Lotus Responses to Peer Review Comments

TOPIC	COMMENT	WHO in Peer Rev	COMMENT FROM LOTUS
Material Properties Stress/strain **Simon/Kai/ Gregg**	The sources cited for the material data are credible; however the Al yield stresses used appear to be on the high side of the expected properties for the alloy-temper systems proposed here. The authors may need to address the use of the slightly higher numbers (for example, 6061-T6 is shown with a yield stress of 308 MPa, where standard reported values are usually closer to 275 MPa). Reviewers would like to see min/max material specifications taken into consideration.	Ques 1. Joost	The material suppliers, including Alcoa, Meridian, Henkel and Allied Composites provided the material properties. These companies were chosen because they are experts in their respective fields and could provide accurate information for the materials used in the modeling. The input data supplied by the material manufactures was sufficient to create a model with an estimated fidelity of +/- 10%. This is an acceptable range for this stage of the design. Based on our modeling experience, the global performance of the vehicle (overall pulse, intrusions, time to zero velocity, etc.) is typically within ±5% using finalized and more detailed input data generated for a production program.
	A list detailing the constitutive model formulation for each of the materials of structural significance in the study would help to clarify this issue. Also the design rationale for dimensioning and selection of materials for the main structural parts would help in understanding the design decisions made by the authors of the study. The included material data does not include strain rate sensitivity, so it is assumed that the strain rate effect was not considered. Strain rate sensitivity can be an important strengthening mechanism in metals. For hcp (hexagonal close-packed) materials, such as AM60, high strain rate may also lead to change in the underlying mechanism of deformation, damage evolution, failure criterion, etc.	Ques 1 OSU	Strain rate was not considered for any of the constitutive material models. Tensile testing on a material sample under static and then dynamic conditions would show that the dynamic results give a higher stress/strain response. Because of this, the modeling could be considered conservative. . The AM60 material model was provided to Lotus by Meridian in LS-Dyna format and was based on production experience with similar parts.

	These assignments were not possible to confirm from the crash model since the input files were encrypted. In any case, since Mg AM60 alloy is used in such important role for the frontal crash, a more detailed material model than the one implied by the graph on page 32 of Phase 2 report [1] would be warranted. More accurate failure model is needed, as well. The failure criteria in LS-DYNA [6] are mostly limited to threshold values of equivalent strains and/or stresses. However, combination of damage model with plasticity and damage-initiated failure would probably yield a better accuracy for AM60.	Ques 1 OSU	The constitutive material models contain the material data that was provided by the respective supplier and where no data was supplied values were found on www.matweb.com. The material stress vs. strain information is shown in section 4.2.2 of the report. The LS-Dyna material model used was #24 (piecewise linear plasticity) with the exception of the AM60 which was #123 (modified piecewise linear plasticity)
	Understanding of mechanical properties for material denoted as Nylon_45_2a (reference [1] page 33) would be much more improved if the constituents and fiber arrangement were described in more detail. Numbers 45 and 2 may be indicating +/- 45^0 fiber arrangement, however, a short addition of material configuration would eliminate unnecessary speculation. An ideal plasticity model of 60% limit strain for this material seems to be overly optimistic. Other composite models available in LS-DYNA may be a much better option.	Ques 1 Simunovic	Henkel provided an LS-Dyna material model with all of the fields completed. Portions of this material information were considered proprietary and were disclosed. If additional information would have been provided it would have been possible to use one of the other material models in LS-Dyna that would allow for the modeling of the fibers and 'resin' as separate components. The results would be substantially the same as the Henkel data is based on the performance of production parts.
	While appropriate forming methods and materials appear to have been selected, a detailed description of the material selection and trade-off process is not provided. One significant exception is the discussion and tables regarding the replacement of Mg components with Al and steel components in order to meet crash requirements.	Ques 2 Joost	The material selection for the various 'crash' components' was based on initial analyses that were carried out during Phase I and at the start of phase II. It became clear that the use of the Mg would have to be limited to the areas of the vehicle which would be considered non-critical load-paths and thus the design of the structure evolved following numerous analyses that improved the crash performance. The material selection was driven primarily by the structural requirements to ensure that the vehicle would have adequate crash performance. Magnesium, while lightweight, has a lower elastic modulus, yield strength

			and elongation to failure than both steel and aluminum so it was not considered a viable material for these areas of large deformation and energy absorption.
	Addition of the strain rate sensitivity to a material model can both improve fidelity of the material model, and as an added benefit, it can also help to regularize the response during strain localization. Depending on the amount of stored internal energy and stiffness in the deleted elements, the entire simulation can be polluted by the element deletion errors and become unstable. Assuming that only AM60 parts in the Lotus model have failure criterion, it would not be too difficult for the authors to describe it in more depth. Since AM60 is such a critical material in the design, perturbation of its properties, mesh geometry perturbations and different discretization densities, should be considered and investigate how do they affect the convergence of the critical measures, such as crash distances.	Ques 2 Simunovic	Material failure, in LS-Dyna can be represented in two ways: - firstly, the material model being used can represent the yielding of the material and the subsequent post yield characteristics. This method on its own will leave the physical elements in place and thus they will continue to absorb energy beyond the limit at which material fracturing would have occurred under a tensile load. Secondly the material model can be defined to allow for the elements to be deleted from the analyses to represent the fracturing of the material that would be seen in tensile loading (as was the case with the material data that was supplied by Meridian). The CAE crash models were created using typical modeling parameters (mesh size, element quality, time-step, etc.) as used in the automotive industry. It was not an academic study aimed at evaluating the details of different mesh size/element formulations/etc. The fidelity of the model is estimated to be +/- 10% which is an acceptable range for this stage of body development. Lotus assumed a -10% error (worst case) for all models; as a result the model exceeded the requirements in some areas, e.g., roof crush, and may be heavier than necessary to meet the structural and impact targets. The next step in a production process is to build a body structure based on an acceptable FEA model and use that as the basis for the final tuning.
	Regarding my comment on joint failure under complex stress states, note that in figure 4.3.12.a the significant plastic strains are	Ques 3 Joost	The figure shows that the potential damage was predicted to be in the replaceable bumper structure

	all located at the bumper-rail joints. While this particular test was only to indicate the damage (and cost to repair), the localization of plastic strain at the joint is somewhat concerning.		only. It would be impractical to design for a case where under this loading the plastic strain would be limited to the armature only. There is a welded joint between the armature and crush can which due to the effects of welding on aluminum causes a heat affected zone that both reduces the material yield strength and increases the elongation at failure ('localized annealing'). Under this type of low speed impact the complete front 'low-speed' structure is intended to be replaced.
Welds and Joints **Simon/Kai/ Gregg**	This particular connection contains welds (for joining aluminum parts) and bolts (for joining aluminum and magnesium). HAZ properties were not given in the report and they could not be checked in the model due to encryption. The bolt model properties were described that it fails at 130 MPa (page 38 of the report [1]), which corresponds to the yield stress of AM60. The importance of these joints cannot be overstated. They enforce stability of the axial deformation mode in the rails that in turn enables dissipation of the impact energy. The crash sequence of the connection between the front end module and the front rail is shown in Figure 3.	Ques 1 Simunovic	Figure 4.2.4.a. added to show typical joint sections and an explanation of the overall boding and attachment methodology. Joining methodologies are specified in section 4.2.4 for the MIG welds, friction spot welds, rivets and adhesive. HAZ material information used in the models were stated as follows: - Heat affected zones with 'seam' welding were modeled with reduced material properties. Based on experience, a 40-percent reduction in the base material was used (i.e. for 6061-T6 a yield stress of 184.8MPa was used) – page #47. This is a conservative estimation as the amount of reduction in material strength depends upon the amount of heat applied during the welding process. The specification of the mechanical fastener shear strength properties should be 500MPa and not 130MPa as originally specified (corrected in the report). The 'failure' (element deletion) was modeled using a force limit criterion of 10-12kN.
	It is not clear from the simulations which failure criterion dominates the process. Is it the failure of the HAZ or is it the spot weld limit force or stress. Given the importance of this joint on the overall	Ques 1 Simunovic	To go through each crash event and say what is the sequence of the failure (i.e. weld/material/etc.) would be a substantial task under any situation and was

	crash response, additional information about the joint sub-models would be very beneficial to a reader.		beyond the scope of this investigation. The next step for a production program would be to fully document this failure criterion. The 'failure criterion' in the model would not be dominated by failure in the HAZ as this is only found in the front end of the vehicle in the low-speed crush can and end of the high speed rail.
	Similarly, while appropriate joining techniques seem to have been used, the process for selecting the processes and materials is not clear. Additionally, little detail is provided on the joining techniques used here. A major technical hurdle in the implementation of multi-material systems is the quality, durability, and performance of the joints. Additional effort should be expended towards describing the joining techniques used here and characterizing the performance.	Ques 2 Joost	A detailed explanation of friction spot joining and several illustrations of the process were added to the typical section in Figure 4.2.4.a.
	Some discussion of joining system for magnesium closure inner panels to aluminum external skin and AHSS "B" pillar to aluminum body would improve understanding and confidence in those elements of the design.	Ques 2 Richman	Mechanical fastener discussion added in section 4.2.4. noting that this discussion applies to the closures as well as the BIW. The magnesium components were utilized in areas that would not be subject to significant levels of crash loads. It was determined that in these areas the material would have to be either high strength steel or aluminum. The magnesium front end is in production on several Ford models including the Ford Flex. The B-Pillar construction consists of hot stamped boron steel inner and outer components spot-welded at the flanges with a nylon structural insert that is bonded to the B-Pillar outer using Terocore 1811 (no mechanical fasteners used). This was chosen after consultation with Henkel and based upon their experience in structural inserts which they have successfully used in production vehicles.

