

Design, Development and Validation of the 2013 Penn State University E85 Series Plug-In Hybrid Vehicle

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ABSTRACT

The Pennsylvania State University Advanced Vehicle Team (PSU AVT) is one of the fifteen (15) participating teams at the EcoCAR 2 “Plugging In to the Future” challenge. The team has worked in the design, development and validation of converting a 2013 Chevrolet Malibu, into an advanced technology hybrid vehicle. The PSU AVT has determined that a Plug-In Series Electric Hybrid architecture best meets the design goals of the EcoCAR 2 competition. The vehicle will utilize a front-wheel drivetrain powered by a Magna E-drive; an Auxiliary Power Unit (APU) based on a naturally aspirated Weber MPE 750 engine, converted for use with E85, coupled to a UQM PowerPhase 75 generator; an Energy Storage System (ESS) based on six A123, 15s3p battery modules; and a Mototron ECM-5554-112-0904 controller as the Master Vehicle Controller (MVC). This paper will present the details of the proposed architecture, including the selection process and validation as well as future engineering considerations in order to implement the design into the vehicle.

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INTRODUCTION

With the aim of reducing dependence on foreign fuel supplies and diminishing environmental impact, recent research has been focused on alternative fuels, sustainable energy sources, and energy efficiency. On this basis, the Department of Energy (DOE) has launched the EcoCAR 2 “Plugging In to the Future” challenge, a three-year intercollegiate competition, to allow students from fifteen (15) North American universities to have the opportunity to gain valuable experience with the design process of increasingly popular hybrid-electric vehicles (HEVs). The first year of the competition is the conceptual design stage where teams are required to select vehicle architectures and components, run simulations, develop computer-aided design (CAD) models, and run hardware-in-the-loop (HIL) testing. The second year consists on integrating year one's design by converting the production vehicles into a 65%-buyoff level of vehicle readiness in terms of production-ready hardware/software, vehicle performance, vehicle integration, consumer appeal (known as mule vehicles). The third year is vehicle refinement of the mechanical components and control algorithm to complete the competition. In this phase the teams are tasked to reach a 99%-buyoff level of vehicle readiness. The overall goal of the EcoCAR 2 competition is to design and build vehicles to reduce greenhouse emissions,

increase efficiency, and reduce the stock vehicle's petroleum usage, while ensuring customer satisfaction.

During year one of the EcoCAR 2 competition, the PSU AVT has the task of designing an advanced technology conversion of a stock 2013 Chevrolet Malibu donated by General Motors (GM). The vehicle must meet the specifications set in the competition rules to ensure the new advanced vehicle technology retains its consumer appeal, safety, and performance while delivering superior fuel economy and emissions. After utilizing the vehicle modeling software Autonomie to simulate various potential vehicle architectures, PSU AVT determined that a series Plug-In Hybrid Electric Vehicle (PHEV) is the best architecture to be implemented on the Chevrolet Malibu.

Following continued modeling, PSU AVT created Vehicle Technical Specifications (VTS) defining the requirements to be met by the new vehicle design. The team selected and modeled the powertrain components to determine if these components adequately satisfied the VTS requirements and established goals.

The PSU AVT determined that the series PHEV architecture will operate using the following subsystems and key components:

- Drivetrain
 - Magna E-Drive

- Auxiliary Power Unit (APU)
 - Weber MPE 750
 - UQM PowerPhase 75
- Energy Storage System
 - Six A123 15s3p Modules
 - A123 Battery Control Module (BCM)
 - A123 Current Shunt Module (CSM)
 - A123 Electrical Distribution Module (EDM)
- Master Vehicle Controller
 - Motohawk ECM-5554-112-0904

The following sections detail how the design decisions made by the PSU AVT support the team goals and meet the VTS requirements set both by the PSU AVT and the EcoCAR 2 competition.

VEHICLE DEVELOPMENT PROCESS

The vehicle development process (VDP) set by the EcoCAR 2 competition was used by the PSU AVT in order to define, conceptualize, design, integrate, and validate the powertrain design of the team's vehicle in a high-quality manner. The EcoCAR 2 VDP mimics GM's Global Vehicle Development Process (GVDP). The VDP is a process that contains pre-defined activities linked in time to achieve the desired result of designing, fabricating and validating a proposed vehicle technology. Each job function in the VDP has a list of work instructions that have been developed to maximize the efficiency and working hours. These detailed work instructions are key to developing all the activities involved in such a high level project and to keep the team on track of its desired goals. The overall VDP scheme can be observed in [Appendix A](#).

