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EcoCAR Design and Development Process for a Plug-in E85 Split Parallel Architecture Hybrid Electric Vehicle

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Abstract

The Hybrid Electric Vehicle Team of Virginia Tech (HEVT) is participating in the 2009 – 2011 EcoCAR: The NeXt Challenge advanced vehicle technology competition series, sponsored by General Motors Corporation, the U.S. Department of Energy, Natural Resources Canada, and Argonne National Lab. Following GM the Vehicle Development Process (VDP), HEVT established team goals that meet or exceed the competition requirements. A literature review was performed to understand the potential of vehicle subsystems and their interactions on a total vehicle level. The Controls Subteam utilized the Powertrain Systems Analysis Toolkit (PSAT) to model the stock vehicle. This information is used in the hybrid component selection and sizing. The result of this design process is a hybrid vehicle powertrain that can be classified as an Extended Range Electric Vehicle (EREV), built on a Split Parallel Architecture (SPA) that uses grid electric energy and E85 fuel. The platform can meet or exceed the stock performance requirements while reducing petroleum energy consumption by an estimated 80 %. The vehicle design is predicted to achieve an SAE J1711 utility factor corrected fuel consumption of 2.4 l/100 km (100 mpgge) with an estimated all electric range of 75 km (47 miles). Using E-85 fuel (corn-based in North America for the 2015 timeframe), the well-to-wheel petroleum energy use and greenhouse gas emissions are reduced by 80 % and 40 % respectively when compared to the stock 4-cylinder gasoline vehicle. The design and control strategy are tested on a controller Hardware-in-the-Loop (HIL) chassis combined with the actual Hybrid Vehicle Supervisory Controller and software for the competition vehicle.

Keywords: PHEV, energy source, range, vehicle design

1 Introduction

The Hybrid Electric Vehicle Team of Virginia Tech (HEVT) is participating in the 2009 – 2011 EcoCAR: The NeXt Challenge advanced vehicle technology competition series, sponsored by General Motors Corporation, the U.S. Department of Energy, Natural Resources Canada, and Argonne National Lab. This paper documents the powertrain architecture selection and vehicle design to meet the EcoCAR competition and team goals. This work presents the vehicle design process and the hybrid architecture selection results based on vehicle modeling and analysis. Each subteam is working on tasks specific to the competition year one design process.

The paper includes a literature review which is used to generate vehicle concepts and document previous solutions to the problem of reducing petroleum consumption, improving vehicle fuel efficiency, reducing vehicle emissions and maintaining vehicle performance. Next, the stock vehicle performance and fuel economy are documented. From this information HEVT can define the vehicle technical specifications (VTS) to be competitive with the stock gasoline fueled Vue while meeting the HEVT goals. This overall process can be seen in Figure 1 which shows the pathways from design to concept realization. Since this vehicle design process entails changing the vehicle powertrain, the impact of vehicle fuel selection on powertrain design is the next consideration. Based on detailed vehicle models with appropriately sized components, a final vehicle design is established for a SPA hybrid electric vehicle with a 2.4 L inline 4-cylinder E85 engine that incorporates a Belted Alternator Starter (BAS) and a Rear Traction Motor (RTM) for all-electric propulsion using stored grid electric energy. Vehicle mass, component packaging, safety and consumer features are also considered before drawing final conclusions. A robust and effective hybrid vehicle supervisory (HSV) control system are developed using National Instruments (NI) CompactRIO hardware and software tools. The controller and algorithms are tested on a NI HIL (hardware-in-the-loop) system to verify safe operation before deployment on the vehicle.

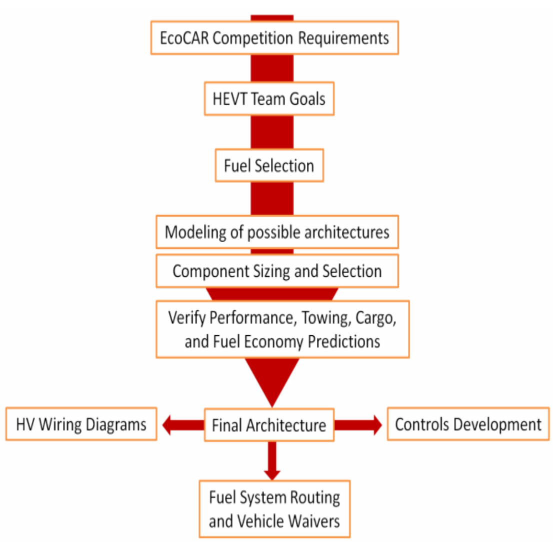

Figure 1: HEVT design pathways

2 Team Goals

Through the EcoCAR competition, HEVT was supplied minimum requirements for vehicle efficiency, vehicle parameters, and performance. HEVT decided to increase the goals set forth by competition by adding goals for petroleum reduction, all electric operation, cargo space, and towing as shown in Table 1. The goal of all electric range leads HEVT to pick a battery pack with a large energy storage of 14.7 kWh useable on the vehicle (21 kWh total) to displace petroleum. Another attempt to reduce the dependence on oil is the inclusion of E85 as a fuel which means that the stock engine would have to be replaced, with a FlexFuel engine from GM.