	Parts integration information is vague and appears inconsistent. Parts integration. Major mass and cost savings are attributed to parts integration. Data presented does not appear to results.	Ques 2 Richman	The parts count for the baseline vehicle is 269 parts; the Phase 2 BIW has 169 parts.
	More details are needed on the various aspects of joining and fastening. Comment on assembly.	Ques 2 OSU	The joining and fastening section revised to include more details. The assembly is addressed in the 100 page assembly plant section.
Durability	One area that is omitted from the analysis is durability (fatigue and corrosion) performance of the structure. Significant use of Al, Al joints, and multi-material joints introduces the potential for both fatigue and corrosion failure that are unacceptable in an automotive product. It would be helpful to include narrative describing the good durability performance of conventional (i.e. not Bentley, Ferrari, etc.) vehicles that use similar materials and joints in production without significant durability problems. In some cases, (say the weld-bonded Al-Mg joints), production examples do not exist so there should be an explanation of how these could meet durability requirements.	Ques 2 Joost	Fatigue and corrosion modeling was beyond the scope of the study. Although not specifically addressed, Lotus has built cars using steel and aluminum joints for 18 years without fatigue/corrosion issues and this experience was applied to the model as well as that of the production aluminum (Alcoa) and magnesium (Meridian) suppliers. Ford uses magnesium-steel joints in on their production vehicles that have been validated for corrosion and fatigue. Jaguar and Audi use aluminum bodies on a number of current production vehicles which must meet the same corrosion and fatigue requirements as their steel bodies. Ford is also reportedly introducing an aluminum body for their 2014 F150 body (http://online.wsj.com/article/SB10001424052702303612804577531282227138686.html) which must meet Ford's internal truck standards for durability (more abusive duty cycle than a passenger car). There are no welded Al-Mg joints on the Phase 2 BIW; there was no process that could demonstrate this capability in the time frame of this study. Al-Mg and Al-Fe joints are joined with structural adhesive and mechanical fasteners on the Phase 2 BIW.

	As discussed above, durability is a major factor in vehicle design and it is not addressed here. The use of advanced materials and joints calls into question the durability performance of a vehicle like this. NVH may also be unacceptable given the low density materials and extraordinary vehicle stiffness.	Ques 6 Joost	As discussed above, a detailed durability analysis was outside the project scope. However, similar materials and joints are used on production vehicles; Lotus has had riv-bonded aluminum bodies with bolt –on steel structures in production for eighteen years. The baseline Venza NVH materials were used. The body has high stiffness (>32,000 Nm/degree torsional stiffness, 6x curb weight roof crush capability) indicating that it has the ability to be tuned for NVH and still have adequate rigidity. The BMW X5 (the target for BIW stiffness) has a higher torsional stiffness than many world class sports cars but has commercial NVH isolation. High end passenger cars with aluminum bodies like the Audi A8 and Jaguar XJ have demonstrated acceptable NVH characteristics. Additionally, active noise cancellation is expected to play a major role in improving vehicle NVH in the near future. The Lotus Phase 1 paper discussed ANC.
Wheel Mass Reduction	Road wheel mass reduction is 5.6 Kg (54%) per wheel. It is not clear from the report how this magnitude of reduction is achieved. The report attributes wheel mass reduction to possibilities with the Ablation casting process. PH 1 report discussion of Ablation casting states: "The process would be expected to save approximately 1 Kg per wheel." Considering the magnitude of this mass reduction a more detailed description of wheel mass reduction would be appropriate. Elimination of the spare tire and jack reduces vehicle mass by 23 Kg. This is feasible but has customer perceptions of vehicle utility implications. Past OEM initiatives to eliminate a spare tire have encountered consumer resistance leading to reinstatement of the	Ques 2 Richman	The Phase 1 wheel was based on a production Prius wheel and normalized to the Venza. Ablation casting was applied to save additional weight. This is detailed in the Phase 1 report. A very significant portion of the savings, 3 kg., came from reducing the tire section width from 245 to 225. Because of the greatly reduced vehicle mass the tire section could be safely reduced even more. Appearance considerations precluded the use of a smaller width tire. The 19" tire size is very large for this class of vehicle; using a 17" or 18" tire would allow a further reduction in tire/wheel mass. A spare tire is an option or not available on a number of

	spare system in some vehicles.		cars including the Dodge Challenger and the Chevrolet Cruze Eco (manual).
Interior	[9] Interior: Lotus PH 2 design includes major redesign of the baseline Venza interior. Interior design changes achieve 97 Kg (40%) weight reduction from the baseline interior. Majority of interior weight reduction is achieved in the seating (43 Kg) and trim (28 Kg). Interior weight reduction strategies in the PH 2 design represent significant departures from baseline Venza interior. New seating designs and interior concepts (i.e.: replacing carpeting with bare floors and floor mats) may not be consistent with consumer wants and expectations in those areas.	Ques 2 Richman	Ph 2 report utilizes all Ph 1 HD masses and designs including the interior (except for BIW). Interior design is trending towards the Lotus/Faurecia interior concept. The 2012 Hyundai Elantra rear seat system weighs 20% less than the lightweight 2020 MY projection for the CUV rear seat and incorporates concepts published in the Phase 1 report. The carpeting modules are larger than floor mats, are 3d in shape and use more luxurious deep pile material than traditional one piece carpets. They help to reduce mass and cost while providing an upscale look and feel.
Energy Balance	Energy balance does not confirm model accuracy in simulating a given physical structure.	Ques 2 Richman	Revised section 4.4 to specifically state that an energy balance does not confirm the model accuracy.
	FEM validation was presented in the form of an energy balance for each load case. Energy balance is useful in confirming certain internal aspects of the model are working correctly. Energy balance does not validate how accurately the model simulates the physical structure. Presenting energy balance for each load case and suggesting balance implies FEM accuracy is misleading.	Ques 3 Joost	The plotting of the energy balance only serves as one indication to the CAE engineer that the analysis being performed correctly (from a mathematical code perspective) and is not undergoing any anomalies due to the complex nature of definitions utilized. This would not typically be included in a report to customers but was only included as during the various meetings that were held between Lotus, NHTSA and CARB, NHTSA indicated that they had problems running the models and this was used to show that these 'problems' did not exist in the models run by Lotus.
Modeling observations **Simon/Kai/ Gregg**	The cracks in the front end module (Figure 3.2) and the separation between the front end module and the front rail (Figure 3.3) are clearly visible. This zone experiences very large permanent deformations, as shown in Figure 4.	Ques 1 Simunovic	Cracks are typical in a magnesium front end structure in following a high speed front impact; the Ford Flex uses a magnesium front structure.
	However, in my opinion, there are two issues that need to be addressed. One is the modeling of material failure/fracture and the other is the design of the crush zone with respect to the overall	Ques 2 Simunovic	The dynamic crush zone was 555mm; a graph is included in the report in Figure 4.3.1.f..

	stopping distance. While the former may be a part of proprietary technology, the latter issue should be added to the description in order to better understand the design at hand.		Material failure/fracture is modeled only where data was provided by the material supplier. The data for the aluminum was provided by Alcoa and no 'failure of material' (represented by element deletion is utilized). Element deletion was assumed for the areas of HAZ in the lows speed crush cans and ends of the high speed rails. The failure strain used for the 6061 & 6063-T6 material was 11%. Based on Lotus experience, this is a conservative value. The full crush zone of the vehicle is not fully utilized under the flat frontal impact loadcase as there is not enough mass in the vehicle to enable this to occur. One of the governing factors for the design was that it was based upon a vehicle with proportions such that it would use up all of the available space under the front impact loading. The process for producing extruded aluminum as used in the front rails dictated a minimum gage that could be used whilst assuring no issues due to material warping during the manufacturing phase. The above paragraph was added to the report.
	Notice large cracks open in the mid span, on the sides, and punched out holes at the locations of the connection with the front rail and the shotgun. Mesh refinement study of this component would be interesting and could also indicate the robustness of the design. Decision to design such a structurally important part out of Mg would be interesting to a reader. There are other components that also include failure model even though they are clearly not made out of magnesium nor are their failure criteria defined in the Phase 2 report. Figure 6 ***[See Simunovic Comments, p. 8.]*** shows the sequence of deformation of the front left rail as viewed from the right side of the vehicle.		The "shotgun" causes the magnesium front end module to completely separate at the attachment. This, although not ideal, does not have a significant effect on the results due to the 'S-shape' of the shotguns. The shotgun bends under the front impact load rather than crushing axially. The majority of the front crash load is taken by the main rail.