PSU AVT followed the VDP, starting with evaluating potential architectures and generating VTS for these architectures. VTS are a set of requirements that define critical vehicle parameters such as fuel economy, emissions, acceleration, stopping distance, and safety requirements among others. Based on the VTS and team goals, the team selected the architecture and initiated the concept design phase. In this phase, components required for implementing the selected architecture were evaluated in terms of performance, aesthetics, and cost in order to meet the established VTS and competition goals. Modeling and testing tools are utilized in order to assess the proposed design within the Chevrolet Malibu. Once the final concept was selected, detail design of the system and subsystem components was completed. The next step consists of manufacture, integration, and optimization of the powertrain components and auxiliary systems. The final stage consists of testing and validating the developed vehicle.

PSU AVT is on schedule with mechanical design in relation to the VDP as the design of the mechanical systems

that will be integrated into the 2013 Chevy Malibu has been completed. Additionally, PSU AVT has obtained the internal combustion engine (ICE) and is in the process of procuring additional powertrain components. Future tasks include conversion of the internal combustion engine to operate with the team's selected fuel (E85) and testing.

The electrical design of the proposed vehicle is also on track. The battery pack design has been reviewed and approved by Argonne National Lab (ANL) and A123 Systems Inc. PSU AVT will begin the manufacture phase including milling of the complex cooling plate, welding of the outer aluminum shell, and installation of the battery modules and control units.

PSU AVT is slightly behind with the vehicle's control design. While the PSU AVT should be completing testing with the HIL setup, the team is currently finalizing the control algorithm, HIL model, and HIL hardware design. These projects will be completed by the end of Year 1 final competition. However, the level of testing will be behind the goals set forth for this year. In order to mitigate this for future competition years, PSU AVT will continue testing over the summer with remaining personnel. The team is confident to reach Year 1 goals in preparation for the beginning of Year 2 of competition.

POWERTRAIN CONFIGURATION

PSU AVT's main goal is to create a powertrain configuration that maximizes overall system efficiency, minimizes harmful emissions, and provides superior performance while providing a safe and reliable operating environment. The team also has numerous consumer acceptability goals in terms of powertrain integration including minimizing noise, vibration, and harshness associated with the added powertrain systems, specifically pump and engine noise. In previous competitions, the vehicle's diesel engine and battery cooling fans added a considerable vehicle noise. While the vehicle was moving, noise levels were comparable to that of a traditional vehicle, but, while stopped, the vehicle was rather noisy when the internal combustion engine was running. In order to continue seamless integration of the vehicle components, the team wishes to continue its award winning success in drive quality. The key to this is ensuring driver interfaces function the same as a traditional vehicle design. Specifically, the brake pedal and accelerator pedal must stay in the very narrow band where the pedal inputs feel comfortable and not too "hard" or too "spongy".

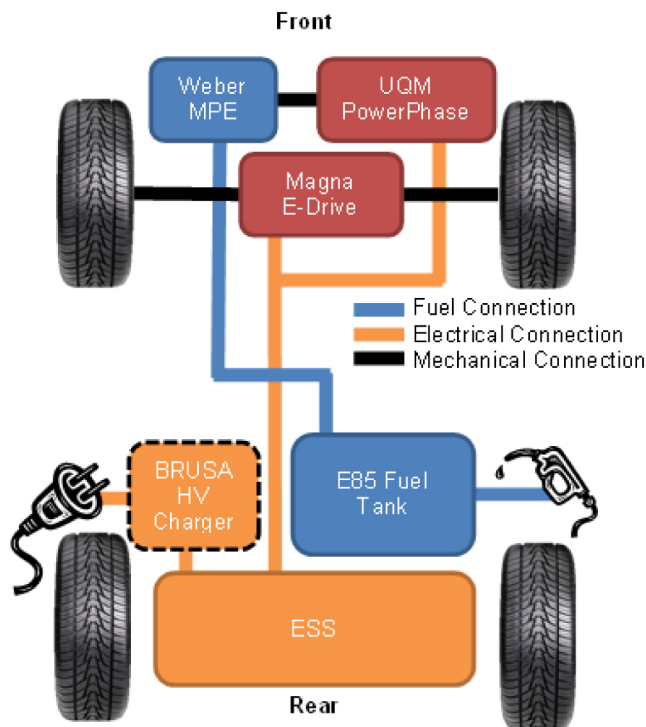
PSU AVT also has several goals for static consumer acceptability. Maximizing vehicle trunk space, while still retaining all five seats, is a major goal for consumer acceptability of the vehicle. The final goal is to integrate components such as the emergency disconnect switches, indicators, control switches, and any added displays in a manner which is visually appealing and of production grade.

Table 1. WTW Factors by kWh of Fuel

[g/kWh]	E10	E85	B20	H2	Electricity
Petroleum Energy Use	0.98	0.32	0.86	0.01	0.034
GHGs Emissions	322	260	288	392	648
THC	0.061	0.048	0.01	0.03	0.003
CO	0.012	0.005	0.009	0.014	0.033
NO_x	0.028	0.014	0.021	0.032	0.101

Taking these goals into consideration, the team thoroughly investigated and compared different potential architectures by conducting packaging studies and powertrain simulations. The selection criteria was based on vehicle modeling, packaging and integration (including components and materials compatibility, mass and size limitations), facilities and availability (fuel, components and external support), team experience, energy consumption and environmental impact (E&EC), budget, and uniqueness.

