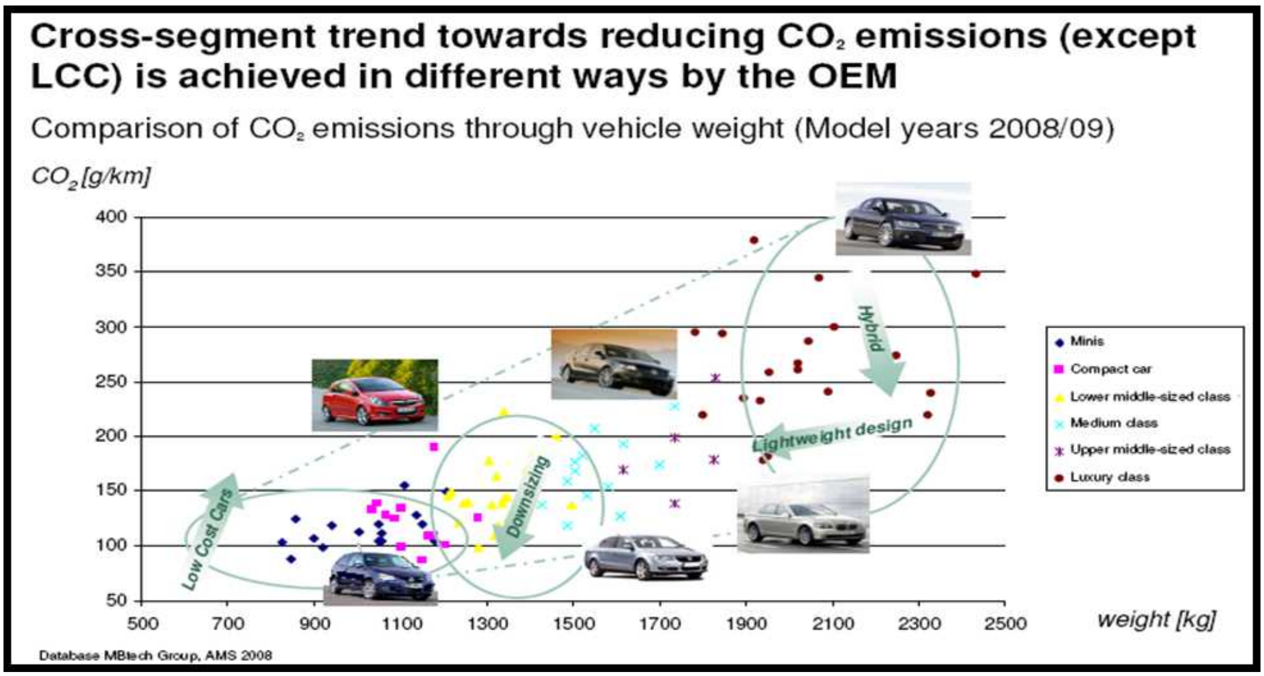


Figure 2.0: Trends toward reducing CO_2

Trends: Aluminum

Depending on material, Audi Space Frame (ASF) or profile intensive constructions are prevailing in the industry. Problems exist in finding the required experience in forming and surface technology. As an example, spot welding aluminum alloys is not reliably applicable in the automotive arena. Alternative processes, such as friction steel welding, are not yet applicable in automotive manufacture due to the low wall thicknesses. Rather, in this area, there is a trend towards low-temperature diffusion soldering, bonding or a combination of glue and riveting.

Trends: Magnesium Castings

Magnesium continues to be used to a high degree in several automotive series for interior application such as steering wheels, switchboards, seat frames, and electric components casings. Magnesium is only rarely used in exterior application due to surface protection issues. However, there are a few applications of usage for exterior systems such as the current Mercedes-Benz E-Class trunk lid. Currently there is a push within the industry to develop new technologies focused on improving the surface protection of magnesium sheets (ex. MOCVD processes, ZnMgAl layers). As new technologies are available that resolve the surface protection issue; magnesium components used by automotive manufacture will increase. The manufacturing effects must be understood and incorporated into the cost study.

The actual tooling cost for a magnesium casting tool would not be significantly greater than that for other material options. However, due to the abrasiveness of magnesium, tool life would be 70% of standard steel based tools.

Trends: Composites

The primary European OEMs are focused on the development of fiber reinforced bodies. There is a concentrated effort in the development of new matrix systems with ductile and graded material behaviors. The use of suitable joining processes, surface protection, long-term suitability and availability of sustainable and cost effective repairing concepts are still not resolved. In particular, with respect to fiber composites, there is a trend from isotropic materials towards anisotropic, micro dispersed and nano materials in material selection. The potential of these material properties in the area of automotive light weight manufacture is not yet understood. As an example: The combination of material and dimensional properties, as noted in the Thyssen Krupp report, (tailored blanks, tailored rolled tubes) results in a cost neutral approach and some potential savings.

Benchmarking

In comparison to current European vehicle series, the benchmark shows similar approaches and values. European OEMs rely on functional light weight construction and multi-material design concepts. As noted in the Lotus study, the largest applications are in body, chassis and the drivetrain.

Architecture Notes

There are a variety of possibilities with respect to vehicle construction. With the introduction of new drive technologies the possibilities will increase. In general the realization of these concepts depends on available of robust and cost effective processing, joining and surface technologies. New processes newly implemented in series production or in development for near-term deployment are: super plastic reshaping, hydro forming, mechanical joining, glue, clinching, visible frame structure, targeted application of "bulk structures", and bionic design.

Floor and Under Body

As noted by Lotus, there is an increased usage of micro disperse thermal insulation and sandwich materials in the floor and under body assemblies. To validate Lotus' findings, MBtech finds that thermal insulation will result in a cost neutral weight reduction of 4.8kg. Additionally, MBtech studies have shown that the thermal insulation introduction results in a modular design concept resulting in the elimination of up to ten stand alone sub-components based on historical design reviews (Figure 3.0).

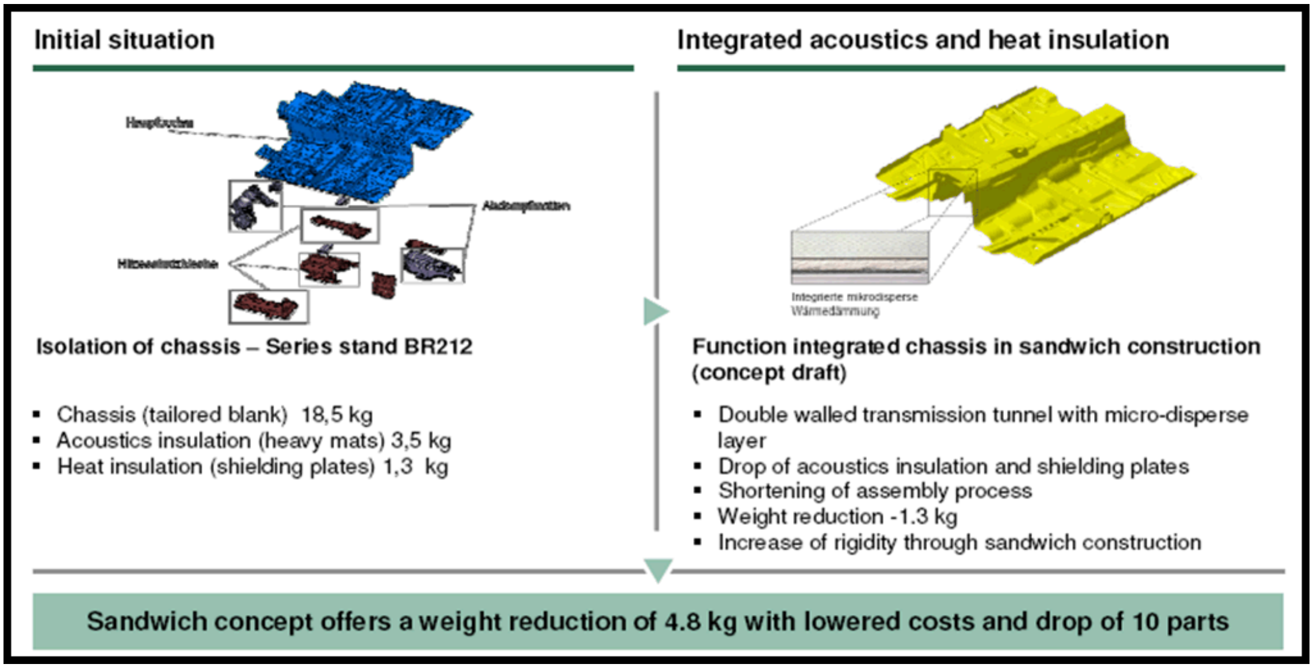


Figure 3.0: Integrated Acoustics and Insulation Study

High Development Summary

Based on the information presented, a weight reduction of approximately 60kg with the cost impact of more than 135% is moderately achievable for the Toyota Venza and, perhaps, other vehicles in this segment. It is the estimation of MBtech that 40-50% of the hypothesized weight saving is achievable. The total landed cost and cost of ownerships must be considered, MBtech proposes that the overall cost impact will be much higher than noted in the Lotus report.

To realize this potential weight savings, the materials, forming and processing technologies have to be developed and deployed. This will affect the fast-follower OEMs and suppliers. Further weight reduction potential can be achieved with new designs and the functional integration of concepts within the development organizations.

Finally, these findings cannot be extrapolated to other vehicle segments or OEMs currently deploying the technologies presented in this Body Structure HD review. The findings are very vehicle and model specific. Extrapolation must be done only with a detailed understanding of how each OEM is using the proposed technologies. (Figure 4.0)

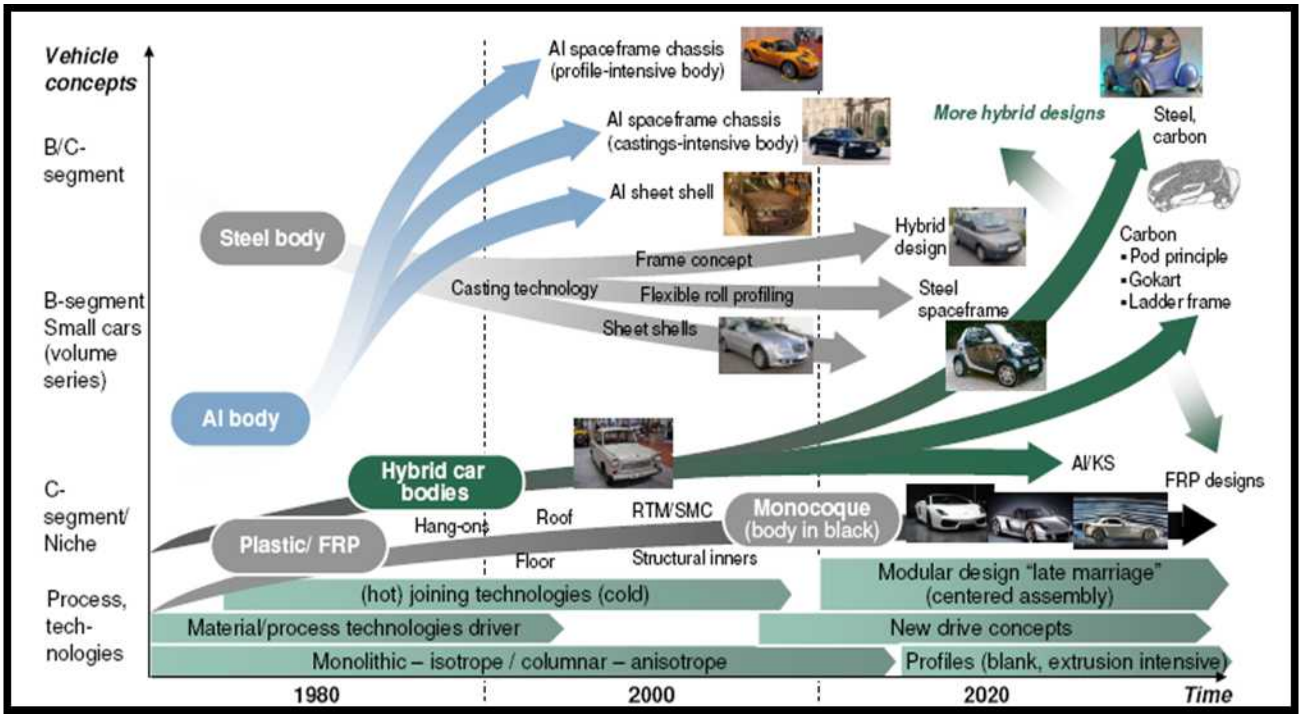


Figure 4.0: Body Desings of the Future

Section 11.0 Air Conditioning System:

Trends

The basic automotive air condition system has been in use for over 60 years. However, there have been some systematic advancements that boost overall improvements. The latest systems are primarily based in the energy saving combination of an IR-reflected insulated glass, solar roofs, electric fans and compact air conditioners. With this combination, it is possible to reduce the cabin temperature by 20 degrees while realizing a considerable weight reduction in the air conditioner and cooling liquid required. Other technologies are based on the recuperation of thermal energy from exhaust gas, efficient insulation with micro dispersed materials and the use of heat exchanger made of plastic.

Benchmarking

Additional weight reducing technologies can be expected in this arena with the use of smart structures and electric drives for a load dependent control.

Results

In spite of the highly refined and developed air conditioning system technologies, there will be new developments and advancement in the future. The new systems will incorporate the use of solar energy and/or rejected heat. These advancements are expected to further reduce the weight of the current HVAC systems.

Section 9.3 Instrument Panel, Console and Insulation:

Trends

As described in the report, there are numerous opportunities for "Plug and Play" and integration of E/E Components for mass reduction, however, that there is mismatch in life cycle between Consumer Electronics and Automotive Electronics product development. When planned for mass reduction, the life cycle implication must be considered. The differences in the traditional product development processes for automobiles versus electronics are emphasized and demonstrated below.

The first challenge is the timeline. Automobiles are developed over three to five years, approximately, before production begins. In electronics the development phase for many technologies, especially consumer electronics that might be used for infotainment and telematics, is often under twelve months. There are also differences in product quality expectations and validation, which will be discussed later. The vehicle development process is another aspect of co-product development that differs significantly between auto companies. Companies in Japan tend to make fewer performance requirements demands on the supplier. Specifically, Honda is identified as the most straightforward companies to work with. Generally, they provided the performance expectations, geometric requirements (space), and connectivity requirements, and kept these items constant for the supplier across their vehicle platforms. Experiences with other OEMs, both in the U.S. and in Europe, are less stable and supplier demands are higher.

Wi-Fi / Entertainment / Wireless

Infotainment products have a short lifecycle which resembles that of consumer electronics more closely than it does the relatively long lifecycle of automobiles. This lifecycle results in consumers replacing external infotainment products more often than they replace their vehicles, giving producers of infotainment products potential for more frequent sales. This will place an additional burden on both parties as newly developed products would have to be backward compatible.

While wireless connectivity, particularly through widespread application of Bluetooth technology, is already in use in current vehicles, care must be taken with Electromagnetic Compatibility (EMC) and other possible interferences. Not to mention hackers ability to disrupt the intended functions. This measure must be taken for the critical vehicle features like safety and propulsion systems. The next hurdle is the transfer of power wirelessly, the trend is continuing and the EMC issues are becoming more prominent.

Information Display / Open Integration

While earlier versions of head-up displays have been available in the marketplace for a number of years, the future designs will address the brightness and resolution challenges of current systems while also being capable of displaying much more complex images, such as instrumentation, on the vehicle's windshield. The streaming of customized or on-demand content to vehicles is expected to appear this year. The challenge automakers and suppliers face in providing this capability is not the technology necessary to display content. Rather, finding the necessary bandwidth or accomplishing sufficient compression to stream the content to the vehicle is the main obstacle.

Telematics, the use of telecommunications and information technology, are the first step towards deploying a true Intelligent Transportation System (ITS). By enabling communication between the vehicle and the road system (Vehicle Infrastructure Integration, or VII) and between vehicles (Vehicle to Vehicle, or V2V), telematics promises to benefit both the driver and society as a whole by easing traffic congestion and improving traffic system efficiency. This year, the first examples of Vehicle Infrastructure Integration (VII) are expected to be deployed. A year later, in 2011, the first examples of Vehicle to Vehicle (V2V) communication are anticipated. Each of these telematics systems is then expected to continue increasing its market penetration, with the potential for universal adoption being ultimately mandated by government authorities. Telematics technologies are extremely challenging to deploy as they require close cooperation between automakers, suppliers, government, and local officials. This will be one of the next hurdles faced by the automotive industry.

Telematics navigation products have enjoyed popularity with consumers and are beginning to migrate to less expensive vehicle segments. The chief benefit of these benefits includes turn-by-turn navigation that is integrated into the vehicle's audio system, as well as local information such as restaurants and points of interest for tourism. Information on traffic congestion and suggested re-routing is beginning to be made available in North America after having been available in many European and Asian countries for several years.

This type of plug & play requires open E/E Architecture and requires non-proprietary technology that minimizes development risk. Additionally, OEMs will develop significant firewalls between the vehicle electronic systems and any consumer product that connects to the vehicle. The computer on wheels concept is inaccurate because of the open operating system that exists on a computer will never likely exist on an automobile.

There is a growing trend toward non-OEM accessorizing and personalizing of the vehicle with options available through the dealer network in multiple areas including electronics. The aftermarket availability of accessories, especially electronics, has mushroomed in North America with the huge growth of the Specialty Equipment Manufacturers' Association (SEMA). SEMA products represent hundreds of electronic technologies that, in some instances, are intended to replace ones from the OEM (e.g., radios, powertrain controllers, DVDs, televisions, etc.), or interact with OEM equipment. There are several issues that confront the SEMA companies:

- SEMA involves an eclectic group of companies that are difficult to coordinate.
- Warranty issues when an aftermarket technology affects the vehicle's performance.
- Many companies work in isolation from the OEM even though their technology may interact with OEM devices. The ability of the aftermarket companies to integrate their technologies into improving system performance is limited.
- There may be legal issues involving safety and liability.