	Tearing of the top of the support (blue) can be clearly observed in Figure 7. The importance of this connection for the overall response may warrant parametric studies for failure parameters and mesh discretization.	Ques 2 Simunovic	The role of this support is relatively minor. See above. There are 995,000 mesh elements. Mesh quality checks were made to ensure the elements met the criteria set for the following: Element mesh size Number of triangles per panel Tria. Interior angle Quad Interior angle Warping Jacobian Aspect Ratio Total %age of failed elements <1% (from all element quality criteria's)
	It can be seen that almost all deformation occurs in the space spanned by the front frame rails. As marked in Figure 1, the front transition member (or a differently named component in case my material assignment assumption was not correct), supports the front rail so that it axially crushed and dissipated as much energy, as possible. For that purpose, this front rail rear support was made extremely stiff and it does not appreciably deform during the crash (Figure 10). ***[See Simunovic Comments, p. 10.]*** It has internal reinforcing structure that has not been described in the report. These reinforcements enables it to reduce bending and axial deformations in order to provide steady support for the axial crush of the aluminum rail tube.	Ques 2 Simunovic	The design/analysis process went through numerous iterations to improve the performance of the rail transition so that the predominant deformation would be seen in the front rails and not in the transition. The transition pieces are 3mm thick permanent mold castings with extensive ribbing which helps prevent significant deformation. Contrary to the reviewers comment, the rail (6061-T6) and the side wall gauges are 2.25mm and the top surfaces are 2.75mm to allow axial crushing to take place. A central rib was evaluated as part of the structure but was eliminated as it made the rail was too stiff and did not provide a reliable crush mode. A sensitivity analysis was carried out to reduce the gauges further; this improved the overall vehicle pulse and increased the overall time to zero velocity. However, the thinner gauge materials were not used because of potentially affecting durability and fatigue

			(beyond the scope of this study but a consideration throughout the design process). The thicker gauge materials provided a pulse compatible with current airbag technology (per TRW) and maintained the target "G" level of 10% below the baseline peak.
	To quickly evaluate the feasibility of the proposed design, we can use the concept of the Equivalent Square Wave (ESW) ["Vehicle crashworthiness and occupant protection", American Iron and Steel Institute, Priya, Prasad and Belwafa, Jamel E., Eds. (2004).]. ESW assumes constant, rectangular, impact pulse for the entire length of the stopping distance (in our case equal to 22 in) from initial velocity (35 mph). ESW represents an equivalent constant rectangular shaped pulse to an arbitrary input pulse. In our case ESW is about 22 g. Sled tests and occupant model simulations indicate that crash pulses exceeding ESW of 20 g will have difficulties to satisfy FMVSS 208 crash dummy performance criteria [11]. For a flat front barrier crash of 35 mph and an ESW of 20 g, the minimum stopping distance is 24 in. Advanced restraint systems and early trigger airbags may need to be used in order to satisfy the injury criteria and provide sufficient ride down time for the vehicle occupants.	Ques 2 Simunovic	Front NCAP test results for the 2009 Toyota Venza (see http://www-nrd.nhtsa.dot.gov/database/aspx/searchmedia2.aspx?database=v&tstno=6601&mediatype=r&r_tstno=6601) the following is observed: time to zero velocity - 75ms, max dynamic crush - 680mm, average acceleration 21G, peak acceleration 49G. The Venza crush distance is 26.77 inches or about 12% greater than a pulse that yields an ESW of 20G; the Venza pulse would be 20/1.12 or about 18G using an ESW analysis. The NHTSA measured average acceleration was 21G or roughly 17% higher than the ESW predicted value. This actual value also exceeds the ESW threshold value of 20G. It may be difficult to meet the requirements of the FMVSS208 requirements with the pulse/TTZ that is predicted but there are small vehicles currently being sold that are able to do this (i.e. Smart ForTwo and Fiat 500); the 2008 Smart ForTwo has a TTZ of 47ms, a dynamic crush of ~400mm (15.75" or 28% less than the Phase 2 model), and a peak acceleration of ~60G (average acceleration ~34G) ref NHTSA test v6332.
	Report does not identify the data used (minimum or typical). Aluminum property data used in for the PH 2 design represents expected minimum values for the alloys and tempers. This reviewer is not able to comment on property values used for the other materials used in the BIW.	Ques 2 Richman	Values from the suppliers were considered typical as were those used for the other material data which was found on www.matweb.com.

	LS-Dyna and MSC-Nastran are current and accepted tools for this kind of analysis. FEM analysis is part art as well as science, the assumption had to be made that Lotus has sufficient skills and experience to generate a valid simulation model.	Ques 3 richman	This is a correct assumption.
	Model indicates the PH 2 structure could sustain a peak load of 108 kN under FMVSS 216 testing. This is unusually high for an SUV roof, and stronger than any roof on any vehicle produced to date. Result questions stiffness and strength results of the simulations.	Ques 3 Richman	IIHS results for the 2009-2012 Toyota Venza indicate a good rating (which is 4* vehicle curb weight). The test resulted in a maximum force of 84.4kN. The strength of the roof structure is comparable to midsize SUV's, e.g., the 2011-2012 Dodge Durango IIHS test results in a maximum force of 105kN (ref: www.iihs.org). The analysis result may be slightly higher than the actual test as the physical test is carried out statically and the analysis is considered quasi-static so there will be some dynamic effects which will increase the apparent load capacity. The analysis method used has been used successfully on previous production vehicle program to be considered acceptable for the studies carried out here. There is a sufficient safety margin in the results to allow for 'dynamic' discrepancies.
	While the report abounds with crash simulations and graphs documenting tremendous amount of work that authors have done, it would have been very valuable to add comparison with the 6602 test even at the expense of some graphs. Page 72 of the Phase 2 report starts with comparison of the simulations with the tests and that is one of the most engaging parts of the document. I suggest that it warrants a section in itself. It is currently located out of place, in between the simulation results and it needs to be emphasized more. This new section would also be a good place for discussion on occupant safety modeling and general formulas for the subject.	Ques 3 Simunovic	The simulation sections are broken out into three separate sections: 4.3., CAE Analysis, 4.4., Discussion, and 4.5. Closures. Occupant safety modeling was beyond the project scope.
	One of the intriguing differences between the simulations and	Ques 3	The difference between the chosen baseline vehicle