Table 1: HEVT Goals

	Description
Petroleum Reduction	Significantly reduce petroleum consumption
Plug-in Range	> 56 km (35 mile) range as a pure all-electric vehicle
Cargo and Passenger space	Keep most of stock cargo space intact and 4 passenger capacity
Towing	Increase EcoCAR speed and grade requirements to a 55 mph test at 5%

The petroleum reduction goal also has a direct influence on the goal of a large electric range since the larger the range the more petroleum displaced. Consumer acceptability features are important design criteria as well, which includes meeting the zero to sixty acceleration performance and meeting all of the drive cycle tests. HEVT will maintain a zero to sixty time of less than 10 seconds while charge sustaining (CS) and will hopefully break 14 seconds in all-electric charge depleting (CD) mode. Consumer acceptability is also a primary factor in the establishment of team goals. The final goal set by HEVT is fuel economy specifications. HEVT is striving for combined fuel economy of 55 mpgge based on the SAE J1711 utility factor correction standard and a 34 mpgge combined fuel economy for CS engine on mode. These goals will help ensure that HEVT creates the best possible, most competitive vehicle for the EcoCAR Challenge.

3 Vehicle Technical Specifications

The vehicle technical specifications (VTS) can be seen in Table 2. The refinement of the goals as provided by the EcoCAR competition organizers into metrics was a result of basic modelling of vehicle architectures in Powertrain Systems Analysis Toolkit (PSAT) from Argonne National Labs (ANL) [1]. The vehicle is designed around these specifications. The specifications are updated as more information is supplied about the components selected and available, so that the VTS remain an accurate representation of the vehicle. This is important because later in the EcoCAR competition HEVT will be judged not only on the best design as compared to the 16 other teams but how well the vehicle performs against the VTS that HEVT specifies.

Table 2: HEVT Vehicle Technical Specifications

HEVT Specifications	Metric
Petroleum Reduction in comparison to the stock Vue	> 80 %
Electric Only Range	> 35 miles
Towing speed	> 55 mph
Towing Grade	> 5 %
Mass additions	< 430 kg
UDDS trace misses	< 2 seconds
HWFET trace misses	< 2 seconds
US06 trace misses	< 12 seconds
IVM – 60 mph, CD mode	< 14 seconds
Fuel economy, CAFE unadjusted, combined with UF correction	> 55 mpgge
Fuel economy, CAFE unadjusted, combined in CS operation	> 34 mpgge

4 Literature Review and Design Parameters

This section focuses on vehicle fuel and powertrain architecture technology advancements. There are many existing studies on improvements in automotive powertrain technologies and their overall impact on energy use and GHG emissions. Information as well as background will be provided via this literature review and sources are used to support each category below.

4.1 HEV Operation Modes

There are multiple operation modes that a plug-in hybrid electric vehicle can utilize. These modes are described in the Boyd and Nelson paper "Hybrid Electric Vehicle Control Strategy Based on Power Loss Calculations" [2]. The four modes are as follows: engine only, engine generate, engine blended, and electric only. HEVT plans to take advantage of three of the modes but will only use the engine blended mode in CS operation. As per the HEVT overall goals of a range extended hybrid during the time the vehicle is in electric only (CD) mode or engine enabled (CS) mode, the design should meet all performance criteria.

4.2 Lithium Ion Batteries

One of the main sources of power for the vehicle and the power source for the all-electric mode will be a Lithium Ion battery pack. Lithium Ion batteries are not a brand new technology, but they are gaining popularity in industry today. Lithium Ion battery packs have a greater specific energy than do a Nickel Metal Hydride pack, allowing for lighter and higher energy density systems [3]. Lithium Ion batteries main disadvantage is that there are more safety considerations than other batteries for charging. Procedures have been developed by HEVT to ensure the safe operation of the vehicle and for the protection of the passengers.

4.3 Hybridization

Hybridization combines two power sources to improve overall powertrain efficiency. Hybrid electric systems are mostly suited for light-duty vehicles, while hydraulic hybrids may have advantages for larger vehicles. A SI engine or CI engine can be used in a hybrid system, which pairs an engine with electric motors and an energy storage system (ESS). One of the most basic hybrid systems is a 42 V system (36 V battery) that has one electric motor coupled to the engine. Commonly referred to as an integrated starter alternator (ISA) or belted alternator starter (BAS), this motor can assist the engine, start the engine to prevent idling, and charge the battery. Studies and testing have shown that this type of mild hybrid system can produce fuel economy gains of around 4-7 % [4,5]. Typically the ISA or BAS does not have enough power to allow electric-only operation, which may improve efficiency.

Engine downsizing is a consideration for hybridization where a full hybrid vehicle incorporates one or two high power electric motors into the vehicle powertrain to make up for the loss due to downsizing. Since these motors are larger than an ISA or BAS, they may be mechanically coupled elsewhere in the vehicle powertrain. Downsizing either a SI or CI engine may raise efficiency by providing relatively higher loading of the engine, possibly at the expense of emission increases.

