GM TEAM 1

General Motors EcoCAR

ME261 Senior Design Report

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Abstract

The purpose of this project was to simulate and research several different powertrain architectures for the 2009 EcoCAR Saturn VUE, as well as select an architecture which best met the General Motors EcoCAR: The NeXt Challenge competition and US DOE Argonne National Laboratory guidelines. To accomplish this goal, the team worked with the Missouri S&T EcoCAR Team to optimize three different concepts. With the help of the EcoCAR Team, the group was able to choose the best design based on analysis from Powertrain System Analysis Toolkit © (PSAT). Important parameters used in deciding which powertrain architecture was the best included: fuel economy, emissions, acceleration, and stopping distance; while meeting safety requirements and not comprising consumer acceptability. Each design was modeled and simulated by the EcoCAR Team in order to compare these requirements. The simulation results were submitted as Report 2A to General Motors and DOE Argonne National Laboratory [5]. In Report 2A, suggestions on which architecture to move forward with were made. Once the findings in Report 2A were evaluated, the suggested architecture to optimize was approved [5]. After, receiving approval from General Motors and DOE Argonne National Laboratory, the group worked with the EcoCAR Team to evaluate all options of optimizing the chosen design.

Table of Contents

Introduction

This report will cover the details of the General Motors EcoCAR senior design project which coincides with the EcoCAR: The NeXt Challenge competition. The EcoCAR: The NeXt Challenge is a three year competition that builds on the 19 year history of DOE advanced vehicle technology competitions by giving engineering students the chance to design and build advanced vehicles that demonstrate leading edge automotive technologies, with the goal of minimizing the environmental impact of personal transportation and illustration pathways to a sustainable transportation future. For this competition the Missouri S&T EcoCAR Team started with three different vehicle powertrain architectures which would meet the competition and DOE qualification, which are detailed in Appendix A [4]. These three powertrain architectures included a Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle (PHEV), and an Extended-Range Electric Vehicle (EREV). The HEV and PHEV will use a hydrogen fuel cell, battery, and electric motor to power the vehicle; while the EREV will have a small internal combustion engine, battery, and electric motor. After these concepts have been introduced, this report will discuss the selection process for obtaining the final design concept. From the EcoCAR Team's results from Report 2B, and a decision made by the US DOE Argonne National Laboratory, the final design concept will be a PHEV with a charge depleting battery [4]. This report will discuss why this powertrain architecture was chosen, and what future developments will be made to this architecture, such as developing and implementing a control strategy.

Background

This design project is sponsored by General Motors and the Department of Energy (DOE) Argonne National Laboratory. General Motors was founded in 1908 in Flint, Michigan; they manufacture cars and trucks under 12 brands. General Motors currently manufactures several types of Hybrid Electric Vehicles (HEV), which started in 2006 with the Saturn VUE Hybrid. General Motors is on a mission to create more efficient hybrids. So far GM has manufactured the 2006 & 2007 Saturn VUE Green Line Hybrid, Saturn Aura Green Line Hybrid, 2008 GMC Yukon Hybrid, and the 2008 Chevrolet Malibu, Tahoe, and Escalade Hybrids.

Argonne National Laboratory has five areas of focus, which are conducting research for physical, life and environmental sciences, building and maintain scientific facilities, researching energy technologies, developing solutions to certain environmental problems, and providing help with nuclear energies providing instruments to help detect dangerous chemicals. The area that is most important to our project is conducting experimental and theoretical research in the physical and life and environmental sciences to further understand the world we inhabit. The project will further their studies in the field of energy and environmental sciences.

Current State of the Art

The current state of art will use the body of a Saturn VUE as provided by General Motors. A FWD Saturn XE with a 169-hp 2.4L 4-cylinder engine and a 4-speed automatic transmission with an EPA estimated 19 city/26 highways mpg will be provided. The powertrain will be modeled after the Fuel Cell Equinox. The VUE is a compact crossover SUV that is currently offered with a wide variety of powertrains ranging from the 169-hp 2.4L 4-cylinder to the 257-hp 3.6L V6, as well as the 172-hp 2.4L ECOTEC 4-cylinder hybrid engine. There is also a choice between 4-speed or 6-speed automatic transmissions. The Fuel Cell Equinox powertrain runs on compressed hydrogen and will function similar to a conventional battery. However, the fuel cell will need to be recharged and may need to be replaced overtime. Also the Equinox powertrain only emits water and heat.

Architecture Concepts

Architecture One (Fuel Cell Hybrid Electric Charge Sustaining Vehicle)

The HEV vehicle will use a hydrogen fuel cell to generate power for a Lithium-ion battery and a continuous electric motor [4]. The combinations of these power sources allow the vehicle to work efficiently without allowing the battery charge to move out of a predetermined band (percentage of charge). A HEV vehicle continuously operates in its most efficient state. The fuel cell drives a generator to run at optimum performance. Figure 1 shows the analysis of the weight on different performance specifications [4]. The gradeability was also analyzed for this architecture concept by using a velocity of 60mph. Figure 2 shows the gradeability for different vehicle masses [4]. Figures 3 and 4 show how the architecture will be integrated into the vehicle [4]. In Figure 4 the area highlighted in red is where the electric motor will be placed, and the area in blue is where the lithium ion battery with be placed.

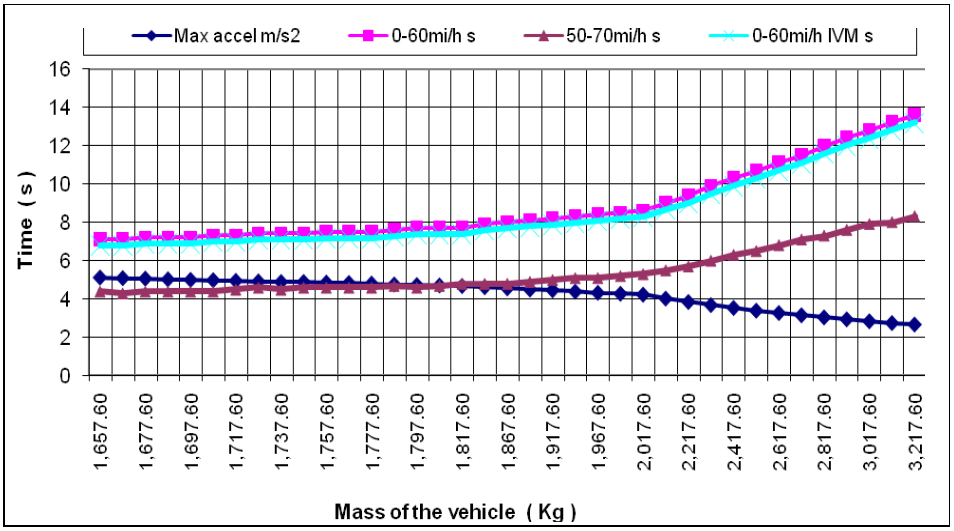


Figure 1: Performance vs. mass of the vehicle

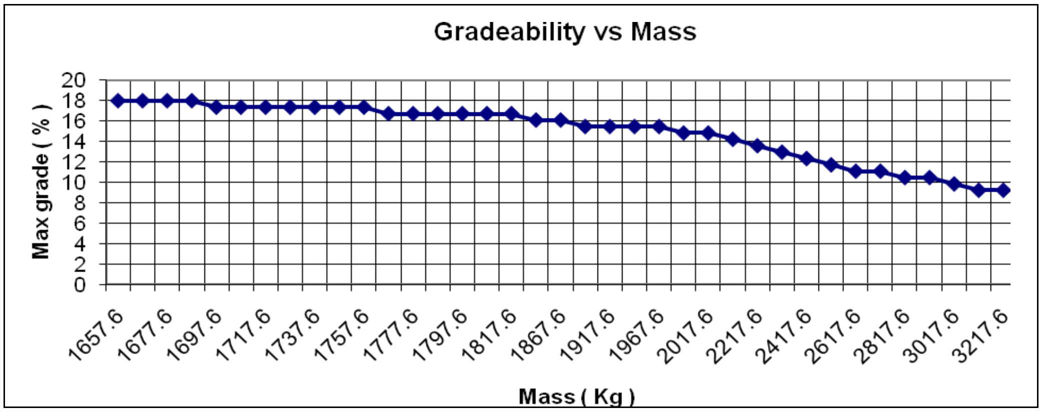


Figure 2: Gradeability test for maintaining 60mph

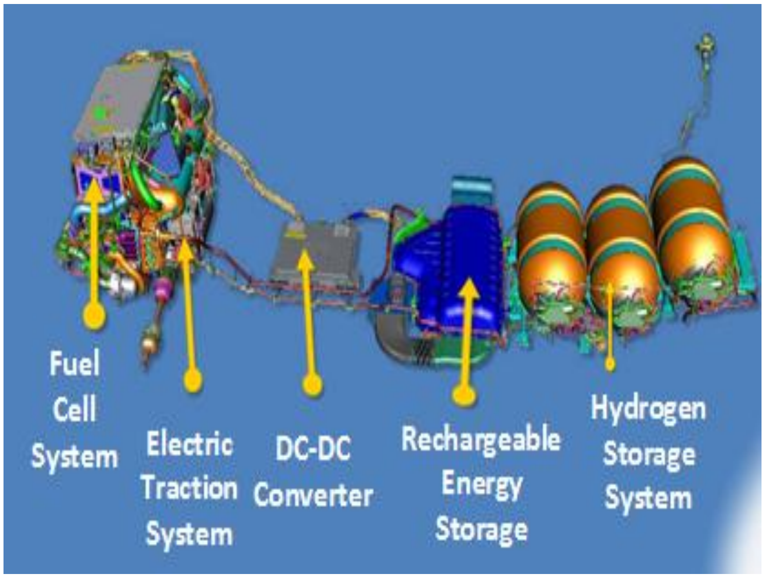


Figure 3: Model of architecture one

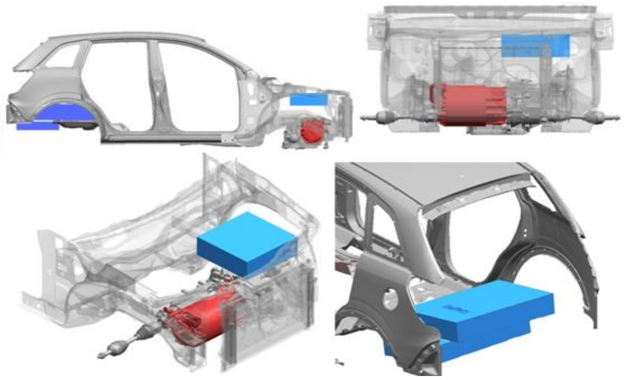


Figure 4: Packaging for architecture one

Architecture Two (Fuel Cell Plug-In Hybrid Electric Charge Depleting/Sustaining Vehicle)

This architecture involves using a Lithium-ion battery to power the vehicle in a charge-depleting mode. By charge depleting until a certain level is reached, the lowest vehicle emissions will obtained, because it causes a charge sustaining mode to be turned on. This architecture will use a 95kW fuel cell along with an ESS module and a 55 kW continuous electric motor with a 110 kW peak output connected in series [4]. The battery will be charged by plugging into an external power source. Once it is fully charged it should be able to power the car for a predetermined range under normal driving conditions without using any other power source. However, if the battery were to become depleted the alternative power source, in this case a hydrogen fuel cell, would engage and power the vehicle.