	baseline vehicle crash test is the amount and the type of deformation in the frontal crash. As noted previously, computational model is very stiff with very limited crush zone. Viewed from the left side (Figure 14) ***[See Simunovic Comments, p. 14.]***, and from below (Figure 15) ***[See Simunovic Comments, p. 15.]***, we can see that the majority of the deformation is in the frame rail, and that the subframe's rear supports do not fail. The strong rear support to the frame rail, does not appreciably deform, and thereby establishes the limit to the crash deformation.	Simunovic	and the simulation lies in the mass of the overall vehicle. The baseline vehicle curb mass is ~1815kg while the simulation curb mass is only 1150kg. this reduction in mass has significant effects on frontal crash performance, (1) the vehicle appears to be 'stiffer' as shown by the higher average acceleration and shorter time to zero velocity and (2) the total dynamic crush is less. Additional analyses were carried out to study the results predicted by the analysis for the roof crush. These analyses involved removing the entire adhesive bond on the vehicle structure and also removing the windshield. This was a "worst case" test condition; the roof crush test is performed with the windshield in place. The restrictions applied to the vehicle design for packaging, manufacturing/assembly/durability have affected the part size/gauge/etc. As a result, some components are similar to their counterparts on the 57% heavier baseline vehicle, e.g., the steel "B" pillar.
	There is an obvious difference between the simulations and the tests. The developed lightweight model and the baseline vehicle do represent two different types of that share general dimensions, so that the differences in the responses can be large. However, diving down during impact is so common across the passenger vehicles so that different kinematics automatically raises questions about the accuracy of the suspension system and the mass distribution. If such kinematic outcome was a design objective, than it can be stated in the tests.	Ques 3 Richman	The motion of the vehicle under crash is substantially dictated by the CoG for the vehicle. The simulation model was 'mass adjusted' to give the correct weight distribution between to front and rear axles (55/45). There was no information available for the height of the baseline vehicle CG and so this was not adjusted for the simulation model. The CG height in the simulation model was 560mm above the ground plane. In the flat frontal load case there is a minimal amount of vehicle pitching. This is because the location of the front rails spans the vehicle CG location. If the CG was higher up then there could be significantly more pitching during

			impact. The potential for a higher vehicle CG location was not studied; the light weight roof helped to reduce the CG height.
	Another reviewer which did not visit Lotus commented on the following: 1. The powertrain has more than 15% of the vehicle mass and therefore the right powertrains should be used in simulation. 2. The powertrain is always mounted on the body by elastic mounts. The crash behavior of the elastic mounts might easy introduce a 10% error in determination of the peak deceleration (failure vs not failure might be much more than 10%). So modeling a close-to-reality powertrain and bushing looks like a must (at least for me). 3. Although not intuitive, the battery pack might have a worst crash behavior than the fuel tank. Therefore the shoulder to shoulder position might be inferior to a tandem configuration (with the battery towards the center of the vehicle).	Ques 3 OSU	The EPA provided a parallel hybrid powertrain using a Lotus Sable engine was used. While further powertrain mass optimization was possible, it was beyond the scope of this study to develop a new powertrain for the Phase 2 BIW study. Lotus spent a substantial amount of time developing the powertrain mounts to optimize the engine motion during front impacts. A 2 kWh battery pack was engineered along with a 20% smaller fuel tank to provide an equivalent driving range. The total energy system weight was equivalent to original fuel system weight. Each storage system (fuel, battery) is constrained independently so the restraints have less mass to retain than the baseline system.
	Here the geometric configuration, many materials and many joining methods are essentially new. Can Lotus provide examples that show how accurate such 'blind' predictions may be?	Ques 3 OSU	All materials and joining processes described in the report are in production today although not on a single vehicle. The materials were joined and tested and the results used in the modeling. There are no examples that can be provided to indicate how accurate the model will be compared to a physical test. A prototype build was beyond the scope of this project. The current state of the model is such that if this were

			an OEM vehicle program, it would only provide confidence in the ideology that a lightweight vehicle structure is capable of meeting the required vehicle requirement (concept validation). As the vehicle program developed and the designs of the other components were finalized (i.e. interior structure/doors/etc.) the confidence in the predicted results would improve. The methods that were used to build the finite element crash models have been used successfully on previous vehicle programs to predict crash performance. It would therefore be expected that the results predicted here would be within 10% of the actual tested results if a prototype were built.
Compare models to tests	For instance, intrusion velocities for side impacts are reported. But, no analytical comparison is made to similar vehicles that currently meet the requirements. Comparable crash tests are often available from NHTSA or IIHS.	Ques 3 Richman	NHTSA has carried out crash tests on the baseline production vehicle. These test results can be found on the NHSTA website (http://www-nrd.nhtsa.dot.gov/database/veh/veh.htm). The front impact test report (35mph flat frontal) used to compare the simulation results can be accessed from the following link (http://www-nrd.nhtsa.dot.gov/database/aspx/searchmedia2.aspx?database=v&tstno=6601&mediatype=r&r_tstno=6601). Results from IIHS testing can be found on the following website (www.iihs.org). While a direct comparison cannot be made between the Lotus model and the production Venza NHTSA and IIHS test results, the reader can use the results presented in this report to determine relative levels of performance, e.g., comparing the front of dash

			intrusion levels from the Venza 208 test to the Lotus model 208 results.
Treatment of aluminum and other metals **Simon/Kai/ Gregg**	From the report it is not clear that pretreatment is also applied to extruded elements. The majority of high volume aluminum programs in North America have moved away from electrochemical anodizing as a pre-treatment. Current practice is use of a more effective, lower cost and environmentally compatible chemical conversion process. These processes are similar to Alodine treatment. Predominant aluminum pre-treatments today are provided by Novelis (formerly Alcan Rolled Products) and Alcoa (Alcoa 951). Both processes achieve similar results and need to be applied to the sheet and extruded elements that will be bonded in assembly.	Ques 2 Richman	Alodine, a Henkel product, was used as the aluminum pre-treatment including the extrusions. The Alcoa products were not evaluated.
	Study is very thorough in their crash loadcase selections and generated a lot of data for evaluation. Might have included IIHS Offset ODB and IIHS Side Impact test conditions which most OEM's consider.	Ques 3 Richman	The customer specified the required load cases. FMVSS 214 side impact included barrier & pole tests. FMVSS 208 included offset barrier.
	Some effort was made in the report to discuss joining and corrosion protection techniques, however it is possible that new techniques will be available prior to 2025. For example, there was very little discussion on how a vehicle which combines so many different materials could be pre-treated, e-coated, and painted in an existing shop. There will likely be new technologies in this area.	Ques 6 Joost	The steel B pillar would be pre-treated, e-coated and primed prior to delivery to BIW assembly plant. The aluminum panels would use pre-treatments similar to the current aluminum bodied Lotus production sports cars. Non-metallic washers provide galvanic isolation. The assembly methodology is detailed in the body in white plant section.
Stiffness **Gregg/Kai**	but the authors may need to address whether or not such extreme stiffness values would be appealing to consumers of this type of vehicle. While there doesn't appear to be a major source of error in the torsional stiffness analysis, the result does call into question the accuracy; this is either an extraordinarily stiff vehicle, or there was an error during the analysis.	Ques 3 Joost	Allowing for a 10% error in the modeling capability, the predicted stiffness is about 10% higher than the BMW X5. The current X5 body stiffness was increased by 15% vs. the previous generation. The expectation is that the Phase 2 BIW torsional stiffness will be achieved by the next generation X5. Increased body stiffness allows the suspension to be better optimized for both ride and handling.

	Remarkable strength exhibited by the FEM roof under an FMVSS test load raises questions validity of the model.	Ques 3 Richman	The roof structure is comparable to midsize SUV's, e.g., the 2011-2012 Dodge Durango IIHS test results in a maximum force of 105kN (ref: www.iihs.org). The high strength steel B pillars, similar to those used on most production steel vehicles, are key contributors to this
	Unusual simulation results – [1] Models appear reasonable and indicate the structure has the potential to meet collision safety requirements. Some unusual simulation results raise questions about detail accuracy of the models. [2] FMVSS 216 quasi-static roof strength: Model indicates peak roof strength of 108 KN. This is unusually high strength for an SUV type vehicle. The report attributes this high strength to the major load being resisted by the B-pillar. Several current vehicles employ this construction but have not demonstrated roof strength at this level. The report indicates the requirement of 3X curb weight is reached within 20 mm which is typically prior to the test platen applying significant load directly into the b-pillar. [3] 35 MPH frontal rigid barrier simulation: Report indicates the front tires do not contact the sill in a 35 MPH impact. This is highly unusual structural performance. Implications are the model or the structure is overly stiff. 4] Body torsional stiffness: Torsional stiffness is indicated to be 32.9 kN/deg. Higher than any comparable vehicles listed in the report. PH 2 structure torsional stiffness is comparable to significantly more compact body structures like the Porsche Carrera, BMW 5 series, Audi A8. It is not clear what elements of the PH 2 structure contribute to achieving the predicted stiffness. 5] Door beam modeling: Door beams appear to stay tightly joined to the body structure with no tilting, twisting or separation at the lock attachments in the various side impact load modes. This is highly unusual structural behavior. No door opening deformation is observed in any frontal crash simulations. This suggests the door structure is modeled as an integral load path. FMVSS requires that doors are operable after crash testing. Door operability is not	Ques 3 Richman	performance. The model was evaluated for FMVSS 216 performance (3x curb weight) using the Venza weight and met the standard; this implies that the roof strength is similar to the Venza. Because of the much lower curb weight, the projected roof crush performance is improved vs. the baseline vehicle. FMVSS 208 rigid barrier performance addressed previously. 4. Body stiffness addressed previously. The Lotus model is 4" shorter than the referenced BMW 5 and 13" shorter than the Audi A8 . The high torsional stiffness was the result of a substantial amount of fine tuning the model. The key was triangulating and boxing sections and minimizing the affect of open sections. 5. The door beam system was bolted to the "A" and "B" pillars using conventional iron mounting brackets; there is a minimal amount of deflection. The result is that the doors are predicted to open following the impact.

