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Design and Deployment of a Mule Plugin Split-Parallel Chevrolet Malibu: Integration

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Short Abstract

As a selected participant in the EcoCAR2: Plugging In to the Future competition, headline sponsored by General Motors and the US Department of Energy, the Rose-Hulman team has completed the second year of a three year design cycle. This paper focuses on the mechanical integration of powertrain components based on the year one design. The selected architecture, a plugin split-parallel, utilizes a GM LE9 2.4L Flexfuel engine, a GM MHH eAssist 6-speed automatic transmission, a modified GM BAS and inverter, a Remy HVH250 rear traction motor with Rinehart inverter, and custom A123 battery.

1 Introduction

Rose-Hulman Institute of Technology (RHIT) is an undergraduate focused college of engineering, science, and mathematics located in Terre Haute, Indiana USA. RHIT has been participating in the General Motor (GM) and US Department of Energy (DoE) headline sponsored Advanced Vehicle Technology Competitions (AVTCs) since 2004 when selected to join the Challenge-X competition. These AVTCs are rigorous three year design sequences which challenge 15 North American universities and colleges to design, produce, and validate a hybrid vehicle. These vehicles utilize alternative fuels to decrease petroleum consumption and emissions production on a Well-to-Wheels basis without compromising consumer acceptability in performance, utility, and/or safety. The first year of the competition focuses on vehicle system modelling; utilizing Matlab and Simulink to predict performance specifications in parallel with investigating component fitment using Siemens NX 7.5. Year two culminates with the testing of a 60% buyoff mule vehicle which is then optimized and refined to 99% buyoff quality during year three. For the current AVTC EcoCAR2: Plugging In to the Future the vehicle platform is a 2013 Chevrolet Malibu.

A key team decision was to create a performance oriented vehicle as a market differentiator: the Malibu eco^{sport}. Modelling and simulation work performed during year one, presented in EVS27 paper titled "Design of a Plugin Split-Parallel Chevrolet Malibu: Control Strategy Development", within the constraints of available GM or third party resources, indicated that a plugin split-parallel architecture would best meet the team and competition goals. The components selected are presented in Table 1 and high-level architecture layout is presented in Figure 1.

Component	Source
Engine	GM LE9 2.4l four cylinder (using E85)
Transmission	GM MHH 6-speed automatic with eAssist
Belt Electric Machine	Modified GM BAS, Rinehart Inverter
Rear Traction Motor	Remy HVH250p
Energy Storage System (ESS)	A123 7m15s2p