5 Stock Vehicle Modeling

5.1 Energy Losses

Using PSAT, the team investigated the amount of energy lost in various drivetrain components. Knowing where energy losses occur will be beneficial in choosing an architecture for the HEVT vehicle. Figure 2 shows where and how much energy is being lost through the driveline. The largest loss occurs from converting the fuel energy into mechanical energy in the engine. Because of this, HEVT wants to minimize the amount of time the engine is running, and then load level the engine to make the running operation as efficient as possible.

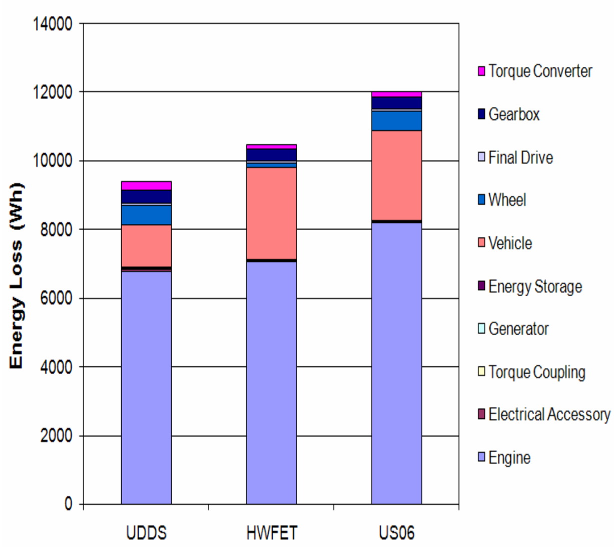

Figure 2: Breakdown of energy losses for the UDDS, HWFET and US06 drive cycles for the stock Saturn Vue.

5.2 Towing Power Requirements

The competition requires that the EcoCAR hybrid Vue must be able to tow 680 kg on a 3.5 % grade at a minimum speed of 72 kph (45 mph). HEVT established a design goal to increase the towing requirement from EcoCAR to make the vehicle meet a more stringent power demand. The requirement was increased to a vehicle speed of 82 kph (55 mph) with the vehicle loaded at GVWR of 2620 kg. The design pursed by HEVT will be able to tow a test mass of 680 kg (1500 lb) over a drive cycle modeled after the Baker grade in California, USA in CS operation mode. Due to the limitation of energy stored in the battery pack, the vehicle will need to be able to perform this task in engine only mode to meet consumer acceptability requirements. HEVT also investigated the power necessary to maintain 160 kph (roughly 100 mph) with a vehicle test mass of 2310 kg on a 0 % grade. This is illustrated in Figure 3. At 160 kph, the required tractive power is 69 kW (92 hp).

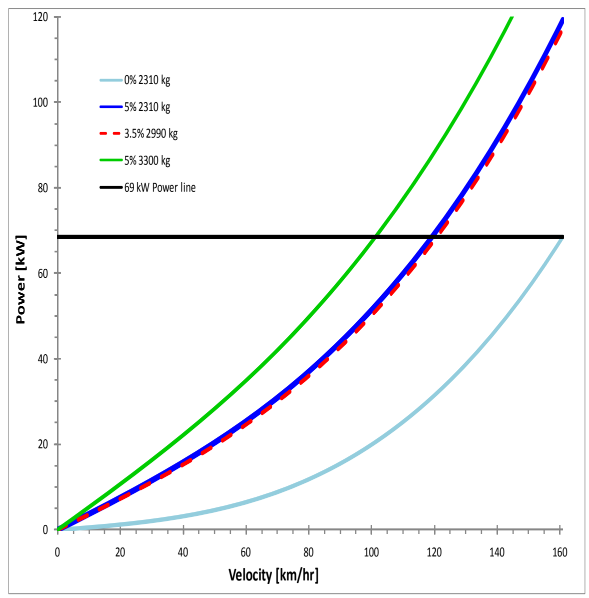

Figure 3: Plot of road load calculations to determine power requirements at the wheels.

The black line on Figure 3 represents a constant power of 69 kW, which allows the potential speed at other road loads to be acquired. Included in Figure 3 are the plots for the two towing criteria along with a plot for the power required by a Vue weighing 2310 kg on a 5 % grade which happens to also coincide with the minimum towing criteria line. Full acceleration performance to meet the towing requirements requires that 120 kW peak be available. A minimum continuous power of 69 kW is also established to meet the basic towing requirements of EcoCAR. Engine downsizing is therefore not a consideration for HEVT to meet the full performance characteristics from the goals established. Also it should be noted that the electric drive should be sized greater than the minimum of 69 kW in order to have the vehicle feel powerful enough to meet consumer performance standards.

5.3 Fuel Economy Modeling

To help choose a final architecture, fuel economy modeling was performed using PERE [6]. PERE modeling allowed the team to see probable fuel economies of gasoline, diesel, hydrogen and electricity. A limitation is that PERE does not include E85 but the E85 fuel economy can be estimated from gasoline. Table 3 shows the results of the PERE modeling for stock Vue masses, including the Vue XE and the Vue Green Line. The Vue Green Line's fuel economy improvements are due primarily to mild hybridization and aerodynamic improvements. Both mass (inertia) and road load are important in the calculation of fuel economy and to optimize the energy use of the powertrain. The lightest possible vehicle will usually be the best case when performance, safety, utility, and costumer acceptability are not reduced in the process. The reason for the increase in fuel economy for the HEVT SPA is due in large part to powertrain improvements. Some aerodynamic features will be implemented from the Vue GL based on improvements of estimated fuel economy in Table 3.