Figures 5 and 6 show how the architecture will be incorporated into the vehicle [4]. Figure 7 shows an example of the H2 storage tank placement [4]. Notice that two of the tanks will interfere with the current VUE configuration. For future development, the cargo space and seats will have to be moved to make room for the storage tanks. Figure 8 shows the possible configurations for the placement of the hydrogen tanks. The placement of the 4th tank decreases the amount of useable cargo space; however, it will increase the range of the vehicle and provides greater safety than placing the tank around the rear bumper area. The weight and range specifications for each hydrogen configuration were determined and can be found in Table 1 [4]. Several modifications will be necessary for the installation and packaging of this architecture. Appendix B shows some different options for vehicle packaging [4]. Since these modifications will need to be made, it is currently unclear as to which of the hydrogen tank setups will be the most beneficial. Some key problems that the Missouri S&T Team will face can be seen in Appendix B which includes: hood clearance, battery clearance, and several different battery configurations. Each one of these provides component packaging difficulties. Optimizing component placement will be critical in the overall design of the vehicle. Other key modifications are listed below [4]:

- Design radiator/heat exchanger for fuel cell
- Cooling package for batteries
- Suspension to accommodate increased weight
- Support frames for fuel cell and ETS system

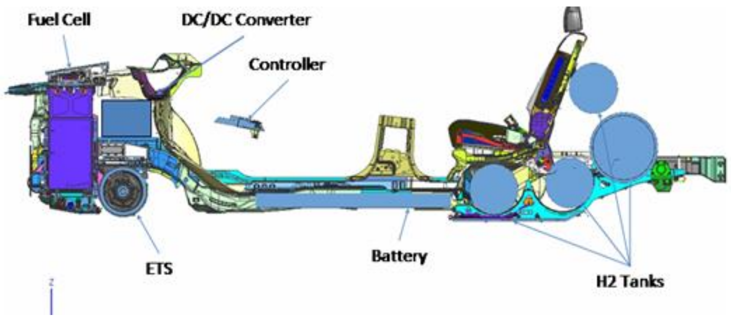


Figure 5: Placement of major components for architecture two

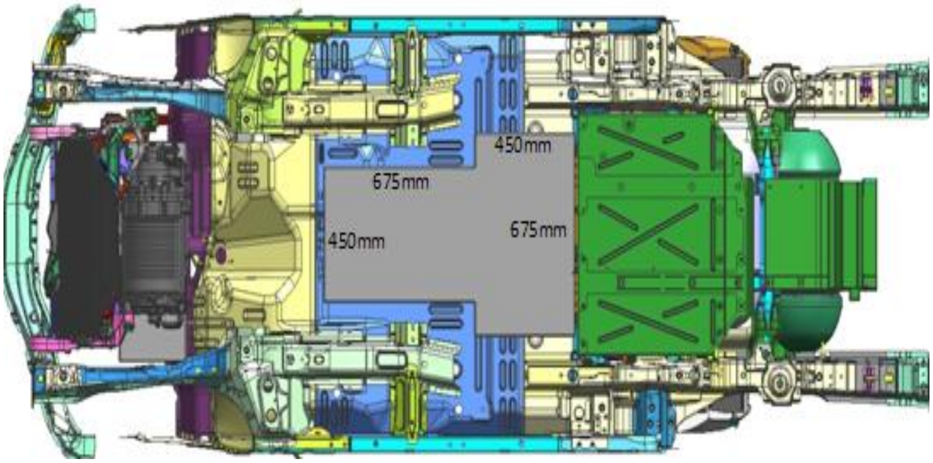


Figure 6: Bottom view of architecture two

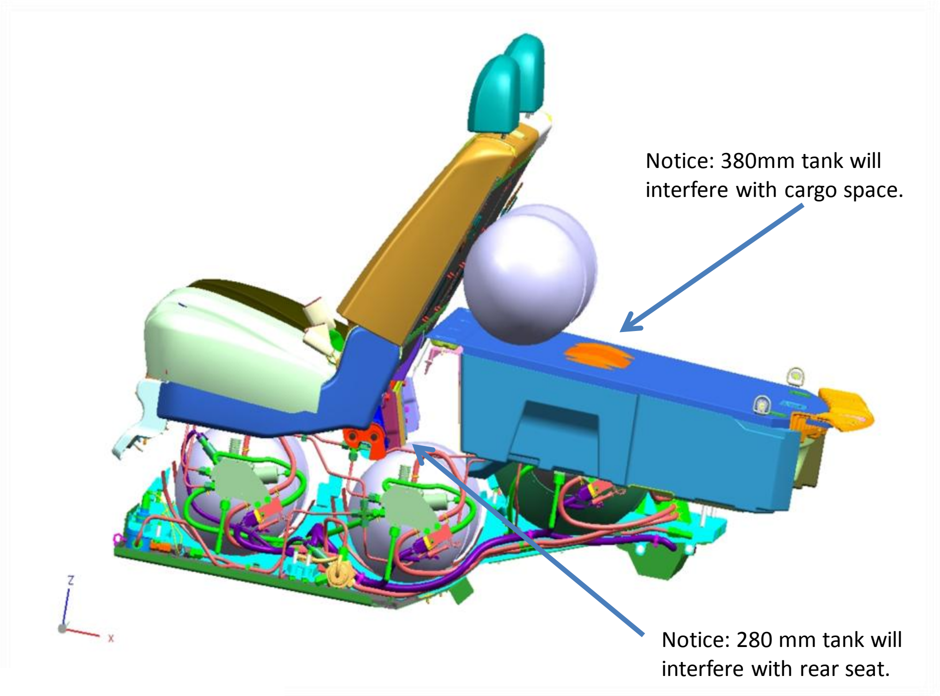


Figure 7: Hydrogen storage tanks interference

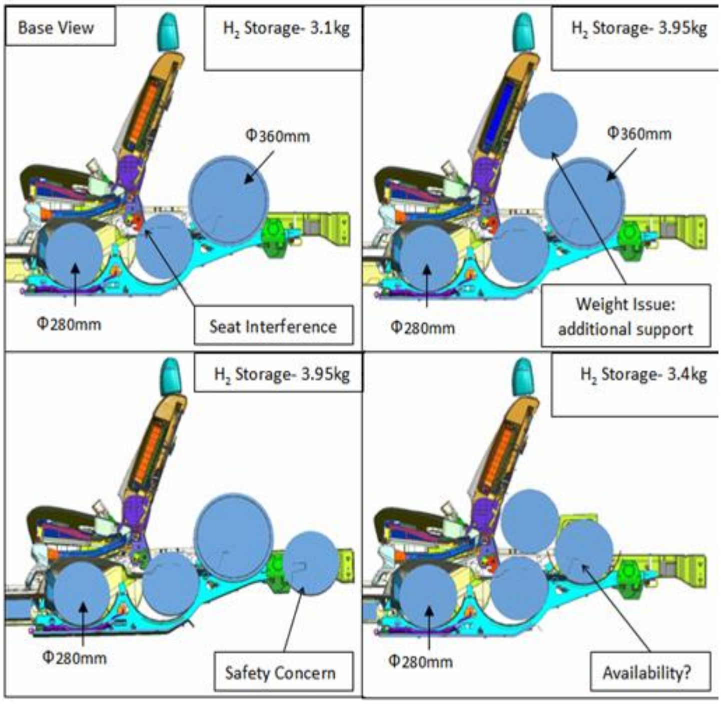


Figure 8: Possible configurations for the hydrogen tanks

Table 1: Analysis of tank configurations

		Config. 1		Config. 2		Config. 3/4	
Number of Tanks	Large | Small	1	2	0	4	1	3
Hydrogen [kg]	Total | Usable	3.10	2.80	3.40	3.10	3.95	3.55
Total Vehicle Mass [kg]		2218		2243		2248	
Combined Range (miles)		160		175		190	

Architecture Three (Extended Range Electric Vehicle)

The EREV vehicle uses a gasoline engine to recharge the battery. Using an ICE that runs on gasoline allows the car to be filled all over the country, but releases greenhouse emissions. However, the series charge sustaining model will allow the vehicle to run in the most efficient state and reduce greenhouse emissions. This architecture concept was designed to use one of four engines: 1.6L gasoline, 1.8L gasoline, 1.0 L gasoline, 1.3L diesel, and 2.0L diesel internal combustion engines.

The chosen engine is a 1.0L SI engine powering a 55 kW continuous power generator with a 110 kW peak output electric motor [4]. The generator will provide electrical energy to the battery which in turn provides energy to the electric motor. Figure 9 shows how well the architecture meets competition goals of acceleration 0-60mph and 50-70mph with different towing capacity [4]. Figure 10 demonstrates how the architecture will be packaged in the vehicle [4]. The green component in Figure 10 represents the electric motor, they blue component represents the fuel cell assembly, and the red represents the DC/DC converter.

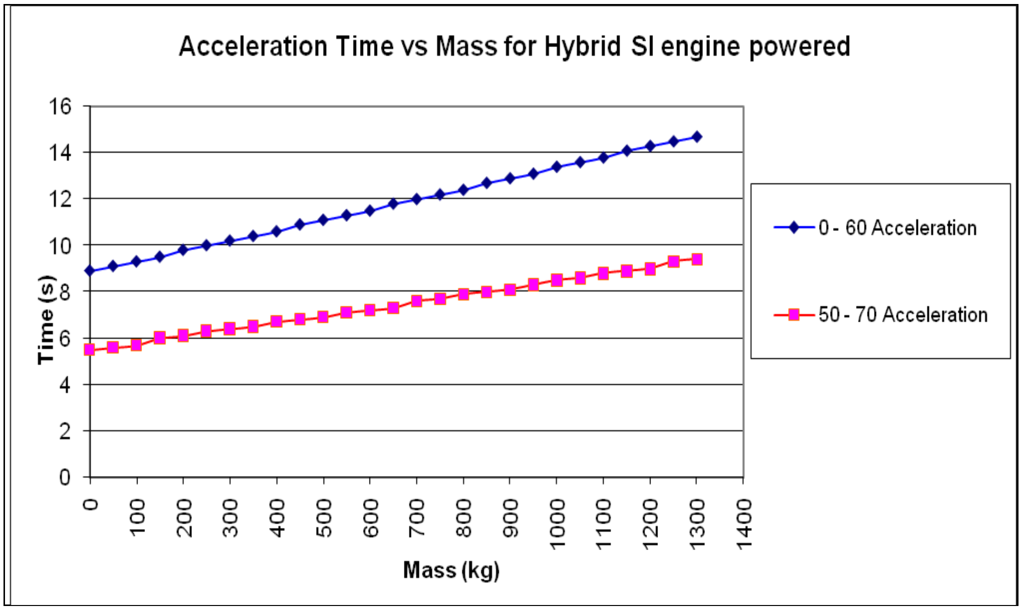


Figure 9: Acceleration time vs. mass for a hybrid SI engine

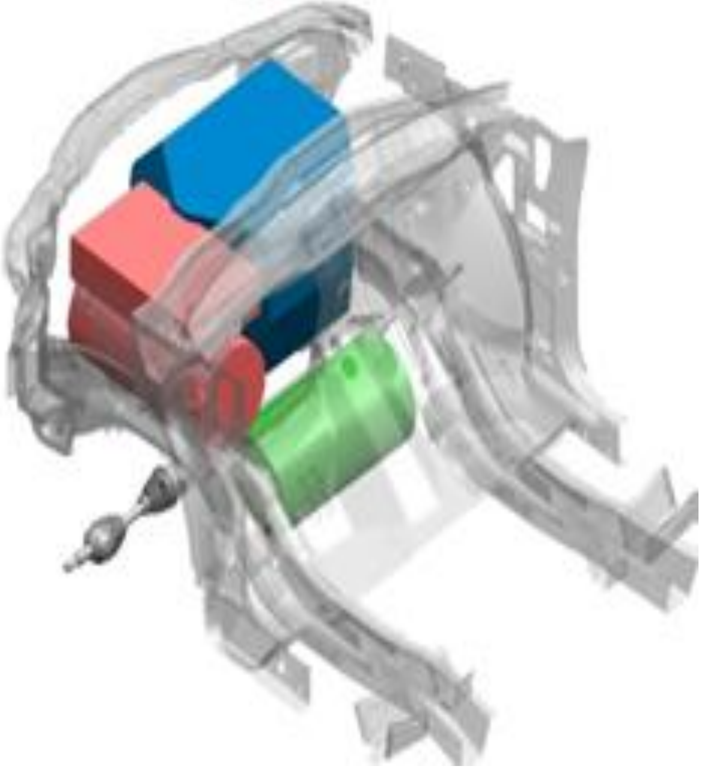


Figure 10: Packaging of EREV architecture

Concept Selection

The final architecture was chosen by using several different comparison models. These models include a comparison of fuel consumption and engine startups, a competition point comparison, a competition requirements comparison, and a PSAT simulation comparison.