Table 1: Selected Powertrain Components

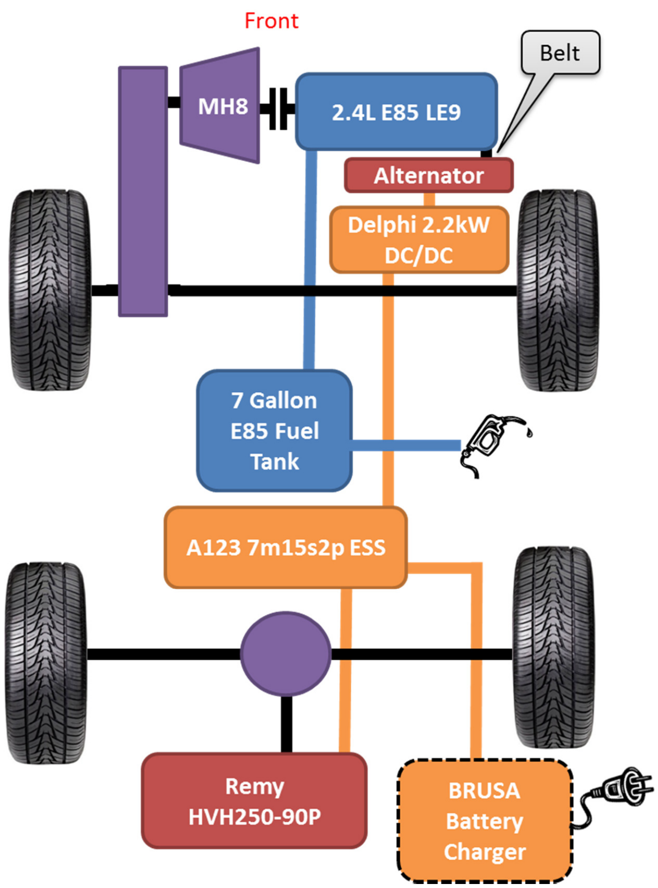

Figure 1: High Level Vehicle Architecture

The control strategy has two primary operating modes: charge depleting and charge sustaining. In charge depleting mode, the vehicle operates electrically, powered by the rear traction motor (HVH250). When the Energy Storage System (ESS) drops to a threshold level, the vehicle switches to the front powertrain and operates traditionally, powered by the engine and transmission. The BAS will be employed during year three as a refinement to enable start stop. To achieve the performance goal of the Malibu eco^{sport}, a high throttle request from the driver over-rides the current mode and activates both the engine and the motor yielding power levels near 330 HP while still achieving a combined cycle fuel economy of 38 mpg when in normal operating modes.

2 Component Layout

After spending year one and the ensuing summer exploring and verifying fitment, the finalized locations are presented in Figure 2.

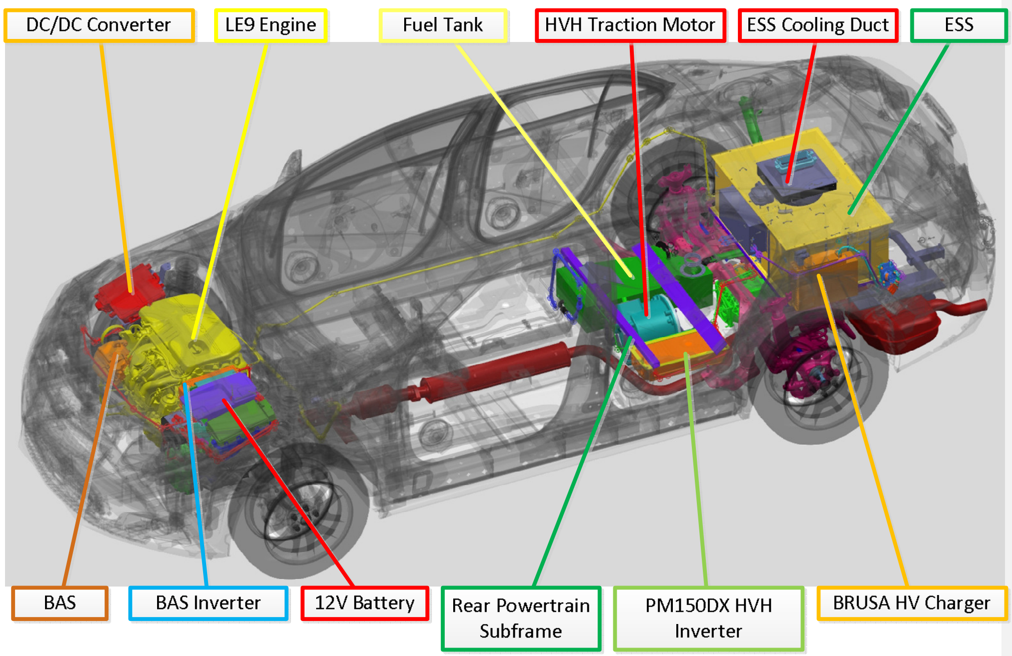

Figure 2: Powertrain Component Locations

3 FEA Analysis

EcoCAR2 competition rules require an FEA analysis of non-stock powertrain mounts to be performed to ensure crash worthiness. Static loads of 20g were applied longitudinally and laterally and a static load of 8g was applied vertically in succession to the ESS subframe (Figure 3: ESS Subframe Model) and the HVH/Fuel Tank (HVH/FT) subframe (Figure 5: HVH/FT Subframe) which are new structural additions to the vehicle. The same loading conditions were then applied to the brackets which mount the HVH250 to its subframe (Figure 7 and Figure 8).

The ESS will be secured to the vehicle by mounting to an ESS subframe. The design material for the ESS Subframe is 1020 cold rolled steel. This readily available variant of both the 1020 tube steel (3/4" x ¾" x 1/8" wall thickness) and the 1020 flat bar (1.75"x 1/8" thick), that will be used to fabricate the ESS subframe are listed as having a yield strength of 350 MPa. Other properties of 1020 cold rolled steel include a poison's ratio of 0.290, an ultimate tensile strength of 420MPa, a modulus of elasticity of 205 GPa and a density of 7.87 g/cc.

As shown in Figure 4: ESS Subframe FEA Results (Longitudinal), the highest stresses were observed in the longitudinal direction which yielded a maximum value of 55 MPa.