Section 9.5 Control Systems Benchmarking:

Trends

The need and opportunity from integrating multiple electronic systems on the vehicle greatly outweighs the challenge of developing isolated technologies. In the case of alternative fuel vehicles, for example, development of comprehensive energy management and control systems is lagging the development of the powertrain systems themselves. Current electronic systems are poorly integrated and far from optimal. The challenge for OEMs and electronic systems suppliers to develop comprehensive, integrated technology solutions has been uniformly identified as a critical issue. U.S. companies (OEM and suppliers) tend to be functionally organized with different functional groups possessing deep knowledge in narrow fields (brakes, powertrain, body, etc.), and the expertise to integrate technologies is a barrier to developing integrated solutions. However, the new Lexus is consolidating the number of on-board controllers from 70 to 4 through systems integration, resulting in significant cost and complexity reduction. The opportunity to integrate the communication function of the wiring harness (e.g., with fiber optics) and elimination of redundant electrical components (like numerous controllers) could result in a mass savings of nearly 200 pounds. At roughly a $2.00/pound value, this could be worth nearly $400 per vehicle.

The key areas of growth opportunity from the Electrical area will result from technology integration. Individual technologies will continue to grow rapidly, but the biggest benefit will occur from integration of different technologies. This is true for both safety and infotainment applications and such materials substitution would need to be evaluated individually and against other light-weight materials options. At the end, a full evaluation must be done in light of cost and function versus the number of pounds saved.

Electronics/New Technologies

There are additional possibilities to reduce weight by using new technologies in the electrical arena. These technologies include zero current switch technology. The technology is based on electrostatic fields, which are used in substitution of wired switching functions. The switches can be used for the adoption of wireless and switch less sensor systems, adoption of non-contact switches, anti-trap systems or safety equipment (e.g. roofs of cabriolets, electric door), and connection with bus systems. The possibilities for system supplier/ vehicle manufacturer are endless. They provide the opportunity for new materials, surface design and functionality, reduction of wiring, reduction of space required, decoupling of technical function and feel of the surface, and easy update and expansion of function by software updates. This technology has a high potential due to its estimated weight reduction impact of 20-25%, approximately 30% reduction of installation costs, reworking costs and quality costs, improved freedom of design without higher complexity of E/E systems, increasing the degree of confectioning with concurrent cost reduction, high degree of standardization, improved user's ease of use, improved comfort by recognizing the approach to operating elements, and option to personalize various functions.

Section 12 Electrical:

Trends

The Copper Clad Aluminum (CCA) approach noted in the report is Toyota specific, the technology was used by some suppliers for U.S. customers at a low implementation rate. At German OEMs, the trend is focused on pure-bred (stranded) aluminum cable. The pure-bred (stranded) aluminum cable weight reduction potential is minimal. However, with cost as the primary driver, there are significant cost disadvantage between the connecting method of aluminum cable and the contacts. In the Lotus study, it is assumed that Toyota uses CCA for all cable sections.

In contrast, the German OEMs will only see an aluminum (Cu-) cross section of 2.5 mm². The cross-sectional distribution based on the currents leads to an accumulation in 0.35-0.5 mm² (aluminum replacement due to lack of strength is not represented here) and only 2.5 mm² is an aluminum wire in the combination of number of lines times the mass over the line. In the previously mentioned range, 0.35 to 0.5 mm², a very different approach is available and is already in production: the copper line from 0.35 to 0.5 mm² is replaced by a 0.13 mm² conductor with high strength core (usually copper base alloy). Additionally, 0.08mm² is already in the development process. Weight reduction potential in the mid-class is greater than 3kg. However, the potential of aluminum must be taken into account, thus the delta could remain within the specified 3kg. At the current copper prices, this technology is almost cost-neutral, but decreases with further development of mass manufacturing and with the increasing demand resulting in higher prices of copper.

The weight reduction through the thin-wall cladding/coating or ultra-thin walled insulation is already available and on pilot projects and in series production in the USA and Europe. Thus, MBtech opines this should not be included in the HD category.

Pilot projects can usually accomplish 20-40% of the theoretical weight saving potential due to the imposed boundaries such as the existing contacting systems, space limitations, the specific requirements for strength, flexibility, corrosions resistance and temperature stability. However, MBtech believes that no more than 75% of the HD electrical results could be realized during the period being considered.

There is a high potential for weight reduction within the electrical architecture: reduced number of bus lines, optimization line lengths with optimized placement of components and channel layout, minimizing cross-sections with improved design methodology and possibly improved separation elements. This can only achieve by a holistic design approach that currently fails due to many functional and organization limitations.

High Voltage Applications Considerations

Interestingly, there is no mention of the forty-two volt electric system in future vehicles that would have a significant impact on the introduction of electronic technologies on the vehicle. This will help reduce the wiring bundle size to a minimum, as less current is required to power up similar electrical devise. Forty-two volt systems will be an important step toward introducing more electro-mechanical systems. In order to fulfill the 2017-2020 expectations, particular attention must be placed on the alternative drive systems developments.

These areas include fundamental areas of potential weight reduction as a result of the substitution of metal and polymer materials in the hybrid and electric drivetrain. Electro technique polymer materials are preferably suitable for the isolation of live parts and components. They form the material for the case, cable and connector. Polymers are mainly electrical insulators. Properties such as resistance, dielectric strength and tracking resistance are important for the use of insulating material. The thermal properties of the polymers include thermal conductivity, dimensional stability in heat and specific fire behavior. Today the current polymer technology enables the replacement of non-metallic ingredients in many motor vehicle applications. In the case of the electrical control units, which require an electromagnetic shielding, metal casings have been the best solution until now. Although polymers are currently used for some shielding of motor vehicles, they are molded components, which are coated with a metallic layer with an additional immersion or spraying process. The main disadvantage of this approach is limitation of cost savings potential. The progress in digital electronics are the essential facts which explain the large number of new vehicle systems and the increasing number of modules with high component density. The decreasing digital circuits support the need for space savings. The use of these components in harsh electrical environments (e.g. at existing HV systems) induce constructive and technical design problems.

In the light of the preceding paragraph, it is necessary to develop shielded electronic casings to avoid interferences with other modules and to prevent emissions of interfering signals which could influence other systems.

Conductive polymers, which can be manufactured in one step, are as powerful as the metallic components on the market today. These new materials offer significant advantages in design and application. They enable the replacement of metal casings in many motor vehicle applications such as in the high voltage ranges. The following list provides examples of areas were metal was substituted by high performance polymers:

- Electric axle drive and starter generator – use of polymer material as casing or casing components (also hybrid versions)
- Power electronics and inverter – substitution of aluminum by plastic in the cooling system of DC/DC-converter
- HV harness – narrow-banded partially shielded for the decoupling of high and low voltage circuit to reduce weight of the proportion of shielding of harness
- HV battery – casing or bearing structure made of polymer composites or mixed material design (e.g. aluminum foam, steel, polymer mix)

Electric conductive polymers with Carbon Nano Tubes (CNT) could be used for light weight casing material in future. CNT comprise of one to several graphite layers, which are rolled up into tubes. Because of their structure they have extremely high electric conductivity properties. Furthermore, they have excellent mechanical characteristic values such as elastic modulus and tensile strength. The expected applications are ideal to fulfill the requirements in terms of weight reduction and EMC security.

Another economically and environmentally important point: the development of low-emission vehicles has become a critical issue for all OEMs. The motivation for OEMs comes from mounting pressures from lawmakers (emission legislation, consumption rules, driving bans, limitations, local fees, and ZEV laws), society (awareness on costs and environment, climate change concerns, lobbyists and organizations), the competition (global push and hybrid positioning), and the energy industry (fuel availability, reserve stocks, and the decline of oil delivery). Due to the limited availability of oil and the continued reduction of emission limits, many automobile manufacturers are placing more emphasis on "e-mobility" to offer mobility solutions in future. The trend towards battery-powered electric vehicles will replace conventional vehicle components such as combustion engine and transmission. Electric motor, power electronics and high-voltage batteries now appear in our vehicles. However, this development and the production of battery-powered electric vehicles requires fundamental modifications to many of the conventional components in the areas of body, chassis and of course of electronics. They have to be redesigned and reinterpreted.

Intellectual Property (IP) Rights/Security/Architectural Integration

The Lotus study is based on utilizing commercially available, open source solutions to replace proprietary architecture. However, MBtech suggests that the integration of the Apple iTouch for use as Center Console Human Machine Interface (HMI) will not be as streamlined and cost effective as noted in the report. The following IP rights, security and architectural issues hurdles will have to be eliminated: access to base/core technology, application development, and architectural integration.

Finally, for most OEMs the interior and customer interface are brand specific and closely associated with brand identity. Commonizing the HMI globally or even across vehicle brands within an OEM will reduce the end-consumer appeal, especially in mid-level or luxury vehicles. Thus, MBtech feels this concept will not be widely adopted as this is a tightly held image consideration for all OEMs.

Conclusion:

The Lotus report has merit; specifically as it apply to the Toyota Venza. However, Mbtech recommends additional studies to validate the materials, technologies and methodologies referenced in the Lotus Engineering report. Feasibility of the various technologies presented in the report is not proven for series production implementation. These technologies must be reviewed and the impact must be taken into account on the overall proposed weight reduction calculations. As an example, the proposed plastic injection molded fenders versus steel is not realistic as demonstrated based on various MBtech investigations.

MBtech finds that maximizing value-added propositions by developing complete systems or system-focused solutions will result in overall fuel economy gains via weight reductions. This concept is explored in the report and is directionally correct. Achieving progress and improving fuel economy must be done with the optimization of the following areas in addition to weight reduction: quality, durability, compatibility, aerodynamic efficiency, parasitic reduction and machine efficiency improvements, differentiation from competitors, and innovativeness which some end-consumers demand. When focused on light weighting, true potential can be realized with a holistic approach of efficient material processing, innovating joining technologies, reduced complexity, functional integration, modular designs, and flexible manufacturing concepts (Figure 5.0). MBtech finds the primary technologies in which to invest time and resources are: light weight materials and the other noted enablers to achieve mass reduction, aerodynamics, operating efficiency of the vehicle, and the total value proposition to the end-consumer.

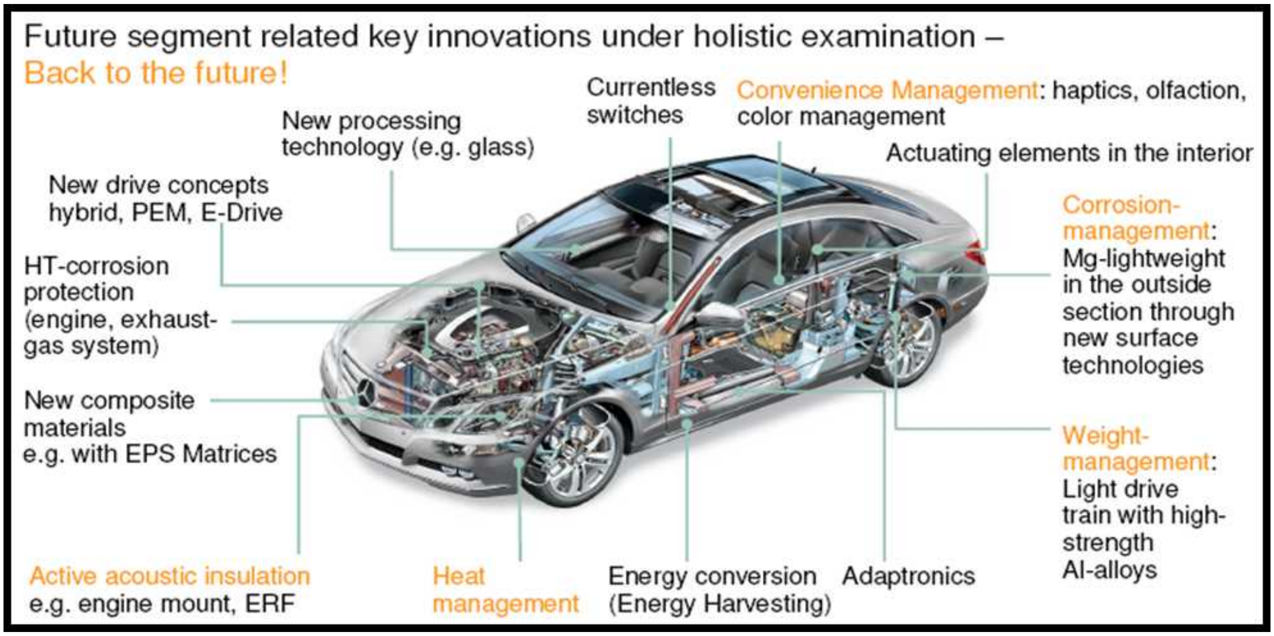


Figure 5.0: Trends in Technology

Finally, it is critical to note that many of the Low Development technologies are already in production. To that end, MBtech finds that many of the High Development technologies are in production or planed for near-term mass production. An assessment of OEM usages of the various technologies presented in the LD and HD concepts should be undertaken. This effort would allow for statistically valid review of the industry and would provide an understanding of what is achievable versus a generic extrapolation based on a sample size of one vehicle.

MBtech's findings are summarized as follows:

<u>Body-In-White Requirements:</u> Additional studies must be done that consider the following vehicle body-in-white requirements: crash, NVH, strength, corrosion, repair costs, manufacturing and associated costs, environment and recycling concerns, and material availability. All aspects in the vehicle life cycle must be reviewed and considered in the overall weight reaction analysis. Impact of weight reduction on other vehicle requirements - safety, fatigue strength, NVH, corrosion - have not been considered in the report.

Additionally, vehicle packaging issues were not fundamentally considered in the Lotus report. This will have a considerable impact on the feasibility of various proposed technologies and the downstream cost with respect to manufacturing, dunnage, transportation, and repair cost.

Costing Methodology:

a) Piece Cost Calculation. In the initial Lotus study, many of the selected lightweight technologies are cast a favorable Piece Cost comparison. While the piece cost comparison might have been favorable; total costs, whether measured as Total Landed Cost or Total Cost of Ownership, would show a more realistic view on the impact of select lightweight technologies to the industry.

b) Technology Selection and Weight Calculations: It is MBtech's recommendation that a systematic tool, such as regression-based analysis, be used to select and normalize the impact of selected technology. This would result in the desired and repetitive trade off of weight, cost, fit feature and functional requirements noted within the study. (ex. Hood)

Technology Development Timing: In many of the presented examples, the time to fully design, develop, and test would exceed the expressed implementation timing. This will have a varying effect on the industry based on the technical advancement and market segments targeted by each OEM. This will drive varying cost, timing and quality advantages to those currently using the proposed LD and HD technologies.

Additionally, the majority of the weight saving technologies can only be implemented in conjunction with a completely new vehicle design and development program. Mid-model year face lifts or "top hats" will not be able to realize the majority of these technologies.

Finally, the proposed weight reducing technologies not only require significant development time but often major changes in production technologies and facilities. Therefore, lead time is also a limiting factor. The time period 2017 - 2025 is only one and a half of the required vehicle development life-cycle. This needs to be considered when assessing the total weight reduction potential in the targeted time period.

Future Technology / Legislation: As the industry is tasked with more stringent safety and exhaust gas emission requirements, the impact on weight must be considered in more detail in any future study. These technology applications are expected to result in weight increases in future vehicle designs.

Propulsion Systems: By 2030, the number of vehicles on the road is expected to nearly double. As a result, CO_2 production would increase by 54%. However, carbon emission reductions of 50% are required to stabilize atmospheric carbon levels, therefore stabilizing average global temperatures. The impact of advanced technology on the total vehicle weight must be a fundamental consideration on overall vehicle weight reduction. As fuel cells, CNG, hybrids enter the market place, the overall weight of these systems range from 11% to 40% more than the standard ICE powertrain systems. This must be a consideration as environmental and oil dependency concerns drive the non-traditional powertrain configurations. The implementation of advanced powertrain technologies well add significant weight to the vehicle which has not been adequately considered in the initial study completed by Lotus.

Intellectual Property/Security/Architectural Issues: While commercially available technology might be used to replace proprietary systems, further delays/issues will ensue as automakers attempt to modify provided core technology, as well as integrate these systems into their own architecture.

Assessment of OEM Deployment of the Lotus LD & HD Technologies:
Finally, it is critical to note most luxury vehicle OEMs, including Mercedes-Benz, have already reached the Low Development weight reduction level and have implemented the majority of the High Development body material concepts. Thus, MBtech fundamentally disagrees with the Louts Engineering report on the following two points:

- 21% total vehicle (less powertrain) mass reduction will not be achievable by 2017
- 38% total vehicle (less powertrain) mass reduction will not be achievable by 2020

It is not possible to reach an additional 20% vehicle reduction by 2017 for OEMs which have already implemented these concepts. MBtech estimates that an additional 10-12% vehicle mass reduction is possible by 2020 for ICE based vehicles. Most OEMs, especially those working within the high tech / luxury vehicle market segment, are using many of the technology concepts noted in the LD and HD sections of the Louts report.

Finally, in reviewing luxury vehicle OEMs that have implemented the proposed LD and the majority of the HD technologies, the overall vehicle weight has not been drastically reduced. This is primarily due to the introduction of new technologies which add to the overall vehicle complexity and weight.

Acknowledgements:

The following MB-tech team contributed to the peer review of the U.S. Environmental Protection Agency / Lotus Engineering: "An Assessment of Mass Reduction Opportunities for a 2017 – 2020 Model Year Vehicle Program" report:

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2. Eric Jork Zeiss, Technology & Innovation Management
3. Peter Klose, Body in White & Innovation Management
4. Mike Vitek, Strategy & Operational Consulting, Program Management
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Review-2 by: Sujit Das (ORNL-UT-Battelle).

Review of Lotus Engineering Study "An Assessment of Mass Reduction Opportunities for a 2017 – 2020 Model Year Vehicle Program."

This document provides expert opinions on the review of 2010 Lotus study "An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Model Year Vehicle Program." This study has received a lot of attention in the industry because of its timeliness and the growing importance of vehicle lightweighting to meet anticipated fuel economy and emissions regulations. The level of detail considered for a complete vehicle in this study (with the exception of powertrain components) using the teardown approach in order to assess mass reduction opportunities is first of its kind in the industry. The approach involves identifying the baseline component masses using the teardown approach, then selection of lightweighitng components based on a combination of benchmarking data and available data in the industry, and finally cost estimation of the lightweight components. Since the approach used to assess mass reduction opportunities is more or less similar across major nine vehicle subsystems, the first section summarizes the overall comments that are applicable to the entire report. The following sections then attempt to address the specific comments related to each of the nine vehicle subsystems as organized in the report. Overall, the identification of baseline vehicle component masses was found to be quite satisfactory, but the technology selection of lightweight components and subsequently its cost estimation has been found to be inconsistent among various subsystems and particularly the overall final component cost estimation procedure needs a lot of reevaluation in order to validate some of the findings of the report.