	addressed in the report.		
Bending Stiffness and modal frequency analysis - not reported	Report indicates "Phase 2 vehicle model was validated for conforming to the existing external data for the Toyota Venza, meeting best-in-class torsional and bending stiffness, and managing customary running loads." Only torsional stiffness is reported. Modal frequency analysis data Is not reported.	Ques 3 Richman	All references to "validation" are being changed to "model analysis results" or "FEA" results or their equivalent; the reference to customary running loads has been deleted. The BMW X5 torsional stiffness and the test methodology has been published by BMW. The Lotus model was evaluated using identical constraints. BMW did not publish bending data so no comparison was possible. The modal frequency reference was deleted from the report.
	Report Summary of Safety Testing Results" indicates the mass reduced body exhibits "best in class" torsional and bending stiffness. The report discusses torsional stiffness but there is no information on predicted bending stiffness. No data on modal performance data or analysis is presented.	Ques 3 OSU	The baseline X5 was chosen because benchmarking indicated it was the stiffest production SUV/CUV body structure and significantly stiffer than the Venza which Lotus tested. BMW published the torsional stiffness but did not disclose the X5 bending stiffness so a comparison was not possible.
	Most areas of vehicle performance other than crash performance were not addressed at all. Even basic bending stiffness and service loads (jacking, towing, 2-g bump, etc) were not addressed. The report claims to address bending stiffness and bending/torsional modal frequencies, but that analysis is not included in the report.	Ques 6 Richman	Service loads were not part of the project scope.
Simulation alone not validation **Gregg**	Simulation results alone would not be considered "validation" of PH 2 structure safety performance.	Ques 1. Joost	"Validation" comments deleted from the report.
	Report states that "the mass-reduced vehicle was validated for meeting the listed FMVSS requirements." This is an overstatement of what the analysis accomplished….. "Acceptable" levels were defined by Lotus without explanation. Results may be good, but would not be sufficient to "validate" the design for meeting FMVSS requirements.	Ques 3 Richman	Acceptable is based on Lotus experience internally and externally and indicates that the performance level is consistent with the test requirements for the specific stage of development.

	Cannot truly be validated without building a physical prototype for comparison.	Ques 3 Richman	All validation references have been deleted.
	the models cannot be regarded as validated without some correlation to physical test results.	Ques 3 OSU	Context changed to reflect that the modeling indicates a level of performance that, if an actual vehicle were built, there is a reasonable potential to meet the test requirements.
	Report Conclusions overstate the level of design “validation” achievable utilizing state-of-the- art modeling techniques with no physical test of a representative structure. From the work in this study it is reasonable to conclude the PH 2 structure has the potential to pass FMVSS and IIHS safety criteria.	Ques 5 Richman	Validation references eliminated.
	The PH 2 study did not include physical evaluation of a prototype vehicle or major vehicle sub system. Majority of the chassis and suspension content was derived from similar components for which there is extensive volume production experience. Some of the technologies included in the design are “speculative” and may not mature to production readiness or achieve projected mass reduction estimates by 2020. For those reasons, the PH 2 study is a “high side” estimate of practical overall vehicle mass reduction potential.	Ques 5 Richman	It could turn out that some Phase 1 estimates were aggressive. Most Phase 1 mass reducing opportunities were at a late prototype or production level; not all applications were automotive based. There could be attrition in the technologies as well as the inability to cost effectively transfer into the automotive sector. The report doesn’t include technologies created after 2009 so there is the potential for new materials and processes to be developed that reduce mass. Some 2020 MY goals have already been achieved less than three years after the study was initially written. For example, the 2012 Hyundai Elantra rear seat system weighs 20 kg or about 20% less than the 25 kg target set for the Phase 1 2020 MY vehicle. The baseline 2009 Venza rear seat weight was 48 kg. Adding 15% mass to the Elantra seat to normalize and add structure still results in less mass than the Phase 1 2020 MY rear seat. A key unknown to reducing mass is the ability of OEM’s to adopt a holistic, total vehicle approach. Setting system mass and cost goals frequently creates conflicts

			between groups that result in increased vehicle mass and cost even though some systems achieve their individual goals. Additionally, isolated single system mass reductions, such as those achieved by light weight closure systems, although helpful, will not drive mass decompounding that leads to a lighter weight suspension re-design and replacing a V6 engine with a DI turbocharged, cylinder de-activated three cylinder engine. A synergistic, total vehicle approach is required to reach a "tipping" point that enables mass decompounding.
	Overstating the implications of available safety results discredits the good design work and conclusions of this study.	Ques 5 Richman	The report has been revised to be conservative in what the implications are as a result of the theoretical modeling.
	FMVSS test performance conclusions are based on simulated results using an un-validated FE model. Accuracy of the model is unknown. Some simulation results are not typical of similar structures suggesting the model may not accurately represent the actual structure under all loading conditions.	Ques 5 Richman	The model uses the same analysis techniques used for current production vehicles. The fidelity is estimated at 10% of a finished production vehicle based on OEM experience. The model can only be validated by building an actual test vehicle.
	Safety performance and cost conclusions are not clearly support by data provided. A major objective of the PH 2 study is to "validate" the light weight vehicle structure for compliance with FMVSS requirements. State of the art FEM and dynamic simulations models were developed. Those models indicate the body structure has the potential to satisfy FMVSS requirements. FMVSS requirements for dynamic crash test performance is defined with respect to occupant loads and accelerations as measured using calibrated test dummies. The FEM simulations did not include interior, seats, restraint systems or occupants. Analytical models in this project evaluate displacements, velocities, and accelerations of the body structure. Predicting occupant response based on body structural	Ques 5 Richman	Model indicates feasibility for meeting performance requirements as a result of the accelerations and displacements of the model. References to occupant responses have been deleted. Validation occurs with the testing of an actual vehicle.

	displacements velocities and accelerations is speculative. Simulation results presented are a good indicator of potential performance. These simulations alone would not be considered adequate validation the structure for FMVSS required safety performance.		
	Most studies employing a finite element model validate a base model against physical testing, then do variational studies to look at effect. Going directly from an unvalidated FEM to quantitative results is risky, and the level of accuracy is questionable	Ques 5 Richman	A physical model is required to validate the theoretical modeling results.
Costing **IC/Gregg/Kai**	Cost estimates for the PH 2 vehicle are questionable. Cost modeling methodology relies on engineering estimates and supplier cost projections. The level of analytical rigor in this approach raises uncertainties about resulting cost estimates. Inconsistencies in reported piece count differences between baseline and PH 2 structures challenge a major reported source of cost savings. Impact of blanking recovery on aluminum sheet product net cost was explicitly not considered. Labor rates assumed for BIW manufacturing were $20/Hr below prevailing Toyota labor rate implicit in baseline Venza cost analysis. Cost estimates for individual stamping tool are substantially below typical tooling cost experienced for similar products. Impact of blanking recovery and labor rates alone would increase BIW cost by over $200.	Ques 1. Joost	Intellicosting completed a forensic level cost analysis. Intellicosting does not obtain supplier quotes. All costs and prices are based on research and experience. Intellicosting quoted a U.S. labor rate of $20.72 per hour base. Fully fringed is $20.72 + 50% = $31.08 per hour. Intellicosting uses a standard die / tooling cost estimating worksheet Intellicosting reviewed and updated the part count including only parts where cost was applied. Part count = 259
	Section 4.5.8.1 uses current "production" vehicles as examples for the feasibility of these techniques. However, many of the examples are for extremely high-end vehicles (Bentley, Lotus Evora, McLaren) and the remaining examples are for low-production, high-end vehicles (MB E class, Dodge Viper, etc.). The cost of some technologies can be expected to come down before 2020, but it is not reasonable to assume that (for example) the composites technologies used in Lamborghinis will be cost competitive on any time scale; significant advances in composite technology will need to be made in order to be cost competitive on a Venza, and the	Ques 2 Joost	Carbon fiber did not meet the cost criteria set for the BIW and was not used on the Phase 2 BIW. The composite material used for the floor was recycled PET (the plastic used in water bottles). The "sandwich" panels used directional glass reinforced PET outer plies with a PET foam inner. The cost of this material is substantially lower than carbon fiber. Carbon fiber, currently used on high end sports cars, will be used for the upcoming BMW i3 EV body