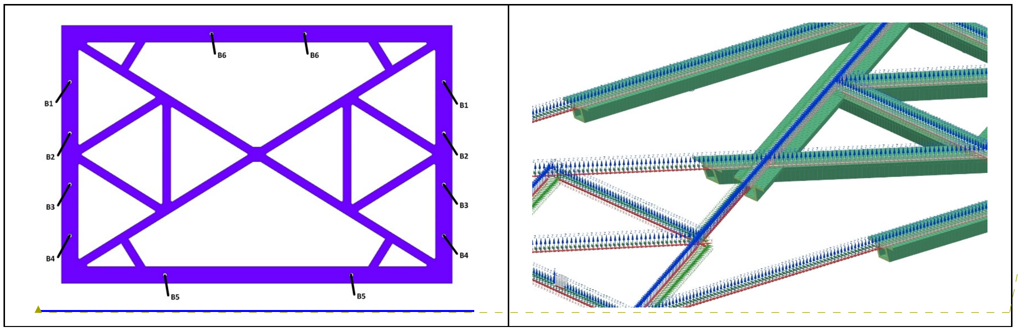

Figure 3: ESS Subframe Model

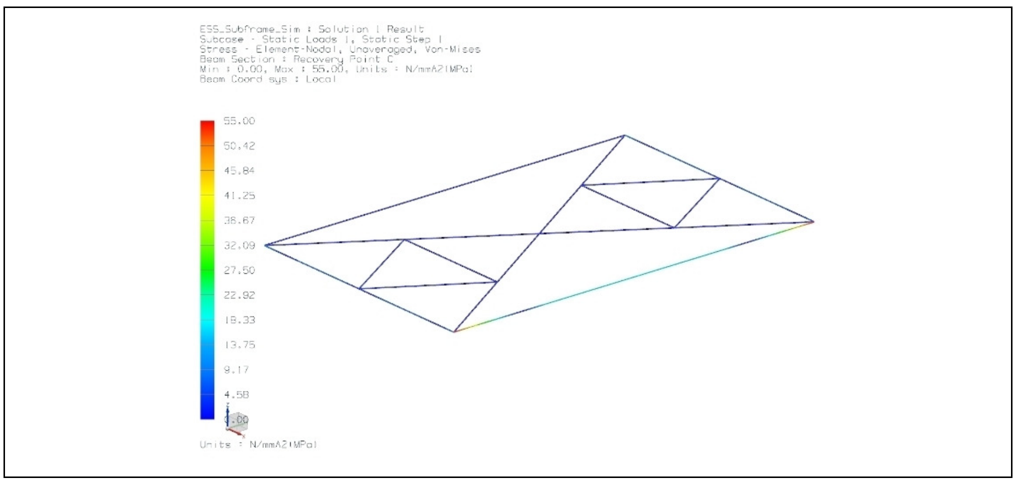

Figure 4: ESS Subframe FEA Results (Longitudinal)

The HVH/FT subframe is also constructed using 1020 cold rolled rectangular steel tubing; one piece that measures 1 " x 1.5" x 1/8" and the other one 1" x 3" x 1/8". The yield strength of the material is 350 MPa. The HVH250 traction motor and the fuel tank are mounted to the HVH/FT subframe using threaded standoffs which are shown in Figure 5: HVH/FT Subframe. The HVH/FT subframe was modelled in NX NASTRAN using a beam model as shown on the left in HVH/FT Subframe FEA Results (Longitudinal). The mesh used was a 1D Element Section which gives the user the ability to define the cross section of each beam element. The element size used for the mesh was 10mm.

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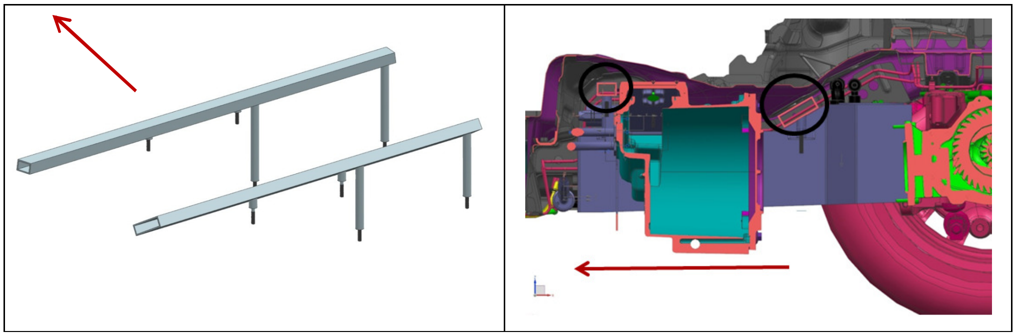