A. SUMMARY

1. Overall, the detailed vehicle teardown approach used for identifying mass reduction opportunities seems to be a reasonable one. However, this approach seems to be prohibitively expensive and time-consuming for a regular use when other vehicle segments such as passenger cars and trucks need to be considered for similar analysis in the future. It was mentioned that the benchmarking approach was used for the selection of various lightweighting options at the specific component level, particularly for LD components, which was then used as reference for HD components. This approach was not evident in most cases of components and the benchmarking instead was used to determine the viability of overall desired system level weight reduction goal in majority of cases. Although the approach is considered to be a synergestic one providing a high level of flexibility in selecting feasible materials, processes, manufacturing and assembly methods, but the design feasibility yet remains to be proven since the interdependency of designs of vehicle components if at all considered in the analysis was not explicitly discussed in the report. The initial teardown approach was a good start, but afterwards the ad-hoc approach used for the estimation of component mass reduction and cost lacks repeatability and validity.

2. A lot of lightweighting technology options considered in the analysis include such materials which are yet to be introduced in a large volume in the automotive market, particularly magnesium. The viability of using magnesium in high development scenario which requires to have a technology readiness within the next seven years, i.e., by 2017 appears to be too optimistic. Some of the technology options considered to be applicable for high-end niche vehicles, not for an average vehicle even in the latest technology readiness year of 2017. Technology maturity remains a concern for component technology selections, such as composites and magnesium made for high development scenario.

3. It'd have been useful if a table in regard to component breakdown under nine major vehicle systems, including its baseline weights were presented at the very outset of the report. Also, a summary table showing the major differences in vehicle subsystem technologies among three scenarios would have been useful. On what basis was the system definition made? It doesn't seem to have any resemblance to the Uniform Parts Grouping (UPG) system most commonly used by OEMs. There appears to be inconsistency in the number of vehicle systems considered between the earlier chapters on discussion of specific non-powertrain eight systems and while the final results on pg. 244 were discussed. On pg. 244, there were ten (all but powertrain) systems (no air conditioning instead thermal, lighting, and Misc.) than the original eight systems which make the evaluation of final results difficult.

4. The vehicle component cost estimation approach using a cost factor method is completely unsatisfactory as these cannot be validated without knowing underlying assumptions which have not been adequately discussed in the report. In addition, since indirect costs, including tooling and assembly plant architecture were mentioned to be beyond the scope of this study, the comparative costs were not true representative since they are important for advanced materials costs due to part consolidation potential that these materials offer. In most cases the derivation of cost factor appears to be either based on supplier quote without explicit reference of the basis or metal prices. The source of metal prices was mentioned to be Intellicosting, which is a consulting company involved in the actual vehicle component cost estimation and not a renowned metal price supply information source (as also mentioned in the report). However, in the case of chassis components as discussed on p. 189, the right data source, i.e., www.metalprices.com was used. For composite metal prices, no specific supplier names for the information source were provided. Although under Executive Summary section it has been mentioned that costs were estimated using supplier input, material costs, and projected manufacturing costs – particularly the last cost estimation approach was found to be the least one mentioned and discussed in the subsequent chapters on the discussion of various vehicle system components. The cost analysis approach used seems to be inconsistent among various vehicle subsystems and thereby needs to be definitely revisited before the results can be of any value.

5. p. 25 is the only place that has provided some details regarding the cost estimation procedure in addition to later in Sect. 10 on chassis. The procedure provided is as follows which is quite an ad-hoc and on a qualitative basis as it consisted of the following steps, i.e., material costs were provided by industry experts; costs for all comparative

lightweight systems sub-systems, and components were then assigned a value relative to the cost of the Venza component by the original system assessor. The approach used in the last two above steps was not clear in the report. It is difficult to verify the cost estimates since it was mentioned that the underlying cost assumptions were supplier dependent which further demonstrates the inconsistency in the cost methodology used.

6. The overall cost factors estimated for two scenarios seem to be incorrect. Due to a lack of one-to-one correspondence between the systems mentioned on Table 14.a (pg. 244) and a discussion of actual estimates by specific systems presented in earlier chapters, it is hard to compare the estimates at the specific system level. Also, in cases where they do match, values are different. For example, the cost factor under Low development scenario for Closures/Fenders is estimated to be 1.08 (p. 64) but Table 14.a indicates a value of 1.02. Also in the case of High development scenario, assuming that cost factors are correct for each system, using the mass distribution by various systems for the baseline (Chart 14.a p. 237), the overall cost factor is estimated to be 105% and not 103% as noted in Table 14.a. The overall cost factor definitely needs to be rechecked.

7. In general cost factors estimated particularly for the High Development vehicle components appear to be too optimistic, i.e., for a 38% mass reduction a cost penalty of only 103%. This generally contradicts the general findings of the literature today. For example, the 2010 NRC study on assessment of fuel economy technologies for light-duty vehicles indicates a vehicle price penalty in the range of \$1,660-\$2,625 per vehicle depending on the engine size in the range of I4 – V8 for a 20% vehicle mass reduction.

8. One of the major factors affecting the vehicle component cost would be the assumption made for annual production volume. It hasn't been mentioned anywhere within the main body of the report, and only single mention of it was made in Appendix, Sect. 18, p. 304 under the economic analysis discussion of the MuCell option. It looks like most the suppliers contacted for cost information are low-volume vehicle system suppliers and the applicability of the report results for a high-production volume vehicle platform needs to be validated. Whether the overall project scope is for mass-produced or niche vehicles, thereby needs to be explicitly mentioned at the outset of the report.

9. Results of a crossover utility vehicle presented need some adjustments if they need to be applied for a generic baseline mid-size car. In addition, p. 250 in Appendix classifies Toyota Venza as MPV. It is unclear why a crossover utility vehicle was selected if the study results were meant to be representative of the light-duty vehicle market.

10. Is a trial-and-error process used to insure the upper limits of +20% and +50% on the total vehicle system piece costs for low development and high development cases, respectively?

11. It is not clear whether secondary mass savings has been taken into consideration in the analysis since at various vehicle subsystem levels, the percentage mass reduction targets have been assumed to be the same.

12. What specific estimation procedure was used to maintain the system and vehicle level cost targets without having any such targets at the sub-system and component levels?

13. It is hard to determine the consumer acceptance of low and high development vehicles till the follow-on validation of vehicle component materials and technologies, particularly in regard to vehicle safety performance is completed. Since the estimated vehicle cost as one of the major elements of consumer acceptance looks attractive, its validity remains to be seen after revised cost estimates are available based on the suggestions made here.

14. p.24 – It looks like the selection of lightest component part was derived from the A2Mac1 library of vehicles and vehicles outside the database. Since A2Mac1 has a limited number of teardown vehicle data and that too mostly for European vehicles, and so most of vehicle systems and component benchmark data should have been based on the outside A2Mac1 database. What was the specific other database source used since no documentation was available in the report?

15. p. 25 – It was mentioned that the cost variability among different suppliers was addressed by reporting nominal values. Since no actual part cost values were estimated and so not sure in what respect this was used. The use of cost factor should avoid the use of nominal values, as long as both baseline and lightweight technology option part costs are based on the same supplier quote.

B. BODY STRUCTURE

16. p. 32 provides the cost estimation procedure for baseline body which is inaccurate since entirely based on material cost. It is likely then that lightweighting option body cost was based entirely on the difference in material price and part weight.

17. In tables 17.2.b-17.2.d (p. 290-292) how % reduction in thickness due to high strength steel was derived for various body structure components.

18. p. 36 – It was explicitly mentioned that that for high development body scenario property considerations were taken into account at the level of five major sections, i.e., floor and underbody, dash panel assembly, front structure, body sides, and roof assembly. Was it as well for low development body scenario?

19. p. 43 It was mentioned that for body side inner all aluminum was rejected because of cost. How does the selected option of using composite aluminum and magnesium body side instead provide lower the cost compared to all aluminum? Needs explanation.

20. Table 17.2.e p. 293 – An assumption of 54% weight reduction in Panel-Body Side OTR due to use of PP G30 seems unrealistic.

21. p. 46-47: it'd be good to know the unit material price assumptions made for aluminum, magnesium, and composites in order to derive the cost factors for various systems of body structure for both scenarios. Under high development scenario, although a significant mass reduction is shown for body exterior trim items, but no corresponding cost impacts have been taken into account. Estimated -2% and 35% cost penalty for low development and high development body structure seem reasonable. It is not sure whether cost premium necessary for joining of dissimilar materials particularly in the case of high development scenario has been taken into consideration. The market viability of projected use of such a large amount of magnesium under high development

scenario in underbody, dash panel, and body sides, particularly for the high development case is questionable.

C. CLOSURES

22. Inconsistent definition of vehicle systems. For example, Sect. 6 on Closures starts with the definition as doors, hood, and liftgate. But latter in the section fenders were also included as a part of this system.

23. p. 51-54 provide a benchmarking for closure components and demonstrated the feasibility of 50% cost reduction with a cost factor of 185%. But not sure why subsequently for various scenarios none of the benchmarked components were used.

24. p. 56 Table 6.4.1.a -- Not sure why the cost of aluminum outer panels with cast magnesium inner panels is lower than aluminum outer panels with stamped steel inner panels? Same in the case of tailgate as well as shown in Table 6.4.1.b. Not sure why the magnesium inner panels for tailgate was selected but not in the case of panels. In the former case, it says the reason being for meeting the overall mass reduction objective.

25. p. 59 -- the cost factor of 0.44 used for injection molded plastic fenders under Low Development scenario seems to be too optimistic.

26. p. 62 For hood under low development scenario, the cost factor of only 102% with 18% mass reduction using aluminum seems to be too optimistic.

27. p. 66-67: An overall cost factor of 0.76 for High Development Closure and Fenders mass reduction seems to be optimistic even with the use of 33% magnesium. Particularly, the use of thermoplastic and magnesium in the case of side door rear and tailgate shows a cost factor in the range of 0.28-0.52.

28. p. 70 (Table 6.5.3.b): What was the purpose of showing the comparison of Venza closures in MS & HSS although not specifically considered none of these options in any of the two scenarios considered?

D. FRONT AND REAR BUMPERS

29. p. 73: The cost factor for bumper systems was estimated to be 106% under Sect. 7.4 but mentions a value of 103% instead in Sect. 7.5.

E. GLAZING (WINDSHEILD, BACKLIGHT, DOORS, SUNROOF, FIXED)

30. p. 74-75: For glazing no change in both mass and cost was assumed since the benchmarking study showed that the current Venza was competitive in terms of mass for the windshield, liftgate glass and door dropping glass. Not sure whether and how the cost competitiveness was determined.

F. INTERIOR

31. More than 1/3rd of the report has focused on interior components although it has the least weight reduction potential in the overall vehicle weight reduction context.

32. p. 96 -- No cost details were available to verify the seat cost estimation done by Faurecia. For low development, the estimated cost factor of 0.88 appears to be too optimistic.

33. High Development seat was based on Faurecia design with an extensive use of polymer materials and for which Faurecia estimated no cost penalty. No cost penalty appears to be too optimistic in the absence of a discussion on the procedure and underlying assumptions in the report.

34. p. 100 – For high development passenger seat it was assumed that a composite seat frame under development by Faurecia could offer the same mass reduction as magnesium with no cost increase relative to the baseline Venza seat frame. Reference and a discussion on this would be useful.

35. p. 101 – It is hard to believe that the high development proposal could offer high levels of mass reduction at a reduced cost compared to the Venza baseline.

36. p. 103 – 106 -- Low development front driver and passenger seat are estimated to have the same cost factor of 0.88 although % mass reduction in the latter case is considerably higher. Not sure why no additional mass included for 300C power equipment replacement in the case of front passenger seat (although its inclusion was mentioned on p. 95). Same true in the case of high development scenario as well. An excellent breakdown of mass savings for seat has been provided on these pages, and so a similar breakdown of cost factor accompanying the mass reduction estimates would have been extremely useful.

37. It is strange that cost factors were constant across the three major seat components for a given scenario (i.e., 0.88 for Low Development vs.0.94 for High Development), although % mass savings varied among the seat components.

38. p. 109-121 have provided an excellent technology trend background information related to instrument panel, console, and insulation. But it lacks specific reference list for the potential mass and cost reduction related to various technologies. This section has focused relatively more on technology description rather than actual mass and cost reduction potential – the report focus.

39. p. 124-125 has a detailed mass breakdown for IP, center console, and insulation, but the table title as sensitivity analysis is confusing. The table title needs to be appropriately changed.

40. p. 133 second paragraph (table 9.3..1 a should be 9.3.4.1.a)

41. p. 134 has no mention of Table 9.3.4.2.a about the details of mass savings breakdown being presented later on. For high development instrument panel (using cast magnesium and composite dash panel, Faurecia airbag door system) a cost penalty of 10% same as

that in the Low development scenario for a 45% mass reduction seems to be too optimistic (Table 9.3.4.2.a)

42. For both low and high development scenarios had no cost penalty although mass reduction was assumed to be almost double in the latter case compared to the former case. Is it with timing technology maturity will cause cost reductions in the latter case and so providing at the same cost higher mass reduction?

43. Sect. 9.4.1 indicates that the Venza hard trim integration and system is mass competitive although a hard trim benchmarking (Table 9.4.2.a, p. 145) indicates a mass range of 5.423 kg. It is unclear on what basis the mass competitiveness was determined.

44. p. 147 Table 9.4.3.a Table title of trim sensitivity analysis is misleading since it provides a sub-system mass breakdown and nothing any sort of sensitivity information.

45. p. 148 Intentionally left blank?

46. p. 147-149: No references of Table 9.4.3.a and 9.4.3.b are being made in the document.

47. p. 145-152 provides a discussion on hard trim results, but overall interior trim results are being immediately followed without providing any discussion on soft trim.

48. p. 150 shows a 20% mass reduction for low development hard trim and an overall estimated cost factor of 105% without a cost factor breakdown at the specific component level.

49. p. 151 indicates for high development hard trim scenario a 42% mass savings but the same cost factor of 105% as in the case of low development hard trim scenario in spite of using aluminum roof panel combined with magnesium cross bows in the former case.

50. For both low development and high development interior trim scenarios the cost factor is estimated to be the same although the mass savings in the latter scenario is almost double than that in the former scenario.

51. p. 155 -- 80% weight reduction assumed for using MuCell technology for panels under both scenarios for interior trim seem to be too optimistic. A reference included in this regard would be useful.

52. For control systems, no different lightiweighting options were considered between low and high development scenarios, and thereby the mass reduction and cost factors were the same in both cases. Although magnesium material substitution has been considered in several other vehicle components, why then the use of magnesium for steering wheel column not considered, particularly for high development scenario.

53. p. 165 mentions that only difference in high development controls from low development controls is in a small mass reduction due to more integrated voice command interfaces. But the detailed control systems results on p. 166-167 do not indicate any mass difference, in fact both are identical.

54. p. 170: The sentence "The total Venza mass was 9.57 kg" should instead read as "The total Venza heating system mass was 9.57 kg".

55. p. 171: Low development scenario for HVA/C & Ducting indicates a 26% mass savings for a cost factor of 99% using MuCel l foamed plastic technology. No reason was provided for resulting one percent cost premium for mass savings. The mass savings should be 24% as indicated later on the same page below. As in other cases, a detailed breakdown of cost factor estimates would have been useful.

56. p. 173: Although high development HVA/C & Ducting scenario used the low development enhancements and incorporated a higher level of integration and the MuCell technology but mass savings achieved in this case was lower, i.e., 17% vs. 26% for low development. Needs explanation.

57. It doesn't make sense why closure trim has been considered as an additional item in Sect. 9.7 from the earlier discussion of interior trim in Sect. 9.4.

58. Consideration of Zero Power Concept for the closure trim components seems to be a far-fetched technology whose implementation is unlikely during the period considered in the analysis.

59. For both low and high development closure trim scenarios, the effect of mass decompounding was explicitly mentioned. As observed earlier for other components, the cost factor was lower for high development scenario even with a higher mass reduction compared to low development scenario.

60. Sect. 9.8.3 Summary interior mass distribution by material indicates that wood fiber content will occur under higher development scenario, compared to magnesium use in low development scenario. The material distribution charts need to be re-examined.

G. CHASSIS

61. P. 188 It was mentioned that projected costs were also used as selection criteria for the low and high development chassis components. What's the information source and is it for chassis components only projected costs were used since not explicitly mentioned earlier for other vehicle subsystem components?

62. High development chassis subsystems utilized the selected low development mass subsystems normalized to a 40% mass reduction plus systems integration and innovations in component design and materials that are expected to be production feasible by the 2020 model year (p. 188). It is unclear how this was implemented. Is it by decreasing the weights of low development subsystem components by an additional 20% in order to obtain the overall 40% subsystem reduction?

63. Chassis subsystem weights were determined based on benchmarking of current production chassis hardware, and adjusted mass reduction only as a straight proportion to the vehicle mass (p. 188). It looks like weights of other subsystem components were not considered while determining the chassis subsystem component weights. Specific components technology and mass selection have been done in isolation without

consideration of any secondary mass savings effect. No evidence of the consideration of subsystem interdependency was noted in the report.

64. p. 189 Table 10.1.a shows the same powertrain weight under both scenarios, thereby it indicates that same vehicle performance has not been maintained between the two scenarios. It is clear here that the effect of secondary mass savings has not been explicitly considered.

65. An excellent overview of cost estimation procedure for chassis components was provided on pg. 189. It'd have been better if similar level of discussion was provided earlier for other vehicle subsystems. Use of a standard costing methodology in addition to the use of standard material prices rather than varying methodologies used by suppliers would have provided consistency in the cost estimates among various vehicle subsystems.

66. The example given to demonstrate the chassis component cost estimation procedure on p. 189 doesn't seem to have applied the right value of low development GAWR as shown in Table 10.1.a. This example further proves that the cost factor has been mainly based on metal prices and processing cost was not taken into consideration. In addition, no details were available how the mass reduction value was estimated. It seems in most cases, the estimated mass reduction value was positive (i.e., cost savings) which cannot be verified due to a lack of discussion of methodology and underlying assumptions in the report.

67. p. 199 Tables 12.4.1.a and 12.4.1.b are missing.

68. A mass reduction of 32% and 33% in front and rear suspension, respectively had corresponding cost factors of 108% and 96%, respectively. It is hard to verify the lower cost with higher savings due to a lack of information.

69. p. 205 Table 10.4.1.c referred to on this page for brakes is missing.