	resulting material is likely to differ considerably (in both properties and manufacturing technique) from the Lamborghini grade material.		structure. Per BMW, the pricing will be “very competitive”; preliminary cost estimates from Automobilwoche, a German magazine, put the cost at between $44,000 and $50,000 depending on options. The Nissan Leaf EV 2012 MSRP is $36,050. The i3 plus cost is about 22%. This is much less than the typical cost differential between a Nissan and a BMW and an indicator that BMW has greatly reduced the manufacturing cost for a carbon fiber body structure. Another example that the automotive industry is making substantial progress on utilizing light weight materials and new construction processes into higher volume, more mainstream vehicles is the Ford F-150. The 2014 Ford F-150 (about 400,000 sales annually per Edmunds.com) will reportedly have a riv-bonded aluminum body (http://online.wsj.com/article/SB100014240527023036128045775312822227138686.html). This is the same type of construction used for Lotus production sports cars and the Phase 2 model.
	Main weakness of the cost analysis is the fragmented approach of comparing costs derived in different approaches and different sources, and trying to infer relevant information from these differences.	Ques 4 joost	This was a customer driven requirement.
	Flat year-over-year wages for the cost analysis seems unrealistic.	Ques 4 OSU	The trend is towards lower wages such as those currently paid by Volkswagen at its US plant. See GM-VW cost discussion below.
	Vulnerability in this cost study appears to be validity and functional equivalence of BIW design with 169 pieces vs. 407 for the baseline Venza.	Ques 4 Richman	Parts count revised from 407 to 269 to reflect only costed parts.
	Total tooling investment of $28MM for the BIW not consistent with typical OEM production experience. BIW tooling of $150-200MM	Ques 4 richman	Intellicosting quotes tooling based on volume. The $28MM is based on the low volume of vehicles

	would not be uncommon for conventional BIW manufacturing. If significant parts reduction could be achieved, it would mean less tools, but usually larger and more complex ones, requiring larger presses and slower cycle times.		required. Tooling life is 250,000 parts.
	Tooling estimates from Intellicosting are significantly lower than have been seen in other similar studies or production programs and will be challenged by most knowledgeable automotive industry readers. Intellicosting estimates total BIW tooling at $28MM in the tooling summary and $70 MM in the report summary. On similar production OEM programs complete BIW tooling has been in the range of $150MM to $200MM. The report attributes low tooling cost to parts consolidation. This does not appear to completely explain the significant cost differences between PH 2 tooling and actual production experience. Parts consolidation typically results in fewer tools while increasing size, complexity and cost of tools used. The impact of parts consolidation on PH 2 weight and cost appears to be major. The report does not provide specific examples of where parts consolidation was achieved and the specific impact of consolidation. Considering the significant impact attributed to parts consolidation, it would be helpful provide specific examples of where this was achieved and the specific impact on mass, cost and tooling. Based on actual production experience, PH 2 estimates for plant capital investment, tooling cost and labor rates would be viewed as extremely optimistic	Ques 4 Richman	Intellicosting quoted low volume tooling verses high volume. Examples of part consolidation have been added to the report.
	Difficult to evaluate since this portion of the report was completed by a subcontractor. The forming dies seem to be inexpensive as compared to standard steel sheet metal forming dies.	Ques 4 osu	Intellicosting quoted low volume tooling verses high volume.
	Applying a consistent costing approach to each vehicle and vehicle system using a manufacturing cost model approach. This approach would establish a more consistent and understandable assessment of cost impacts of vehicle mass reduction design and technologies.	Ques 4 richman	Intellicosting applies a consistent methodology using our company developed application. An example of Intellicosting methodology has been added to the report.
	The assessment of the energy supply includes a description of solar, wind, and biomass derived energy. While the narrative is quite positive on the potential for each of these energy sources, it’s not	Ques 4 Joost	This is a 2020 model vs. a current production plant. The study was done by an experienced manufacturing team, EBZ, who builds plants for major European OEMs

	clear in the analysis how much of the power for the plant is produced using these techniques. If the renewable sources provide a significant portion of the plant power, then the comparison of the Ph2 BIW cost against the production Venza cost may not be fair. The cost of the Venza BIW is determined based on the RPE and several other assumptions and therefore includes the cost of electricity at the existing plant. Therefore, if an automotive company was going to invest in a new plant to build either the Ph2 BIW or the current Venza BIW (and the new plant would have the lower cost power) then the cost delta between the two BIWs would be different than shown here (because the current Venza BIW produced at a new plant would be less expensive). The same argument could be made for the labor costs and their impact on BIW cost. By including factors such as power and labor costs into the analysis, it's difficult to determine what the cost savings/penalty is due only to the change in materials and assembly – the impact of labor and energy are mixed into the result.		including BMW, Audi and VW. Lotus believes that OEMs will incorporate what Europe is doing today in terms of low environmental impact and sustainable energy into their US assembly plants. This trend is already starting in the US. The Subaru of Indiana assembly plant has "zero landfill" meaning that all plant waste is either recycled or turned into electricity. A single-family home produces more waste in a day than the Subaru Indiana plant does in a year. Source: Subaru.com No attempt was made to predict how Toyota would build a CUV eight years from now.
	The number of workers assigned to vehicle assembly in this report seems quite low. Extra personal need to be available to replace those with unexcused absences. Do these assembly numbers also include material handling personnel to stock each of the workstations? While this work does make a compelling case it downplays some of the very real issues that slow such innovation in auto manufacturing. Examples: multi-material structures can suffer accelerated corrosion if not properly isolated in joining. Fatigue may also limit durability in aluminum, magnesium or novel joints. Neither of these durability concerns is raised. Also, automotive manufacturing is very conservative in using new processes because one small process problem can stop an entire auto manufacturing plant. Manufacturing engineers may be justifiably weary of extensive use of adhesives, until these are proven in mass production in other environments. These very real impediments to	Ques 4 OSU	Labor figures include material handling personnel. They do not include paying for extra plant personnel with no assignments. See previous discussion. The 2014 Ford F-150 (400,000 sales) will reportedly use a riv-bonded all aluminum body structure.

	change should be mentioned in the background and conclusions.		
IC	<u>Summary</u> – Cost projections . . . lack sufficient rigor to support confidence in cost projections and in some cases are based on "optimistic" assumptions. Significant cost reduction is attributed to parts consolidation in the body structure. Part count data presented in the report appears to reflect inconsistent content between baseline and PH 2 designs. Body manufacturing labor rates and material blanking recovery are not consistent with actual industry experience. Using normal industry experience for those two factors alone would add $273 to body manufacturing cost. Tooling cost estimates for individual body dies appear to be less than half normal industry experience for dies of this type.	Ques 4 richman	Intellicosting applies a consistent methodology using our company developed application. See example of Intellicosting methodology. Intellicosting uses their methodology to support many international OEMs.
	System cost assumptions based on average sales margin and detailed engineering judgments can be a reasonable first order estimate. These estimates can be useful in allocation of relative to costs to individual vehicle systems, but lack sufficient rigor to support definitive cost conclusions	Ques 4 Richman	Intellicosting does not apply recovery for scrap material in our calculation / methodology. This information was also added to the report as clarification.
	Body costs for PH 2 design were estimated by combining scaled material content from baseline vehicle (Venza) and projected manufacturing cost from a new production processes and facility developed for this project. This approach is logical and practical, but lacks the rigor to support reliable estimates of new design cost implications when the design changes represent significant departures from the baseline design content.	Ques 4 Richman	Intellicosting applies a consistent methodology using our company developed application. See example of Intellicosting methodology. Intellicosting uses their methodology to support many international OEMs.
	Body piece cost and tooling investment estimates were developed by Intellicosting. No information was provided on Intellicosting methodology. Purchased component piece cost estimates (excluding BIW) are in line with findings in similar studies. Tooling costs supplied by Intellicosting are significantly lower than actual production experience would suggest.	Ques 4 Richman	Intellicosting applies a consistent methodology using our company developed application. See example of Intellicosting methodology. Intellicosting uses their methodology to support many international OEMs. Intellicosting quotes tooling based on volume. The $28MM is based on the low volume of vehicles required. Tooling life is 250,000 parts.
	The PH 2 study indicates and aluminum based multi material body (BIW, closures) can be produced for at a cost reduction of $199	Ques 4 Richman	The estimated Phase 2 BIW piece cost increase was over $700 more than the baseline all steel vehicle. The