Figure 5: HVH/FT Subframe

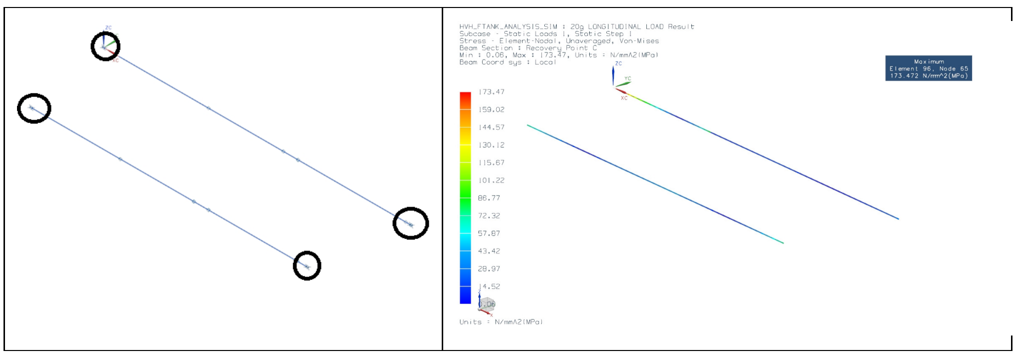

Figure 6: HVH/FT Subframe FEA Results (Longitudinal)

The NX NASTRAN FEA results for the HVH/FT subframe show that the highest stresses seen are in the longitudinal direction in the amount of 173.5 MPa. Since the yield strength of the material is 350 MPa, a value of 173.5 MPa meets the competition mandated Factor of Safety (FOS) of 2. Black circles on the left in Figure 6: HVH/FT Subframe FEA Results, indicate the 4 points where fixed constraints were applied to the beam model. These constraints simulate the points where the subframe will be welded to the vehicle.

The HVH250 front and back brackets will mount the HVH250 to the HVH/FT subframe. The material used to fabricate the HVH250 front bracket will be normalized 4140 Cr-Mo Steel (yield strength of 655 MPa). The HVH250 rear bracket will be made using annelled 4140 Cr-Mo Steel which has a yield strength of 915 MPa.

Material properties for the HVH250 front bracket are given in Table 2: Normalized 4140 Cr-Mo Steel Material Properties. Table 3: Annealed 4140 Cr-Mo Steel Properties gives material properties for the HVH250 rear mounting bracket.

Yield Strength	Poisson's ratio	Ultimate Tensile Strength	Density
655 MPa	0.28	1020 MPa	7.8 g/cm^3

Table 2: Normalized 4140 Cr-Mo Steel Material Properties

Yield Strength	Poisson's ratio	Ultimate Tensile Strength	Density
915 MPa	0.28	1655 MPa	7.8 g/cm^3

Table 3: Annealed 4140 Cr-Mo Steel Properties

The HVH250 front bracket is shown as a 3D model on the left in Figure 7: HVH250 Front Bracket Model and FEA Lateral Loading Results. The highest stresses observed in the HVH250 front bracket occur in the lateral case with a maximum value of 285 MPa. The HVH250 rear bracket is shown as a 3D model on the left in Figure 8: HVH250 Rear Bracket Model and FEA Lateral Loading Results. The highest stresses observed in the HVH250 rear bracket occur in the lateral case with a maximum value of 454 MPa. Both brackets were modelled in NX7.5 and then meshed using a 3D tetrahedral mesh with an element size of 2mm for the front bracket and 1.5mm for the rear bracket.