A test was conducted to compare the different architectures. This test consisted of simulating 175 days of driving a total distance of less than 75 miles per day [2]. From Figure 11 the EREV vehicle requires, on average, less gasoline consumption than all other ICE hybrid vehicles. Air pollution prevention was also considered during this comparison. The majority of harmful emissions occur when an ICE initially starts up because the engine has not yet reached thermal stability [2]. The emissions comparison shown in Figure 12 considers the number of engine start ups or initial trip starts during a given trip [2]. To find the effects of engine start ups and initial trip starts a similar test of simulating 175 days while driving less than 75 miles a day was performed [2]. The EREV vehicle reduced the number of initial trip starts by nearly one third over the other vehicle types. From this comparison it would appear that the EREV vehicle would be the most fuel efficient and would provide for the lowest WTW emissions.

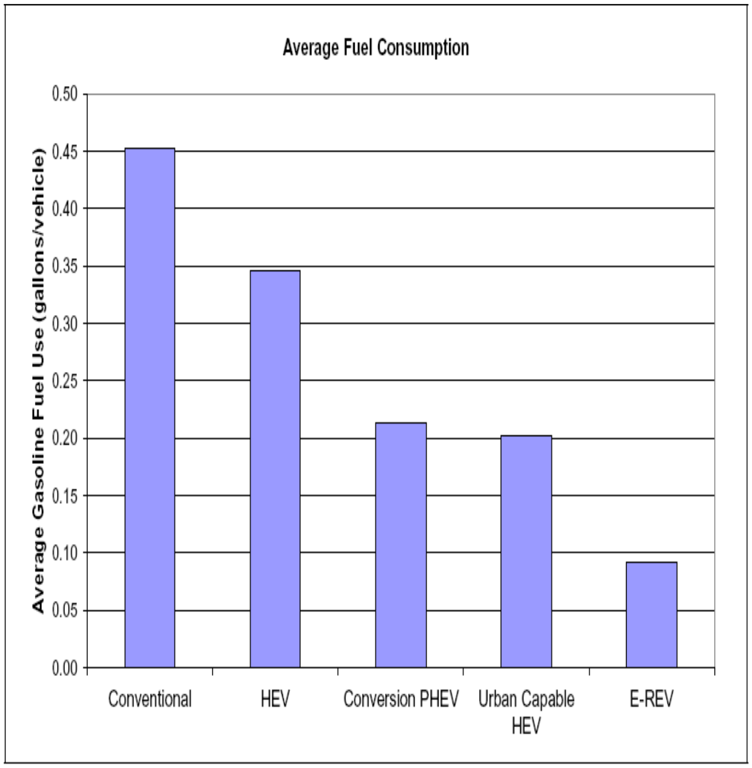


Figure 11: Average fuel consumption

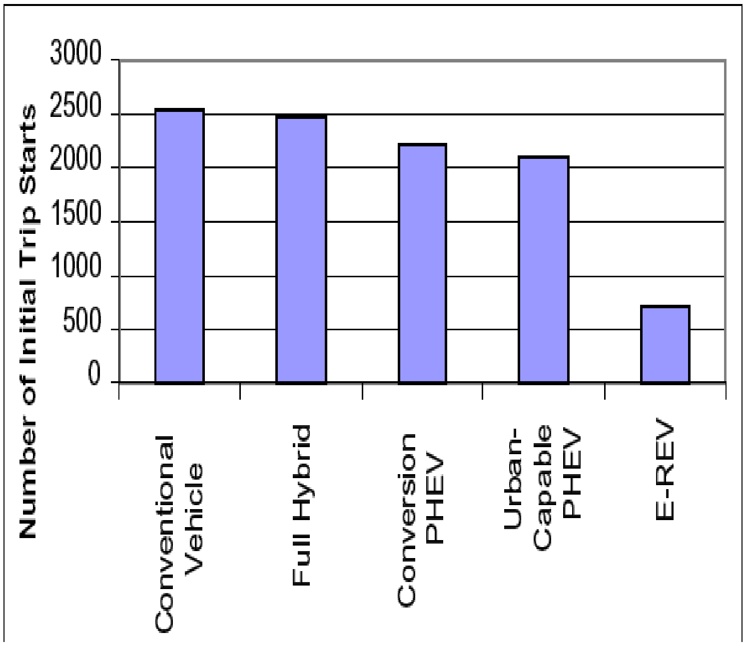


Figure 12: Comparison of initial trip starts

Table 2: Competition point chart comparison

	Max Points	Baseline VTS	Arch 1 Specs	Pts	Arch 2 Specs	Pts	Arch 3 Specs	Pts
0-60 Acceleration (s)	45	10.6	9.2	45	9.8	45	7.2	45
50-70 Acceleration (s)	45	5.7	5.6	45	5.8	44	4.3	45
Range (km)	105	580	370	67	418	76	320	58
Towing (kg)	45	680	680	45	680	45	720	45
Fuel Economy (l/100km)	190	7.4	4.06	190	4.03	190	8.3	169
Petroleum Energy Use (kWh/km)	190	0.72	0.00011	190	0.00409	190	0.77	178
Criteria Tailpipe Emissions (grams/km)	190	213	0	190	0	190	166	190
WTW GHG Emissions (grams/km)	190	224	207	190	85.5	190	224	190
Total	1000			962		970		920

Table 2 compares the estimated total point values that each architecture could obtain in the EcoCAR competition [4]. The point values for each competition requirement are shown and totaled at the bottom of the figure. The table also compares the performance of each architecture to that of the current Saturn VUE model. It is clear from the figure that architecture two would obtain the most points in the competition. This performance data was obtained from using PSAT simulations (performed by the Missouri S&T EcoCAR Team) for each architecture. A sample PSAT model is shown below in Figure 13 [4].

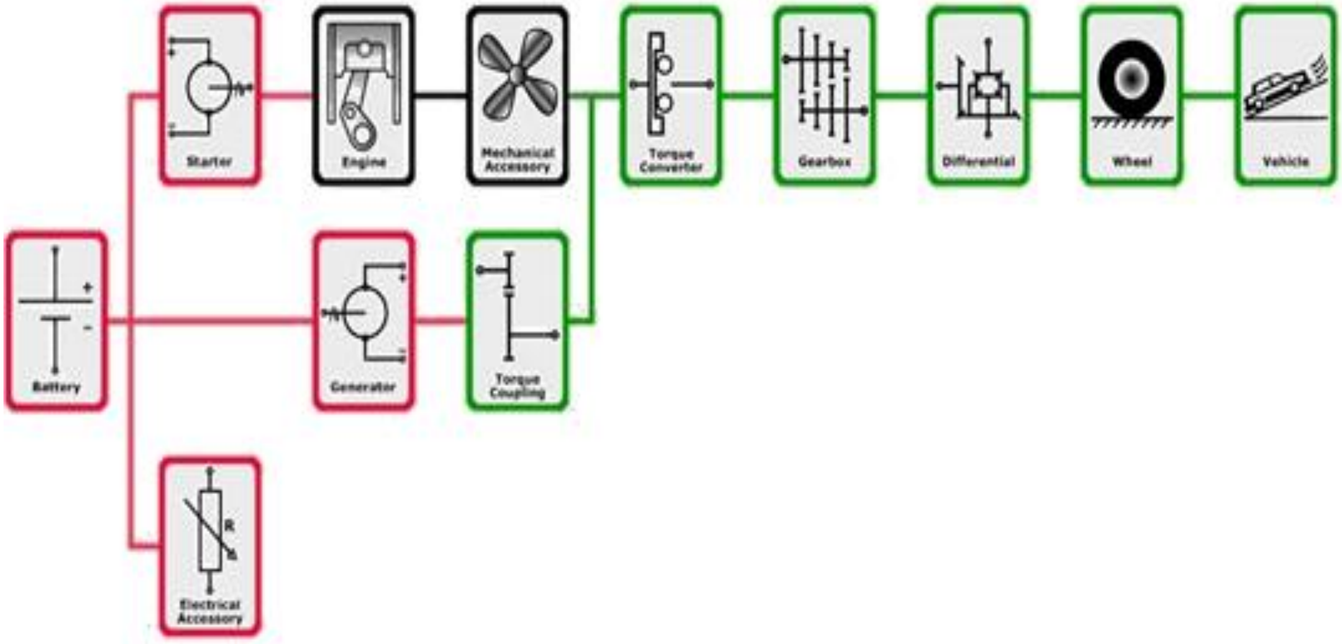


Figure 13: Sample PSAT simulation model

Table 3: Comparison to competition targets

Specification	Competition Requirement	Architecture 1	Architecture 2	Architecture 3
Fuel Economy (L/100km)	7.4	4.06	4.03	8.3
Petroleum Use (kWh/km)	0.65	0.00011	0.00409	0.77
WTW GHG Emissions (g/km)	217	207	85.5	224
Range (km)	≥ 320	370	418	320
0-60 Acceleration (s)	≤ 14	9.2	9.8	7.2
50-70 Acceleration (s)	≤ 10	5.6	5.8	4.3
Towing Capacity (kg)	≥ 680	680	680	720

Table 3 provides a comparison of each architecture's ability to meet or exceed the competition requirements [4]. Several key specifications were used for this comparison such as fuel economy, acceleration, range, and emissions output. From the figure above it is clear that architecture two will provide the lowest emissions output of the three architectures. Architecture two also provides the best fuel economy, which in turn provides the highest vehicle range of the three architectures. However, the acceleration characteristics and the towing capacity of architecture two are the worst of the three architectures. The acceleration times and the towing capacity still meet or exceed the competition requirements, and they will still provide competition point values that are at or near the maximum that can be awarded. For these reasons, architecture two was once again determined to be the best choice for further design.

Table 4: Project timeline

Project Timeline

	Week																
Event	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Setup Weekly Team Meeting Time	■																
Develop Deliverable 1		■															
Review Provided Architectures			■	■													
Develop Deliverable 2					■												
Research in Detail the Assigned Architecture Concept						■	■										
Meet with Assigned EcoCAR Group to Determine Supportive Role								■									
Develop Deliverable 3								■									
Create Mid-Semester Presentation								■									
Help in Development of Report 2A								■									
Develop Simulation of Architecture Concept									■								
Optimize Architecture Design										■	■						
Complete Design Review												■	■				
Create Draft of Design Report												■	■				
Help in Development of Report 2B												■	■				
Finalize Architecture Design														■			
Complete Design Report															■	■	
Complete Design Poster																	■
MAE Design Showcase																	■

Key Deadlines

-Sept. 5, 2008
Deliverable I - Written discussion of project needs

-Sept. 12, 2008
GM Report 1 Due

-Sept. 26, 2008
Deliverable II - Written discussion of concepts

-Oct. 10, 2008
Deliverable III - First draft of project report sections

-Oct. 11, 2008
Mid-Semester Presentations

-Oct. 20, 2008
GM Report 2A Due

-Nov. 3, 2008
Final Architecture Selection

-Nov. 7, 2008
Final Report Outline Due

-Nov. 17 to Nov. 21, 2008
Design Review

-Nov. 20, 2008
GM Report 2B Due

-Nov. 21, 2008
Draft of Design Report

-Dec. 12, 2008
Design Report Due

-Dec. 16, 2008
Design Poster Due

-Dec. 19, 2008
Mechanical and Aerospace Engineering Design Showcase

Cost Estimation

Table 5 lists the complete cost estimations for the powertrain and drivetrain of each architecture. These cost estimates are based on a cost of $205/kW for a hydrogen fuel cell, $715/kg to manufacture a hydrogen storage tank, $3000 for a 55kW electric motor with 110kW peak power output, $1000 for a 1.0L SI engine, and $250/kWh for a lithium ion battery [7, 8, and 9]. The timeframe for this stage will be approximately one year. Table 6 shows the estimated total cost for each architecture configuration, and Table 7 breaks down the cost estimates for the DC-DC converter [4]. The current estimated market price for the completed project is roughly $25,000 to $35,000. This estimate is based on the current MSRP for the 2009 Saturn VUE Hybrid of $28,625 [6]. Since the new vehicle is still in the research and design stage it is difficult to determine what the final cost will actually be. For this reason a $10,000 range based around the cost of the current Saturn VUE is given as the estimated cost.