Table 3: PERE drive cycle fuel economy test used for architecture selection

FUEL ECONOMY				
		Drive Cycle (mpgge)		
Vehicle	**Mass (kg)**	**UDDS**	**HWFET**	**US06**
Vue XE	1814	25.6	35.3	22.8
Vue GL	1900	35.1	39.2	27.7
HEVT SPA	2150	32.7	33.9	22.2

6 Fuel and Energy Source Selection

Vehicle fuel has a larger impact than just tailpipe emissions. Both greenhouse gases and criteria emissions should be measured over the entire fuel cycle, from the well-to-wheels (WTW). For this reason, ANL's version of GREET is used to calculate total well-to-pump (WTP) energy, GHG emissions and criteria emissions for E10, E85, B20, electricity and hydrogen [7]. To find the value of these factors requires assumptions about how the fuel was produced and how it arrived at the pump. This is defined as the fuel pathway in GREET.

In addition to WTW efficiency and GHG emissions, fuel choice affects the amount of petroleum-based energy contained in the fuel and petroleum energy required to produce and distribute the fuel. Table 4 presents the upstream petroleum, actual fuel petroleum and total petroleum energy content for all of the fuels available for EcoCAR [8].

Table 4: Well-to-Pump, Pump-to-Wheel and Total WTW Petroleum Energy content for EcoCAR candidate fuels on a per kWh of fuel energy at the vehicle

	Upstream Petroleum Energy	**Petroleum Energy Content of Fuel**	**Total Petroleum Energy**
Fuel	**[kWh/ kWh]**	**[%]**	**[kWh/ kWh]**
E10	0.0932	90	0.933
E85	0.0832	19	0.272
BD20	0.0642	80	0.864
GH_2	0.0147	0	0.0147
Electricity	0.0785	0	0.0785

A primary goal of HEVT is the reduction of WTW petroleum consumption of our vehicle. In an attempt to meet this goal, and hopefully reduce petroleum consumption by upwards of 80 % a design review of the candidate fuels of E10, E85, BD20, GH2, and Electricity was performed. Table 4 shows the percent of petroleum energy in the fuel while Table 5 displays the total WTW GHG associated with the amount of carbon dioxide produced for every kWh of fuel used on the vehicle. In order to lower the total emissions associated with the vehicle, a fuel that has low vehicle emissions, such as electricity should be selected. However the upstream greenhouse gases associated with electricity is the highest of the candidate fuels which must also be considered in combination with vehicle electric energy efficiency.

HEVT decided to use stored on-board grid energy in the form of a plug-in hybrid to utilize the low vehicle emissions of electricity. This decision was based primarily on the ability to meet the large electric range goal set forth by HEVT, as well as the knowledge that the energy from electricity can be used much more efficiently on the vehicle than energy from a typical liquid fuel like E85. This stored energy from the grid will only allow the vehicle to go so far, and will not meet the total range requirements set forth in the VTS. Therefore a high energy content fuel must be stored and used to produce mechanical energy on the vehicle. The integration of gaseous hydrogen on the vehicle while meeting customer acceptability in addition to tackling the complexity of a fuel cell drive was determined to outweigh the benefits associated with hydrogen fuel. Biodiesel and E10 were eliminated because HEVT is attempting to reduce petroleum energy consumption at the vehicle. Therefore E85 was selected to further reduce the vehicle consumption of petroleum energy. Due to the selection of E85, HEVT will have to integrate a FlexFuel capable engine into the final architecture.

Table 5: Well-to-Pump, Pump-to-Wheel and Total WTW Greenhouse Gas Emissions for EcoCAR candidate fuels on a per kWh of fuel energy at the vehicle

	Upstream GHG	**CO_2 Content of Fuel**	**Total GHG**
Fuel	**[g CO_2equiv/ kWh]**	**[g/ kWh]**	**[g CO_2/ kWh]**
E10	63.3	261	324
E85	1.57	260	262
BD20	1.99	277	279
GH_2	398	0	398
Electricity	699	0	699

7 Powertrain Modelling and Simulation for Performance and Energy Consumption

7.1 Model Structure

HEVT began evaluating the individual components after receiving the stock Vue PSAT model file provided by Argonne National Laboratory. There are 12 separate components used to model a 2009 Saturn Vue XE in PSAT as shown in Figure 4. The first component is the 12V SLI (Starter Lighting and Ignition) battery. The initial state of charge (SOC) is set to 70 % for the purpose of starting the vehicle and powering the lights when the engine is not running. The next three components connected to the battery are the electrical accessory load, the starter and the generator. The electrical accessory provides a constant power load of 0.24 kW during simulation. The starter is set to simulate the stock engine starter system. The generator is connected to the engine by a torque coupling and acts as the stock 12V alternator. The engine is linked to the starter and is modeled to perform like the 2.4 L 4-cylinder stock engine. The mechanical accessory is included in the link between the engine and the torque converter, but is currently not applying a load to the engine. The torque converter, gearbox and differential are setup to imitate the stock drivetrain. The vehicle and wheels were given characteristics comparable to the stock Vue XE. Model alterations included changing the vehicle mass from 1858 kg to 1900 kg and the drag coefficient from 0.376 to 0.417 to reflect the properties of the stock vehicle. The coefficient of rolling resistance was set to 0.009 for these models.