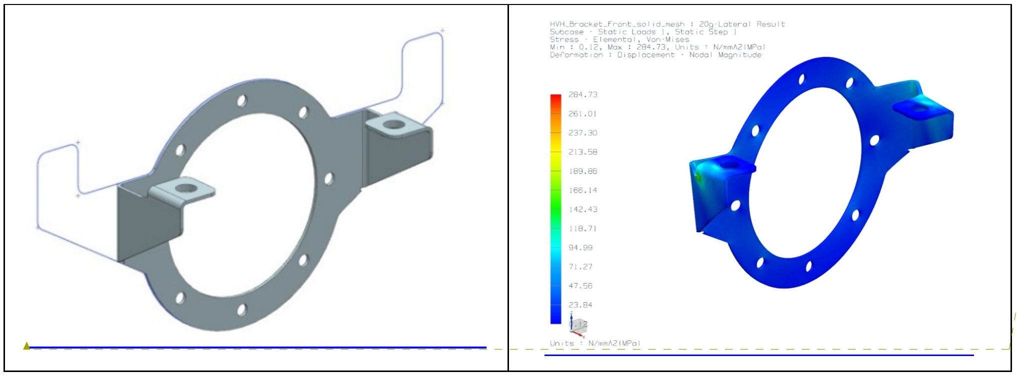

Figure 7: HVH250 Front Bracket Model and FEA Lateral Loading Results

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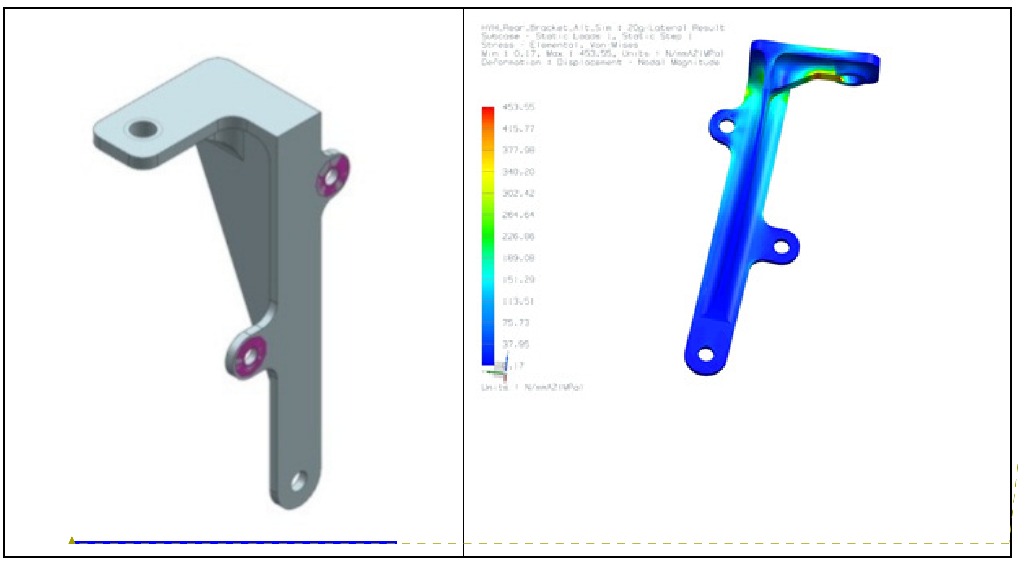

Figure 8: HVH250 Rear Bracket Model and FEA Lateral Loading Results

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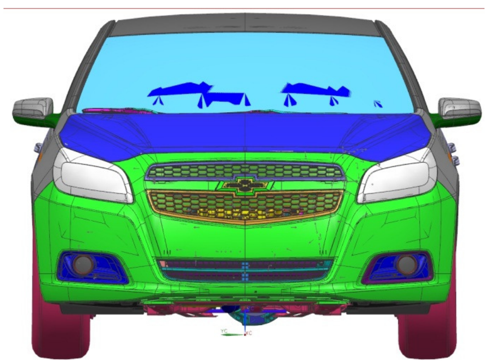
For the material properties given above, the safety factors are given below in **Error! Reference source not found.**

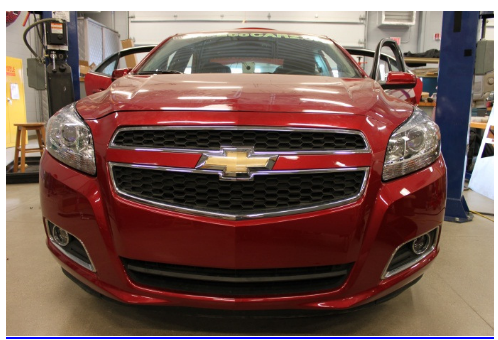
	Longitudinal	Lateral	Vertical
ESS Subframe	6.4	13.0	40.7
HVH/Fuel Tank Subframe	2.0	10.0	3.6
HVH Front Bracket	3.6	2.3	10.4
HVH Rear Bracket	2.5	2.0	10.1