The selected architecture is a series PHEV fueled by E85. A 45 kW continuous power Magna Electric Drive powers the front-wheel drive system. The APU consists of a naturally aspirated Weber MPE 750 engine coupled to a UQM PowerPhase 75 generator. The ESS is a 17 kWh, 300 V battery pack supplied by A123 Systems. Figure 1 shows the general layout of the architecture.

**Figure 1. PSU AVT Architecture**

A series architecture allows the APU to run at its most efficient point because it does not have to follow changes in road load. Furthermore, a series architecture gives flexibility in the control strategy as the APU can be run independently of the wheels to charge the batteries while stopped or the APU can be turned on when additional power is needed for performance scenarios. The major benefits resulting from the extended range series electric vehicle architecture include the ability to travel a finite distance without using liquid fuel. The ability to move without using fuel is derived from the lithium ion battery pack that stores energy to be used at a later time. The battery pack can be charged from a 110 V or 220 V wall outlet using energy pulled from the electric grid.

There are drawbacks to the series architecture selection. One challenge is vehicle powertrain complexity. Higher system complexity translates to more possibilities for failure and added packaging challenges. Moreover, the complexity of the system requires more weight than a conventional vehicle. This increase in vehicle mass decreases overall handling, acceleration, and fuel economy performance.

Fuel selection is a critical step in the development of a hybrid vehicle. When selecting the fuel, it is important to consider multiple factors including availability of the fuel, energy content, materials compatibility, components costs, and environmental impacts. The team considered conventional gasoline (E10), E85, B20, hydrogen, and electricity and performed a Well-to-Wheels analysis (WTW) using the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model developed by ANL. GREET model 1.8d was used with assumptions and projections for a vehicle to go into production in the year of 2018. The default fuel factors provided by ANL for the competition and the different elements evaluated by the WTW analysis are shown in Table 1.

Even though all-electric vehicles and fuel cells have no tailpipe or Green House Gas (GHG) emissions at the vehicle, there are significant emissions upstream due to the production of electricity and hydrogen which is reflected in the total WTW analysis. From Table 1, it can be concluded that E85 produces the least GHGs and lowest CO emission factor of

all fuels. As expected, hydrogen and electricity significantly reduce petroleum usage.

Figure 2 shows that both spark-ignition hybrids and compression-ignition hybrids consume less petroleum than their conventional counterparts. E85 vehicles achieve the highest petroleum usage reduction of this group.

The fuel selected for the team's architecture is E85 because:

- Superior performance on reducing petroleum usage, GHGs and tailpipe emissions.
- Available infrastructure for handling and testing.
- Costs of fuel system in line with proposed budget.

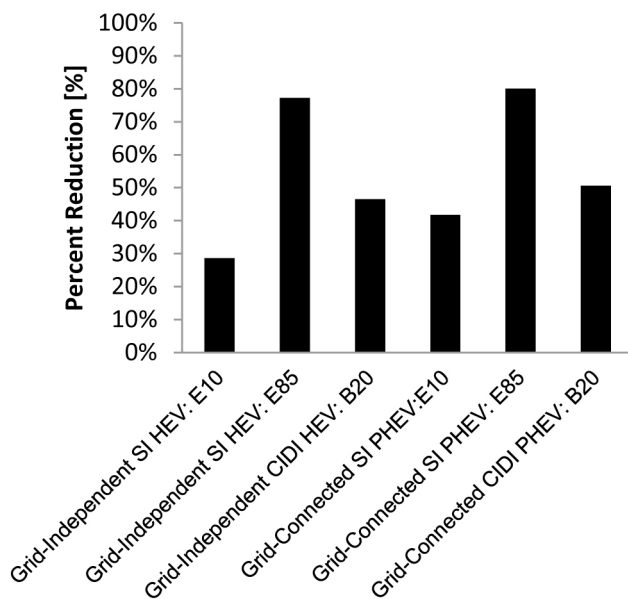


Figure 2. Petroleum Energy Use for Different Vehicle Configurations and Fuels (From GREET Analysis)

Although, the Perm State team has more experience using B20 fuel in past vehicles, there have been some complications by using this fuel in the past. The after treatment system can be expensive to obtain and implement as the use of precious metals as catalysts makes the components expensive to procure. In the event of any part failures, it also becomes expensive to repair. There were consistent reliability problems with getting urea after-treatment to effectively achieve targeted levels of NOx emissions. There were also problems with filter clogging, which impacted overall performance. The selection of E85 is also in line with the team's goal of gaining knowledge and experience working with spark ignition engines and ethanol fuel.