Table 5: Cost estimates for powertrain architectures

Architecture 1	**Cost**
6.84kWh lithium ion battery	$1,710
55kW electric motor (110kW peak)	$3,000
Drive train	$3,800
95kW hydrogen fuel cell	$19,500
Architecture 2	**Cost**
10kWh lithium ion battery	$2,500
95kW hydrogen fuel cell	$19,500
Hydrogen Tank Configuration 1	$6,220
Hydrogen Tank Configuration 2	$8,870
Hydrogen Tank Configuration 3/4	$10,440
Drive train	$3,800
55kW electric motor (110kW peak)	$3,000
Architecture 3	**Cost**
1.0L SI engine	$1,000
55kW electric motor (110kW peak)	$3,000
Drive train	$3,800

Table 6: Total cost of each architecture configuration

Architecture 1	**Total Cost**
Sole Configuration	$28,010
Architecture 2	**Total Cost**
Configuration 1	$35,020
Configuration 2	$37,670
Configuration 3/4	$39,240
Architecture 3	**Total Cost**
Sole Configuration	$7,800

Table 7: Estimated material cost of bi-directional DC-DC converter

Supplies	Manufacture/Dealer	Price	Quantity	Totals
DSP MSK28212 Kit C Pro (24TK180212)	Technosoft	$2,399.00	1	$2,399.00
IGBT 400A 1200V SINGLE (CM400HA-24H)	Galco Industrial Electronics Inc.	$264.00	12	$3,168.00
IGBT Drivers by concept (6SD106EI)	Galco Industrial Electronics Inc.	$205.00	3	$615.00
Extruded Heat Sink (97F953)	Newark	$177.00	3	$531.00
DC Reactor, 600V, 50A, 5mH (195G50)	Digikey	$240.00	3	$720.00
Voltage transducer (CV3-1500)	LEM	$241.00	3	$723.00
Current transducer, 200A (LA205-S)	LEM	$54.00	3	$162.00
Power supplies, +/_ 15V, %5V (SP50U-0533T)	Digikey	$143.00	1	$143.00
Fiber optic transmitter, horizontal (HFBR-2521)	Future Electronics	$6.00	10	$60.00
Fiber optic receiver, horizontal (HFBR-2521)	Future Electronics	$7.00	10	$70.00
Hook up wire (02F9875)	Newark	$109.00	1	$109.00
Enclosure Frame	80-20 Inc.	$1,500.00	1	$1,500.00
Passive Components	Digikey	$500.00	1	$500.00
Total Cost of Supplies				$10,700.00

Concept Design Additions

Front-Wheel Drive and All-Wheel Drive Comparison

AWD provides better handling and on-road safety. This drive system is also capable of superb traction control, which allows the vehicle to overcome yaw while cornering [3]. However, the AWD system requires additional components in order to incorporate the rear axle as a drive component. These extra components include a transfer case or gear box, a drive shaft, and a differential. The FWD system does not provide the same stability features of the AWD system, but it does provide reduced weight and simplicity.

The FWD system was chosen over the AWD system for several reasons. The additional weight of the extra AWD components is one of these reasons. The overall weight target is 5000lbs due to highway safety standards, as well as weight restrictions set by the competition [4]. The extra AWD components will also take up valuable space, which will be needed for other vehicle components. The added complexity of an AWD system also creates some control issues to deal with. These issues include handling the switching from full time, part time, or on demand modes of operation. The AWD components will also come with added cost [3]. The AWD system requires a greater power supply which would increase the sizes of the battery and motor [3].

Control System Architecture

The chosen vehicle powertrain is a series fuel-cell plug-in hybrid electric vehicle (FC PHEV). Fuel cells are not capable of providing power for the electric drive motor upon vehicle start-up, because fuel cells need to build up a charge before they can function [4]. Initially, the battery will have to supply all of the power for the vehicle components. The vehicle will then operate in a charge depleting or charge sustaining mode based off of the battery SOC [4]. A generalized state model of the propelling and braking modes of operation for the PHEV is shown in Figure 14 [4]. The propelling modes are shown in green and the braking modes are shown in blue. This figure provides a general idea of how the vehicle will transition between modes. Architecture 1 will run only in the CS mode, so there will be no need for the “SOC in Depleting Range” of the procedure. The control strategy for this vehicle would involve the FC continuously charging the battery, as opposed to Architecture 2. Architecture 2 will run in a charge depleting mode till, as portrayed in Figure 13, the SOC falls below the SOC Depleting Range. Once this happens the FC will begin to charge the battery (ESS), which in turn will provide power to the electric motor. Architecture 3 would require a similar control strategy to that of Architecture 1. However, instead of having a FC charge the battery, they ICE will charge the battery. This architecture would also run in CS mode. All three powertrains will use regenerative braking which will allow for another mode of power generation to the battery. For example the FC PHEV runs in CD, CS, and regenerative braking.

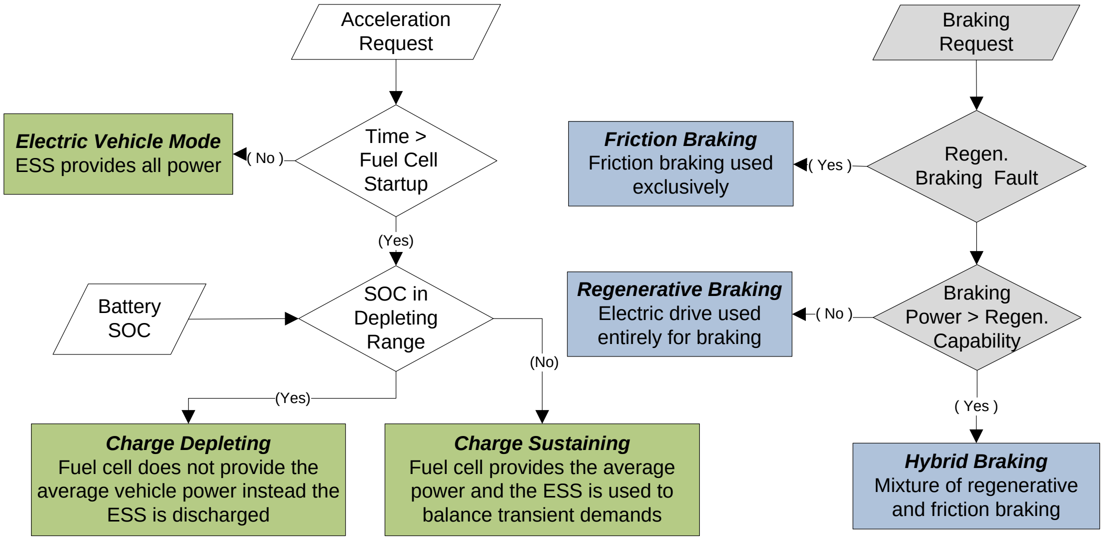


Figure 14: Modes of plug-in hybrid operation

In order to achieve these modes of operation the following subsystems need to be controlled the fuel cell stack and hydrogen storage system, the electric drive motor and inverter, the electrochemical energy storage system, and the power electronics [4]. Each subsystem will be operated by its own controller, but one main controller with govern each of the subsystem controllers. Operational conditions for the vehicle will be set by the main controller and placed in specific operational modes [4]. The subsystem controllers will be used to alert the main controller when the limitations of functional conditions of the vehicle have been met [4]. Table 8 defines the safe state control and functional condition objectives of each subsystem [4].

Table 8: Operational conditions of each subsystem

Subsystem	Safe Operation	Functional Conditions
Fuel Cell Stack and Hydrogen Storage System	• Thermal management • Humidity control • Hydrogen tank pressure	• Standby or powered on state • Hydrogen/air flow rate and pressure • Stack temperature
Electric Drive Motor and Inverter	• Thermal management • Safe rotational speed • Over-current protection	• Torque and rotational speed requests • Determination of regenerative braking capability
Electrochemical Storage System (ESS)	• Thermal management • Overcharge/discharge • Cell balancing	• State of charge to influence source and sinkable power and energy
Power Electronic Converter	• Thermal management • Maintain voltage/current	• Power flow management • Switch duty cycles and frequency

The architecture for the control system is composed of a single vehicle control unit, which contains the overall vehicle control algorithm. The control unit also contains all of the control processes for the accessory subsystems, and it manages high-level functionality for the larger subsystems. Figure 15 shows the tiered architecture control system that will be used [4]. This vehicle control unit will manage the four larger subsystems via the CAN bus: fuel cell and hydrogen system, power electronic converter system, energy storage system and electric drive motor [4]. The individual subsystems such as HVAC, ABS, radio, and automatic windows will be controlled directly through CAN or analog I/O as necessary [4].

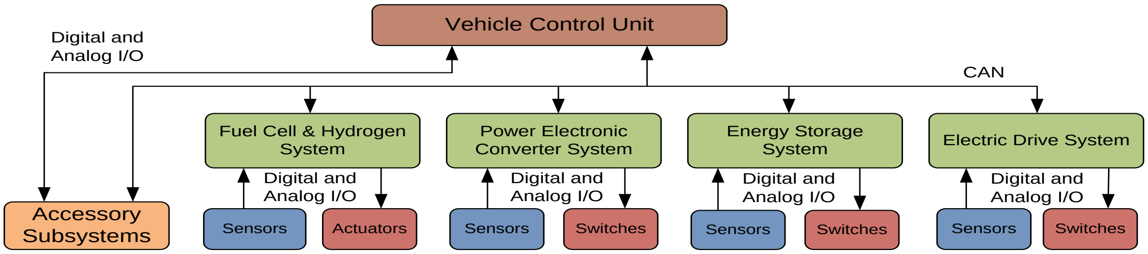


Figure 15: Controller communication plan for the fuel cell plug-in hybrid

Design Analysis

Fuel Economy Procedures

A big parameter in the selection of the final powertrain architecture involves fuel selection. Criteria to consider for the fuel selection include tailpipe Greenhouse Gases (GHG), petroleum energy used, fuel economy, and Well to Wheel (WTW) Greenhouse gases [4]. Since each architecture in this competition is a hybrid vehicle, there are some added complexities to determining the WTW emissions for each vehicle. For example, the PHEV hybrid uses electricity from an external source and hydrogen to power the vehicle. The control system setup for the powertrain also increases the complexity of calculating fuel consumption. To determine the WTW emissions for each of the different powertrains, Powertrain Simulation Analysis Toolkit (PSAT), and GREET simulations were used. GREET mainly deals with determining different Well to Pump (WTP) emissions, while PSAT was used to simulate the Pump to Wheel (PTW) fuel consumption.