70. On p. 206 there is a mention of breakouts for the electric apply for integral park brake caliper but was missing.

71. p. 209: Tables 12.4.2.a and 12.4.2.b are missing

72. p. 209 talks about the potential use of foam reinforced stamped assemblies for control arms and subframes having a 25% weight reduction potential with no cost penalty. A reference needs to be included to substantiate this assumption.

73. For chassis components results in Sect. 10.5 results were at a detail level by including both mass savings as well as cost factors at the component level. A similar detailed approach is suggested for components of other vehicle subsystems.

74. On p. 213 low development cost factor assumption of 1.14 for subframe (cast magnesium) appears to be too optimistic.

75. On p. 214 and 218 the assumption of no cost penalty for low development knuckle (aluminum) for rear suspension seems to be too optimistic. Similarly, a cost factor of

0.90 for high development knuckle (aluminum) for rear suspension. Why in the latter case the cost factor is better?

76. On p. 220 why is the cost factor is better for the overall chassis systems better in the case of high development even with a higher weight reduction potential of 43%?

H. ELECTRICAL

77. Talked about copper clad aluminum (CCA) is the latest trend instead of copper wire use. It is 40% lighter and less sensitive to the market price fluctuations of copper. A reference in this regard would be useful.

78. On p. 226 it is mentioned that copper clad aluminum (CCA) will be less sensitive to the market price fluctuations of copper. The CCA market price sensitivity will remain but to a smaller extent since aluminum prices also fluctuate as are other non-ferrous metals.

79. As in the cases of cost estimation of other vehicle components, the CCA wiring cost reflects only in change in metal price.

I. POWERTRAIN

80. It was good to find the detailed cost factor estimates for various electrical subsystem components along with their assumed mass reduction values.

81. On p. 231 under Sect. 13, the powertrain mass was calculated by accounting for the mass reduction of the major vehicle systems and by allowing a reduction of the powertrain system hp and torque but maintaining similar vehicle performance. If that's the case, why the powertrain mass for a lighter weight high development vehicle is same as that of heavier weight low development vehicle? There was no mention of any specific model used for the powertrain mass estimation. There was a mention about mass decompounding but a discussion of its estimation procedure was not included in the report. If powertrain mass were used to develop the chassis system masses, fuel economy improvement estimates, and downsizing and hybridization, a discussion of these major mass reduction considerations were unavailable in the report. The need for vehicle fuel economy estimate in the overall context of the report was not evident in the report.

82. It was mentioned on p. 231 that a single potential solution and placeholder for powertrain mass, accounting for system mass reductions and allowing a downsized powertrain with emerging technologies capable of production in the 2017 timeframe of the study was used. How the interdependency between powertrain and non-powertrain masses remains to be discussed in the report.

83. Any specific reason why only a charge sustaining hybrid option (IC engine with electric motor assist) was selected for the powertrain?

84. Similarly, why was the engine developed by Lotus called SABRE (Spark-injection Advanced Baseline Research Engine) selected for this study?

85. It'd be good to provide the reference EPA's OMEGA model used for hybrid system component cost estimates in order to provide a better understanding of the cost estimation methodology used. Any specific model used for powertrain component sizing?

86. p. 232 indicates that by maintaining a consistent HP/Mass ratio after vehicle mass reduction and powertrain resizing implies that vehicle performance will remain equivalent. If that's the case, for lower non-powertrain mass of high development scenario would require a lower powertrain mass since HP will be reduced in order to maintain the same HP/mass ratio. It was not the case in the report. The reasoning for that as indicated on p. 236 is: the same powertrain mass used for the high development scenario due to other hybrid systems in production or available in this timeframe may be used and anticipated system mass, cost, and benefits will be similar or improved. This reasoning needs further explanation.

87. On what basis are the powertrain component unit cost assumptions used on p. 235 for the estimation of hybrid system cost? A cost assumption of \$320/kWh for Li-Ion battery pack on Table 13.6.a seems too optimistic when current plug-in-hybrid 10 (PHEV10) battery cost is estimated to be around \$1100/kWh. Since the hybrid system evaluated is based on 2007 Camry hybrid which has a net 192 HP or 143 kW, which translates to about \$20/kW based on total estimated powertrain cost of \$2,820 as noted on p. 235. This cost estimate is overly optimistic since since today's conventional powertrain cost is \$30/kW.

88. Any reason why specifically in Appendix (Sect. 17) a discussion on European Trends was included in the reason? Although this was referenced in Sect. 4, p. 23, how the information was used in the study is unclear. Appendix on Case Study: Volkswagen needs a Sect. no. This section, 17.3, and 18 were not explicitly referenced in the main body of the report.

89. p. 237 mentions that the mass contribution of body, interior, suspension/chassis, and closures was relatively consistent and represented 88% of the total vehicle mass (less powertrain) for each model. In the actual vehicle design this may not be the cause since the % mass reduction assumptions for each of the four systems are rarely the same.

90. On p. 246, Sect. 16 under Recommendations suggested the following mass and cost analysis including tooling and piece cost for: BIW (high and low development), closures (high development), and chassis/suspension and interior (high and low development). Any specific reason for no follow-on mass and cost analysis for low development closures? It is highly recommended for a follow-on cost estimation using a consistent methodology for all vehicle non-powertrain subsystems in order to improve its validity and traceability.

Review-3 by: John Fillion (Engineering Society of Detroit).

Review of Lotus Engineering Study "An Assessment of Mass Reduction Opportunities for a 2017 – 2020 Model Year Vehicle Program."

Background

The purpose of the Lotus study was to identify mass savings potential for a new vehicle with a program start in 2014 and production in 2017, and a second new vehicle with a program start of 2017 and production start of 2020. The study used the 2009 Toyota Venza as the baseline vehicle. The first vehicle was called the low development vehicle and had a cost target of less than 20% increase relative to the Venza. The second vehicle was called the high development vehicle and had a cost target of less than a 50% cost increase relative to the Venza. The study concludes that both targets can be met. To evaluate the Lotus claims this writer has relied on his experience in the area of automotive vehicle lightweighting. During the years of 1978 through 2007 this writer was employed by Chrysler in the area of Materials Engineering and from 1992 through 2007 the writer was Chrysler's subject matter expert assigned to the United States Council for Automotive Research (USCAR) for projects regarding lightweighting of future vehicles.

The Lotus report Figure 4.1.a shows the mass distribution for the vehicle; the chassis and suspension, body, and interior make up the bulk of the vehicle mass. This is a credible mass distribution and shows where to look for the main opportunities to reduce mass. The Lotus report correctly focused on these areas, for both the low and high development vehicles. To develop mass savings opportunities the Lotus report took a holistic approach to each section of the vehicle using benchmarking, materials trends, and parts consolidation through new design. This approach was used for both the low and high development vehicles and is the standard method used in the automotive industry for this type of engineering effort.

For the purpose of the Lotus study all mass savings opportunities were measured against the Venza as a baseline. So the mass savings claim, in percentage form, is only accurate for this vehicle. The bill of materials for vehicles is forever evolving; the new bill of materials recommended by Lotus could have either greater or less mass savings when compared to another vehicle on a percentage basis, simply because any other vehicle would have a different starting point. In evaluating the mass saving potential for both the low and high development vehicle it is useful to look at the recommended bill of materials, and determine the likelihood of new vehicles being built to that recipe in the year 2017, for the low development vehicle, and in the year 2020 for the high development vehicle.

Low Development Vehicle

Section 15 of the Lotus report concludes, "This study indicates that a 21% total vehicle(less powertrain) mass reduction may be achievable for 2017 production year vehicle using current and near term technologies with little or no cost impact by using a synergist, total vehicle approach to reducing mass". A reasonable way to validate this claim is to evaluate the viability of the recommended bill of materials for other vehicles in the 2017 timeframe. Table

14.d lists the materials distribution used in the baseline Venza and Table 14.e lists the materials distribution for the low development (LD) vehicle. The data for the major materials is summarized in the table below.

Table 1: **Summary of Materials Distribution taken from the Lotus Report**

Material	Venza (%)	Low Dev (%)	point change
Mild Steel & iron	52	15	(37)
Aluminum	5	6	1
HSS & AHSS	15	48	33
Plastics & composites	9	9	0
Magnesium	0	2	2
Other	19	20	1

The Lotus recommended bill of materials has a strong increase in the use of high strength steel (HSS) and advanced high strength steel (AHSS) at the expense of mild steel and iron and there is some increase in aluminum (Al) usage along with the introduction of magnesium (Mg).

Below is a link to a presentation given by Jodi Hall from GM at the 2008 Great Design Steel conference.

"50 year Perspective of Automotive Engineering Body Materials and an Analysis of the Future" Jody Hall, General Motors Corporation.

Available at:

http://www.steel.org/AM/TemplateRedirect.cfm?Template=/CM/ContentDisplay.cfm&ContentID=24026

The table below summarizes data taken from the Hall presentation that is similar to the Lotus study in that the presentation compares the typical bill of materials for a 2007 vehicle to the typical bill of materials for a future 2015 vehicle.

Table 2: Summary of Material Distribution data taken from the Hall Presentation

Material	2007 MY (%)	2015 MY (%)	point change
Mild Steel & iron	52	42	(10)
Aluminum	8	10	2
HSS & AHSS	12	18	6
Plastics & composites	8	9	1
Magnesium	0	1	1
Other	19	20	1

The 2007 base data is in strong agreement with the Venza baseline data. The Hall presentation suggests that the shift in bill of materials for a 2015 vehicle will be largely due to the increased usage of HSS and AHSS at the expense of mild steel and iron; and like the Lotus study the presentation shows some increase in the use of aluminum and an introduction of the use of magnesium. The primary difference between the Lotus study and the Hall presentation is the amount of mild steel converted to HSS and AHSS and the time frame the year 2015 versus the year 2017. Table 3 below, is a summary of data also taken from the Hall presentation. This table shows the trends in the automotive bill of materials from 1975 to 2015 and the overall vehicle mass. The table shows two basic trends. First the mass of vehicles has not seen much change in 30 years, and that mild steel and iron have been steadily losing their share of the vehicle to mostly HSS and AHSS steel. The growth of HSS and AHSS has been greater than the growth of aluminum, plastics and composites combined.

A reasonable explanation for the fact the bill of materials for the automobile has steadily increased in the use of lightweight materials, while the total mass of the vehicle has remained constant, is that the content of safety and customer features has also steadily increased over the same period. So the increased mass caused by the growth in vehicle content has been substantially paid for by the reduction of mild steel and iron through the increased use of HSS, AHSS, aluminum, plastics, and composites. In others words the technology shift to lightweight materials has been an enabler for improvements in vehicle functionality.

Table 3: North American Vehicle Materials Trends in Pounds

	1975	**2007**	**2015**	**Change from 1975**
Mild Steel & iron	2830	2108	1635	(1195)
Aluminum	84	327	374	290
HSS & AHSS	140	483	718	578
Plastics & composites	180	340	365	185
Magnesium	0	9	22	22
Other	666	783	794	128
Vehicle total	3900	4050	3908	8

For the typical vehicle in the Hall presentation to reach the level of HSS and AHSS recommended by the Lotus study, the switch to these materials would require acceleration compared to the already increasing trend. There are no significant technical barriers for the automotive industry to switch to more HSS and AHSS. The primary driver for the change is to offset mass increases in the vehicle due to increases in mass driven by new components with greater capability. In other words the low development vehicle bill of materials will be accomplished if it is an enabler for the new vehicle to meet its new functional targets.

Restating the study target: “This study indicates that a 21% total vehicle(less powertrain) mass reduction may be achievable for 2017 production year vehicle using current and near term technologies, with little or no cost impact by using a synergist, total vehicle approach to reducing mass”. With the exception of the precise percent of reduction the statement is credible. The problem with the 21% number is that a new vehicle, designed for 2017, will likely replace a vehicle that already is using a bill of materials that is lighter than the Venza baseline, thus mass savings opportunity will be numerically smaller than 21%. The bill of materials suggested by the Lotus study is, however, entirely viable. Since the new bill of materials will be developed at the initial stages of the vehicle program, the material cost will be part of the vehicle's overall cost targets, and would be considered neutral at that point. Overall the Lotus methodology for the low development vehicle is sound.

High Development Vehicle

Section 15 of the Lotus report concludes, "This study indicates that a 38% total vehicle(less powertrain) mass reduction may be achievable for 2020 production year vehicle using current and near term technologies with a moderate cost impact by using a synergist, total vehicle approach to reducing mass". To accomplish this target Lotus used primarily new designs with an emphasis on aluminum, magnesium, and composites. A summary taken from figure 14.f of the Lotus report is listed below in Table 4.

Table 4.

Material	Venza (%)	High Dev (%)	point change
Mild Steel & iron	52	7	(45)
Aluminum	5	23	18
HSS & AHSS	15	14	(1)
Plastics & composites	9	16	7
Magnesium	0	16	16
Other	19	24	5

When something new is added to a vehicle, the mass of the vehicle increases, which in turn requires the vehicle structure to be increased, which then adds additional mass to the vehicle. This concept that mass additions increase secondary mass was seen in the low development vehicle. Through the years new content has added mass to the vehicle, and mass savings countermeasures such as HSS were needed just to keep the vehicle mass constant. To achieve the mass savings for the high development vehicle Lotus used the reverse concept of reducing structural mass enough to allow the supporting structure to be reduced, thus gaining additional mass savings. The concept of secondary mass savings or penalty has always been part of the automotive industry; however, Professor Donald Malen, from U of M, has explained this concept well in a series of papers and presentations. The following links to theses write-ups have been taken from the Auto/Steel Partnership web site and are offered as support for the Lotus methodology used for the high development vehicle.

The Mass Compounding Report available at:
http://www.a-sp.org/database/custom/Mass%20Compounding%20-%20Final%20Report.pdf
Date: June 2007
Committee: FGPC Committee
Description: This report defines and quantifies the mass compounding effect during vehicle design with current mass influence coefficients developed from mass data of 35 contemporary vehicles. Mass compounding considers that a mass increase in a component has a ripple effect throughout the vehicle; other components need to be resized increasing vehicle mass even more. A more encouraging view of this behavior is considering a reduction in a component mass resulting in a greater mass saving.

The Mass Compounding Calculator available at:
http://www.a-sp.org/database/custom/Mass%20Compounding%20Calculator.xls
Date: June 2007
Committee: FGPC Committee
Description: This Excel Spreadsheet implements the findings of the mass compounding study into a tool for estimating initial vehicle mass based on conventional vehicle baselines and calculating the additional mass savings possible from an initial mass reduction of a vehicle system(s) or component(s).
PowerPoint Version available at:
http://www.steel.org/AM/Template.cfm?Section=Home&CONTENTID=24041&TEMPLATE=/CM/ContentDisplay.cfm

Professor Malen used benchmarking techniques like those used by Lotus and developed empirical formulas that related primary mass savings to secondary mass savings. In an example used in the PowerPoint Version above, a 1500 kg vehicle was resized for a new vehicle program using both primary and secondary mass reduction. The calculations suggested a vehicle mass target goal of 883 kg was possible, a 42% reduction in mass. An important part of this analysis was the downsizing of the powertrain. If downsizing the powertrain is not possible the mass target was 1022 kg or a mass savings of 32%.

These studies support the methodology used by Lotus for high development vehicle. In addition to leveraging secondary mass savings, the Lotus study relies on the technical readiness of AHHS, aluminum, magnesium, and composites for the year 2020. The automotive industry has been working on these issues since about 1993, through a cooperative agreement between the Department of Energy (DOE), Chrysler, Ford, and GM. This agreement is managed through The United States Automotive Materials Partnership (USAMP). The stated goal of USAMP is to significantly reduce the mass of the vehicle at affordable costs. USAMP envisions that a vehicle in the time frame of 2020, that was significantly lighter than current vehicles, would be a multi-material vehicle consisting of AHSS, HSS, aluminum, magnesium, and composites, similar to the bill of materials proposed by the Lotus study. The following information was taken from the USAMP web site:

2010 USAMP-AMD Lightweight Materials and Enabling Technologies Symposium, Presented by the United States Automotive Materials Partnership – Automotive Metals Division Lightweighting Automotive Metals and Enabling Technologies Symposium (LAMETS), Tuesday, October 5, 2010, 8:00 am to 3:30 pm.
Location: United States Council for Automotive Research (USCAR), 1000 Town Center, Suite 300, Southfield, Michigan. A complete listing of presentation abstracts/ agenda is available at: http://www.uscar.org/guest/news/433/

A review of the presentation abstracts shows that significant research has been performed in the area of both magnesium and aluminum. The HSS and AHSS and composites research is reported in separate symposiums.

Since little magnesium is used on vehicles today this material requires more development than others. In recognition of this fact, USAMP has developed a separate strategy for the development of magnesium for the 2020 time frame.

From the USCAR website, USAMP consortia, Automotive Metals Division. "Magnesium Vision 2020: A North American Automotive Strategic Vision for Magnesium." Is available at:
http://www.uscar.org/commands/files_download.php?files_id=99

These links are offered as support evidence that the high development bill of materials would achieve technical readiness by the year 2020. The Lotus report concludes, "This study indicates that a 38% total vehicle(less powertrain) mass reduction may be achievable for 2020 production year vehicle, using current and near term technologies with a moderate cost impact by using a synergist, total vehicle approach to reducing mass". With the exception of the precise percentage number, the statement is credible. A vehicle introduced in 2020 will have as a baseline a bill of materials that is significantly different from the Venza and likely to already be much richer in lightweight materials. As a consequence a 2020 vehicle will likely not be 38% lighter than the vehicle it replaces simply because it would have a lighter bill of materials as a starting point. The methodology used by Lotus for the development of the high development vehicle is sound.

Discussion

The Lotus study suggests that mass reduction, through changing the automotive vehicle bill of materials, is possible at a reasonable cost if the mass reduction effort is done at the beginning of a program using a holistic system approach. I find this conclusion consistent with my career work experience. It was my experience that mass reduction efforts applied on a part to part substitution method were not significantly meaningful. To be effective, mass reduction efforts need to be an enabler technology for meeting an important vehicle target. While there are technical challenges to making the bill of materials for the high development vehicle a reality, the primary barriers to vehicle lightweighting are not issues in the materials engineering domain. A basic non materials technology issue that needs to be solved, to enable the use of lightweight materials, is a better understanding of the financial payback to a customer that purchases a vehicle at a higher price, but receives lower operational costs over the life of ownership as a consequence. The Lotus study suggested that the cost penalty for using a hybrid engine for the 2020 high development vehicle was $2820. The report does not give a dollar figure for the cost penalty for the high development vehicle bill of materials; for discussion purposes I will assume it is $1000. The following table shows the time it would take for a driver to be paid back for purchasing a vehicle that cost $3820 more than the conventional alternative vehicle.

