

Designing a Rear Suspension Cradle for Usage in a Parallel-Through-the-Road Plug-In Hybrid Electric Vehicle

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ABSTRACT

In order to continue the effort of converting traditional internal combustion engine (ICE)-based vehicles into hybrid-electric vehicles (HEV), it is important to consider a variety of design architectures in which hybrid-electric operation is achieved. Such architectures include power split, parallel, and series.

Of the previously stated architectures, the Purdue EcoMakers of the EcoCar 2 international Advanced Vehicle Technology Competition (AVTC) have chosen a parallel-through-the-road architecture for their 2013 Chevrolet Malibu provided by General Motors. From this, the Purdue EcoMaker vehicle design will be used as a case study for the design challenges and optimization strategies that are experienced when choosing this specific architecture for a light-duty passenger vehicle.

This paper will focus on the design procedure and structural analysis of the custom rear suspension cradle created by the Purdue EcoMakers. Additionally, this paper will consider the benefits and practicality of using the structure of the custom suspension cradle as a design format for future suspension cradles to be used in light-duty passenger vehicles.

CITATION: Fogarty, A. and Oswald, K., "Designing a Rear Suspension Cradle for usage in a Parallel-Through-the-Road Plug-In Hybrid Electric Vehicle," *SAE Int. J. Passeng. Cars - Mech. Syst.* 7(1):2014, doi:10.4271/2014-01-1928.

INTRODUCTION

EcoCar 2 is a three year AVTC that is managed by Argonne National Laboratory and is co-sponsored by General Motors and the U.S. department of Energy. It is the intent of the competition to allow students of varying backgrounds and educational experience to work together in order to modify a 2013 Chevrolet Malibu so that it may maintain or improve the performance, consumer acceptability, Well-to-Wheel (WTW) petroleum use, WTW energy consumption and tailpipe and Greenhouse Gas (GHG) emissions. Shown below is a figure which includes several Vehicle Technical Specification (VTS) goals for each team's modified vehicles.

Specification	Production 2013 Malibu	Competition Design Target
Acceleration 0–60 mph	8.2 sec	9.5 sec
Acceleration 50–70 mph (Passing)	8.0 sec	8.0 sec
Braking 60–0 mph	143.4 ft. (43.7 m)	143.4 ft. (43.7 m)
Highway Gradeability @ 20 min	10+% @ 60 mph	3.5% @ 60 mph
Cargo Capacity	16.3 ft ³	16.3 ft ³
Passenger Capacity	5	≥4
Mass	1,589.6 kg	<2,250 kg
Starting Time	<2 sec	<2 sec
Ground Clearance	155 mm	155 mm
Vehicle Range	736 km [457 mi] (CAFE)	322 km [200 mi]*

Figure 1. Competition Design Targets and Requirements

The first year of the competition began during the summer of 2011 and ended in May of 2012. The focus of year one was to create accurate simulations of a of a light duty passenger vehicle with varying components in order to weigh the advantages and disadvantages of different HEV architectures. Additionally, the packaging and purchasing challenges included with each component to be selected was considered throughout the initial design procedure.

During year one, the Purdue EcoMakers had chosen to implement a PTTR plug-in-hybrid-electric-vehicle (PHEV) architecture by switching the stock 2.4L gasoline engine with a 1.7L CI engine as well as install a 103 kW AC electric motor and a 16.2 kW-Hr Li-ion battery pack. As can be seen below, the PTTR architecture will be achieved by having the electric traction motor power the rear wheels of the vehicle and have the CI engine power the front wheels of the vehicle.

While the CI drivetrain of the vehicle would be capable of using conventional packaging and integration techniques, the same could not be said for the electric drivetrain since the 2013 Malibu is not intended to have rear wheel drive. Additionally, the choice to have both a fuel tank and battery pack made it difficult to package both energy storage devices without invading the passenger compartment of the vehicle.