Since the PHEV concept has multiple modes of operation, the fuel economy cannot be determined in the conventional form [4]. These multiple modes include charge sustaining (CS) and charge depleting (CD) modes. While operating in CS mode, the vehicle will only be using the electricity stored in the battery [4]. However, in CD mode the vehicle will consume both electricity from an external source and hydrogen [4]. Since the vehicle runs in both of these modes, a different test must be conducted in order to calculate the estimated fuel economy. This test consists of 16 cycles of FTP and 16 cycles of HWFET, which are used to test fuel economy for vehicle configuration [4]. The equation below shows how to calculate the combined fuel economy for the PHEV [4].

$$Fuel\ Economy_{combined} = \frac{1}{\dfrac{0.55}{FE_{FTP}} + \dfrac{0.45}{FE_{HWFET}}}$$

Table 9 shows some of the factors used in determing the fuel economy for the PHEV powertrain [4]. Notice that there are low cycle distances for Highway Fuel Economy Test (HWFET), Urban Dynamometer Driving Schedule (UDDS), US 06, and Los Angeles 92 (LA 92) that correspond to a high gasoline equivalent fuel economy. The reason for this high equivalent fuel economy is the fact that the data is obtained during charge depleting (CD) mode [4]. It should be noted that the resulting fuel economy will go down as the vehicle swtiches to Charge Sustaining (CS) mode [4]. The Federal Test Procedure (FTP) and HWFET cycles where used for selecting Architecture 2 [4]. If another cycle such as US 06 or LA 92 were used they fuel economy would not have been as good. The US 06 and LA 92 are much more aggressive test which include higher acceleration and deceleration rates at higher speeds [9]. Archictecture 1 and 3 would have better fuel economy using these test than Architecture 2. The FC PHEV is capable of runnning in both CD and CS modes in, which will add to the complexity of determing fuel economy.

Table 9: PHEV fuel economy for different cycles

	HWFET	UDDS	US 06	LA 92	Combined (HWFET + FTP)	PHEV 1711	
						FTP	HWFET
Cycle distance (miles)	10.26	7.45	8.01	9.84	10.26	119	164.16
Fuel Economy	16.3	7.42	10.58	9.24	4.03	3.6	4.55
Fuel Economy gasoline equivalent	270.3	109.6	156.3	136	59.52	53	67.13

All of these factors were taken into account while simulating the data with PSAT and GREET for the concept selection [4]. These factors will be further explored as the Missouri S&T EcoCAR Team continues through the three year competition. These results are covered further in the Concepts Selection portion of the report.

Powertrain Performance

This section will discuss the results obtained during PSAT simulation of the PHEV powertrain, which was conducted by the EcoCAR Team. Several simulations have been run so far, and more will be run as more control strategies for battery SOC percent ranges are developed. The current control strategy uses seven Ah-Li-ion batteries connected in parallel. This gives an ESS module of 42 Ah, which produces a nominal voltage of 270 volts, and 11.34 kWh of stored energy [4]. The useable energy in this simulation was 5.67 kWh [4]. The fuel cell used in the PSAT simulations was a 95 kW fuel cell, and the electric motor was a 55 kW continuous power with a 110 kW peak output motor [4]. When simulated using these parameters, the vehicle traveled 0-60 mpg in 9.8 seconds, 50-70 mph in 5.8 seconds, and had a range of 418 km [4]. As stated before, these results will change as a more intense control strategy is developed by the Missouri S&T EcoCAR Team.

Weight Analysis

The weight of the vehicle was another important parameter that was considered for the architecture design. All three powertrains met competition requirements of weight (<2268 kg), but none of the architectures met the production VUE baseline specifications [4]. This was due to a very large increase in weight from the fuel cell system, battery, and H2 tanks. Table 10 below shows the added and subtracted major components for each architecture [4]. It is important to notice that the only difference in components for Architecture one and two is that two will has a larger battery.

Table 10: Weight additions and subtractions of architectures

	FC HEV	**FC PHEV**	**1.0 L HEV**
Components Removed	**Weight (kg)**	**Weight (kg)**	**Weight (kg)**
Engine 2.4L ECOTEC ASM	122	122	122
TRANSAXLE ASM	85	85	85
MUFFLER ASM-EXH(W/RESO,EXH & TAIL PIP)	17.6	17.6	17.6
RADIATOR ASM(W/AC CNDSR & CHRG AIR COMP)	16.6	16.6	16.6
TANK ASM (COMPLETELY FILLED)	127	127	127
GENERATOR ASM	5.9	5.9	5.9
STARTER ASM	2.9	2.9	2.9
TOTAL	**377**	**377**	**377**
ELECTRICAL MOTOR (55 kW continuous power with 110 kW peak output)	51	51	51
BATTERY ASM	86	170	200
SI ICE 1.0L	-	-	100
FUEL CELL ASM	441	441	-
HYDROGEN STORAGE ASM	191	191	-
POWER CONVERTER	45	45	-
TOTAL	**814**	**898**	**351**
PRODUCTION VUE	1758	1758	1758
WEIGHT OF INDIVIDUAL ARCHTECTURES	**2195**	**2279**	**1732**
WEIGHT GAINED	437	521	-26

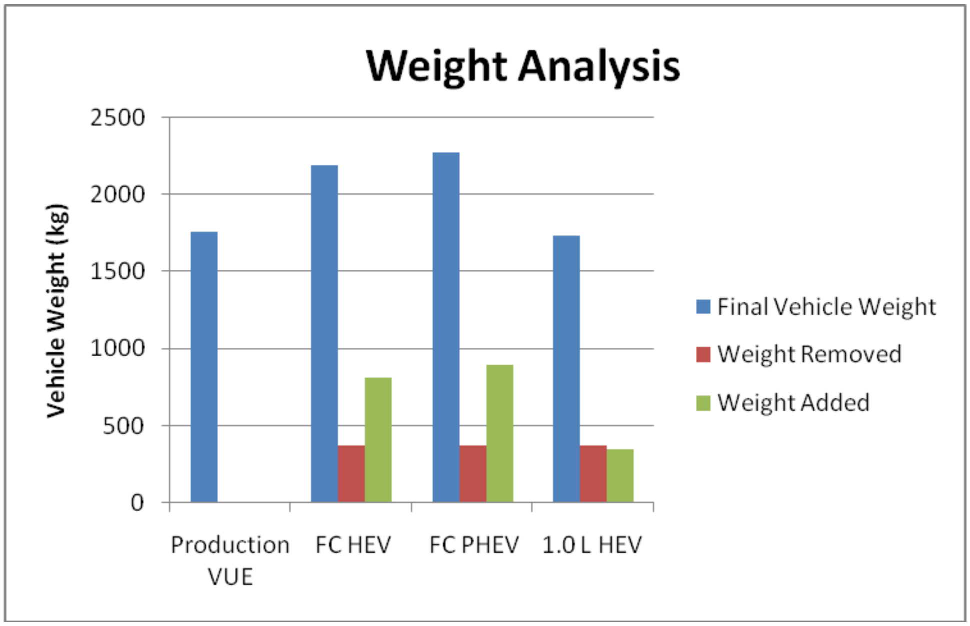


Figure 16: Weight analysis different architectures

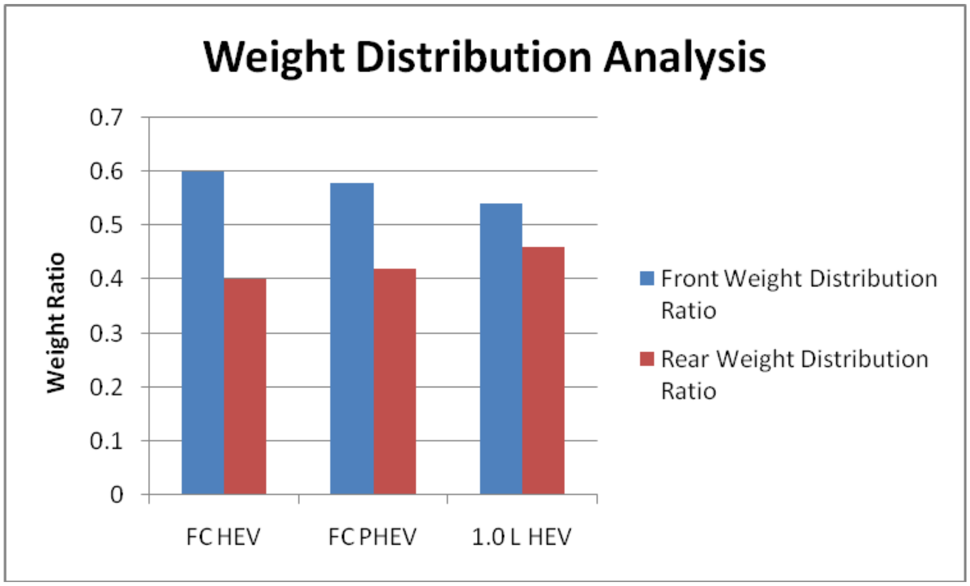


Figure 17: Weight Distribution analysis of different architectures

All of the components that are removed will remain the same for both the 1.0L HEV and the FC PHEV except for battery size. The total weight gained for the three architectures are shown in Figure 16. It is important to notice that the 1.0L HEV will actually lose weight, however, because of parameters discussed in the Concept selection portion of the report, it will not be selected as the final design. For both FC architectures the weight increases significantly. This is mostly due to the very large weight attributed to the Fuel Cell assembly, which weighs 441 kg. While there is a significant amount of weight added to the vehicles for Architecture 1 and 2, the weight distribution does not change significantly. The weight distributions of all three architectures can be seen in Figure 17. Notice that the original weight distribution, .58/.42, is relatively close to all three architectures [4]. These weight distributions were calculated using the weight distribution of the current VUE with the replaced parts defined in the table above. The weight distributions were similar, even though there was a significant weight gain for both FC architectures. One important effect of weight is braking distance. From the PSAT simulation, provided by the Missouri S&T EcoCAR Team, and through a basic energy balance calculation it was determined that the braking distance would meet the competition requirements. The energy balance of the system for force required to stop the car is estimated at:

$$Force = mgu$$

$$KE = \frac{1}{2}mv^2$$

From this calculation it can be seen that the mass of the vehicle cancels out. This suggest that, while mass does factor into braking distance, it should not dramatically affect the results for this competition at this time. None of the architectures will meet production VUE standards according to these initial results. The weight analysis will continue to be modeled and experimented with as the competition continues.

Hardware in the Loop (HIL)

As part of developing a control strategy for the PHEV hybrid, a HIL will have to be implemented. Figure 18 shows the HIL system setup with the system [4].

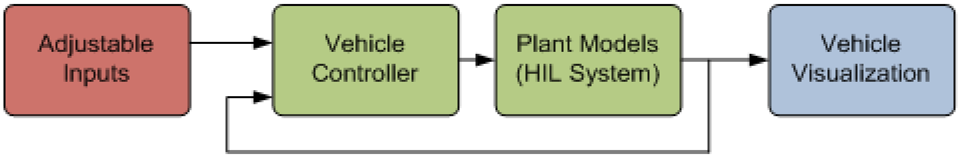


Figure 18 HIL Setup

The Missouri S&T EcoCAR Team is currently looking at two possible companies to donate HIL systems. These companies include dSpace and National Instruments [4]. The dSpace controller is a midsized HIL system that uses a Simulink interface and contains its own processor [4]. The National Instruments HIL system relies on a LabVIEW interface and a pc processor [4]. More information can be found in Appendix C [4]. It has been determined that the dSpace system is far superior in performance but is slight more complicated to operate. However, it allows all steps of the system to be integrated by software for a closed-loop mechatronic control system, and it was initially designed for automotive industry use. The HIL system will help validate and help continue development of the vehicle before implementing anything to the vehicle. The system will work at tuning the control strategy and will find faults in the strategy. Tables 11& 12 illustrate some of the pros and cons of each companies HIL system [4]. The HIL system is extremely important in testing and implementing a proper control strategy for the vehicle. This will save money and will allow the vehicle's performance specifications to become optimized.

Table 11: Pros and cons of dSpace HIL system

Pros	Cons
Developed specifically for automotive applications	Intricate software interface
Customized 2.6 GHz processor	
Multiple input output ports	
Programmable power supply	
Support advantage (alum at dSpace & GM)	
Experience with wide range of automotive hardware	

Table 12: Pros and cons of national instrument HIL system

Pros	Cons
Wide range of I/O expansion cards	Fewer expansion card slots
User friendly software interface	Suited only to NI compactRIO controller
Configurable FPGA	Lack of automotive hardware experience

Robustness Analysis

It is always important to consider robustness during conceptual design. For these concepts feasibility and robustness clashed. All the powertrain architectures used a series powertrain design to lower the complexity of the control strategy of the vehicle. This made the vehicle more sensitive and reliant on all the parts to work. In a parallel series powertrain the vehicle is less susceptible to total failure if one component fails. This allows for a more robust design but greatly increases the complexity of the vehicle. However, in series there is less complexity, which reduces the possibility for things to go wrong. Due to the complexity of the parallel series powertrains, the concepts being considered will use a series powertrain.