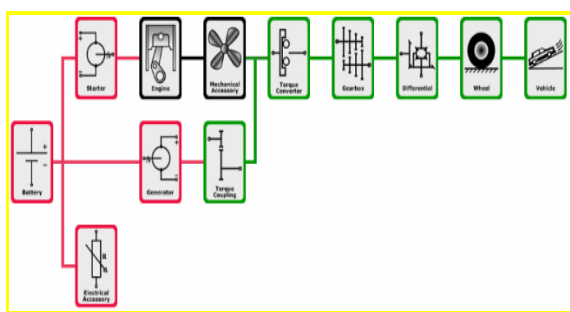

Figure 4: Layout of components in PSAT model used for stock vehicle modeling.

7.2 Acceleration Simulation

To replicate the acceleration data provided by GM, simulations were run to model the 0-60 mph (97 kph) and 50-70 mph (80-113 kph) acceleration times. Table 6 shows the results of the model compared to production test data. The differences between the PSAT results and the stock vehicle data may be due to uncertainty in the powertrain rotating inertia. The 50-70 mph acceleration test was run using a drive cycle that began at steady speed of 50 mph (80 kph).

Table 6: Model prediction and production test results for acceleration times.

Acceleration Range (mph)	PSAT Model Prediction (s)	Production Vue Performance Data (s)
0-60	10.9	10.6
50-70	6.8	7.2

7.3 Drive Cycle Simulations

To model the vehicle's fuel economy over a wide range of operating conditions, simulations were conducted utilizing the UDDS, HWFET and US06 drive cycles. The UDDS drive cycle is used to represent city driving conditions for light duty vehicles. The HWFET simulates highway driving conditions for light duty vehicles. The US06 is an aggressive drive cycle that emphasizes the high power and high speed demands seen in today's drivers.

7.4 Modelling Conclusions

Overall, the simulations HEVT conducted adequately modeled the performance of the stock vehicle. The acceleration and fuel economy results showed some deviation from the test data, which is hypothesized to be a product of the model limitation and sensitivities described above. The results of these simulations demonstrate that HEVT is able to effectively use PSAT and is ready to move on to modeling possible team vehicle powertrain architectures.

8 Component Sizing and Selection

The next step in the vehicle design process for HEVT is the selection and sizing of the components for the hybrid vehicle based on the analysis performed in the previous sections. The goals established specifically by HEVT are meant to meet and exceed the competition goals as established by EcoCAR. These goals and the modelling of the stock vehicle were the driving factors towards the final design of the vehicle. Figure 5 shows a basic representation of the components that will be integrated into the vehicle.

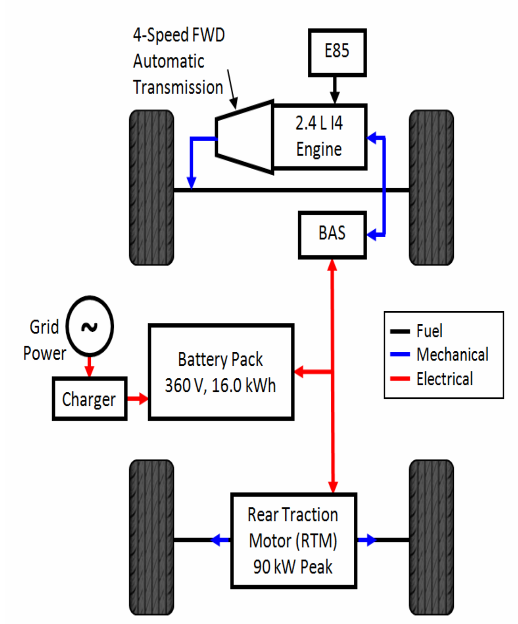

Figure 5: Energy flow diagram of the HEVT SPA

A123 Systems is currently providing 2 different configurations of their prismatic modules for the EcoCAR teams to construct a custom pack. More on this topic is explained in section 9. HEVT decided to use the pack configuration that has more energy, so that a large all electric range would be available for customer acceptability. Because of this the design constraint, the electric motor or RTM needs to be sized for vehicle performance in order to meet customer needs in CD mode. Through talks with Danaher Motion the motor supplier for HEVT, a decision was made that a smaller motor would need to be used. The size of a full performance motor will not allow for integration of the motor into the rear sub frame of the vehicle. A compromise was made to build a 90 kW motor and inverter system that is still well above the minimum power requirements. This power decrease will only be noticeable in certain small hard quick accelerations as can be seen in the

US06 drive cycle, which the vehicle will not be able to meet without some small trace misses in CD mode.

The stock engine will be replaced with a GM LE9 FlexFuel engine to reduce the amount of petroleum consumed on board the vehicle during operation in charge sustaining mode. The engine will only operate in certain bands of operation, and the BAS as built by Danaher Motion will load level the engine to shift engine operation into higher efficiency regions. With the RTM capable of performing electric launch, and a BAS to start the engine with the transmission in neutral, HEVT decided to keep the 4 speed transmission rather than integrate a newer 6 speed transmission. The stock transmission will be replaced with a GM ME7 transmission that comes with a hybrid auxiliary pump that will allow the vehicle to move in electric only mode or engine restart mode. Table 7 shows an overview of the components on board the HEVT VUE.