Table 4: Safety Factors

4 Integration Validation

The final step in the deployment of the mule vehicle was to validate the integration per the year one design, noting any deviations. Presented in the figures below are the CAD as intended integration and the associated in-vehicle validation photograph. Vehicle exterior is presented first followed by the engine and under-body and concludes with the interior. Vehicle integration followed the CAD in all instances with the exception of the GM BASS and front Rinehart invertor. A supplier issue resulted in the stock GM BAS not being rewound which necessitated a last minute change in design. The stock 12V alternator was retained and the DC/DC converter was used to step the 12V up to the 350V bus voltage to provide stationary charging as opposed to going from 350V down to 12V to power the hotel loads.





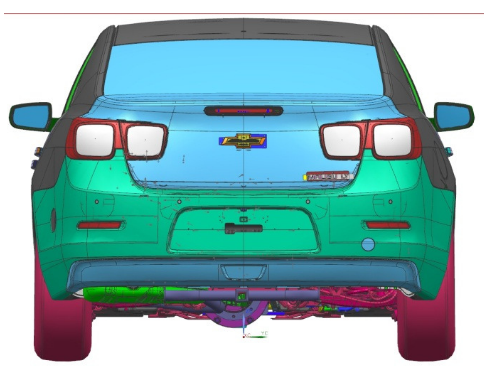
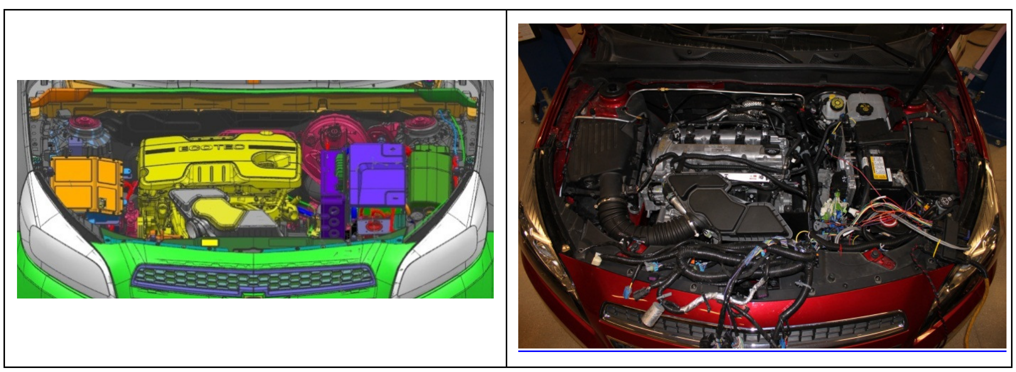