Conclusion

In conclusion the PHEV powertrain architecture has the most upside of the three powertrains. This can be seen from the concept selection chart, however all three powertrain architectures had good scores. The next step for the Missouri S&T Team will involve refining and implementing a control strategy, designing a DC/DC converter, optimizing weight reduction, and refining component packaging. These four main steps will increase feasibility of the vehicle by optimizing performance while not sacrificing consumer acceptability.

Appendix A

(Competition architecture selection data)

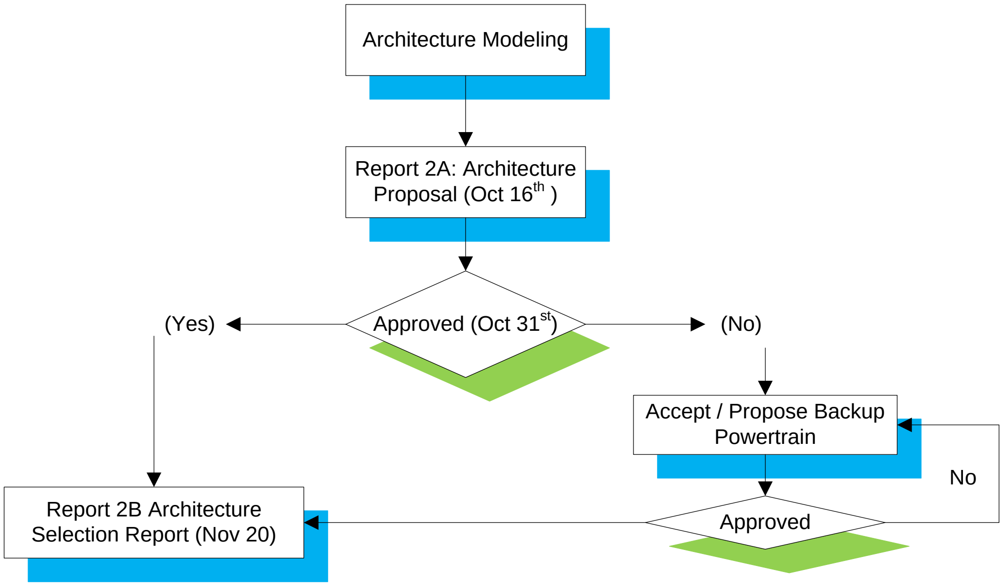


Figure A.1: Competition architecture selection process

Table A.1: Competition deliverable dates

Fall 2008 Dates	EcoCAR Team Deliverable
September 12th, 2008	Report 1: Production vehicle modeling report
October 20th, 2008	Report 2A: Architecture Selection Proposal
November 20th, 2008	Report 2B: Architecture Selection Report

Appendix B

(Packaging)

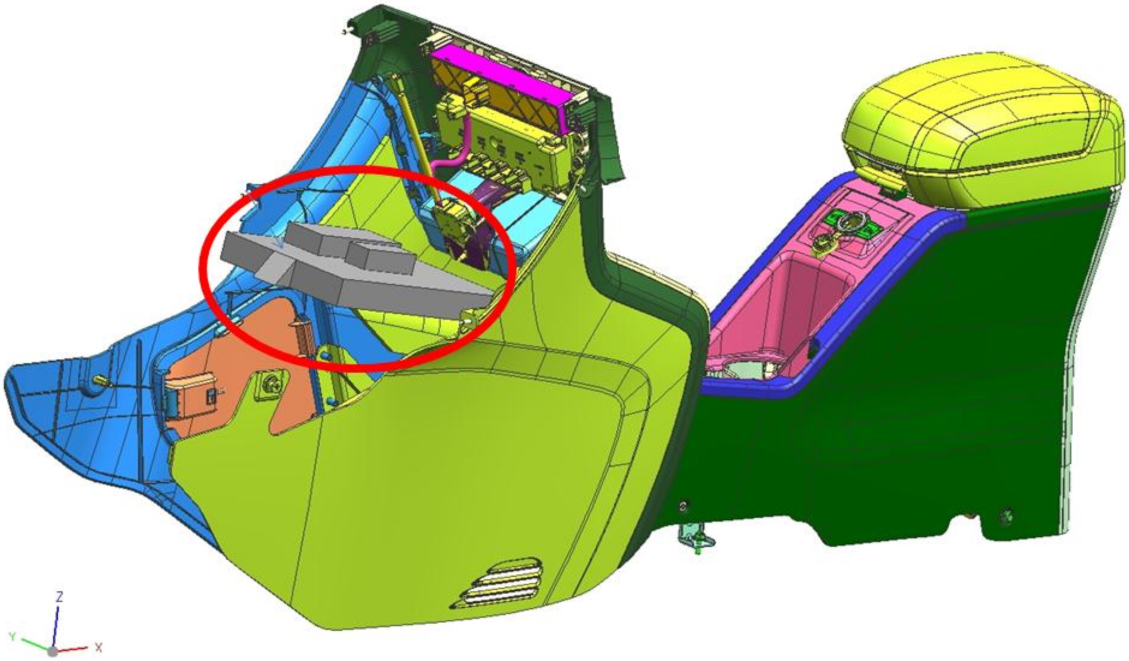


Figure B.1: Controller placement

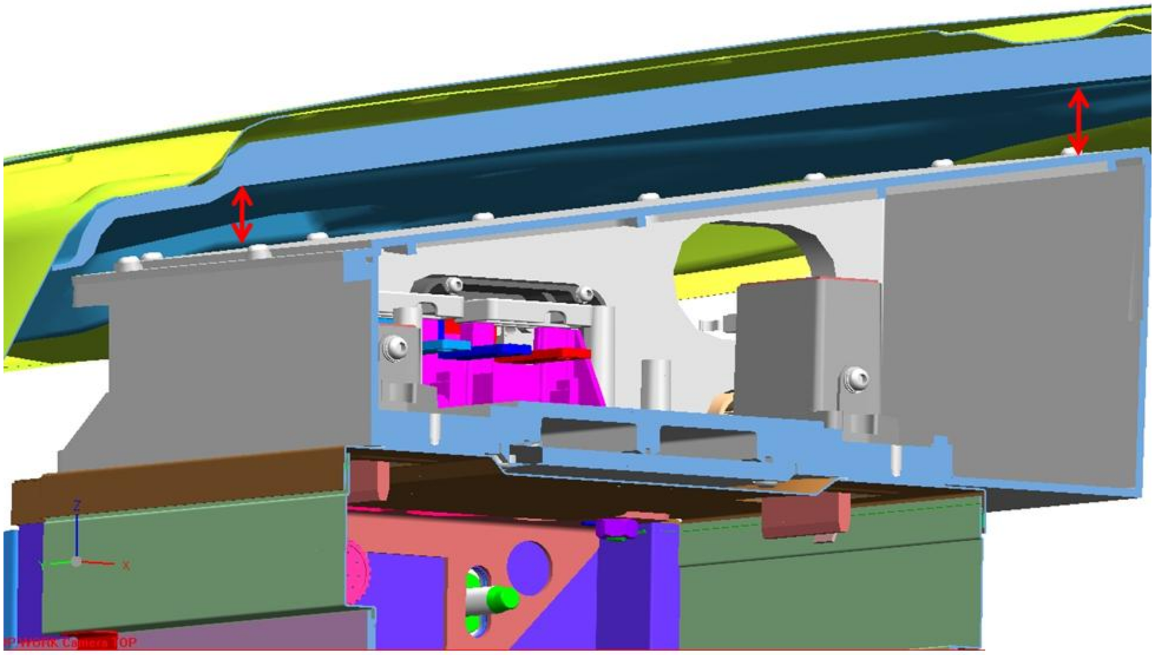


Figure B.2: Hood clearance

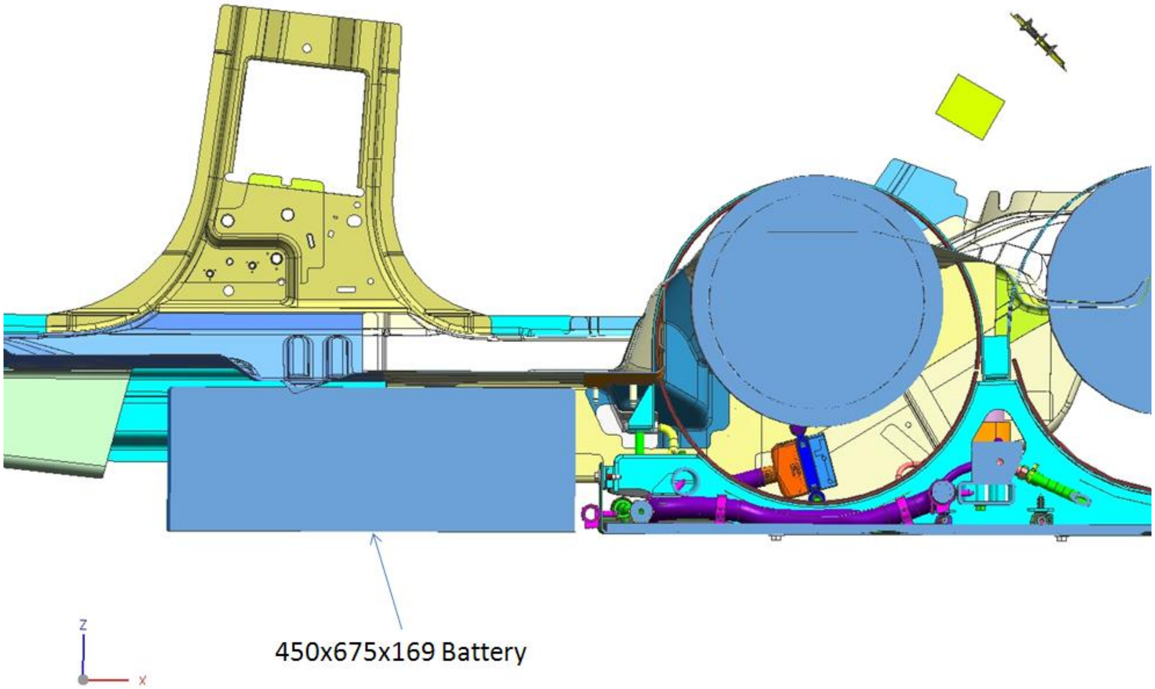


Figure B.3: Version of battery placement: this case does not allow for extra design clearance