Table 7: HEVT VUE Component Specifications

Architecture	**E85 Range Extended Split Parallel Architecture**	
Components	**Size**	**Type**
Engine	130 kW peak	GM LE9 2.4 L ECOTEC VVT DOHC 16V I4 FlexFuel SI
Transmission	-	ME7 4-speed automatic FWD
Belted Alternator Starter	8 kW cont.	Danaher custom permanent magnet motor
Rear Traction Motor	90 kW peak	Danaher custom permanent magnet motor
Energy Storage	360 V	A123 custom prismatic built pack, 14.7 kWh useable
12 V Supply	1 kW cont.	DC/DC Converter from 360 V to 13.8 V
A/C System	10 kW	HV electric drive, high efficiency, variable speed
HV Charger	3.0 kW cont.	120/240 V 60 Hz AC
Controls	-	NI cRIO and code

Since there will be large amounts of time at which the vehicle will be operating in some type of engine off mode, an electric Air Conditioning compressor will be installed on the vehicle that will operate directly off of the high voltage bus through an inverter. This high efficiency drive will allow for consumer comfort regardless of what mode the vehicle is currently operating in.

A DC/DC converter will also be added to the vehicle to allow for a supply of 12 V loads directly from the high voltage battery pack. This device will provide power to the stock 12 V distribution system on the Vue.

9 Energy Storage Considerations

HEVT will be using a custom built battery pack consisting of 5 prismatic modules from A123 systems as shown in Figure 6. The limitations of the pack are still being defined and will be safely addressed in the future. The thermal consideration for the pack are based on the assumption that the pack is to be depleted in charge depleting mode and then allowed to cool convectively over a long period of time before being used again. In the design phase of the project the stock 2.4 L engine was kept so that charge sustaining mode would not require large electric assistance to meet the drive cycles. This means that the conventional drive can be utilized for the majority of the vehicle charge sustaining propulsion energy which would not continue to heat the pack beyond its normal operating temperature. The system will capture regenerative braking energy and perform load leveling on the engine to a peak efficiency range. In addition to this, engine idle stop will be possible because of the belted alternator starter (BAS) drive. These modes all require the use of the high voltage pack and will thus heat the thermal mass inside of this EV pack slightly, but within its rms power and thermal limitations.

The control strategy implemented in the vehicle monitors the current flowing into the battery pack from regenerative braking. If at any point the regen capture starts to get close to the upper limit of the pack voltage, more friction braking is blended in so as not to damage the battery or RTM inverter. The SOC of the battery pack is also a consideration for how much energy recapture is allowed to prevent damage to the pack. With the use of the prismatic pack and the thermal concern that exists, the pack temperature will be very closely monitored. Steps will be taken to ensure the safety and longevity of the pack if it starts to reach temperatures above 50 ^{0}C. The upper temperature limit of the operation is 60 ^{0}C and the contactors will automatically open if the pack reaches this temperature. The vehicle hybrid control strategy will be designed to prevent this from happening, but HEVT is aware of its possibility and is prepared to deal with any issues that may result from these conditions.

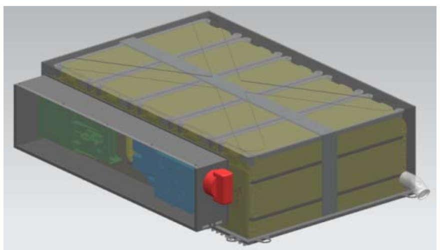

Figure 6: Isometric view of the proposed custom battery pack of 5 Prismatic modules.

10 Packaging and Mass Considerations

HEVT has worked hard to develop a plan for the integration of all of the hybrid components on the vehicle. Placing components on the vehicle must consider ground clearance, ramp angle, and break over angles, while safety is of primary importance in the design phase. Placement of components will also affect the handling of the vehicle because of the change in mass and distribution. The current concept vehicle can be seen in Figure 7.

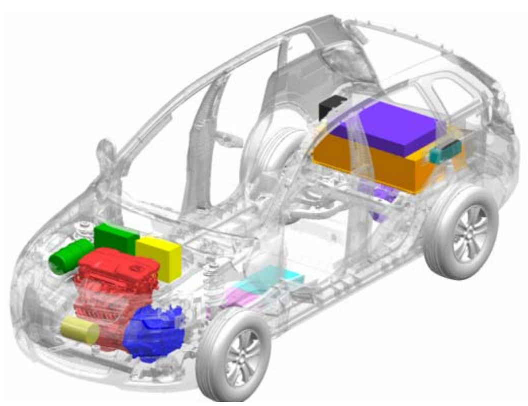

Figure 7: CAD model of the HEVT SPA

One of the design parameters established by HEVT was to only modify the stock components when necessary. This approach includes an attempt to keep the stock fuel lines, vehicle exhaust routing, and engine mounting all in their stock locations. Figure 8 displays the Fuel and Exhaust Systems of the Vue and how these areas are used as static design points that should not be touched unless absolutely necessary. The stock muffler will need to be slightly modified in order to allow clearance for the RTM. This design will result in less time required for integration and more time for future team members to work on refinement and improvements.