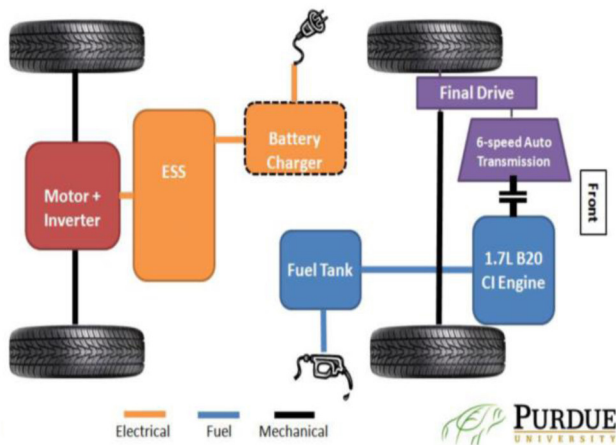


Figure 2. Purdue EcoMaker Vehicle Architecture

PACKAGING CONSTRAINTS

Of the battery options that were available for the competition, the EcoMakers chose to use six Li-ion modules provided by A-123 systems, where each module contains a total of 45 individual cells; 3 parallel sets of 15 cells in series (6×15s3p). The total battery pack maximum voltage is 324 V and maximum pack energy is 16.2 kW-Hrs. This battery pack was chosen because it allowed for a desirable electric-only range of the vehicle, which greatly reduced the Utility-Factored (UF) WTW GHG emissions and Petroleum Energy (PE) use. However, the dimensions of each battery module, along with the rules specified by ANL created distinct packaging constraints for the electric Energy Storage System (ESS). For instance, in the Non-Year-Specific-Rules (NYSR) provided by ANL, it is specified that any energy storage system components must be located above the joining seam of the chassis frame rail and the upper structure of the vehicle as shown by the black line in the image below.

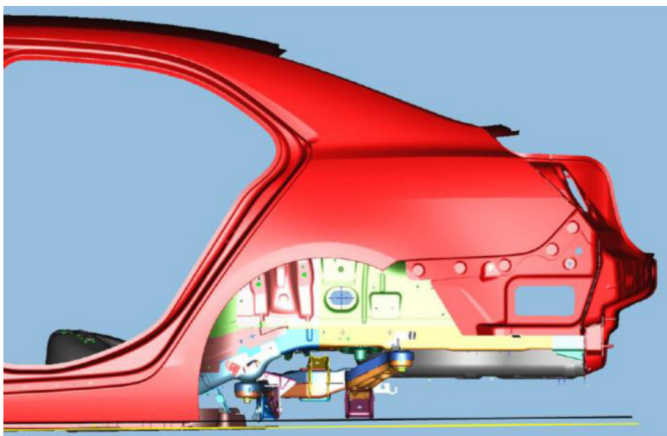


Figure 3. Fuel and ESS mounting restrictions

Because of this packaging constraint, it was very difficult to package both electrical modules and a fuel tank underneath the passenger seat of the Malibu. Therefore, it was determined that the batteries be located in the trunk-space and spare tire well of the vehicle. Additionally, it was decided that the fuel tank

would be placed underneath the passenger seat for easy accessibility, since the NYSR specify that the fuel tank be able to be removed in less than 10 minutes for periodic weighing in petroleum usage events. Therefore, since the fuel tank would be located in front of the rear axle and the ESS battery box would be located in the spare tire well, there was only one remaining space to be used to store the electric motor: in-line with the rear axle and in-between the suspension links of the vehicle.

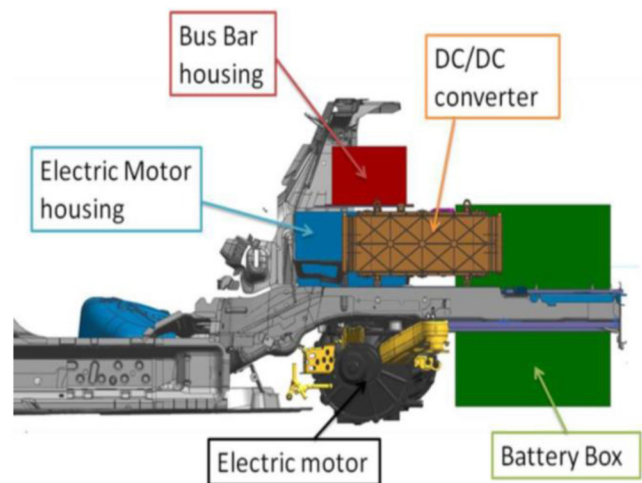


Figure 4. Electric Drivetrain Component locations

Before this could be done, the suspension linkages were required to change since the inboard bearings of the Malibu rear suspension linkages would interfere with the rear traction motor. Therefore, it was decided that the rear suspension from a 2013 Buick Lacrosse should be used. Since the 2013 LaCrosse is available as an All-Wheel-Drive (AWD) vehicle, the linkages of the rear suspension are capable of allowing a rear differential to be placed in-between the inboard bearings of the suspension control arms. Additionally, since the Buick Lacrosse and the Chevrolet Malibu are both built using the GM epsilon format, the suspensions would be compatible with both vehicles. Shown below is an image of the LaCrosse linkages in relation to the desired placement of the rear traction motor.