Table 5. Pay back to improve a vehicle of 22 MPG to 30 MPG at a cost of $3820.

Cost of gas	$3		
miles driven per year	10000	15000	20000
years for pay back	10.51	7.00	5.25
Cost of gas	$5		
miles driven per year	10000	15000	20000
years for pay back	6.30	4.20	3.15
Cost of gas	$7		
miles driven per year	10000	15000	20000
years for pay back	4.37	2.91	2.19

From this simple analysis the following qualitative statement can be made. At $7 per gallon for gas, it is possible to support the new technology for improved fuel economy with a reasonable payback for the customer, and much harder to do so at $3 per gallon.

Looking at the Lotus study another way, they could have shown that the mass savings from the high development vehicle bill of materials enables a 4 cylinder engine to reasonably match the performance of the baseline 6 cylinder engine. Since the 4 cylinder engine is less expensive than the 6 cylinder engine, the costs saved could be applied to the bill of materials. While the fuel economy would not be as great, the cost would be much less. For discussion purposes I will assume the net cost penalty would be $820. (A savings of $180 applied to the $1000 bill of materials penalty) The table below displays the new payback time for the customer, using the new assumptions.

Table 6. Pay back to improve a vehicle of 22 MPG to 26 MPG at a cost of $820

Cost of gas	$3		
miles driven per year	10000	15000	20000
years for pay back	3.91	2.61	1.95
Cost of gas	$5		
miles driven per year	10000	15000	20000
years for pay back	2.35	1.56	1.17
Cost of gas	$7		
miles driven per year	10000	15000	20000
years for pay back	0.94	0.63	0.47

From this simple analysis the following qualitative statement can be made. At $7 per gallon for gas, it is easy to support the new technology for improved fuel economy with a short payback for the customer, and it is possible to support the new technology with a reasonable payback at $3 per gallon. While my analysis has some degree of speculation, it opens a question not answered by the Lotus study. Is the advanced technology approach for high development vehicle bill of materials viable with conventional powertrain systems?

The Lotus study recommends several follow on studies for both the low and high development vehicles. The low development vehicle follow on projects would be of little value. The automotive industry has the know how to use the HSS and AHSS materials recommended and will be close to deploying the recommended 2017 bill of materials for new vehicles released in MY 2017. The work for the high vehicle development would supplement efforts already underway in the automotive industry. While the supplemental efforts would be nice to have, the efforts underway, by the automotive industry, should be sufficient to support the technical readiness of the 2020 bill of materials.

Alternative Suggestion for a Follow on Project

I agree with the Lotus study that more work is required to make technically ready the bill of materials for the high development vehicle, which I prefer to call the 2020 bill of materials. However, there are considerable efforts underway throughout the automotive industry, its suppliers, Universities, and in both United States and Canadian governments. There seems little need to add to these programs. The hole in the research efforts that I see is the answer to this question: Are the advanced technologies for the 2020 bill of materials commercially viable with conventional powertrain and chassis systems?

Today there are considerable efforts in research and new production vehicles using both hybrid electric and pure electric vehicles. As time passes their viability will be demonstrated through actual use data for cost and performance. Over time these new fuel efficient vehicles will gain their appropriate share of the market. But what about the rest of the market, especially the lower cost end of the market? To truly be successful in the societal goal of reducing greenhouse gasses and improving the nation's aggregate fleet fuel economy, the needs of this end of the market must be addressed as well.

I believe the timing is good to address this issue. The first step in answering the above question is to select a high technology vehicle to be used as a demonstration vehicle, sometimes called a mule in the automotive industry. While there are several choices, I like the GM Volt as the demonstration vehicle mule.

The GM volt is soon to be a commercial vehicle that will have a lightweight body and interior. I do not have any specific knowledge of the GM Volt bill of materials, but it is likely to resemble the mass of the Lotus high development body and interior. For the Volt development at GM, I am certain that the pressure to keep the non powertrain aspects of the GM Volt as light as possible were great, so the GM Volt should, from a body and interior point of view, represent the state of the art for lightweighting that is both reasonable in cost and suitable for high volume production. The Volt bill of materials is critical technology that enables its new powertrain and chassis components to be successful. The program I suggest leverages mass compounding concepts used in the Lotus study and echoed in the Professor Malen paper "Mass Compounding". I believe the term mass decompounding better describes the concept. The program is simple:

Use the GM Volt as a representation of 2020 bill of materials vehicle, and use the mass decompounding concept to select downsized conventional, commercial powertrain and chassis components, and retrofit several GM Volt vehicles with these components. To complete the study, a baseline vehicle is needed for comparison purposes. The Chevrolet Cobalt is similar in size to the Volt and represents a good baseline vehicle for the lower cost end of the market. The goal for the project is to determine if the retrofitted Volt can beat the Cobalt in a straight up competition.

The Cobalt has a combined fuel economy of 29 MPG. My speculation is that by fully exploiting the concept of mass decompounding the mass of the retrofitted Volt would approach that of the Smart Fortwo, which has a combined fuel economy rating of 36 MPG. For the purpose of discussion I have assumed the retrofitted Volt would achieve 34 MPG at a cost increase relative to the Cobalt of $1000. Using these assumptions the following payback table was developed.

Table 7. Pay back to improve a vehicle of 29 MPG to 34 MPG at a cost of $1000

Cost of gas	$3		
miles driven per year	10000	15000	20000
years for pay back	2.08	1.39	1.04
Cost of gas	$5		
miles driven per year	10000	15000	20000
years for pay back	3.94	2.63	1.97
Cost of gas	$7		
miles driven per year	10000	15000	20000
years for pay back	1.14	0.76	0.57

From this simple calculation the following qualitative statement can be made. A retrofitted GM Volt that uses powertrain and chassis components that are commercially available and selected using the full effect of mass decompounding, may have a favorable payback to the customer, for even low miles per year drivers, at $3 per gallon for gas.

This project could be executed by Lotus or a number of other companies. The project could flow as follows:

- Fill in any holes in the benchmarking data for powertrain and chassis components
- Use the mass decompounding concept to select the best powertrain and chassis components based on mass, cost, performance and ease of retrofitting to the Volt body
- Strip the GM Volt of all its high tech chassis and powertrain components and replace them with current commercial components
- Use the lightweight Volt body and interior as the starting point to begin to reconfigure the vehicle making sure that the appearance of both the exterior body and interior are well protected
- Purchase several standard Chevrolet Cobalts as baseline vehicles
- Retrofit the GM Volt with selected powertrain and chassis components
- Drive the vehicles at a proving grounds and resolve any handling issues
- Measure the actual fuel economy of both the retrofitted Volt and the Cobalt
- Develop accurate vehicle operational costs
- Develop accurate vehicle costs

- Determine true driver payback time
- Dress up both the retrofitted Volt and Cobalt vehicles for first class appearance
- Arrange for ride and drive events for key automotive and government leaders to promote the fuel economy gains possible with the 2020 bill of materials.

The cost for the approximately one year project is estimated as follows:

Purchase of several GM Volts, Cobalts, and downsized powertrain and chassis components.	$250,000
Engineering and mechanic time for retrofitting the Volt and vehicle test plan	$200,000
Vehicle testing and problem resolution	$175,000
Promoting the results	$75,000
Total	$700,000

While a company such as Lotus would execute this program, I recommend the project have an oversight council that consists of automotive industry vehicle development executives and government officials from DOE and EPA. The USCAR organization could be used as the forum for this project. I believe this step is critical in order to gain acceptance of the results by key decision makers in both the automotive industry and government.

The retrofitted Volt would provide tremendous credibility to the viability of the 2020 bill of materials. Having a drivable retrofitted Volt, that meet or exceeds the performance of the Cobalt through measured data, and that is made completely from commercial components, greatly reduces doubt regarding the technology. If the hard data is as favorable as my simple calculation suggests, the retrofitted Volt could be deemed best in class, in this market segment, including for cost effectiveness. As a consequence, there would be a significant acceleration of 2020 bill of materials throughout the automotive industry. Perhaps many new vehicles would use the technology years before 2020. As a result the aggregate US vehicle fleet fuel economy could be improved in a shorter timeframe.

Appendix Review by John Fillion

1. Executive Summary

Methodology used by Lotus was acceptable. The follow on project recommended by Lotus is not supported by this peer review writer. See the peer review discussion above.

2. Nomenclature

OK as written

3. Introduction

The general method for comparing the low development vehicle and the high development vehicle to the baseline is acceptable. The deliverables defined by the report were met.

4. Work scope

The approach of using benchmarking to establish a baseline bill of materials is the standard approach used within the automotive industry. The pie chart that depicts how mass is distributed across the vehicle is consistent with data that I have seen within the automotive industry except that typically powertrain is included. The Lotus study mentions the benefits of mass decompounding; however I would have preferred that Lotus had studied the effect that mass reduction has on engine downsizing within the technology of the Venza. For example, that mass reduction of the primary structure for the high development vehicle might have made it possible to do with a four cylinder engine what was done with a six.

5. Body

The Lotus approach of using benchmarking data to establish the baseline data is sound is an approach typically used in the automotive industry. Also the approach to look at trend data in material selection is also consistent with standard automotive engineering practice. The Lotus report remarks on the usage trends for high strength steel, aluminum, magnesium and composites are consistent with the current thinking of automotive materials engineers. The table included from the Auto Steel Partnership is valid.

The vehicle benchmarking data is a reasonable foundation for establishing baseline data for the report.

The Venza materials distribution chart, figure 5.4.1.b, appears to be accurate in that current vehicles from other manufacturers use a similar distribution of materials for their body construction.

The Lotus report cited several steel industry studies that suggest significant mass reduction possibilities through the use of a new gage of high performing steel. These studies are found to be credible by automotive materials engineers and are a good source of background data for the Lotus study.

The new materials distribution chart, figure 5.4.2.b, suggested in the report for the low development vehicle is reasonable and should be found credible by most automotive materials engineers.

For the high development vehicle the Lotus report cited several industry studies as backgrounds which are appropriate sources for establishing a base of information for the report.

The proposed architecture for the high development vehicle body in white, figure 5.4.3.c is a reasonable approach. The report suggests breaking the body into sections consisting of the floor and underbody, dash panel assembly, front structure, body sides, and roof assembly.

For the floor and underbody Lotus suggests a multiple materials approach using aluminum extrusions, aluminum sheet, molded composites and magnesium castings. This approach would be accepted by most automotive materials engineers as a reasonable method to reduce the mass of this section of the vehicle. While technologies proposed are not used in today's high volume vehicles, they are technically viable; their primary barrier has been their cost effectiveness.

For the dash panel and front structure assembly Lotus suggests a large magnesium casting with aluminum extrusions. Like the above this approach would be seen as technically viable by automotive materials engineers. The primary barrier to its application is cost and a ready supply base to produce the large magnesium in the quantities needed.

For the front end module Lotus proposes a large magnesium casting. This approach would be seen as viable by automotive materials engineers. Like above the primary barrier is cost and adequate supply base.

For the body side Lotus suggests a multiple material approach of aluminum sheet, aluminum extrusions, magnesium casts and structural composites. Lotus recognized that the body side could be made from all aluminum, but chose a multiple material approach based on cost. Most automotive materials engineers would agree with this approach, with the understanding that commercial supply issues would need to be resolved.

For the roof Lotus suggests an aluminum sheet approach which is viable technology.

Table 5.5.1 lists the results for the low development vehicle claiming a mass savings of 15.9% and a cost of 98% of the baseline vehicle. Since there are many assumptions and variables in the study it is better to list the results as a range. A more appropriate result would be a 10% to 15% mass savings with the cost being 100% to 105 % of the baseline.

Table 5.5.2 lists the results for the high development vehicle claiming a mass savings of 42.2% and a cost of 135% relative to the baseline. A more appropriate result would be to list the results as a range: a mass savings potential of 30% to 40% and a cost of 135% to 150% of the baseline vehicle.

The materials distributions for both the low and high development vehicles listed in charts 5.5.3.a and 5.5.3.b are reasonable expectations.

6. Closures

The Lotus report recognizes that in the area of closures the automotive industry has done considerable work in the area of lightweighting. The benchmarking tables, 6.3.a, 6.3.b, 6.3.c, and 6.3.d, for the front door, the rear door, the tailgate and the hood are accurate. The rough mass savings of 50% as listed in table 6.3.e is credible.

For the low development vehicle the Lotus report considered high steel strength stampings, aluminum stampings, magnesium castings, and thermoplastics for side doors, tailgates, hoods and fenders. The analysis tables 6.4.1.a, 6.4.1.b, 6.4.1.c, and 6.4.1.d present reasonable mass savings opportunities and cost factors. The report summarizes the mass savings and cost factors for the low development vehicle in table 6.5.1.a. The mass savings of 24.7% at a cost factor of 108% is credible.

For the high development vehicle Lotus considered changes in architectural design as well as alternate materials to achieve mass savings. The results are reported in table 6.5.2.a; the mass savings is reported as 41.3 % with a cost factor of 76%. The primary cost gains are through parts consolidation.

7. Front and Rear Bumpers

Table 7.3.a is a good benchmarking summary for front and rear bumpers. The Lotus report suggests that mass savings opportunities in this area are small which is a credible.

8. Glazing (windshield, backlight, doors, sunroof, fixed)

The Lotus report suggests that there is little opportunity for mass savings in the area of glazing. This is a credible result.

9. Interior

Lotus spent considerable effort analyzing the interior, page 76 through page 185. The information presented demonstrates that the automotive designer has significant degrees of freedom on which approach to take to execute the interior of the vehicle. Historically the automotive designers and engineers have used the interiors to make tradeoffs for content, mass, and cost for the vehicle targets as a whole. While far from a complete review of interior design possibilities, the Lotus report is a good summary of the types of choices that could be made for interiors.

Table 9.8.1.a shows a potential mass savings of 27% for the low development vehicle and a cost factor of 97%. This result is credible given the large degrees of freedom that are possible.

Table 9.8.2.a shows a potential mass savings of 39% for the high development vehicle and a cost factor of 96%. This result is also credible given the degrees of freedom that are possible.

10. Chassis

Like the interior area the chassis and suspension of the vehicle offer the automotive engineer many choices in executing the function. The Lotus report reviewed many of the possibilities that are viable, pages 190 though 194, which is evidence of a large body of technical information and products available for the chassis system.

Tables 4.3.a and 4.3.b represent good benchmarking data for the front and rear suspension systems. The benchmarking tables for suspension architecture, low mass brakes system, and tire wheel systems are also good background information.

The Lotus report details possible design and materials changes for the chassis and suspension, from pages 199 through 208, which are credible suggestions for mass reduction.
The high development vehicle design changes are discussed in pages 209 through 212. The suggested technologies are viable in the 2020 timeframe, including the ablation casting technology listed on page 212. This technology is promising; however, large scale commercial readiness must be developed. However, this could be accomplished in the 2020 time frame.

The low development chassis summary, table 10.6.1.a, lists a mass savings potential of 26% at a cost factor of 100%. This result is credible on the mass savings, but appears to be too generous on cost. A 110% cost factor would be more credible.

The high development chassis summary, table 10.6.2.a, lists a mass savings potential of 43% at a cost factor of 95%. The cost factor appears to understate the costs; a 100% or 105% cost factor would seem more credible.

The materials distribution charts 10.5.3.a and 10.5.3.b are credible.

11. Air conditioning system

The Lotus study suggests that there is little opportunity for mass reduction in the air conditioning system. This is a credible result.

12. Electrical

The study suggests that the automotive industry will begin using Aluminum clad copper wire as a substitute for pure copper wire which is a credible assumption.

Table 12.5.1.a suggests a mass savings of 29.3% for the low development vehicle at a cost factor of 95%. This is a credible result.

Table 12.5.2.a suggests a mass savings of 36.4% for the high development vehicle at a cost factor of 96%. This is a credible result.

13. Powertrain

The Lotus study took advantage of mass reductions for both the low and high development vehicles to resize the engines downward and maintain the vehicle performance. The reduced mass powertrain also aided in downsizing chassis components. The selection of hybrid engine technology is an acceptable assumption for the study and Lotus recognizes that other choices could also be made. Lotus could have added additional value to the study by also selecting conventional powertrain approaches. For example, Lotus could have shown the effect of using the 2020 bill of materials along with a 4 cylinder engine and compared performance to the baseline 6 cylinder engine, thereby showing the benefits of engine downsizing through primary mass reduction. In addition Lotus could have selected a smaller 4 cylinder engine and compared it to the baseline larger 4 cylinder engine. For more discussion on this see the discussion in the "Alternative Suggestion for a Follow on Project" section of this report. In general the methodology used by the Lotus study was sound.

14. Discussion of results

Covered in the main body of this report.

15. Conclusions

Covered in the main body of this report.

16. Recommendations

Covered in the main body of this report.

17. Appendix

Seems complete.

18. Footnotes

Seems complete.

19. References

Seems complete.

Review-4 by: Donald E. Malen (University of Michigan).

Review of Lotus Engineering Study "An Assessment of Mass Reduction Opportunities for a 2017 – 2020 Model Year Vehicle Program."

This review addresses *An Assessment of Mass Reduction Opportunities for a 2017 – 2020 Model Year Vehicle Program,* prepared by Lotus Engineering, Inc, March 2010 Rev 006A (the 'Report' hereafter). The specific charge questions posed to the reviewer are:

> Specifically, EPA is seeking the reviewer's expert opinion on the methodologies being used in this mass reduction work and whether they are likely to yield accurate results. Toward this end, we ask that each subject matter expert comment on all aspects of the report, with particular emphasis on the mass reduction methodology, the feasibility of the proposed solutions to meet all vehicle and manufacturing requirements, cost conclusions, and other key factors, such as the customer acceptance and technology maturity.
>
> In preparing their comments, each reviewer should distinguish between recommendations for clearly defined improvements that can be readily made, based on data or literature reasonably available to EPA, and improvements that are more exploratory or dependent, which would be based on information not readily available to EPA

This review is organized as follows: First, a brief summary of the reviewer's understanding of the facts of the report are provided in Section 1. In Section 2, are comments on the overall methodology. A response to the charge questions is provided in Section 3. In the appendices are more specific comments; Appendix A contains comments for each specific subsystem, and Appendix B contains a detailed recommendation on methodology enhancements.