	relative to a conventional steel body. That conclusion is not consistent with general industry experience. This inconsistency may result from PH 2 assumptions of material recovery, labor rates and pars consolidation. A recent study conducted by IBIS Associates "Aluminum Vehicle Structure: Manufacturing and Life Cycle Cost Analysis" estimated a cost increase $560 for an aluminum vehicle BIW and closures. http://aluminumintransportation.org/members/files/active/0/IBIS%20Powertrain%20Study%20w%20cover.pdf That study was conducted with a major high volume OEM vehicle producer and included part cost estimates using detailed individual part cost estimates. Majority of cost increases for the low mass body are offset by weight related cost reductions in powertrain, chassis and suspension components. Conclusions from the IBIS study are consistent with similar studies and production experience at other OEM producers.		use of less expensive tools, such as extrusions, the reduced number of tools due to fewer parts required, lower assembly costs due to the use of less expensive joining methods and fewer parts to be handled partially offset the more expensive body. The synergistic cost savings from other areas of the vehicle (from the Phase 1 report) were also included and further offset the Phase 2 body cost. The peer reviewed Phase 1 2020 model achieved an estimated mass reduction of near 40% for all non-BIW systems (less powertrain) while using primarily similar materials. The savings associated with the elimination of 40% of the materials from the baseline vehicle systems helps to further offset the BIW cost. This resulted in an estimated average savings of about 4% for the non-BIW systems. Because this was approximately 80% of the manufacturing cost, the total weighted cost with the BIW included was at near parity with the baseline vehicle.
	Material Recovery -- Report states estimates of material recovery in processing were not included in the cost analysis. Omitting this cost factor can have a significant impact on cost of sheet based aluminum products used in this study. Typical auto body panel blanking process recovery is 60%. This recovery rate is typical for steel and aluminum sheet. When evaluation material cost of an aluminum product the impact of recovery losses should be included in the analysis. Potential impact of material recovery for body panels: Approximate aluminum content (BIW, Closures) 240 Kg Input material required at 60% recovery 400 Kg Blanking off-all 160 Kg Devaluation of blanking off-all (rough estimate)	Ques 4 Richman	Sheet utilization varied from part to part. The full sheet cost was used with no allowance for the unused material, i.e., Intellicosting did not apply scrap material recovery in their calculation / methodology. There was no allowance for the lost material from blanking operations to be recovered as an offset to material costs.

	Difference between raw material and Blanking off-all $1.30/Kg $211 Blanking devaluation increases cost of aluminum sheet products by over $ 0.90/Kg. Appropriate estimates of blanking recoveries and material devaluation should be included in cost estimates for stamped aluminum sheet components. Recovery rates for steel sheet products are similar to aluminum, but the economic impact of steel sheet devaluation is a significantly lower factor in finished part cost per pound. Report indicates total cost of resistance spot welding (RSW) is 5X the cost of friction spot welding (FSW). Typical total body shop cost (energy, labor, maintenance, consumable tips) of a RSW is $0.05 - $0.10. For the stated ratio to be accurate, FSW total cost would be $0.01-$0.02 which appears unlikely. It is possible the 5X cost differential apply to energy consumption and not total cost.		FSW (friction stir welding) was not used. Friction Spot Joining (FSJ), a process developed by Kawasaki Heavy Industries, was utilized. The FSJ process uses a small servo-motor to spin a unique drill bit that engages two sheets of aluminum and flows the parts together. The material remains in the plastic (not molten) region so the parent material properties are maintained. Per Kawasaki (www.khi.co.jp/english/robot/product/fsj.html) " the FSJ system uses less than 1/20th the power consumed by resistance spot welding equipment. In addition, there is no need for large-capacity power supply equipment resulting in a reduction in overall equipment costs."
	Labor rates -- Average body plant labor rates used in BIW costing average $35 fully loaded. Current North American average labor rates for auto manufacturing (typically stamping, body production and vehicle assembly) Toyota $55 GM $56 (including two tier) Ford $58 Honda $50	Ques 4 Richman	The industry trend is towards lower labor costs. GM is targeting a 40% reduction in labor costs at the Lake Orion, Michigan plant that builds the Chevrolet Sonic and will use that as a model for other US plants (http://www.gminsidenews.com/forums/f12/how-small-car-helping-rewrite-labor-costs-u-s-plant-104321/). Improved efficiency, using contract non-union labor (about $20/hr with benefits) as well as continued

	Nissan $47 Hyundai $44 VW $38 Labor rate of $35 may be achievable (VW) in some regions and circumstances. The issue of labor rate is peripheral to the central costing issue of this study which is assessing the cost impact of light weight engineering design. Method used to establish baseline BIW component costs inherently used current Toyota labor rates. Objective assessment of design impact on vehicle cost would use same labor rates for both configurations. Labor cost or BIW production is reported to be $108 using an average rate of $35. Typical actual BIW labor content from other cost studies with North American OEM's found actual BIW labor content approaching $200. Applying the current Toyota labor rate of $55 to the PH 2 BIW production plan increases labor content to $170 (+$62) per vehicle.		replacement of retiring workers with Tier 2 workers (about 60% of the existing hourly rate) are expected to continue to reduce GM labor rates. This trend was projected to the 2020 timeframe but VW is already very close to this rate today. The Volkswagen Tennessee assembly plant pays $14.50/hr and utilizes $12/hr contract employees. http://www.wsws.org/articles/2011/sep2011/chat-s23.shtml Identical labor rates were used for both the Venza body costs and the Phase 2 body costs. Two keys to lower assembly costs are: 1. reducing assembly time by substantially reducing the parts count and 2. utilizing less costly joining processes. The Phase 2 BIW uses structural adhesives which allow greater spacing between the joints (needed for peel) which reduces the number of joints significantly. A typical CUV/SUV requires 5,000 welds at about $0.05/weld. That is approximately $250 in joining costs; reducing the number of joints by about 50% and substantially decreasing the joint costs more than offsets the added cost of using structural adhesive bonding. This cost savings was applied to offset the more expensive Phase 2 BIW piece costs.
	Clallam county, WA is an interesting choice for the plant location (I grew up relatively nearby). Port Angeles is not a "major port" (total population <20,000 people) and access to the area from anywhere else in the state is inconvenient.	Ques 6 Joost	Section eliminated.
Piece count reduction	BIW Design Integration -- Report identifies BIW piece count reduction from a baseline of 419 pieces to 169 for PH 2. Significant	Ques 4 Richman	Intellicosting reviewed and updated the part count including only parts where cost was applied. Part count

concerning	piece cost and labor cost savings are attributed to the reduction in piece count. Venza BOM lists 407 pieces in the baseline BIW. A total of 120 pieces are identified as having "0" weight and "0" cost. Another 47 pieces are listed as nuts or bolts. PH 2 Venza BOM lists no nuts or bolts and has no "0" mass/cost components. With the importance attributed to parts integration, these differences need to be addressed. Closure BOM for PH 2 appears to not include a number of detail components that are typically necessary in a production ready design. An example of this is the PH 2 hood. PH 2 Hood BOM lists 4 parts, an inner and outer panel and 2 hinges. Virtually all practical aluminum hood designs include 2 hinge bracket reinforcements, a latch support and a palm reinforcement. Absence of these practical elements of a production hood raise questions about the functional equivalency (mounting and reinforcement points, NVH, aesthetics,…) of the two vehicle designs. Contents of the Venza BOM should be reviewed for accuracy and content in the PH 2 BOM should be reviewed for practical completeness.		= 259. There were two scenarios used for the hood: 1. a typical hinged hood system; and 2. a fixed (bolt on) hood. For the fixed hood, a lightweight hinged panel for fluid checking and fluid filling is incorporated into the front fascia . The bolt-on hood mass was used for the BOM. The crash models were evaluated using a "worst case" hinged hood system. There is no need for local hood hinge reinforcements on this model nor is there a need for a "palm" reinforcement since there are no hinges and the hood doesn't open. This approach saves a significant amount of weight by eliminating the hinge system and is an example of mass decompounding.
Failure specifications for materials	Materials properties describing failure are not indicated (with the exception of Mg, which shows an in-plane failure strain of 6%). It seems unlikely that the Al and Steel components in the vehicle will remain below the strain localization or failure limits of the material; it's not clear how failure of these materials was determined in the models. The authors should indicate how failure was accounted for; if it was not, the authors will need to explain why the assumption of uniform plasticity throughout the crash event is valid for these materials. This could be done by showing that the maximum strain conditions predicted in the model are below the typical localization or failure limits of the materials (if that is true, anyway).	Ques 1 Joost	Addressed previously.
	Model assumes no failures of adhesive bonding in materials during	Ques 3	There could be some degradation in the areas that are