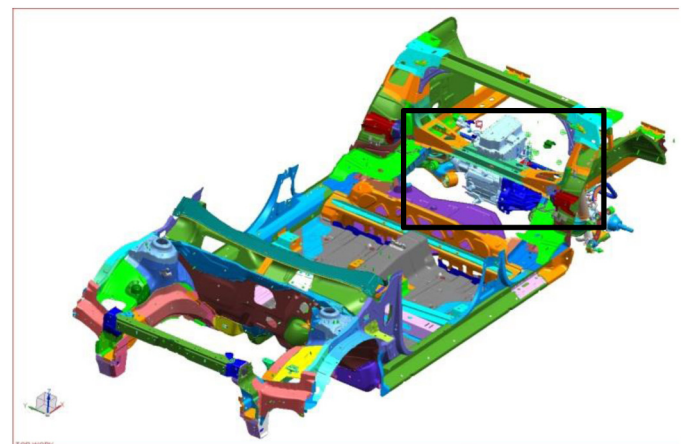


Figure 5. Lower Body Structure of Vehicle

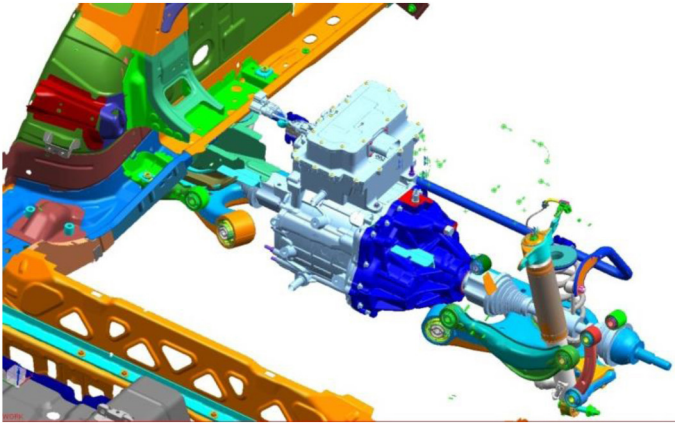


Figure 6. Rear Suspension assembly

If the motor is placed with its axle collinear with the axle of the LaCrosse suspension, it can be assumed that a set of drive shafts may be made for usage by the motor which would not interfere with the linkages of the LaCrosse, given that the drive shafts perform similarly to those of the LaCrosse suspension. Although the suspension links would not interfere with the rear traction motor, the rear suspension cradle would greatly interfere if used.