1. Brief Description of the Report

This report describes mass reducing technology recommendations for the subsystems of two vehicle programs using a reference vehicle—2009 Toyota Venza— to establish vehicle size and market needs. The two vehicles are 1) a *Low Development* vehicle using technologies available in 2014 with start of production in 2017, and 2) a *High Development* vehicle using technologies available in 2017 with start of production in 2020.

Investigation targets for the Low Development vehicle were at 20% mass reduction (less powertrain) within a 20% piece cost increase; and for the High Development vehicle a 40% mass reduction (less powertrain) within a 50% piece cost increase.

Constraints on the investigation included maintaining the functional performance of the Venza in the areas of seating, cargo space, noise-vibration-harshness qualities, driving range, power-to-weight ratio, and compliance with current and near term federal regulations. The overall length, wheelbase, and track were constrained to that of the Venza for the Low

Development vehicle, but wheelbase and track were increased for the High Development vehicle. The 4 cylinder, FWD configuration was used as the baseline. (The Venza is a 5 passenger, 1700 kg cross-over vehicle with FWD and AWD available. It achieves a five star rating for both front and side impact, with a fuel economy of 21 mpg city/29 mpg highway.) Additional constraints were those subsystems carried over directly from the Venza to the development vehicles; these include supplemental occupant restraints, the HVAC system, and front and rear suspension architecture to maintain ride and handling performance, p20.
The mass reducing technologies were focused on eight of the major vehicle subsystems: Body Structure, Closures, Bumpers, Glazing, Interior, Chassis, Air Conditioning System, and Electrical. (The report states that the powertrain investigation was performed separately by the US Environmental Protection Agency) Alternatives for each of these categories were discussed and recommendations made for subsystems for each of the development vehicles. These subsystems were then consolidated for each development vehicle to arrive at the potential vehicle mass reduction and cost deviation from the reference Toyota Venza. A pro forma high level Bill of Materials (report Table 14a) was also provided. Structural analysis and design of the subsystems for the development vehicles was beyond the scope of this investigation.

The general methodology used consisted of (the reviewer's summary):
1) Analysis of Toyota Venza mass distribution by subsystem.
2) For key subsystems, benchmark a set of current mass-efficient production vehicles in the A2Mac1 database. Considering functional requirements and size, scale mass for comparison.
3) Survey trends and technologies appropriate for inclusion (including those from step 2).
4) Analysis to determine mass and piece cost estimate. (Suppliers experienced in the specific subsystem provided piece cost information)
5) Final selection of technologies by Lotus experts to arrive at recommendations.

Also, "…it was recognized that a holistic approach …would yield the best opportunity to meet the vehicle mass targets. The vehicle systems interdependency was a key factor…" An example of this philosophy was given as the side door where the target was to incorporate multiple functions for each component, resulting in a relatively small number of light weight modules which enabled further mass reduction in other areas such as door latch and wiring.

The benchmarking data was provided by A2Mac1 and this data identified the Venza subsystem mass distribution. The eight highest mass subsystems (those mentioned above) were chosen for primary focus.

The report includes detail sections for each subsystem describing the alternatives considered, the recommended subsystem for each of the development vehicles, and the estimated mass and cost. These are summarized in Appendix A.

The Venza costs were estimated, and then the proposed low mass subsystem costs were quoted as a percent of that cost. These subsystem costs were estimated by component suppliers and industry experts. Significant variability in quoted cost across suppliers was observed. The cost included piece cost only, and for those subsystems manufactured by the OEM the estimate did not include tooling. ("Indirect costs, including tooling and assembly plant architecture, were beyond the scope of this study", p6.)

The results are summarized in report Table 14a which shows the estimated mass and cost of each development vehicle less powertrain. Given the recommended subsystems the Low Development vehicle is estimated to be at 78.5 % that of the Venza and cost at 97.9 %. For the High Development vehicle the mass is at 61.6 % and cost at 103 %.

The report includes recommendations for follow-up design and analysis work on a select set of subsystems:

- Design and analysis of the body structure for stiffness, vibration, and impact performance; and estimation of the resulting mass and cost for High and/or Low Development Vehicle.
- Design and analysis of the High Development vehicle side closures including impact performance, and estimation of the resulting mass and cost.
- Design and analysis of the suspension system including geometry analysis, suspension loads, and estimation of the resulting mass and cost for High and Low Development Vehicle.
- Design and analysis of interior models for occupant packaging and head impact, and estimation of the resulting mass and cost for High and Low Development Vehicle.

2. Comments on the Methodology

This investigation relies heavily on the expert evaluation of Lotus engineers and automotive suppliers to identify the mass reduction technologies, to evaluate technical readiness, to estimate subsystem cost, and to make the final selection of subsystems to include in the development vehicles. Lotus is highly regarded internationally as a premier engineering house, and the recommendations are very likely to meet the stated objectives (see some specific reservations are contained in Appendix A, especially those related to the High Development body structure and to cost estimation methods). The subsystem recommendations (less cost estimates) would not be unexpected to those in advance design at an OEM.

However, the question is open as to whether the proposed subsystems are the best or most cost efficient set of subsystems. An OEM seeking to apply these recommendations would be very interested in ensuring that they are. In the absence of a more traceable methodology in which explicit data is provided for all the alternatives, this critical question of efficiency is not answered. For example, for each subsystem a set of technology alternatives are reported *(Are these <u>all</u> the reasonable alternatives; What criteria were used to be included this specific set; How was technical readiness determined?).* Following a short discussion of alternatives, a subsystem recommendation is given *(What process was used to screen out the other alternatives; Was there a formal ranking of all the alternatives; Where is the comparative data for mass saved and for cost of each alternative considered; Might it not be more effective to reduce the percent mass of one subsystem much more than another to meet the overall vehicle mass target and minimize risk; What about the interactions with other subsystems?).* Subsystem cost is given with the caution that it is piece cost only (investment not included on OEM components), and is based on supplier estimates which have substantial variability *(Smaller volumes favor materials which are conducive to part integration and low cost tooling-How was this bias handled; Subsystems which can be shared across several vehicle lines will increase volume-Was this considered; Would not application of a simple cost model help clarify this important area?).*

Questions of this nature may have been considered and answered by the investigators, but the report does not share the answers with the reader.

Therefore, this work could be improved by supplementing it with a more transparent methodology in which the resulting information can be examined at each step. Some methodological improvements would:

1. Cast a wider net in gathering potential mass reducing technologies. This would minimize the risk of overlooking a very promising technology.
2. Be more explicitly data driven at each step (see items 3-7 below) so the reader will 'buy in' to the proposed solutions.
3. Show very clear and quantitative mass reduction and cost estimates for each technology (even those not selected).
4. Use some clear metric to group technologies for technical maturity/readiness, rather than just the final judgment.
5. Use a metric to order technologies for inclusion in the final recommendations which insures efficiency. For example, the metric of *ratio of cost increase to the mass reduction* provided by the technology, (i.e. the marginal cost of including the technology). By ranking with this metric, the most cost effective technology set will be selected first.
6. Show all these estimates in a tabular and graphical form which the reader could examine (see Appendix B of this review for an example).
7. Use first order analysis tools to generate and supplement expert opinion (especially for cost). These tools include:
   - Statistical mass benchmark models to compare mass estimates with a large vehicle population.
   - Material selection based on component function. For example, the Ashby method. This is particularly useful in the case of the body structure.
   - Spreadsheet based cost models which include material cost, tooling cost, equipment cost, and assembly cost. This will allow volume sensitivity analysis.
   - A mass compounding model to adjust the subsystem mass estimates to scale to the resized vehicle mass. (This was done in the report in an ad hoc fashion for the suspension systems.)

Appendix B of this review outlines a methodology which would supplement and greatly enhance the conclusions of the report and improve downstream collaboration and buy-in.

3. Response to Charge Questions with Recommendations

-Comments on feasibility of proposed solutions to meet all vehicle and manufacturing requirements:

Appendix A contains more detailed comments on the specific subsystem proposals. Here are comments from a vehicle perspective. In Table 3.1 are shown the Venza baseline mass data in blue, the low development mass data in yellow, and the high development mass data in green. On the far right is the ratio of each subsystem mass to the corresponding vehicle mass. This ratio provides a useful rule-of-thumb to see if the proposed subsystem mass is roughly consistent with the vehicle mass which the subsystem is a part of. Table 3.1 also includes some of the more general comments for selected subsystems, more detailed comments are found in Appendix A.

Table 3.1 Summary and Analysis of Mass for Development Vehicles
[Data taken from report Table 14.a. Values may differ slightly due to rounding]

	RefVeh	Low Development Vehicle				High Development Vehicle					sub sys mass/curb		
	Venza (kg)	low dev (kg)	delta mass (kg)	mass delta / venza	comments	high dev (kg)	delta mass (kg)	mass delta / venza	comments		Venza	low dev	high dev
Body	382.5	324.8	57.7	15%		221	161.5	42%	At the lower edge of most expert opinion for technology regardless of date of use		13%	14%	11%
Closures / fenders	143	107.6	35.4	25%		84	59	41%			4.8%	4.5%	4.3%
bumpers	18	16	2	11%	Should be scaled down for curb mass	16	2	11%	Should be scaled down for curb mass		0.6%	0.7%	0.8%
thermal	9.3	9.3	0	0%		9.3	0	0%			0.3%	0.4%	0.5%
elec	23.6	16.7	6.9	29%		15	8.6	36%			0.8%	0.7%	0.8%
interior	250.6	182	68.6	27%	Low risk subsystem for mass reduction and this large value is very appropriate	153	97.6	39%	Low risk subsystem for mass reduction and this large value is very appropriate		8.4%	7.7%	7.9%
lighting	9.9	9.9	0	0%		9.9	0	0%			0.3%	0.4%	0.5%
suspension / chassis	378.9	275.5	103.4	27%	Scaling used in report may have lead to a greater than achievable reduction in this mature subsystem	217	161.9	43%	Scaling used in report may have lead to a greater than achievable reduction in this mature subsystem		13%	12%	11%
glazing	43.71	43.7	0.01	0%		43.7	0.01	0%	Polycarbonate glazing (at least on side fixed glass) is worth a try here		1.5%	1.8%	2.3%
misc	30	22.9	7.1	24%		22.9	7.1	24%			1.0%	1.0%	1.2%
sum less p.t.	1289.5	1008		78%		792		61%					
engine	410	356	54	13%	Here is where mass compounding would be useful. Engine is not sized for vehicle mass	356	54	13%	Here is where mass compounding would be useful. Engine is not sized for vehicle mass		14%	15%	18%
Curb	2989	2373	616.2	21%		1940	1049	35%					

These subsystem mass-to-curb mass ratios (far right side of Table 3.1) are shown in Figure 3.1. Several general comments can be made based on this bar chart. First, powertrain mass is high relative to curb mass for both development vehicles. This may be due to the change in powertrain type, but a confirmation is needed. Second, the chassis ratio for both development vehicles is lower than the Venza. The changes to the chassis were relatively minor other than the material change in the sub-frame. In such a technically mature subsystem as the suspensions, one would not expect to see such a ratio reduction. The suspensions were scaled linearly using gross axle mass. This procedure may have been overly optimistic (see Appendix A.10 and Equations B.2 & B.3 of this review). Finally, note that the body ratio for the High Development vehicle is low (proportionally much lighter) compared to the Venza. This raises a question as to the acceptable level of risk for the body proposal. This is a great concern; Refer to Appendix A.5 of this review for more detailed comments on the body proposals.

This graph also suggests additional mass reduction opportunities exist for bumpers and glazing.

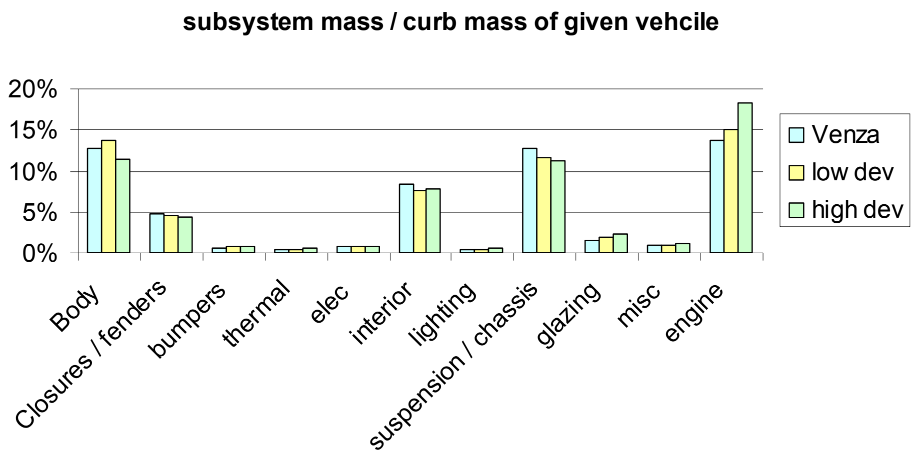

Figure 3.1 Subsystem mass-to-curb weight ratio for study vehicles
(Based on data in Table 3.1)

-Comments on the cost conclusions:

The reliance on supplier estimates may introduce a low-side bias to the cost estimates (suppliers having an interest in promoting their technology). A larger concern is that tooling costs have not explicitly been included in the estimates. Given that many of the proposed technologies have process time slower than the current automobile manufacturing rates, this cost will be an important one to comprehend. The very important yearly volume is only discovered in a footnote (p. 304) and a reference note (12) as 60,000/year. This piece of information is critical to valid cost estimates and needs to be clarified even more. For example, most subsystems in production today support a vehicle platform which is shared across several vehicles. *Is this the case here?* If so, the yearly volume may be much greater than 60k. This is significant because the lower volume will favor materials and systems which allow integration of several parts into one (the module idea mentioned in the report), and which have a lower tooling cost with a slower cycle time (the emphasis on plastics and non-ferrous alloy metals in the report). So, not only is the cost estimate influenced by volume, but the actual configuration design. Given these uncertainties, the cost conclusions need to be clarified and extended.

-Customer acceptance:

The researchers have been very conservative regarding the technology impact on the consumer. The proposed technologies would be transparent to the customer or a positive from a performance aspect. This conservative bias may be excessive in two areas: The proposed large wheels and tires (heavier) were selected to maintain styling proportions. *Given the focus on mass reduction, why not challenge designers to make the smaller wheels visually acceptable?* Also, the lighter rear suspension twist axle was rejected as not appropriate for the market. *Was this based on functionality, or customer perceptions?* If the latter, perhaps perceptions need to be changed.

-Technology maturity:

Other than the body proposal for the High Development Vehicle, the technology maturity of the proposals is appropriate for the timeframes. The High Development body is challenging because of the many and demanding functional requirements (crashworthiness, NVH, durability), because the body is the platform of the vehicle (i.e. presents a high vehicle system failure risk, not just a technology risk for the subsystem), and because so many advanced body technologies are being proposed (alternative materials, joining methods for dissimilar materials, manufacturing strategy, dimensional control,..). In a recommendation below is a suggestion for development work on this subsystem proposal before basing a vehicle program around it.

-Improvements that can be readily made: Concerns and recommendations for improvement:

1) Cost estimates "did not include indirect costs", and "including tooling costs was beyond the scope". This is a serious omission as discussed above in the comments on the cost conclusions.

    Recommendation-Use a simple, transparent cost model to capture tooling and equipment costs, and also consider volume sensitivity. (See Appendix B.3 of this review.)

2) Technology selection relied heavily on expert judgment. Some form of explicit analysis for all alternatives would allow the reader to evaluate the evidence for the report conclusions and also gain downstream buy-in (It is preferable to debate data leading to a conclusion rather than to debate the final outcome).

    Recommendations

    -Present a clearly defined mass reduction number for each technology even for those not adapted, with a ranking by marginal value (e.g. mass savings per unit cost)

    -Some first order analysis should be done beyond expert judgment. For example, comparison of recommendations with a statistical benchmark model would give confidence that the recommendation is neither to aggressive nor not aggressive enough. Material selection procedures like the Ashby method will do the same for material recommendations. (See Appendix B of this review.)

3) The lightest mass rear suspension configuration, the twist axle, was not adapted because "it is not a competitive architecture for the Venza's target market segment".

Recommendation-This decision should be revisited. *Is the twist axle not functionally capable of meeting requirements, or is the rejection due to customer perceptions of this type of axle?*

4) It is not clear if the interactions between the selected subsystems were taken into account. *For example, given the change from I.C. powertrain to hybrid, was the effect of battery packaging and mass taken into account in the body recommendations?*

5) Larger wheels and tires than those functionally required were recommended due to styling constraints. It was estimated that this increased mass by over 4 kg.

   Recommendation-Review this decision in comparison to the more risky technologies used in the High Development body structure to save the same 4kg.

6) The body proposal for the High Development is very high risk. It should be reevaluated.

-Improvements that are more exploratory:

1) There is a risk of omission of a potentially significant mass reducing technology alternatives. A key element of the design process is to generate many, many alternatives before the analysis and selection step. The objective of this is to insure that the risk of overlooking a high value technology is minimized.

   Recommendation-Do a broader search of technologies from sources outside of traditional automotive suppliers; patents, lateral technologies, aerospace, university research.

2) Most technologies suggested were subsystem material or subsystem configuration changes. Suggestions for overall vehicle architecture changes were very limited. (An example of an architecture change which was included in the report is the very effective idea of seat attachment points at the rocker and tunnel.) Often changes to the vehicle architecture can have a large influence on mass and are also very cost effective.

   Recommendation-Perform a similar study but focused on mass reducing vehicle architecture changes. Examples to illustrate this point are:
   a) Bolt-in hood which becomes a structural member thereby reducing body structure mass
   b) Structural door latches and locks which contribute to the overall stiffness of the body
   c) Thinner, larger section roof pillars using a truss-like construction to have minimal vision obscuration.
   d) Interior cross-car beam at the B pillar mid-height to provide a load path for side impact loads (side impact loads are today an important mass driver)

3) Generally, development of a new technology which can be modularized has a much lower risk than those technologies which are part of the vehicle platform. Here a module is defined as a subsystem which fits to the platform at interfaces and can easily be interchanged for another. If the new technology is modular and does not prove to be feasible, an alternative technology can be 'plugged in' its place without causing a system failure. This reduces overall program

risk. If however, the *new platform* does not prove feasible, the whole vehicle system fails. The extremes of this notion in the context of this investigation are the interior components (modules) which provide low system risk and are appropriately aggressively pursed in the report; and the body structure (platform) which has high system risk and should be pursued only with caution.