Figure 9: Integration Validation – Exterior



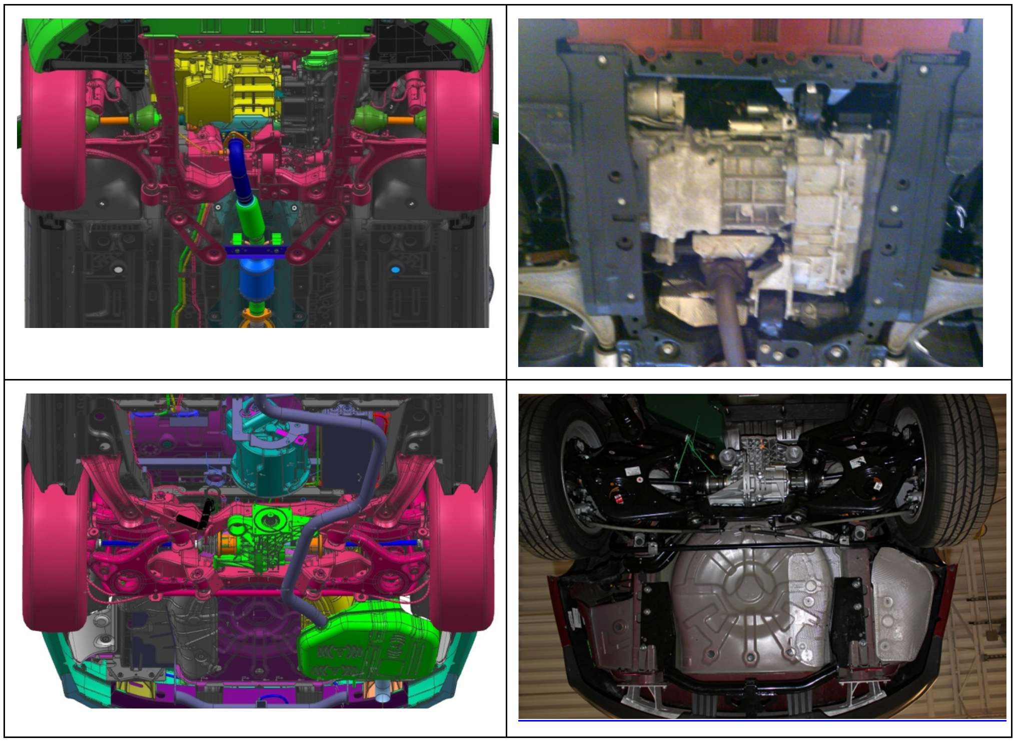
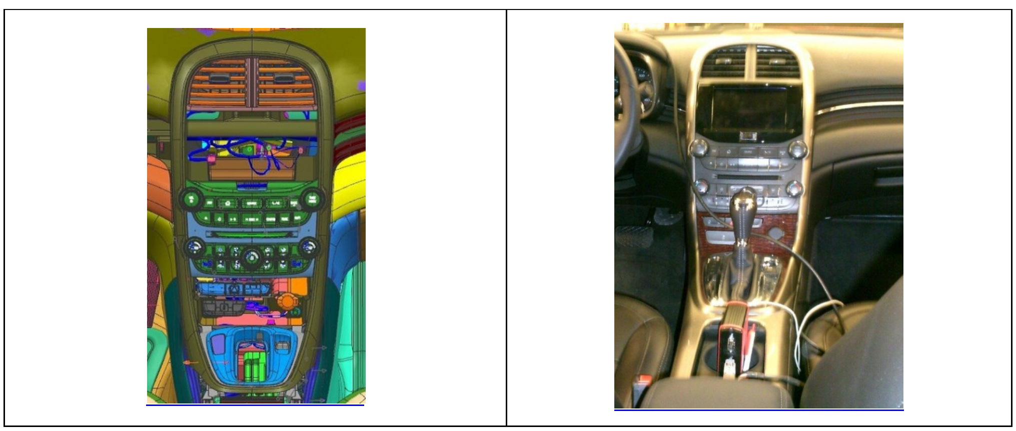