The selected architecture was modeled using Autonomie's four-cycle method to determine performance, fuel, and emissions specifications. A high level energy consumption calculation was performed to study the power required at steady state for the vehicle at a given speed. The calculations

were done using rolling resistance and drag force values from the stock vehicle model with adjustments for mass differences. These calculations were done using a 1000W accessory load, which is what the team experienced in previous competitions. In addition, an efficiency of 90% for the conversion of electrical energy to mechanical energy to drive the wheels was assumed.

Based on these results, the team obtained the last column of the VTS shown in Table 2. The VTS compares the specifications for the production Malibu, the competition targets, and the competition requirements to the simulation results found using Autonomie to model the vehicle. Table 2 also shows this architecture meets all competition targets and requirements.

Based on the VTS, the team proceeded to select powertrain and auxiliary system components. PSU AVT selected the Magna E-Drive as the Propulsion Unit. The system is a 103 kW peak, 45 kW continuous electric motor with operating voltage between 250 to 403 VDC and current rated at 400 A peak, 222 A continuous. The combined weight of the motor, gearbox, and inverter-controller is 95.4 kg.

The Magna E-Drive is an advantageous piece of hardware for numerous reasons. The Magna E-Drive is easy to package due to the small envelope. The E-Drive's continuous power capability, weight, and overall efficiency are very close to those specifications determined during conceptual design. A final advantage of the Magna E-Drive system is the fact that it is Controller Area Network (CAN) controllable, making controlling this unit with the vehicle's built-in CAN seamless. The Magna E-Drive's key drawback is low top end power. In performance events such as the 0-60 mph, the Magna may lag behind other alternatives.

The Weber MPE 750 is the selected internal combustion engine. The Weber MPE 750 is an Environmental Protection Agency (EPA) certified, naturally aspirated, gasoline engine made by Weber Motor based in Markdorf, Germany. The Weber MPE 750 produces 52.5 kW of power at 8000 RPM and a maximum torque of 70 Nm at 7000 rpm. The engine weighs 52 kg and utilizes an 11.5:1 compression ratio.

Utilizing the Weber MPE 750 engine as the base for the APU provides many benefits. The engine has a small profile which makes packaging easier, a main concern in these types of competitions. At only 750 cc, the Weber MPE 750 is ideal for the Malibu packaging constraints and allows PSU AVT to integrate both the APU and Propulsion Unit into the engine bay.

Results in Autonomie show maximum power output required from the Weber engine to maintain a constant State of Charge (SOC) in the battery pack is 38 kW compared to the engine's maximum capability of 56 kW. Autonomie also provided raw energy consumption rates which were then factored in to determine VTS fuel consumption rates.

Mechanical and control modifications are necessary to convert the Weber MPE 750 from E10 to E85. Because the ECU for the production Weber MPE 750 is designed for use with conventional gasoline, a new ECU and engine map will

Table 2. Vehicle Technical Specifications (VTS)

Specification	Production Malibu	Competition Target [Requirement]	PSU Projection
Mass of Vehicle (kg)	1589.6	<2250[<2250]	1882
Acceleration 0-60 mph	8.2	9.5[11.5]	9.4
Acceleration 50-70 (Passing)	8.0	8[10]	5.2
Vehicle Range (mi)	457	200[200]	>200
Charge-Depleting Range (mi)	N/A	**	50
Charge-Depleting Fuel Consumption (Wh/km)	N/A	**	0.00
Charge-Sustaining Fuel Consumption (Wh/km)	N/A	**	658.88
UF-Weighted Fuel Energy Consumption (Wh/km)	787	634	202.09
UF-Weighted AC Electric Energy Consumption (Wh/km)	N/A	**	189.55
UF-Weighted Total Energy Consumption (Wh/km)	787	634	391.64
UF-Weighted WTW Petroleum Energy Use (Wh PE/km)	774	624	70.60
UF-Weighted WTW GHG Emissions (g GHG/km)	253	204	165.64

have to be created in order to optimize the engine for operating with E85. The team plans on changing the camshaft from the stock recreational camshaft to Weber's automotive camshaft to decrease the speed of the engine along with providing lower emissions.

The next set of mechanical changes will be determined by the materials compatibility study of the Weber's stock components and E85. Though it has been confirmed by Weber that this model of engine has been successfully converted to E85 in the past, the team still must confirm that any components which will come in contact with the E85 will be compatible due to the fact that there are two key problems associated with using E85 as opposed to gasoline. First, many materials degrade in the presence of alcohol and second that alcohol is more conductive than gasoline and will promote galvanic corrosion [1]. Key materials which should be identified in the engine include brass, zinc, lead, and aluminum. Plastics and rubber components also are degraded by ethanol as well. Because of this, an ethanol-resistant elastomer such as Viton® will need to be utilized to replace these components [2].