Recommendation

a) Direct future work to the lower risk interior components where the benefits of mass reduction are great and the risk of system failure is low.

b) For the high systemic risk body structure, see the following.

4) A report recommendation was made to "Design and analyze the body structure for stiffness, vibration, and impact performance; and estimation of the resulting mass and cost for High and/or Low Development Vehicle".

Recommendation- Work at the level of the Low Development body structure is already occurring at OEMs and steel supplier groups. There would be very little value in duplicating these. However, the body structure for the High Development vehicle has many challenges even given the advanced timeframe. The High development body proposal would benefit from analysis and investigation of joining methods, structural performance at interfaces, robustness studies (e.g. thermal expansion differences), optimal part breaks and modules, etc.

5) Styling can act as a mass driver in vehicle design in many ways. The proportions a stylist looks for can result in the compromises which increase mass (an example is wheel and tire sizing).

Recommendation- Consider a project in which engineering requirements for mass reduction place constraints on styling. The exploration of the visual results of these constraints would be very useful in future light weight vehicle designs. Example constraints include right-sized wheels and tires, less glass, structurally advantages proportions.

Appendix A. Comments on Specific Subsystems by Dr. Donald Malen

For each of the following sections, the report recommendations are summarized in the box. This is followed by the reviewer's comments. (Sections are denoted A.*X* where *X* denotes the section number in the original report.)

A.5 Body Structure

Material alternatives described: High strength steel, aluminum stampings and castings, magnesium castings, composites (sheet, multi-layer, carbon fiber). For each area a qualitative list of the primary functions was provided.

Recommendations (Part details are in Appendix Table 17b to 17h):
Low Development vehicle-Targeted substitution of high strength and advanced high strength steel grades based on studies performed by TyssenKrupp Steel AG 9-NewSteeelBody concept, and Volkswagen et al.-Superlight-CAR project.

High Development vehicle-
high level of part consolidation (modularization)
floor and underbody:

aluminum roll form section at tunnel
magnesium castings in transition areas
composite load floor using long glass fiber reinforced polypropylene
dash panel: single magnesium casting using over mold process to provide NVH materials
shock tower: magnesium casting
front chassis rail: aluminum extrusion
front transition at dash: magnesium casting
front end module: magnesium casting
body side:
aluminum extrusions at sills
multiple aluminum stampings for inner, rear quarter panel, and shotgun
magnesium castings reinforcements
thermoplastic door aperture
roof assembly:
aluminum stamping surface
magnesium castings cross members

The resulting mass and cost estimate as a percent of the Venza are Low Development: mass 84.1% and cost 98%; High Development: mass 57.8% and cost 135%.

The low development vehicle proposal is low technical risk and should meet cost goals. There is extensive literature on applications of Advanced High Strength Steel, and this proposal is consistent with those estimates for both mass reduction and cost.

There is concern that the high development body proposal has high technical risk even given the 2017 timeframe. While there are some examples of experimental bodies using some of the suggested technologies, the reviewer is not aware of any applications in even limited production which apply all these technologies. The multi-material proposal will have several challenges. For example, 1) joining the dissimilar materials in a means that will meet dimensional control during manufacturing, 2) meeting the process time for an automotive rate of production, 3) meeting durability requirements particularly at the interfaces, 4) meeting robustness requirements over the wide range of thermal, humidity, servicing/repair which the body will be subjected to. The last point is particularly challenging in scaling up the experience from limited production or experimental applications to a mass produced vehicle used in the full range of environments in the US.

Further concern is directed to the extensive part consolidation (modularity) proposed, Figure 5.4.3.e to Figure 5.4.3.f. The benefits of this type of modularity are in part elimination and the resulting joining process elimination. This is motivated by the need to lower total cost when higher cost materials are used (magnesium and composite in this case). An additional motivation for modularity when using these materials is the lower tooling cost. The down-side to modularity is the loss of some ability to optimize the structure for shape, thickness, and tailored material properties at specific locations. Also, the forming process for these large modules places more constraints on the structural shapes which can be achieved. The execution of these very large modules with reasonable die actions and production volumes will be challenging, as will be dimensional control.

Figure 5.4.3.a and b show illustrations of the exterior vehicle design. While attractive appearing, *what is it about these designs that are enabling mass reduction?* The exterior shapes

should be promoting light weight subsystems or a vehicle architecture which in some way uniquely allows mass reduction. For example, specific panel crowns to promote structural stiffness. Perhaps the panel breaks link to the suggested modularity, but the report does not describe these points in detail.

Figure 5.4.3.g illustrates the High Development roof module concept. It is uncertain why a magnesium casting is preferred here, given the aluminum roof panel. Optimal magnesium beams do offer a marginal mass advantage relative to aluminum, however the optimum section size for magnesium is larger. This area of the roof, near the occupant head, is tightly constrained for package space and the full benefit of a magnesium beam might not be fully realized. Also, in this application, the increase in material cost is not offset by parts consolidation as with the other module proposals.

Figure 5.4.3.f illustrates the High Development side assembly concept. A concern with this type of construction is the small package space remaining for roof side rail and pillar structural sections. In this type of construction, the side frame is unexposed and covered by the door. Vision obscuration dictates the overall size of the pillars from the outside, and the build up of door, trim, seal, and flanges leave a relatively small space for the structural section. This package size issue coupled with use of lower modulus materials makes meeting stiffness and roof crush requirements with this proposal a challenge. Only detailed packaging and analysis can assess the degree of risk for this case.

Prior to adoption of this high development body proposal, the report's recommendation to "Design and analysis of the body structure for stiffness, vibration, and impact performance; and estimation of the resulting mass and cost for High ~~and/or Low~~ Development Vehicle" is strongly endorsed.

Finally, given the method for cost estimation focusing on piece cost alone, the cost estimate for the High Development vehicle body is very troublesome. Body components are highly tooling dependent. Most of the technology proposals will require a manufacturing process with very different cycle times (much slower) than today's production rate. The efficient manufacturing volume using current body construction and processes is approximately 200,000 units per year. To reach this volume, OEMs will consider the body to be a platform shared by several vehicles. This makes comparing costs between a current body and an alternative body with a substantially different cost structure difficult at best. A recommendation is made to do a first order analysis of total costs for the high development body which includes a sensitivity analysis with respect to yearly volume. Further, the target volume needs to be clarified for the case of the body.

A.6 Closures

Alternatives: Several alternatives were considered with combinations of materials: high strength steel stampings, aluminum, magnesium, thermoplastic outer panels, composites, and integration of multiple functions (modularity).
Recommendations:

Low Development
Side doors

Faurecia integrated door module

high strength steel inner and outer (94% Venza mass, 108% cost)

aluminum inner and outer (80% Venza mass, 161% cost)

aluminum outer, steel inner (91% Venza mass, 101% cost)

aluminum outer, cast magnesium inner (91% Venza mass, 125% cost)

selected> thermoplastic outer, h. s. steel inner (89% Venza mass, 93% cost)

Hood

high strength steel inner and outer (91% Venza mass, 102% cost)

selected> aluminum inner and outer (77% Venza mass, 185% cost)

aluminum outer, steel inner (85% Venza mass, 137% cost)

Tailgate

high strength steel inner and outer (91% Venza mass, 101% cost)

aluminum inner and outer (87.5% Venza mass, 184% cost)

aluminum outer, steel inner (91% Venza mass, 151% cost)

aluminum outer, cast magnesium inner (60% Venza mass, 196% cost)

selected> thermoplastic outer, cast mag. inner (55% Venza mass, 148% cost)

thermoplastic outer, h. s. steel inner (72% Venza mass, 86% cost)

Fender- polyphenylene oxide/polyamide alloy (57% Venza mass, 44% cost)

High Development

Side doors

Faurecia advanced integrated door module

inner panel: molded composite (trim integrated & carry operating mechanisms)

door structure: cast magnesium (including mounting points for hinges and latch)

outer panel: composite

Hood

aluminum inner and outer

conventional rear hinging and latch

Tailgate see side door description above

The resulting mass and cost estimate as a percent of the Venza are Low Development: mass 75% and cost 108% (Table 6.5.1a); High Development: mass 58.7% and cost 76%. (Table 6.5.2a)

It is not clear why the low development vehicle would use a costly cast magnesium inner Tailgate. Figure A.1 of this review illustrates the cost-mass reduction trade-off. It appears plastic outer, high strength steel inner would be appropriate given the cost constraint of the low development vehicle. The trade-off line shown in Figure A.1 is a 2.4% cost increase for a 1% mass reduction. At this value for mass reduction, both (plastic outer, high strength steel inner) and (plastic outer, magnesium inner) are equally preferred. If the decision maker's value-of-mass-reduction is more than this, the (plastic outer, magnesium inner) would be preferred, if not the (plastic outer, high strength steel inner) would be preferred. More clarification for the basis of this decision would be helpful.

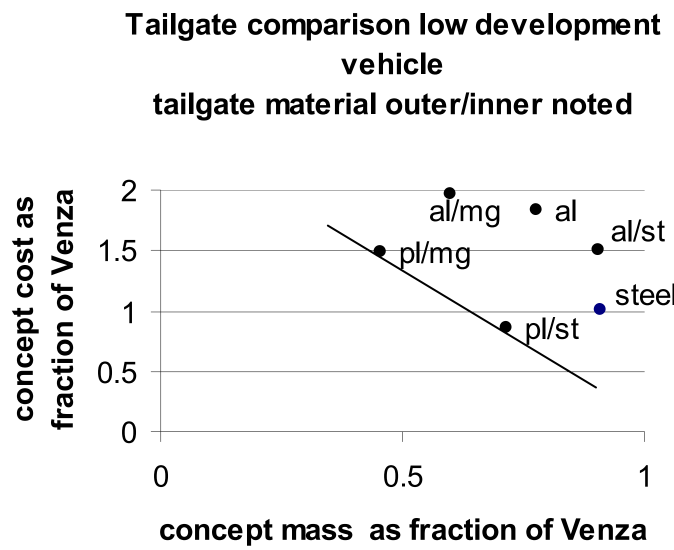

Figure A.1 Low development tailgate alternatives
(Using data from report Table 6.4.1.b)

Has the thermal expansion difference between metal inners and thermoplastic outers been considered? This may drive unanticipated mass into a fastening system which allows relative motion.

A bolt-down hood has synergy with body structure mass. Was this architecture change considered for the high development vehicle?

Figure 6.4.2g illustrates the hood assembly on the styling concept. Does this exterior style enable any mass reduction in the hood?

A.7 Bumpers

Alternatives described: aluminum, magnesium castings, energy absorbing foam. Recommendation: Both Low and High Dev.- alum front and rear (89% mass and 103 % cost)

Bumper mass should be scaled down based on the new curb mass for each vehicle, it appears high based on Figure 3.1 of this review.

Both steel and aluminum are very mass competitive for bumpers. Steel bumpers may be a better mass reduction-to-cost trade-off for the low development vehicle.

A rigidly mounted front bumper has synergy with body structure mass. Was this architecture change considered?

A.8 Glazing

Alternatives: reduce glazed area, reduce glass thickness, lighter substitute material (polycarbonate)
Recommendation: Both Low and High Development- carry over Venza glazing

It would be useful to consider slightly thinner glass (both development vehicles), or polycarbonate on the side fixed glass on the high development vehicle.

A.9 Interior

Seats- see report pp 95-107
Instrument Panel/console- report pp 139-142
Hard trim/interior trim- report pp 150-155
Controls-report pp 163-167
Safety- not targeted, carried over Venza
HVAC and ducting-report pp 171-174
Closure trim-report pp 183-184

The interior is a relatively low risk/high opportunity area for mass reduction and it is appropriate that so much effort has been devoted to this area. The interior mass as a fraction of curb mass for each vehicle appears to be appropriately scaled down; The work on interiors is thorough and appropriate.

A.10 Chassis

Several alternative technologies were identified and described for each of the partitions: front and rear suspensions, steering, wheels & tires, sub-frame, and brake. The methodology for the chassis systems selection differed somewhat from that for the other subsystems. Here the lightest systems from the benchmark data set were selected and scaled using the ratio of Gross Axle Weights (Table 10.1a). These selections were further modified with selected mass reducing parts.

Recommendations:
Front suspension, steering, and sub-frame (both Low and High Development Vehicles)
- Scaled 2005 VW Passat (McPherson strut type)
- High strength steel spring
- Nylon upper spring seat
- Aluminum strut top mount
- Cast Magnesium sub-frame
- Tubular stabilizer bar
- Aluminum Knuckle
- Integral Hub/knuckle/bearing
- Additional technology for High Development Vehicle: Foam filled steel control arm

Rear suspension (both Low and High Development Vehicles)
- Scaled 2005 Alfa Romeo (Three link Chapman strut type)
- High strength steel spring
- Aluminum top mount
- Aluminum knuckle

Brakes (both Low and High Development Vehicles) *(could not locate Table 10.4.1c)*
- Scaled 2008 Toyota Prius
- Modified hydraulic pump, bracket, pipes, Park brake actuator
- Additional technology for High Development Vehicle: Floating cast aluminum caliper

Tires and wheels (both Low and High Development Vehicles) 2009 Toyota Prius (P225/60R19) Additional technology for High Dev. Veh: Ablation cast wheel, eliminate spare & tools

Two decisions seem perplexing given the objective of mass reduction. First, the wheel diameter was constrained to 19 inches for styling reasons (maintaining side view appearance). 'Right sizing' wheels and tires offer a significant mass reduction of 4.4 kg as reported. Is it a forgone conclusion that an attractive vehicle cannot be styled around smaller wheels?

Second, is the selection of other than the lowest mass rear suspension configuration (twist axle), because "it is not a competitive architecture for the Venza's target market segment". (The twist axle is 4.3 kg lighter than the next lightest suspension in the benchmark data of Table 10.3f.) Given the wide range of vehicles using twist axles one would expect that performance could be made acceptable.

The scaling method to down-size the front and rear suspension may have been too aggressive. When the suspensions are compared as a fraction of the curb mass of the vehicle they support, both low and high development vehicle suspensions are a much smaller fraction compared with the original Venza, Figure 3.1 of this review. Given the relatively modest changes to the suspensions this is an area of concern.

A.11 Air Conditioning System

Recommendation: Both Low and High Development- Carry over Venza HVAC module and air distribution systems.

Given the comprehensive nature of the investigation, it would seem there could be some suggestions for this system, even if only for the High Development vehicle. Beyond the AC system mass influence, the power requirement of the AC has a large influence on real fuel consumption. Just as an example technology: The air conditioning module is sized in part by time-to-cool the interior after a hot soak under solar load. A solar powered ventilation fan running during the soak (vehicle parked, engine off) will greatly reduce the interior temperature and allow a smaller A/C unit.

A.12 Electrical

Alternatives: Copper clad aluminum (CCA), aluminum low mass wire coatings, optical based signal transmission and multiplexing. Recommendation: Low Development: CCA for all wiring,- carry over Venza lighting (71% mass and 95 % cost) High Development: CCA for all wiring,- thin wall Noryl cladding, carry over Venza lighting (63.6% mass and 96 % cost)

Was a 24 volt electrical system considered or adapted?

How does the exchange of internal combustion powertrain for hybrid affect wire mass?

A.13 Powertrain

The task for the powertrain investigation of this report was to estimate a powertrain mass consistent with the subsystem mass reductions recommended. This powertrain estimation would act as a placeholder prior to more detailed design and analysis. One powertrain was estimated for both the Low and High Development vehicles, but with the possibility of additional technology applied to the High Development Vehicle for further mass reduction. A hybrid single planetary dual mode system was selected using a resized Lotus project SABRE engine. The three cylinder engine was sized to a displacement of 1 liter to maintain a consistent HP/mass ratio with the Venza. (A balance shaft eliminates the primary shaking couple.) A LiMn2O4-Spinel battery was selected and sized for the vehicle parameters of the Development vehicles. The resulting mass estimate is 356.2 kg for the overall powertrain system including fuel mass, compared with 410.4 kg for the Venza.

When powertrain mass is compared as a fraction of curb mass for the vehicle it moves, the fraction is greater for both the high and low development vehicles as compared with the original Venza fraction, Figure 3.1 in this review. This may be due to the change in powertrain type. The powertrain scaling for the new vehicle mass should be confirmed.

Appendix B: Recommendation for Methodology by Dr. Donald Malen

In Section 2, a recommendation was made to supplement the report with a transparent, data-driven methodology. Such a method is suggested here along with some supporting analysis tools.

A generally accepted approach to mass reduction consists of the following steps [4]:

Step 1: Determine mass for the reference vehicle *(The Toyota Venza)*

Step 2: Identify Mass Reduction Technologies

a) Identify as many technologies as possible meeting the technical risk criteria for the time horizon.
b) Technologies should be sized to function in the reference vehicle at that gross vehicle mass. *(See Section B.1 for a statistical mass benchmarking tool to support this step.)*

Step 3: Sort Mass Reduction Technologies by Cost

a) Determine total mass and total cost for each technology. *(See Section B.2 for a material selection technique and Section B.3 for a cost modeling tool to support this step.)*
b) Calculate the mass increase relative to the subsystem in the reference vehicle, and the cost increase relative to the reference vehicle.
c) Determine the marginal cost of mass, *mc*, (cost increase per unit mass reduction) for each technology.
d) Rank all technologies from the lowest marginal cost to greatest (lower marginal cost technologies are more cost efficient). *(See Section B.4 for an example of selection by marginal cost.)*
e) Beginning at the top of the ranking and moving down, select technologies until the vehicle mass target is met (or the cost budget is exceeded).

Step 4: Estimate the new Vehicle Mass Using Mass Compounding

The mass reduction is step 3 was based on a gross vehicle mass for the reference vehicle (Step 1). Mass compounding will adjust the final subsystem masses as they are resized for secondary mass reductions. *(See Section B.5 for a Mass Compounding Model.)*

Several first order analysis tools support this methodology. The most significant are 1) Statistical mass benchmarking, 2) Quantitative material selection, 3) Cost modeling, 4) Use of marginal cost, and 5) Mass compounding.