Figure 7: Integration Validation – Engine Bay and Underbody



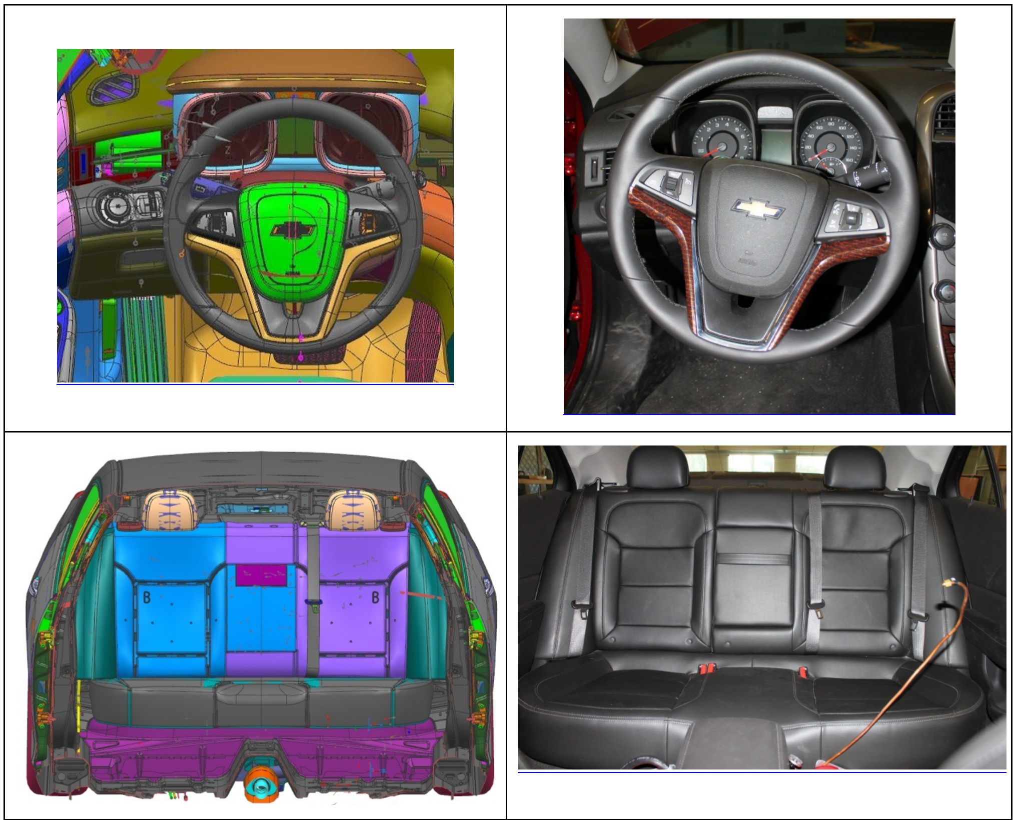


Figure 8: Integration Validation – Interior

5 Conclusion

In conclusion, year 1 of the EcoCAR2 competition established the overall integration plan to be implemented during year 2. During year two, the ESS and HVH/FT subframes were designed and analysed to meet or exceed a safety factor of two for the prescribed loading conditions. Powertrain components were integrated into the vehicle as design for all with the exception of the rewound BAS and inverter.

6 Future Work

Over the next year the team will refine the vehicle to go from a 60% buyoff mule to a 99% buyoff showroom ready final product.

Acknowledgments

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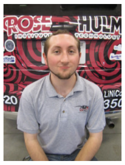
References

[1] *EVS27*, http://www.EVS27.org, accessed on 2013-01-06

[2] http://asm.matweb.com

Authors

	Jon Nibert is an Electrical Systems Integration Engineer at Ford Motor Company in Dearborn, Michigan. He has his B.S. in Computer Engineering and M.S. in Engineering Management from Rose-Hulman Institute of Technology. Prior to joining Ford, Jon spent 4 years in the EcoCAR and EcoCAR2 Advanced Vehicle Technical Challenges, including 1.5 years as the Lead Electrical Engineer and 2 years as the Engineering Manager for the project. His core focuses are in electrical architecture design and implementation, project management, engineering process development, and systems engineering.
	Rose-Hulman Institute of Technology (RHIT'05) alumnus Laura Nash was a senior contributing member of the 2005 Challenge X team. Laura served as the battery research team leader as the team worked to select a split train hybrid electric vehicle architecture for the first year of the competition. After graduating and working in industry, Laura has returned to RHIT for graduate school (RHIT '14) and joined the 2^{nd} and 3^{rd} years of the EcoCAR 2 competition. Laura is a graduate assistant for the team and works on vehicle integration and optimization of the RHIT EcoCAR2 vehicle. Additionally, Laura serves as the Energy Storage System (ESS) team lead; heading the FEA analysis, the assembly of the ESS components, and co-leading any necessary component redesigns. Laura also works closely with the mechanical team in the fabrication of vehicle systems along with the removal/ installation of new components.
	Josh King is a member of the Rose-Hulman Institute of Technology class of 2014 studying to receive his BS in Mechanical Engineering. He is a two-year member of the Rose-Hulman EcoCAR2 team and acted as the Mechanical sub-team lead this past year. He has worked at two internships dealing with the design, test, and product development of hybrid electric motors and has filed a patent on an oil cooling design through one of the internships.
	Zac Chambers has his BS and MS in Mechanical Engineering from Rose-Hulman Institute of Technology and his PhD in Engineering Science and Mechanics from the University of Tennessee, Knoxville. He has been on the ME faculty for Rose-Hulman since 2000 and has worked with Marc Herniter as Mechanical Advisor for ChallengeX, EcoCAR, and now EcoCAR2 racking up 9 years of experience in hybrid vehicle powertrain design and execution. He additionally serves as the Program Director for the Advanced Transportation System Program at Rose-Hulman.
	Marc Herniter is a Professor at Rose-Hulman Institute of Technology (Ph.D., Electrical Engineering, University of Michigan, Ann Arbor, 1989); Dr. Herniter's primary research interests are in the fields of modeling of complex systems, power electronics, hybrid vehicles, and alternative energy systems. He has worked on power electronic systems that range in power levels from 1500 W to 200 KW. He is the author of several text books on simulation software including PSpice, Multisim, and Matlab. He is currently the co-advisor for the Rose-Hulman EcoCAR Hybrid-Electric vehicle team and the faculty supervisor of Rose-Hulman's Model-Based-Systems Design laboratory.