The final mechanical change planned is an increase in fuel injector size to allow for a higher fuel flow rate. On average, 30% more fuel is required when using E85 compared to conventional gasoline since the stoichiometric air to fuel

ratios for gasoline and E85 are 14.54 and 9.765 respectively [3]. By appropriately adjusting fuel injector size, the pulse width duration of the injectors will not be significantly changed from the stock duration time but more fuel will be injected per injection pulse, therefore allowing the ECU to adaptively learn the air to fuel ratio for E85 [4].

One mechanical conversion not being pursued for the Weber MPE 750 is the modification of the engine's compression ratio to better utilize anti-knock characteristics of E85. In the selected engine, this change is not necessary because the stock compression ratio of 11.5:1 requires a fuel with 95 octane rating be utilized. E85 has an octane rating range of 94-96, and therefore is very well matched to the stock compression ratio [5].

An interceptor which modifies messages between the engine ECU and the engine will be used to adapt the control strategy. This is a device that can be bought and wired between the Weber's stock ECU and the engine itself. The module is able to fine tune the control of injectors, timing, and air to fuel ratio to the desired needs.

The Weber engine has a maximum power of 56 kW, which is more than sufficient to meet vehicle needs, because the maximum continuous power of the Magna E-drive is 45 kW. Therefore, in charge sustaining mode, the engine could continuously supply enough power to run the electric motor

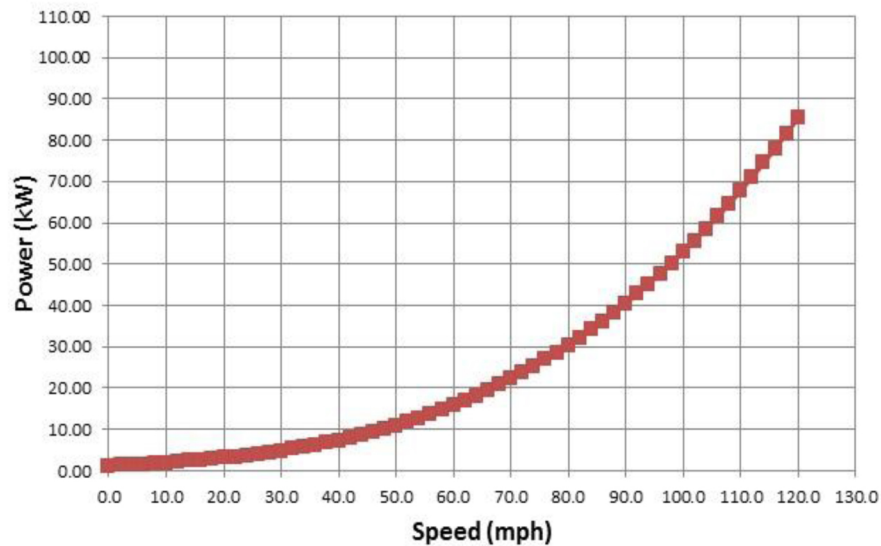


Figure 3. Required Power for PSU AVT Architecture

and still charge the battery pack. Figure 3 shows the curve for the required power to drive the vehicle as speed varies. The Magna E-drive's 45 kW continuous output means the vehicle can drive continuously at up to 95 mph on a straight and level course.

PSU AVT has selected the UQM PowerPhase 75 as the generator to couple to the Weber MPE 750 engine and complete the APU. The PowerPhase 75 is produce by UQM Technologies and is a 75 kW peak, 41 kW continuous 3-phase brushless permanent magnet electric motor. The operating voltage input range is 250 to 400 VDC, and the input current limit is 400 A. The combined motor and inverter/controller weight is 56.9 kg. UQM's inverter is a microprocessor-controlled inverter with sine wave drive. Peak torque for the motor/generator is 240 Nm.

There are many advantages to using the UQM PowerPhase 75 generator. The PowerPhase 75 is CAN controllable, making it easy to interface to the CAN network already in the vehicle. UQM products are also very robust, which is vital in an environment where problems can and do occur. Another important advantage is that PSU AVT has good experience with the device from previous competitions. A final advantage is that the continuous power output by the UQM matches the continuous power requirement for the Magna E-drive. By matching the power output of the APU with the maximum continuous required power of the Magna E-drive, the overall powertrain design is optimized such that the required power is available without oversizing certain components and making packaging difficult. The PowerPhase 75 generator's disadvantages include a heavy and bulky Power Inverter Module and rather expensive cost.

PSU AVT will utilize an A123 Systems donated battery pack. The A123 battery pack will consist of six battery modules, battery control module, manual service disconnect, electrical distribution module, control sense module, and the

hardware needed for integrating the components together. Hardware includes high voltage and low voltage wires and connectors used to close the connections between each component.