B.1 Statistical Mass Benchmarking

In statistical mass benchmarking [2, 3], data from a large population of vehicles are investigated using statistical models. Regression is used to fit predictive equations relating subsystem mass to parameters on which mass depends (mass drivers). For example, Figure B.1 shows McPherson strut lower control arm mass data for several vehicles (using the A2Mac1.com database). Both aluminum arms (dark dots) and steel arms (red dots) were in the sample. The Front Gross Axle Mass proved to be a statistically significant mass driver. Plotting the report recommendations on this graph quickly shows the validity of the recommendations with respect to this population of vehicles. Charts like this enhance the reader's confidence in the recommendations by direct comparison with a large sample of vehicles.

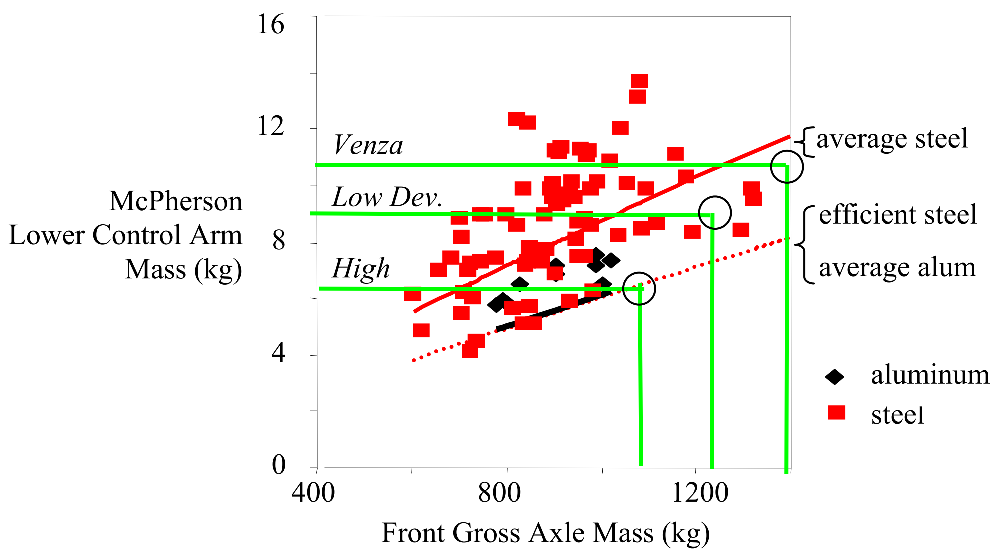

Figure B.1 Example of statistical model application: Lower Control arm mass (with ball joint)

(Report recommendations shown as open circles, Table 10.1.a, 10.5.1.1, and 10.5.5.a)
[Presentation to American Axle Manufacturing, 8/31/2010]

A further application of statistical benchmarking is shown using Equation B.1 which is an empirical relation for front suspension mass as a function of the statistically significant mass drivers. This was fit using the A2Mac1.com data base using 107 vehicles. It can be seen that the suspension mass is not linear with Front Gross Axle Mass, FGAM, but is proportional to approximately the square root (power 0.5). The suspension mass also depends on suspension type and vehicle type.

$$\widehat{m}_{FRONTSUSPENSION} = 1.45(FGAM, kg)^{0.5392} \begin{pmatrix} 0.733\text{McPherson} \\ 1.000\,\text{SLA} \end{pmatrix} \begin{pmatrix} 0.881\text{Passenger Vehicle} \\ 1.000\text{ Utility Vehicle} \end{pmatrix} \quad \text{Eqn. B.1}$$

In the report, the front and rear suspension were assumed to vary linearly with the Gross Axle Mass:

$$\frac{\widehat{m}_1}{\widehat{m}_2} = \frac{FGAM_1}{FGAM_2} \quad \text{Eqn. B.2}$$

Also, a passenger car front suspension was scaled for use in an SUV vehicle. Equation B.1 would suggest a different scaling taking into account both the FGAM difference and the difference in service cycle resulting in Equation B.3 and a heavier mass estimate for the strut:

$$\frac{\widehat{m}_{LOWDEV}}{\widehat{m}_{VWPASSANT}} = \sqrt{\frac{FGAM_{LOWDEV}}{FGAM_{VWPASSANT}}} \left(\frac{1}{0.881}\right) \quad \text{Eqn. B.3}$$

Using this scaling results is a slightly heavier suspension which may explain the low suspension-to-curb mass ratio, Figure 3.1 of this review.

B. 2 Quantitative Material Selection

The Ashby method for material selection [5, 6] is a widely accepted method to quickly screen material alternatives based on functional objectives. For a specific function and objective, a Material Index ranks materials for that purpose. For example, for the application of a light, stiff thin-walled beam the Material Index is:

$$MI = \frac{E^{5/9}}{\rho} \quad \text{Eqn. B.4}$$

Materials with larger MI are preferred in the specific application. Using this approach, a wide range of materials may be assessed for a given application in a very short time. For example, Figure B.2 shows how materials would rank for the roof bow application (report recommends magnesium). Comparing aluminum with magnesium in Figure B.2, we see that magnesium is marginally lighter, but much more expensive (note log scale). Also the optimum magnesium section will require more package space in a highly constrained area.

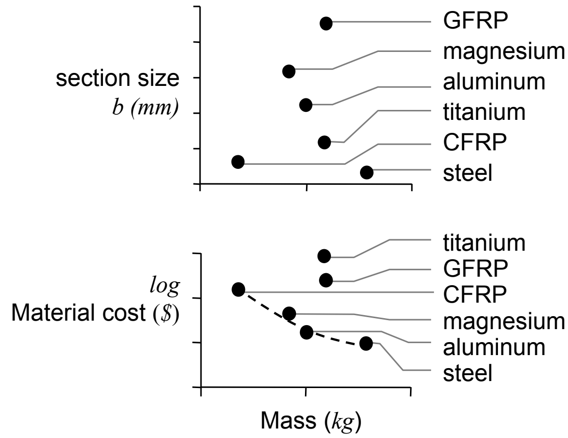

Figure B.2 Example of material selection for a light stiff beam
[*Fundamentals of Auto Body Structure Design*, SAE International, 2011]

Tools such as the Ashby method may not ultimately lead to a different material recommendation (there other factors such as ability to consolidate parts and tooling cost), but the reader can follow the logic, and make the comparisons invited in plots like Figure B.2

B. 3 First Order Cost Model

A full picture of subsystem cost should include volume sensitivity [5, 7]. As an example, Figure B.3 illustrates body-in-white production cost sensitivity to production volume. Typical of this type of analysis, different materials will have different efficient manufacturing volumes due to tooling cost, equipment cost, cycle time differences, and the ability to consolidate parts (modularity).

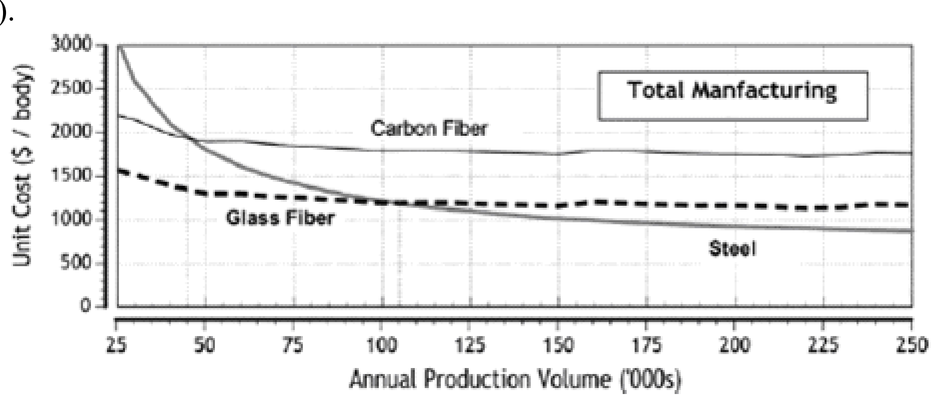

Figure B.3 Example first order cost analysis sensitivity to volume
(Excerpt from *Strategic Materials Selection In The Automobile Body: Economic Opportunities For Polymer Composite Design*, Figure 2 [8])

Rather than quoting only a part cost as in the report, this type of sensitivity analysis will allow more strategic questions to be addressed. What are the break points in volume at which an alternate technology becomes lower cost (total manufacturing cost)? Will it help to consider platforming a subsystem to increase volume?

The data to evaluate such a cost model is modest, at least for screening purposes. Equation B.5 shows the basic equation and the parameters required.

	Material cost	Tooling cost	Equipment cost	Labor, overhead

$$C = \left[\frac{m\,C_m}{1-f}\right] + \left[\frac{(C_t)}{n}\right] + \frac{1}{\dot{n}}\left(\frac{C_c}{L\cdot t_{wo}}\right) + \frac{1}{\dot{n}}\dot{C}_{oh}$$

Characteristics of the material	Cost of material	C_m
	Mass of component	m
	scrap fraction	f
Characteristics of the process	Cost of equipment	C_c
	Cost of tooling	C_t
	Production rate	ń
	Batch size	n
	Capital write-off time	t_{wo}
	Load factor	L
	Overhead rate	C_{oh}

Eqn. B.5

Examples of a spreadsheet implementation of this cost model, which allows rapid volume sensitivity studies, is at reference [9]. Also, the CES software package (www.grantadesign.com) allows rapid evaluation of cost. [5,6]

B. 4 Marginal cost of mass reduction

One means to insure that the selection of technologies is efficient is to rank technologies on marginal cost increase per unit of mass saved. An example of this approach is shown in Figure B.4 where 18 hypothetical mass reduction technologies are ranked by increasing marginal cost, *mc*, in column 4. If the technologies are introduced into the design in this order, we will arrive at the most cost efficient solution. In the right-most two columns are the resulting total cost and total mass for the vehicle including all technologies above that row (the beginning point is cost=100 and mass=100). For this example, assume we hope to reduce mass by 20% (to 80) within a cost budget of a 20% increase (at most 120). The sequence of introducing the technologies is illustrated in Figure B.5. The point on the far right is the starting point. The first point to the left of the starting point is the introduction of technology A, the next left is with the additional introduction of technology B, etc. It can be seen that introducing technologies A to M to the design will meet the mass reduction target of 20% and be within the mass budget of 120. This set of technologies is the most efficient in meeting this goal. Such an analysis would be very useful in supporting the recommendations of the report.

mass reduction technology	mass red.	cost inc.	cost unit mass *(mc)*		total cost	total mass
					100	100
A	1	-1.2	-0.12		98.8	99
B	0.5	-0.5	-0.1		98.3	98.5
C	0.6	0	0		98.3	97.9
D	0.7	0.4	0.057		98.7	97.2
E	1.5	1	0.067		99.7	95.7
F	1	0.7	0.07		100.4	94.7
G	0.7	0.5	0.071		100.9	94
H	6.5	5	0.077		105.9	87.5
I	0.5	0.5	0.1		106.4	87
J	2.1	2.2	0.105		108.6	84.9
K	0.4	0.5	0.125		109.1	84.5
L	4	5.5	0.138		114.6	80.5
M	1.2	2.5	0.208		117.1	79.3
N	0.6	2	0.333		119.1	78.7
O	0.5	1.7	0.34		120.8	78.2
P	0.2	0.7	0.35		121.5	78
Q	2.8	10	0.357		131.5	75.2
R	1.5	7.5	0.5		139	73.7

Figure B.4 Example of mass reduction technologies ranked by margin cost (hypothetical data)

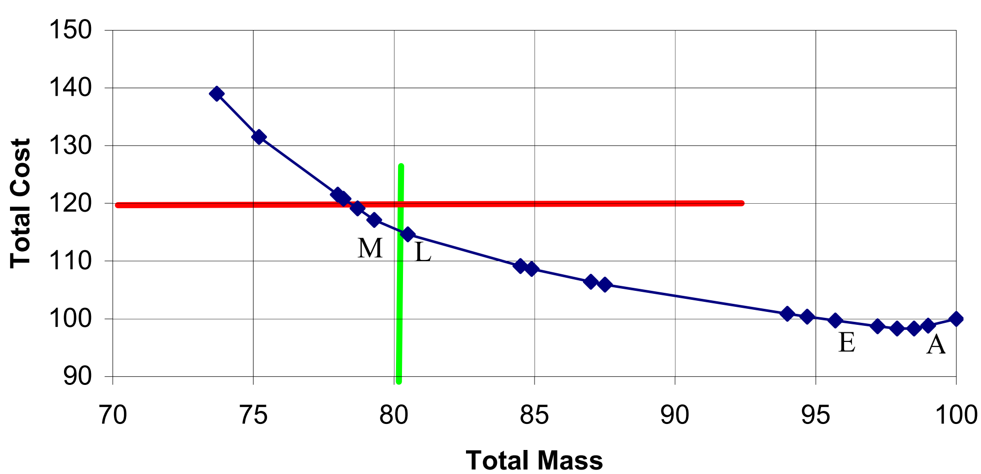

Figure B.5 Efficient mass reduction. Starting point at far right (100, 100)
Mass objective of 20% reduction shown by the vertical line in green,
Cost budget of +20% shown by the horizontal line in red

B.5 Mass Compounding Model

Mass compounding allows a subsystem designed for a reference vehicle mass to be adjusted or downsized to fit the vehicle under consideration. For example, given a balanced vehicle under design, a primary mass reduction occurs before the design is finalized. What is the final vehicle mass after resizing subsystems for this primary mass change? To visualize this situation consider a vehicle with reference mass $M_{GVM} = 1000\ kg$. All subsystems have been sized based on this gross vehicle mass. Now assume a *10 kg* reduction is made in a subsystem—the primary mass reduction. Assume that for this vehicle, the vehicle mass influence coefficient is *0.4*. (The influence coefficient is the incremental change in subsystem mass for a unit change in gross vehicle mass).

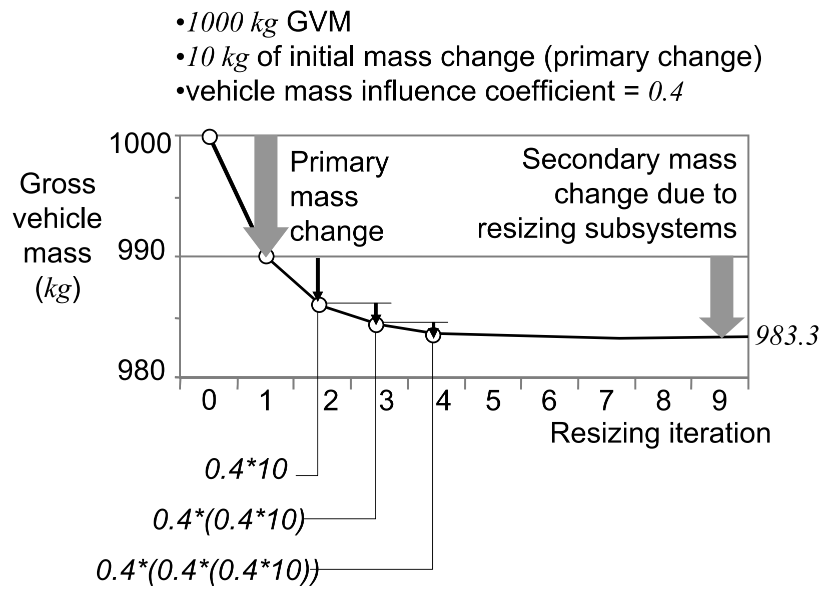

Figure B.6 Mass Compounding Example

Figure B.6 illustrates the changes in gross vehicle mass as this vehicle is redesigned in response to the initial *10 kg* mass reduction. The first change is the primary reduction of *10 kg* resulting in new $M_{GVM}=990\ kg$. All subsystems were based on a *1000 kg* vehicle mass, and subsystems can now be resized to this lower gross vehicle mass. This resizing results in a further reduction of $(0.4)(10kg) =4\ kg$, and a new $M_{GVM}=990-4=986\ kg$. Now the components are sized for *990 kg*, but the vehicle mass is *986 kg* so another resizing can occur, as shown in the figure. The resizing repeats for an infinite number of iterations, but does converge to a final value of $M_{GVM} =983.3\ kg$. This final vehicle mass represents a *primary* reduction of *10 kg*, and a *secondary* reduction due to this resizing of *6.7 kg*.

This mass compounding behavior can be modeled very conveniently to allow adjustments to the subsystem mass estimates. The report makes some adjustments to subsystem mass given the vehicle mass (suspension system and powertrain). But other subsystems appear not to have been adjusted. Mass compounding would facilitate this adjustment. A spreadsheet model is available at reference [4].

Appendix C: Selected References by Dr. Donald Malen

-Statistical based mass estimation and management

[1] de Weck, O., A Systems Approach to Mass Budget Management, Paper AIAA 2006-7055, 11th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, September 2006.

[2] Malen, D., *Automotive Mass Benchmarking*, Internal report of the Auto-Steel Partnership and US Automotive Materials Partnership, May 15, 2010.

[3] *Reinventing Automotive Steel*, Great Designs in Steel conference, May 5, 2010 http://www.steel.org/AM/Template.cfm?Section=Home&TEMPLATE=/CM/HTMLDisplay.cfm&CONTENTID=38292

-Mass compounding

[4] Malen, D., & Reddy, K., *Preliminary Vehicle Mass Estimation Using Empirical Subsystem Influence Coefficients*, American Iron and Steel Institute, April, 2007, http://www.a-sp.org/publications.htm

select: Future Generation Passenger Compartment, then select: Mass Compounding Calculator or http://www.worldautosteel.org/Projects/MassReduction/ASPReport.aspx

-Material selection

[5] Ashby, M. F., **Materials Selection in Mechanical Design**, Elsevier Science, Burlington MA 1992.

[6] Ashby, M. F., **Materials Engineering, Science, Processing and Design**, Elsevier Science, Burlington MA 2007.

-Cost estimation: MIT Materials Systems Laboratory

[7] Field, F., Kirchain, R., and Roth, R. *Process Cost Modeling: Strategic Engineering and Economic Evaluation of Materials Technologies*, **JOM**, October, 2007

[8] Fuchs, E., Field, F., Roth, R., Kirchain, R., *Strategic Materials Selection In The Automobile Body: Economic Opportunities For Polymer Composite Design*, **Composites Science and Technology**, 68 (2008) 1989–2002

[9] Spreadsheet Cost Models Available

http://www.worldautosteel.org/Projects/CostModels/Free-Cost-Models.aspx

-Current Advanced High Strength Steel body projects by suppliers

[10] *Overview Report: FutureSteelVehicle Steel Technology Assessment and Design Methodology*, 30June 2010.
http://www.worldautosteel.org/Projects/Future-Steel-Vehicle.aspx
http://www.worldautosteel.org/Projects/ULSAB-AVC/Programme-Detail.aspx