	collisions. Previous crash testing experience suggest[s] some level of bonding separation and resulting structure strength reduction is likely to occur.	Richman	adhesively bonded; however, the local degradation in the bonded regions would have a minimal impact on the global results. These types of bonding related issues are typically dealt with by doubling up on the adhesive application (2 strips vs. one) or adding a weld or mechanical fastener during development (crash) testing with actual vehicles.
Part Count	The radical part count reduction needs to be more fully explained or de-emphasized. Report also should address the greatly reduced tooling and assembly costs relative to the experience of today's automakers. Some conservatism would be appropriate regarding potential shortcomings in interior design and aesthetics influencing customer expectations and acceptance.	Ques 1 Richman	Parts count revised to eliminate 0 mass parts.
references	References for all of the materials and adhesives would be very helpful.	Ques 1 OSU	References and suppliers included in the report for all materials.
	One broad comment is that this report needs to be more strongly placed in the context of the state of the art as established by available literature. For example the work only contains 7 formal references. Also, it is not clear where material data came from in specific cases (this should be formally referenced, even if a private communication) and the exact source of data such in as the comparative data in Figure 4.3.2 is not clear. Words like Intillicosting are used to denote the source of data and we believe that refers to a specific subcontract let to the firm 'intellicosting' for this work and those results are shown here. This needs to be made explicitly clear.	OSU Ques 1	More detailed references to the suppliers and their background and their role was added. The suppliers included Alcoa (aluminum support), Meridian (magnesium support), Henkel (coating, lab testing and structural composite insert support), Allied Composites (composite support), EBZ (assembly plant design), and Intellicosting (costing support).
Misc	I would suggest that a short summary be added describing the major changes of the Phase 2 design with respect to the original High Development vehicle body design.		Added.
	This reviewer sat down with the person who created and ran the LS-DYNA FEA models. Additional insight into how the model performs and specific questions were answered on specific load cases. All questions were answered.	Ques 3 OSU	The Ohio State University peer reviewers met with Lotus to review confidential portions of the software analysis that could not be publicly released. The OSU team reviewed the background information, how it was set up and how the dropdowns fed into the primary

			analysis that formed the basis of the final FEA models. The below information is a summary of the analysis methodology. The model was created from CAD data that was provided for all of the various components that made up the ARB vehicle structure. A set of guidelines was used to create the model; these are general guidelines for creating an appropriate finite element model. Discretion was used during any meshing to determine the level of detail and quality required. Models were created with the following typical conditions: All holes less than 10mm in diameter ignored Holes >ø10mm should be modeled with a least a single concentric ring of elements At least two rows of elements weld flanges Spot-welds (i.e. friction spot connections) were modeled with single solid elements (type #1) BIW and Closure shell definitions have 5 integration points Tied contact's were defined as *CONTACT_TIED_NODE_TO_SURFACE_OFFSET or *CONTACT_TIED_SHELL_EDGE_TO_SURFACE_OFFSET (*CONTACT_SPOTWELD definition will be used for 'weld' beam definitions) Mesh quality checks were made to ensure the elements met the criteria set for the following: Element mesh size Number of triangles per panel Tria. Interior angle

			Quad Interior angle Warping Jacobian Aspect Ratio Total %age of failed elements <1% (from all element quality criteria's) Components were also checked for: Free edges, duplicate elements, consistent shell element normal, LS-DYNA part names (for easier identification) and that tied contacts attach at all nodes The flat frontal model had ~995,000 elements (1-D, 2-D and 3-D)
	to provide additional credibility to the manufacturing assessment it would be helpful to include a description of other work that EBZ has conducted where their manufacturing design work was implemented for producing vehicles. Lotus is a well-known name, EBZ is less well known.	Ques 4 Joost	EBZ, the firm Lotus contracted to engineer the Phase 2 BIW assembly plant, has designed assembly plants for Audi, BMW, VW, Porsche, Jaguar-Land Rover, Ford (Europe) as well as other international OEM's. This information was added to the report.
	The analysis is based on specific density which assumes that the architecture of the vehicles is the same. For example, the front-end crash energy management system in a micro car is likely quite different from the comparable system in a large luxury car (aside from differences in gauge to account for limited crash space, as discussed in the report). While this analysis provides a good starting point, I do not feel that it is reasonable to expect the weight reduction potential to scale with specific density. In other words, I think that the 32.4 value used in the analysis also changes with vehicle size due to changes in architecture. Similarly, the cost analysis projecting cost factor for other vehicle classes is a good start, but it's unlikely that the numbers scale so simply.	Ques 5 Joost	The objective was to create a predictive model based on current vehicles. The model will change as the size and mass of future vehicles evolve.

	Fundamental engineering work is very good and has the potential to make a substantial and important contribution to industry understanding of mass reduction opportunities. The study will receive intense and detailed critical review by industry specialists. To achieve potential positive impact on industry thinking, study content and conclusions must be recognized as credible. **Unusual safety simulation results** and questionable cost estimates (piece cost, tooling) need to be explained or revised. As currently presented, potential contributions of the study are likely to be obscured by unexplained simulation results and cost estimates that are not consistent with actual program experience. Absolutely. Recommended adjustments summarized in Safety analysis, and cost estimates (recommendations summarized in attached review report). Credibility of study would be significantly enhanced with detail explanations or revisions in areas where unusual and potentially dis-crediting results are reported. Conservatism in assessing CAE based safety simulations and cost estimates (component and tooling) would improve acceptance of main report conclusions. Impact of BIW plant site selection discussion and resulting labor rates confuse important assessment of design driven cost impact. Suggest removing site selection discussion. Using labor and energy cost factors representative of the Toyota Venza production more clearly identifies the true cost impact of PH 2 design content.	Ques 6 Richman	The overall tone of paper was reviewed and revised as required to insure that it is conservative relative to the meaning of the results and their potential implementation. The study indicates potential but does not represent that the model will result in a vehicle that will meet the FMVSS and IIHS requirements. That will require building a vehicle and verifying the performance. The “unusual simulation results”, e.g., roof crush, are consistent with the production 2011-2012 Dodge Durango. The 2011-2012 Dodge Durango IIHS test results in a maximum force of 105kN (ref: www.iihs.org). Additionally, a 10% modeling error vs. actual would reduce the maximum force to 97 kN (from 108 kN). The high strength steel B pillars on the Phase 2 BIW are similar to those used on production steel bodied vehicles and are key contributors to the roof strength. Using a key structural part similar to those designed for much heavier vehicles on the light weight Phase 2 BIW body structure provided a substantial performance margin for roof crush and aided in side impact performance. The “questionable cost results” were addressed earlier including revising the cost analysis and the parts count. The Phase 2 BIW piece cost was $730 higher than the baseline which is consistent with the estimated $560 provided by the reviewer. The tooling and assembly related savings detailed previously helped to offset the increased cost BIW. The Phase 1 peer reviewed paper

			was used as the basis for additional, non-BIW related, cost offsets that impacted the total vehicle cost. The site selection discussion was deleted. The reader can substitute internal labor rates and calculate the impact on the BIW assembly costs. As previously discussed, the future trend is towards lower labor rates; GM is targeting VW's labor rates. VW (Tennessee assembly plant) is currently paying $14.50/hr to direct employees and $12.00/hr to contract employees (as cited previously).
	The proposed engine size is based on the assumption that decreasing the mass of the vehicle and holding the same power–to-weight ratio will keep the vehicle performances alike. This assumption is true only if the coefficient of drag (Cda) will also decrease (practically a perfect match in all the dynamic regards is not possible because the quadratic behavior of the air vs speed). The influence of the airdrag is typically higher than the general perception. In this particular case is very possible that more than half of the engine power will be used to overcome the airdrag at 65 mph. Therefore aerodynamic simulations are mandatory in order to validate the size of the engine.	Ques 6 OSU	The baseline body in white incorporated a variety of aero aids including a flat underbody, 10mm lower roof height, integrated rear vision system and a fixed hood (no fender gaps). The low mass Phase 2 vehicle requires 123 HP to maintain the Venza's wt/HP ratio. Using a 32 ft^2 frontal area, a 0.28 Cd and an 1173 kg weight yields an estimated 12.2 HP required to drive the Phase 2 vehicle at 70 MPH.