One of the issues that plagued previous competition vehicles was the inability of the battery pack to supply high current long enough to complete hard acceleration tests. The 17 kWh battery pack supplies nominally 300 V and a maximum of 600 A to the vehicle's high voltage system. This current will allow for more time during hard acceleration on the Magna E-drive since the maximum current the E-drive can draw is 400 A.

Since these components' performance meet competition required VTS, PSU AVT determined that the components were adequate for the powertrain in the Malibu. The Weber MPE 750 NA engine aids in the VTS since the mass of the engine is significantly less than the stock engine. By using the lighter-weight Weber in the APU, weight is saved and can be allocated more to the battery pack and still maintain weight below VTS goals. The addition of this larger battery pack allows the Malibu to run a further distance in charge-depleting mode, thereby increasing overall system efficiency and reducing harmful emissions.

The fuel tank is designed to provide the required fuel volume to move the Malibu greater than the competition requirement of 200 miles. The fuel consumption rate will vary based upon the control algorithm and can increase or decrease the range based upon where the engine is required to run.

Several tradeoffs were made when determining the architecture for the Malibu. The first tradeoff was the impact of engine selection. The team debated the tradeoffs between the Weber engine and a donated GM engine. The Weber engine is a louder engine and produces more NVH, while its weight makes it highly attractive. By choosing the smaller

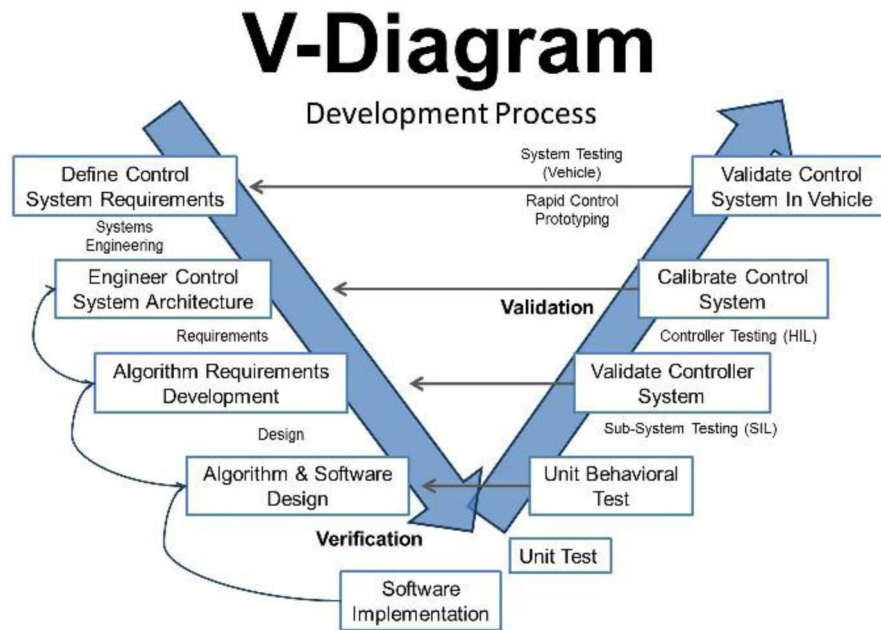


Figure 4. V-Diagram

engine and limiting vehicle weight, a tradeoff was made to focus on vehicle specifications that benefit from a lighter weight vehicle including fuel economy, emissions, acceleration, and handling. The consequence of this decision is that the vehicle may have reduced performance in consumer acceptability due to the louder engine. The team also decided to use the Weber engine to minimize packaging conflicts in the engine bay. While detailed CAD for all engine bay components was not available in the conceptual design phase, conceptual components models were created to give the design team a “rough order of magnitude” idea of packaging constraints. Additionally, past experience with similar architectures dictated packaging all required components in the engine bay would be a challenging endeavor. By choosing the small engine, these interferences would be reduced.

Another tradeoff was to use E85 compared to E10. This tradeoff produces less power and requires additional resources to implement and calibrate a new engine control strategy. However, based on preliminary analysis and modeling using Autonomie, this fuel choice will improve fuel economy and emissions and significantly reduce petroleum use. These are some of the key competition criteria and directly affect performance in some of the highest point competition events.

Externally, no changes were made to the Malibu. By maintaining the stock vehicle appearance and functionality, no aesthetics of the exterior are compromised. Consumer acceptability should be relatively high as vehicle acceleration and handling are relatively unchanged.

CONTROL DEVELOPMENT PROCESS

The PSU AVT has implemented a control development process following the V-diagram (Figure 4) to design and implement a control algorithm for the Chevrolet Malibu. The PSU AVT's control development process, similar to the V-diagram, can be broken up into two sections: verification and validation.