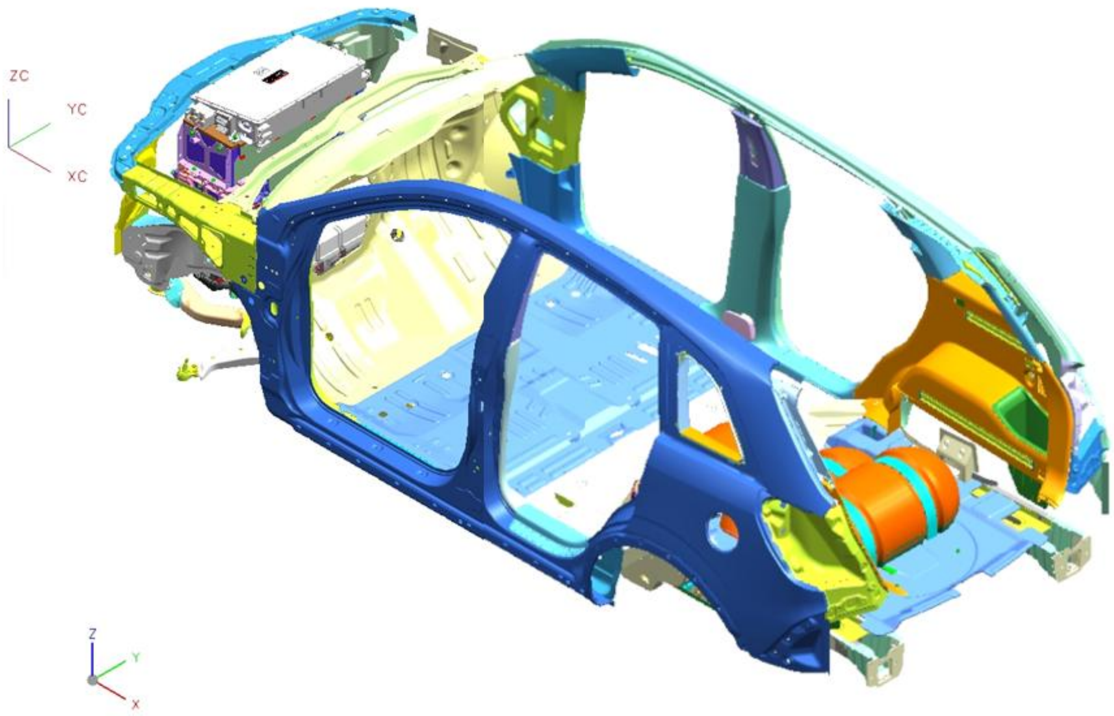


Figure B.4: Architecture 2 top isometric

Figure B.5: Architecture 2 side view

Figure B.6: Architecture 2 isometric view

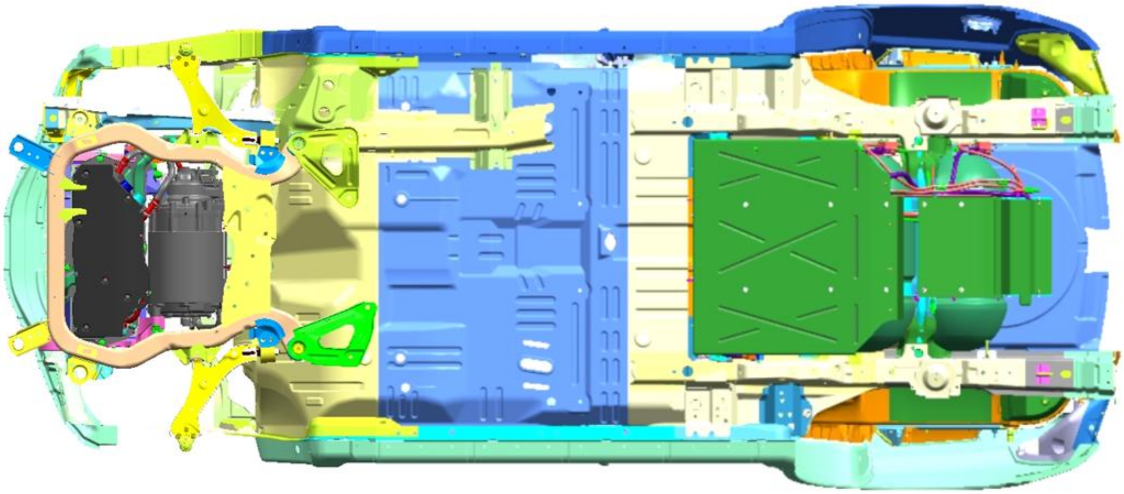


Figure B.7: Architecture 2 bottom view

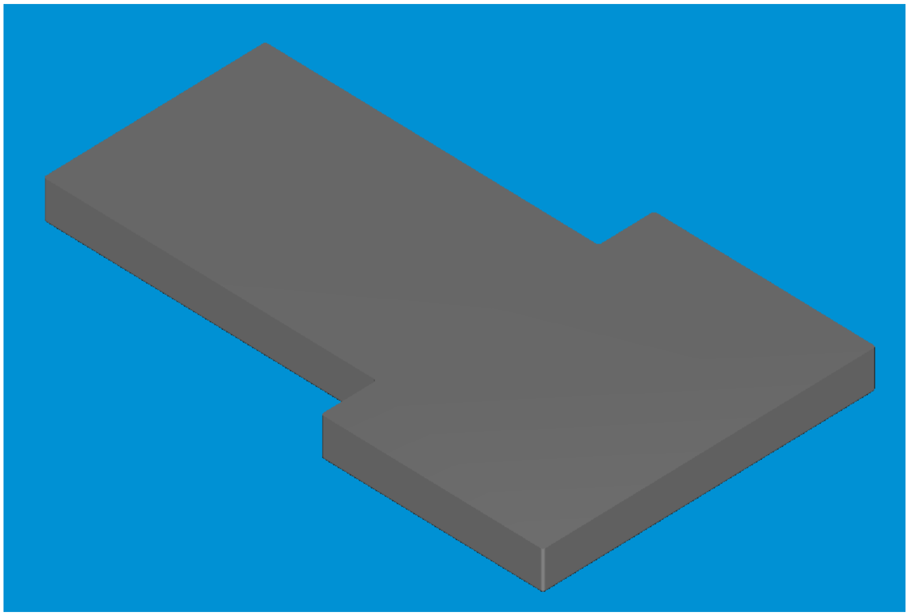


Figure B.9: T-shaped battery

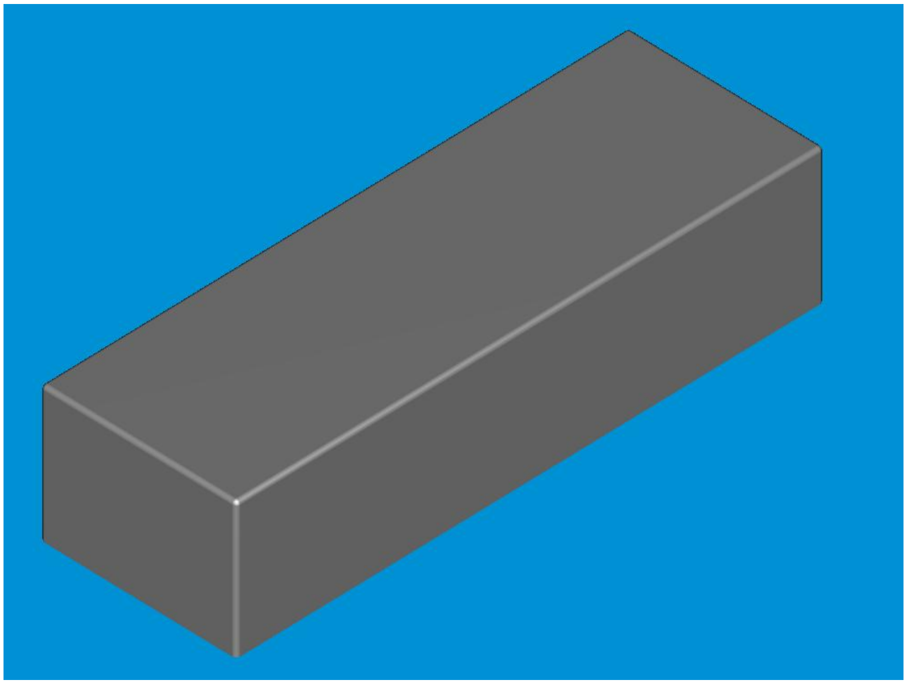


Figure B.10: 225x675x160 battery

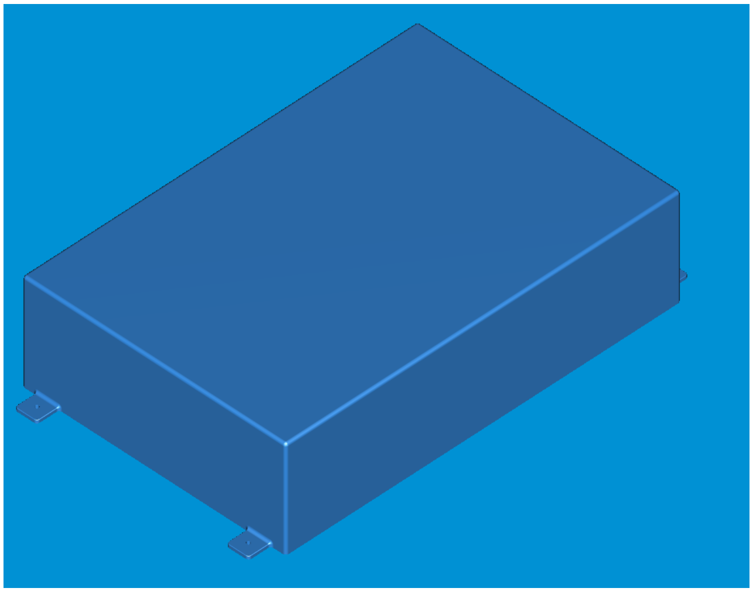


Figure B.11: Architecture 3 445x665x160 battery

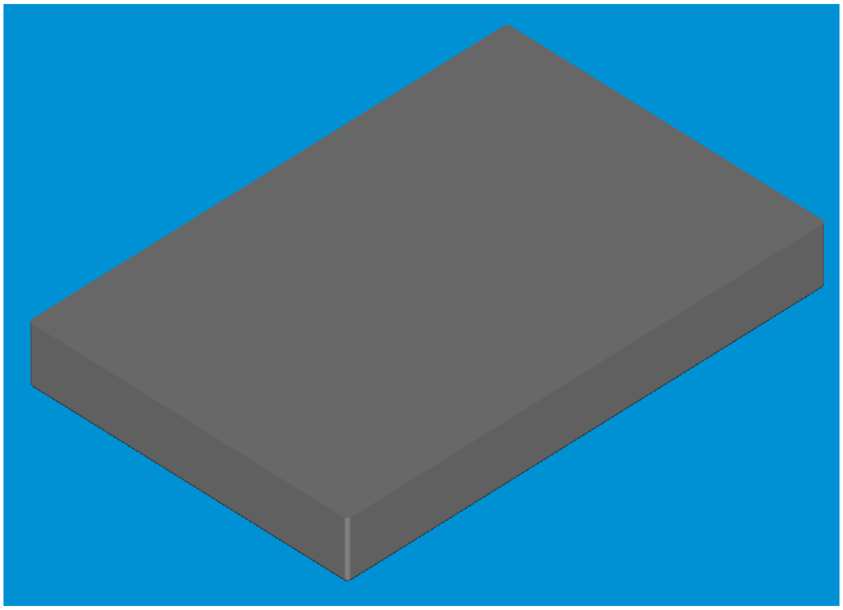


Figure B.12: 450x675x80 battery

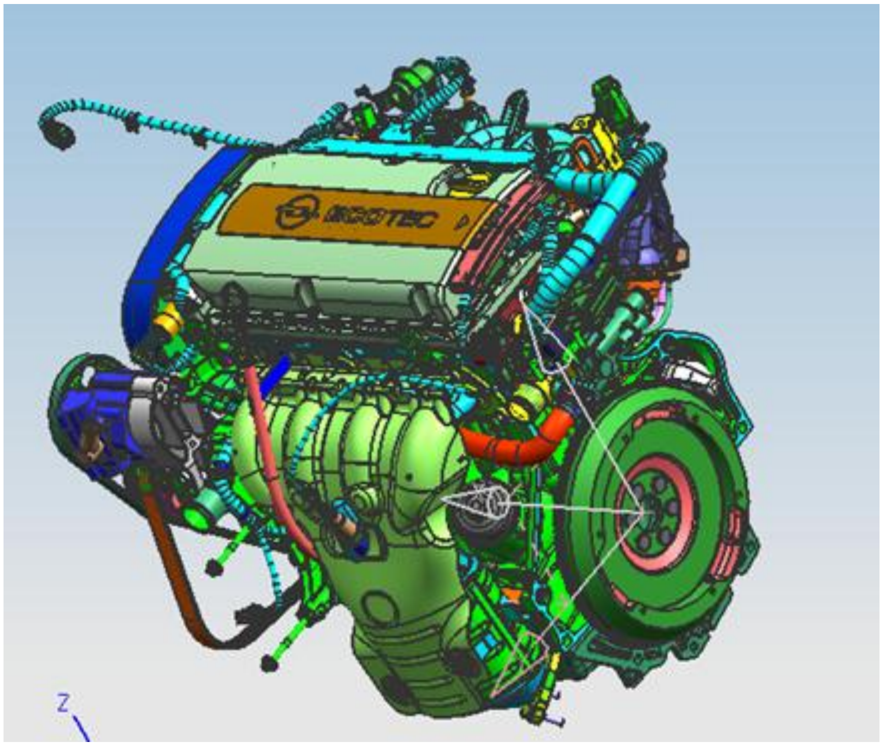


Figure B.13: Architecture 3 internal combustion engine assembly

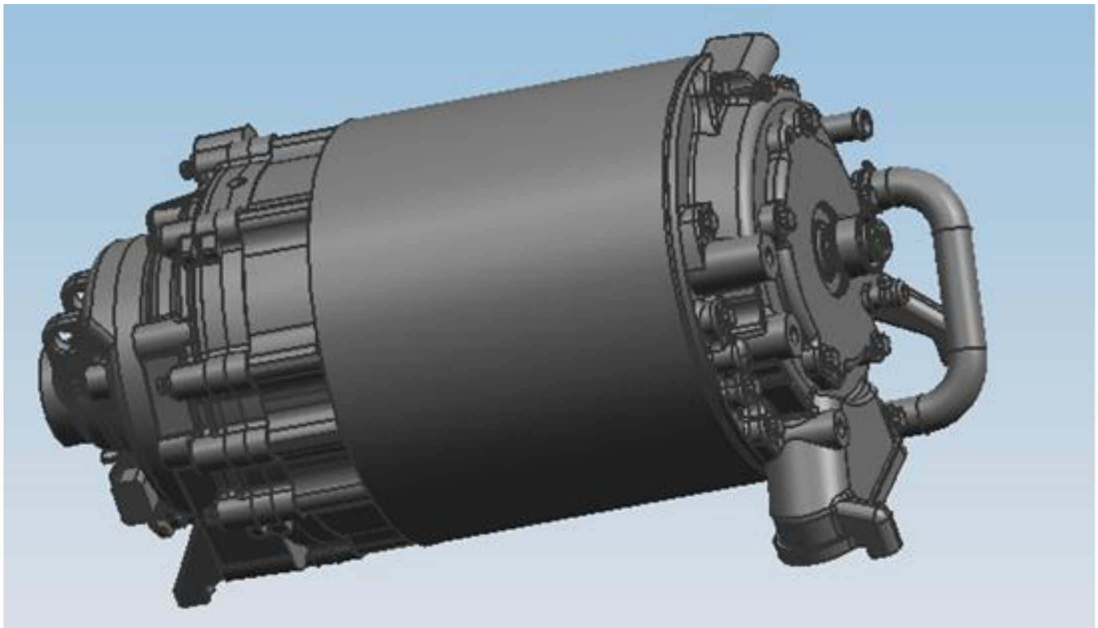
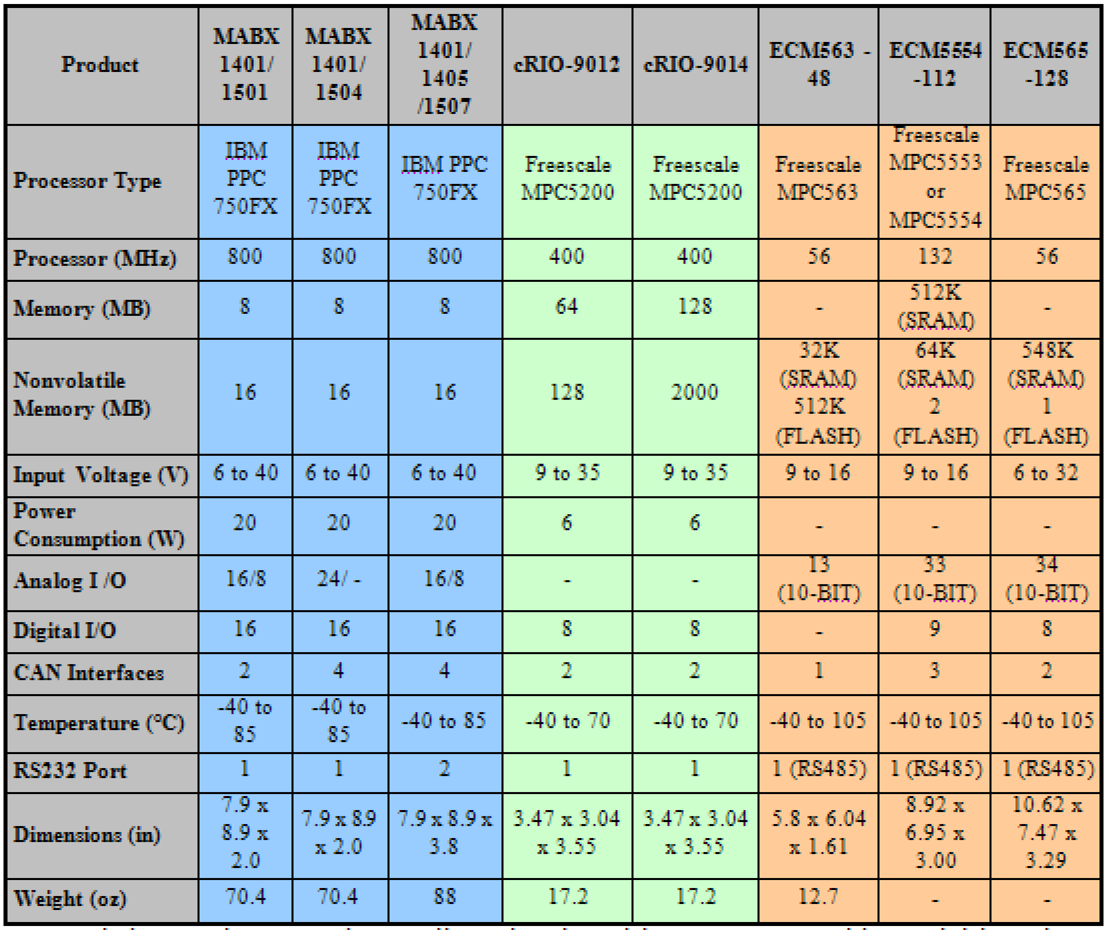


Figure B.14: Architecture 3 motor-transmission assembly

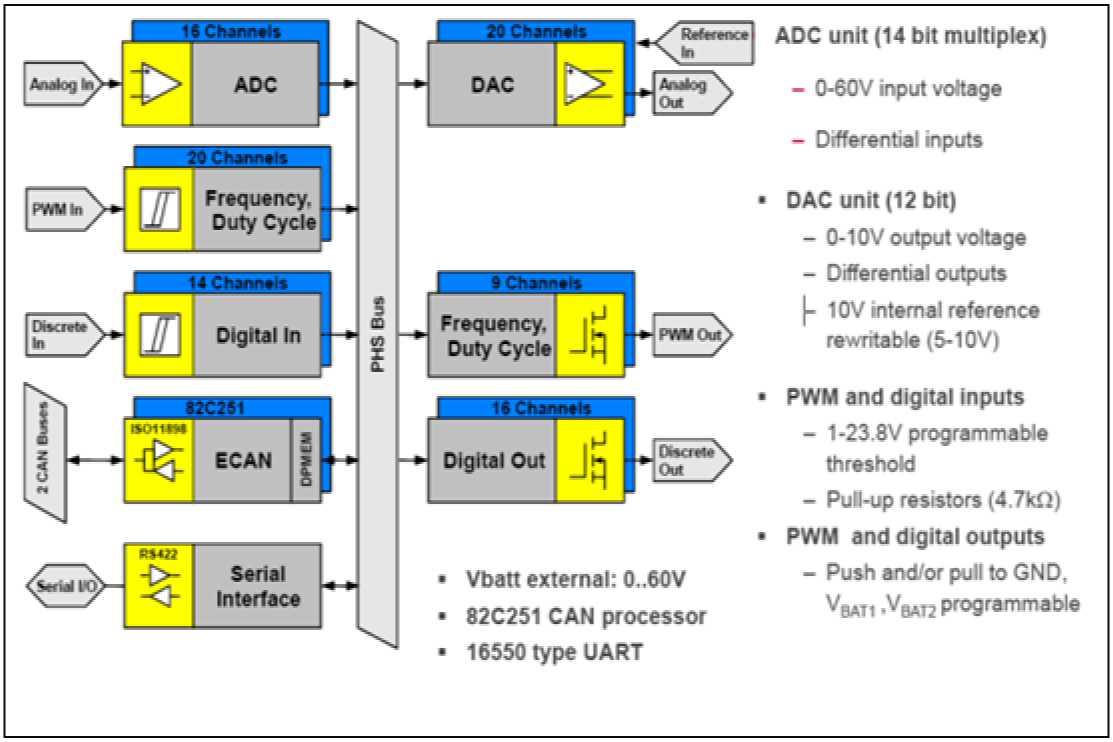
Appendix C

(Controllers and HIL data)

Table C.1: Controller comparison table



Product	MABX 1401/ 1501	MABX 1401/ 1504	MABX 1401/ 1405 /1507	cRIO-9012	cRIO-9014	ECM563 - 48	ECM5554 -112	ECM565 -128
Processor Type	IBM PPC 750FX	IBM PPC 750FX	IBM PPC 750FX	Freescale MPC5200	Freescale MPC5200	Freescale MPC563	Freescale MPC5553 or MPC5554	Freescale MPC565
Processor (MHz)	800	800	800	400	400	56	132	56
Memory (MB)	8	8	8	64	128	-	512K (SRAM)	-