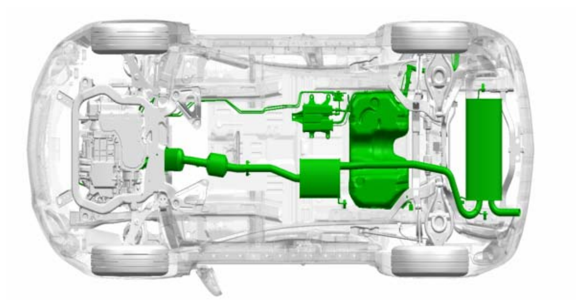

Figure 8: Fuel and Exhaust System

The battery pack is a very substantial piece of hardware that weighs approximately 270 kg and it will greatly affect the curb weight and F/R weight distribution. Preliminary mass estimates show that with a rear brake caliper increase and some weight reduction in other areas of the vehicle, HEVT will have a vehicle capable of carrying 4 passengers. The goal is to light-weight the vehicle enough to once again meet the 5 passenger standard without breaking GVWR limits. Table 8 shows the mass difference in the stock and hybrid vehicles.

Table 8: Vehicle mass comparison

Component	Stock (kg)	SPA Hybrid (kg)
Engine	170	170
Transmission	85	89
Battery	15	270
Starter/BAS	3	26
HV System	0	20
RTM	0	90
Vehicle	1485	1485
Total	1758	2150

A final concern for packaging and mass considerations is the added high voltage distribution system. Figure 9 shows a basic representation of the layout of components and how they will be wired. Special attention will be placed to make sure that the wires do not chafe, pinch, or rub if it passes through any bulkheads.

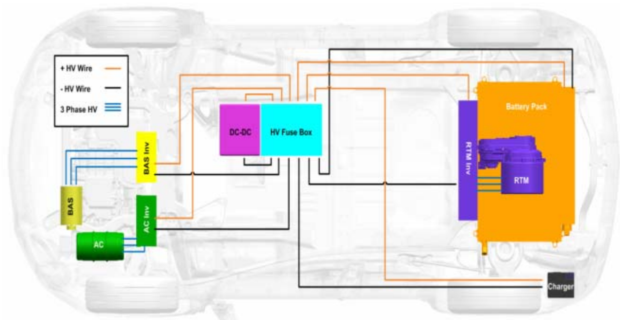

Figure 9: Vehicle Wiring Schematic

11 Hybrid Vehicle Control System

11.1 Design and Planning

The Controls Subteam designed the control system following the VT-Diagram shown in Figure 10. This process allows for a complete, well tested and highly refined control system.

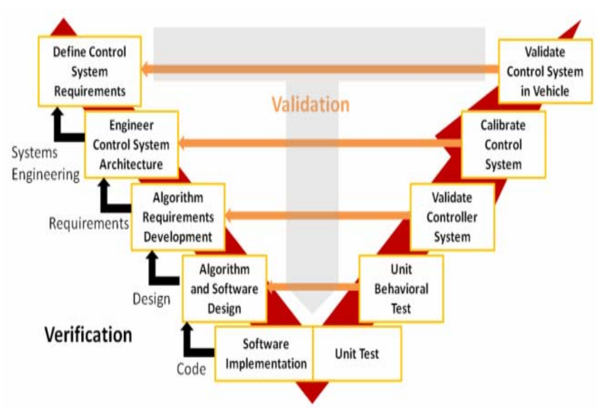

Figure 10: VT Diagram for control system design

The VT diagram begins with the definition and design of the control system architecture. It then moves to the algorithm development and design, and then to software implementation and testing in basic systems. At this point, testing is performed at different levels to ensure that the entire vehicle performs properly under the designed code. One main advantage to the VT-Diagram is the ability to fix problems found at any stage with relative ease. Because each stage is tested separately, problems are identified and corrected. This ensures that the code is optimized for HEVT's specific control system and vehicle architecture.

11.2 Modelling, Modes, and States

Choosing the Split-Parallel Architecture design gave HEVT six operating states (Table 10) to work with in control system design. From these modes, the Controls Subteam chose to create three charging modes: charge sustaining (CS), charge depleting (CD), and normal. The driver will be able to select between these modes, and normal mode will allow the control system to decide which mode is best for proper vehicle performance.

The Controls Subteam utilized PSAT to model the different modes and states of the vehicle control system. This requires performance data on the vehicle components and hybrid components that HEVT will be adding to the vehicle. This data enabled the proper selection of these hybrid components and also provided data on the fuel economy and range in the different modes.

Table 9 shows the performance predictions for the HEVT's SPA with the new prismatic battery pack. These predictions were obtained by running PSAT models for the SPA with current components. While these numbers are considered accurate models, they are predictions for the vehicle. The final data will be different due to model limitations and environmental and vehicle conditions.