Verification

The development process begins by defining the control system requirements, which are derived from the Vehicle Technical Specifications (VTS). This is followed by defining the control system architecture. This includes defining which controllers that will be used, as well as the communication protocols to be used. A controller hierarchy is also created to define which controllers are supervisory, which controllers will interact with the stock GM systems, and which controllers will interact directly with specific components.

Following the definition of the physical control system, a set of control algorithm requirements is created. This includes how the algorithm will be structured, what functions it will provide, how tight tolerances must be, and what programming language and software will be used.

The next phase in development marks the start of code design. In this phase each section of code is created using block diagrams and a high level of abstraction. This focuses on the high level interactions of functions and the algorithm with other controllers, creating a fixed set of inputs and outputs to be used during function creation. The control strategy that each function will utilized should also be determined here.

The final stage of verification is the implementation of all control code in software. This stage does not include the testing of code to ensure its validity, only the creation of the code to be tested.

Validation

With the completion of the software implementation, the validation stage of development begins, the first stage being unit testing. Unit testing involves the testing of the most basic functions of the control algorithm. This validates the each function with the requirements set forth in the verification stage.

Following the testing of basic functional units, larger systems are tested in unit behavioral tests; these tests verify the functionality of subsystems, such as the vehicle propulsion control. This ensures that each functional unit, tested previously, behaves as intended in the larger subsystem.

The validation of all subsystems is followed by the validation of the control algorithm as a whole. This stage contains both a Software-in-the-Loop (SIL) testing phase and a HIL testing phase.

Upon completion of all HIL testing, the control algorithm is deemed to be at a safe and functional state for in vehicle calibration to begin. The PSU AVT's controllers are now integrated into the vehicle for final calibration. After calibration is complete the controllers are placed into a final validation state where the vehicle is deemed safe and ready for final vehicle release.

Development Tools

The PSU AVT utilizes the following tools for the creation of control algorithm code, SIL testing, and HIL testing: MATLAB, Simulink, Stateflow, dSPACE Mid-Size HIL test rack, Mototron controllers, dSPACE ControlDesk, GCC PowerPC compiler, and the Freescale CodeWarrior compiler.

SIL Testing

For SIL testing the PSU AVT utilizes Simulink's ability to run simulations. This allows code to be verified for correct functionality quickly and effectively before a physical implementation of the code. The form of the testing is left to the designer, but is often accomplished by stimulating a functional unit with a set number of inputs, and then analysis of the functional unit's outputs.

HIL Testing

During HIL testing the PSU AVT utilizes a custom created HIL model and hardware to test the control algorithm. The setup includes a dSPACE Mid-Size HIL test rack, a custom designed harness meant to simulate the vehicle harness, and hardware to simulate driver I/O. This allows for HIL testing to be versatile. For example, the PSU AVT can utilize the driver I/O hardware to preform specific tasks for

rapid prototyping of code, or ignore the hardware and run a drive cycle to test the fidelity of the whole algorithm at once.

The PSU AVT's hope is that by simulating the proposed vehicle harness, the supervisory controller will be able to move directly from the HIL test bench into the vehicle for calibration. This will allow for testing and refinement of the control algorithm while the physical integration of components in the vehicle is still in progress.

Unique Features

The PSU AVT has several unique features in its development process. First, the PSU AVT has allowed for rapid prototyping testing in both SIL and HIL testing. For example it may be easier and more effective to test a piece of code dealing with the accelerator pedal detection using the HIL environment to confirm its functionality than in a SIL test. Therefore the PSU AVT allows its control engineers to utilize the HIL for simple, unrecorded tests as well as validation tests. This often allows for code testing to be completed quicker than if SIL testing were only allowed.

A second unique feature of the PSU AVT's development process is HIL model development itself. Because the HIL model is completely custom, the controls team is able to add as much fidelity to the models as is needed to complete a task. For example, the controls team may need to read brake position from a certain CAN message on the GM High Speed CAN network. Instead of taking time to create a very detailed model to simulate all CAN signals in that message, the PSU AVT is able to simulate the single CAN signal needed, and simply null the remaining signals. This saves times, but retains the ability to test the control algorithm in the full fidelity necessary.

CONTROL SYSTEM ARCHITECTURE

The PSU AVT will be utilizing a Mototron ECM-5554-112-0904 for the centralized Master Vehicle Controller (MVC) to control the new powertrain and auxiliary systems implemented into the modified 2013 Chevrolet Malibu. The MVC will also provide safety and diagnostic functionality. In addition to the MVC, there will be the following controllers: A123 Battery Control Module (BCM), BRUSA TBD High Voltage Charger, Chevrolet Volt Auxiliary Power Module (APM), Freescale Infotainment System, Vehicle Instrument Panel, Magna E-Drive Inverter, UQM PowerPhase 75 Inverter, Chevrolet Volt High Voltage Air Compressor (HV AC), Chevrolet Volt Water Pump, and Weber MPE 750 Engine Control Unit (ECU). The function of each controller is listed in [Appendix B](#).