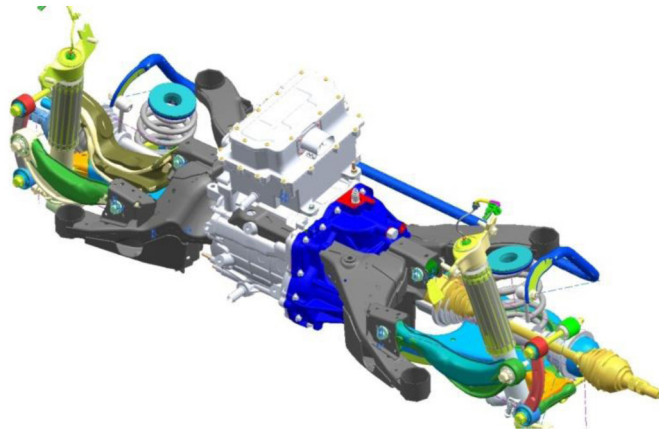


Figure 7. Rear Suspension with Cradle

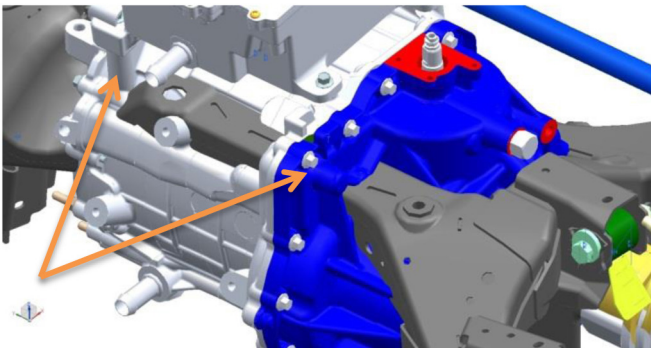


Figure 8. Interference of front of Suspension Cradle

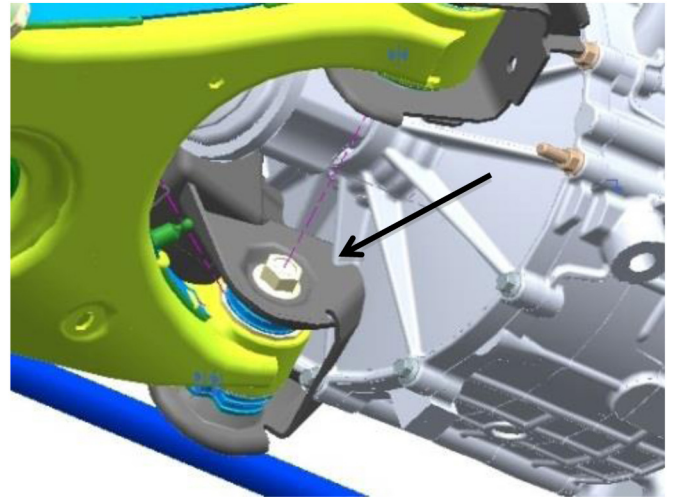


Figure 9. Interference with underside of Cradle

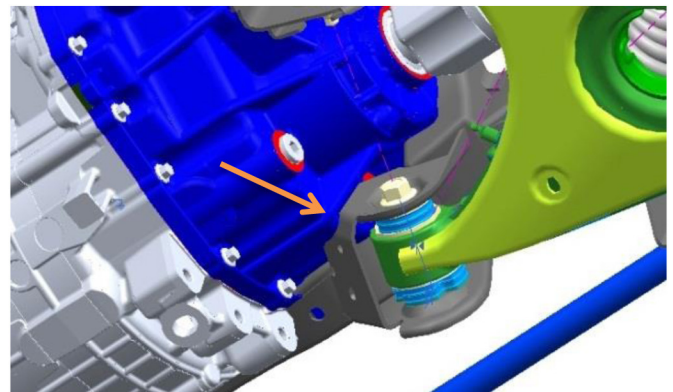


Figure 10. Interference with underside of Cradle

Since this is the desired position of the rear traction motor, it was required that the Purdue EcoMakers create a custom suspension cradle that would safely hold the motor in place and maintain the inboard bearing locations of the rear suspension links. As described by the NYSR, it is necessary that any custom component installed on the vehicle have a Factor of Safety ($FOS = \text{Yield Stress} / \text{Max Stress}$) greater than or equal to 2 when compared to the stock component (ie: Custom Component FOS/ Stock Component FOS). Additionally, it was required by GM that the custom suspension cradle use the same four chassis mounting locations as the stock suspension cradle.

Overall, it can be seen that the packaging constraints determined by the NYSR of the competition caused the Purdue EcoMakers to decide to design, analyze, fabricate and install a custom rear suspension cradle which would also hold the mounting locations of the rear traction motor.

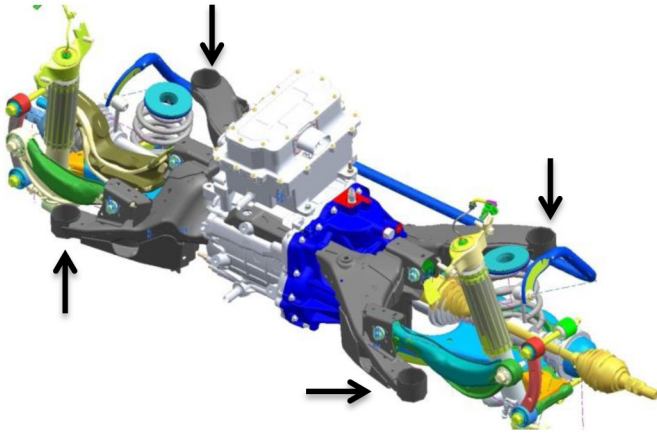


Figure 11. Chassis mount locations of Rear Cradle

DESIGN

The proposed modification will be an entirely custom-made steel structure which will attempt to locate all bearings of the rear suspension while supporting the rear traction motor without interference. Additionally, during the design procedure, the routing path of the exhaust pipe was mentioned frequently. Due to the movement of the rear suspension control arms, and the substantial volume occupied by the rear motor there is very little available cross sectional area to allow an exhaust pipe to pass through. However, there is a gap on the passenger side between the motor and the inner bearing of the upper camber link that is capable of allowing an exhaust tube to pass through, as long as it passes over the CV joint of the half shaft used by the motor. Therefore it is needed for the exhaust pipe to pass over the passenger's side drive shaft of the motor. As a design criterion, the structure must have adequate room to allow an exhaust pipe with ample air cushion to pass through. Shown below is the stock 2013 LaCrosse cradle compared to the proposed custom cradle of the Purdue EcoMakers.