Nonvolatile Memory (MB)	16	16	16	128	2000	32K (SRAM) 512K (FLASH)	64K (SRAM) 2 (FLASH)	548K (SRAM) 1 (FLASH)
Input Voltage (V)	6 to 40	6 to 40	6 to 40	9 to 35	9 to 35	9 to 16	9 to 16	6 to 32
Power Consumption (W)	20	20	20	6	6	-	-	-
Analog I /O	16/8	24/ -	16/8	-	-	13 (10-BIT)	33 (10-BIT)	34 (10-BIT)
Digital I/O	16	16	16	8	8	-	9	8
CAN Interfaces	2	4	4	2	2	1	3	2
Temperature (°C)	-40 to 85	-40 to 85	-40 to 85	-40 to 70	-40 to 70	-40 to 105	-40 to 105	-40 to 105
RS232 Port	1	1	2	1	1	1 (RS485)	1 (RS485)	1 (RS485)
Dimensions (in)	7.9 x 8.9 x 2.0	7.9 x 8.9 x 2.0	7.9 x 8.9 x 3.8	3.47 x 3.04 x 3.55	3.47 x 3.04 x 3.55	5.8 x 6.04 x 1.61	8.92 x 6.95 x 3.00	10.62 x 7.47 x 3.29
Weight (oz)	70.4	70.4	88	17.2	17.2	12.7	-	-



ADC unit (14 bit multiplex)
- 0-60V input voltage
- Differential inputs

- DAC unit (12 bit)
  - 0-10V output voltage
  - Differential outputs
  - 10V internal reference rewritable (5-10V)
- PWM and digital inputs
  - 1-23.8V programmable threshold
  - Pull-up resistors (4.7kΩ)
- PWM and digital outputs
  - Push and/or pull to GND, V_{BAT1}, V_{BAT2} programmable

- Vbatt external: 0..60V
- 82C251 CAN processor
- 16550 type UART

Figure C.1: DS2202 HIL-IO-Board- Sensor/Actuator Interface

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