Table 9: Vehicle Performance Predictions

HEVT Specifications	Prediction
Electric Only Range	47 miles
Towing speed	55 mph
Towing Grade	7.4 %
Mass additions	390 kg
IVM – 60 mph	8.9 s
Utility Factor	0.69
Fuel economy, CAFE unadjusted, combined with UF correction	100 mpgge
Fuel economy, CAFE unadjusted, combined in CS operation	33.3 mpgge
Average Engine Efficiency	33 %

The Controls Subteam is using Matlab Simulink and Stateflow to create different operating states for the vehicle. These states from the selection of the split parallel architecture design, include: Engine Only, Engine Assist, Electric Only, and Regenerative Braking. These states are written into Simulink and are called as needed by the modes. For example, in charge sustaining mode, as braking occurs during driving, the regenerative braking code would be activated and the battery would continue to be charged. Table 10 shows the states possible with HEVT's selected architecture. Each state has an explanation of the torque on the major components of the vehicle. These components are the engine, BAS, and RTM.

Table 10: Vehicle State Explanation

States	Engine Torque	BAS Torque	RTM Torque
Engine Only	+	0	0
Engine Idle Stop	0	0	0
Engine Generate	+	-	0
Engine Assist	+	0	+
Electric Only	0	0	+
Regen Braking	- / 0	- / 0	-

Utilizing the states will ensure the best performance of the vehicle. Because a normal mode has been built into the system, the vehicle will be able to select the necessary states for any given driver torque request.

11.3 NI HIL PXI Chassis and cRIO

The preliminary vehicle model, provided by GM for the year one competition, is loaded onto the controller Hardware-in-Loop (HIL) system, which is shown in Figure 11. The HIL is provided by National Instruments (NI) for the design and testing of the control system.

The NI Compact RIO (cRIO) is used to read and output Controller Area Network (CAN) signals from the vehicle HIL model. This is a vital part of the entire system, as it is the data analysis center for all commands. All of the user inputs and display outputs flow to and from the cRIO controller. NI Labview code is written and loaded on the cRIO, and this code reads and outputs information. Correct, proper functioning code is essential, and utilizing the VT-Diagram will ensure a well-functioning code, and thus an excellent display and demonstration of the hybrid vehicle supervisory (HVS) controller.

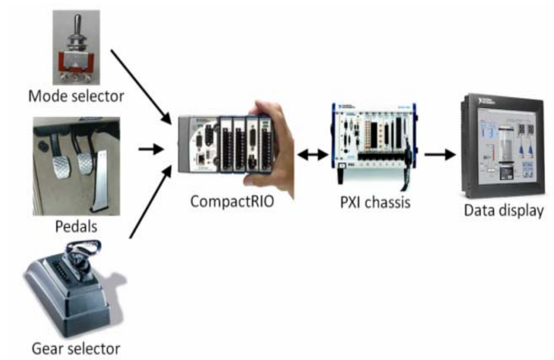

Figure 11: HIL and cRIO system

The HIL implemented with the Compact Rio(cRIO), user interfaces, and the display system, provides the basis for the entire display and demonstration at the EcoCAR year one competition.

12 Conclusions

HEVT is in the end of Year 1 of the EcoCAR competition and is nearing a final vehicle design. Following the vehicle design process as explained by GM and the EcoCAR organizers, the team has developed a plan for the organization of the vehicle. HEVT established individual team goals that meet or exceed the competition targets and requirements. After the establishment of a global VTS, modelling was performed in order to select components. The field of components that meet HEVT goals and VTS was narrowed by performance requirements, fuel selection, and component availability from suppliers and sponsors. With the components selected, HEVT has moved into the planning phase of component integration and vehicle modeling. The Controls Subteam has established a working start on a hybrid vehicle supervisory controller system that will work towards maximizing the efficiency of the vehicle while maintaining vehicle performance and expected response characteristics. HEVT is well on the way to starting actual vehicle integration in August 2009. This can be attributed to HEVT following the vehicle design process as described in this work.

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References

[1] Powertrain Systems Analysis Toolkit (PSAT), http://www.transportation.anl.gov /software/PSAT/index.html

[2] Steven Boyd, and Douglas J. Nelson (2008), "Hybrid Electric Vehicle Control Strategy Based on Power Loss Calculations”, Paper 2008-01-0084, 2008 SAE International World Congress, Detroit, Mi, April 14-17, 2008, 15 pgs.

[3] Johnson, Kurt. “A Plug in Hybrid Electric Vehicle Loss Model to Compare Well to Wheel Energy Use From Multiple Sources.” MS Thesis Virginia Polytechnic Institute and State University, 2008.

[4] Friedman, D., 2003, “A New Road: The Technology and Potential of Hybrid Electric Vehicles”, Union of Concerned Scientists, Cambridge, Mass.

[5] Husted, Harry L., 2003, “A Comparative Study of the Production Applications of Hybrid Electric Powertrains,” SAE paper 2003-01-2307.

[6] EPA, 2006, “Fuel Consumption Modeling of Conventional and Advanced Technology Vehicles in the Physical Emission Rate Estimator (PERE)”, Report 420p05001.

[7] N. Brinkman, T. Weber, M. Wang, T. Darlington,, 2005, “Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems - A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions”, available from ANL.

[8] EcoCAR Rules, Draft 10/17/2008, available from ANL.

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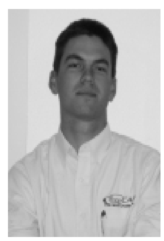

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