The basis for the structure relies on two square-profile steel tubes which bridge the gap between the chassis mounts of the vehicle.

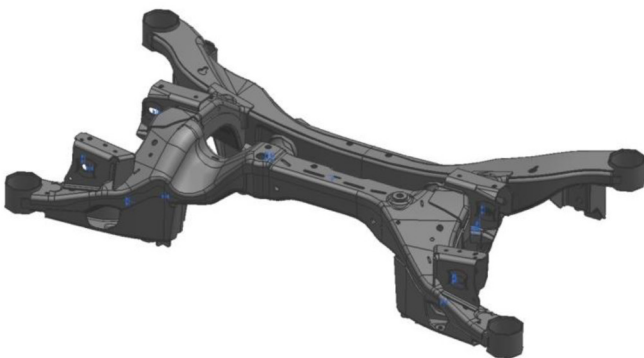


Figure 12. Stock 2013 LaCrosse cradle

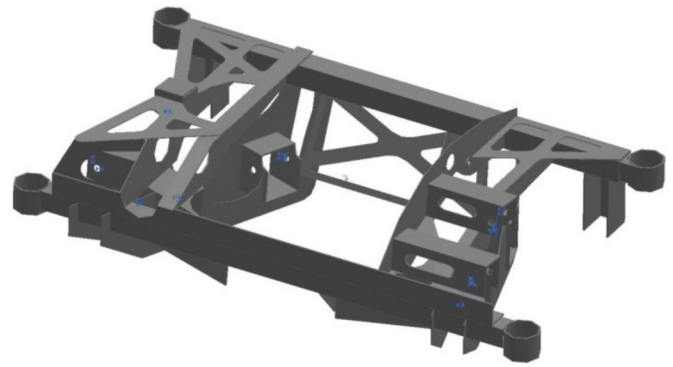


Figure 13. Custom Purdue EcoMakers cradle

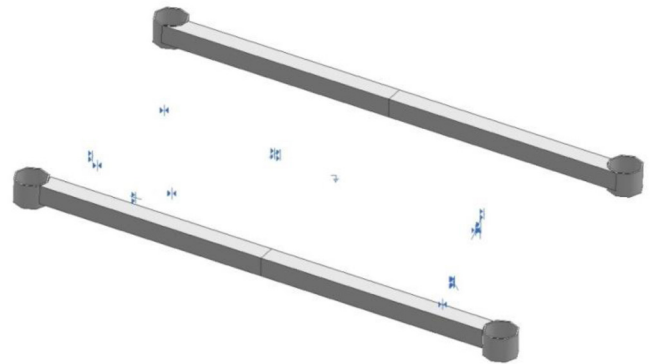


Figure 14. Bridge Components of custom sub-frame

In the proposed design, there are rigid metal components which entirely encompass the motor. Therefore, if the proposed cradle consisted entirely of welded metal components, it would be impossible to remove the motor without undoing irreversible welds of the assembly during fabrication. With this in mind, it is desirable that the assembly be consisted of two or more rigid sections which are connected by reversible connection techniques. Therefore, it was decided that the proposed structure consist of an upper shell and a lower shell, both of which are rigid, welded assemblies. As the two sections connect to each other, they will be bolted together to ensure that the connections may be undone in the case that the motor needed to be removed from the sub-frame. Shown below is the lower section of the structure which will hold the bearings for the lower control arms as well as the torque-resist mount locations of the motor.

In order to ensure proper alignment of the suspension bearings, it was decided that the planes of metal will be cut using a water-jet to ensure accuracy and precision. In order to ensure proper placement of each plane upon the square tube "bridge" sections, it was decided that a precision end-mill will be used to mark the locations upon the square tubing where the planes are desired to sit. Therefore, the square tube sections which will hold the bearings of the lower control arms will fit neatly into the recesses of the planes which connect between the square tube bridge sections.