Control Structure

The MVC will function as the supervisory controller and location of the PSU control algorithm. All other controllers on the PSU CAN bus are slaved to the MVC and will receive commands and provide feedback from the MVC. As

Table 3. Analog and Digital Signaling

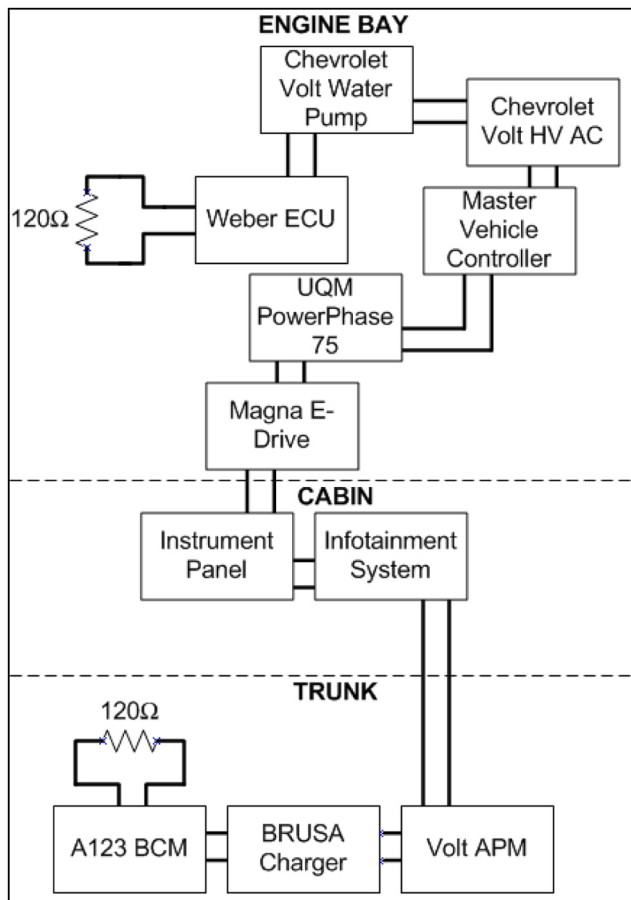
Signal Type	Signals
Analog	• Weber Throttle Position Sensors
Digital	• Magna Enable Lines • ESS Cooling Fan Control Lines • Relayed Power Control Lines • Shifter Position Sensor

a result of this structure, all PSU AVT safety functions must be implemented on the MVC.

Communication Structure

Physical CAN Bus Organization

The PSU AVT's controller network will be based upon the CAN2.0b standard. This CAN bus will operate at 500 kbps and be named "PSU CAN". Each node on the bus will be added in a series fashion to create a "daisy-chain" of controllers as per the CAN2.0b standard's requirement. At each end of the network will be a 120 Ohm resistance provided by either the final controller on the chain or a standard resistor to fulfill the CAN2.0b standard requirement.

**Figure 5. PSU CAN Topology**

The PSU AVT's CAN structure will contain the controllers listed in [Appendix B](#), located approximately as shown in [Figure 5](#) (note daisy chain structure and twisted pair are not shown).

In addition to the PSU CAN bus, General Motors high speed and low speed CAN buses will also be utilized. The MVC will act as the gateway module between the PSU CAN network and the GM CAN networks. In this way stock controllers and hardware can be utilized to monitor vehicle systems, as well allowing the MVC provide "ghost" messages to replace those which have been removed due to stock component removal.

CAN Message Organization

The PSU CAN bus message origination will be driven by the new components added to the bus. The A123 BCM, BRUSA Charger, Magna E-Drive, UQM PowerPhase 75, Chevrolet HV AC, Chevrolet Volt Water Pump, and Weber MPE 750 ECU all have predefined CAN messages which the PSU AVT will utilize to control each component. Therefore the organization of these CAN messages is already defined. The PSU AVT has confirmed the CAN Messages from each controller have unique CAN message ID's and therefore can all be present on a single bus.

For new messages which must be defined by the PSU AVT, each CAN message will be assigned based on the priority of the message. CAN Messages associated with safety-critical items will be given higher priority and therefore a lower CAN ID in order to take advantage of the priority messaging built into the CAN2.0b standard. From current estimations most custom messages by the PSU AVT will be supplemental diagnostic messages and low priority. Therefore the PSU CAN bus will be able to function with reserve bandwidth to ensure uninterrupted control of safety critical systems.

Analog and Digital Signaling

Due to the widespread adoption of CAN, the analog and digital signaling requirements of the new drivetrain are significantly reduced and are summarized in [Table 3](#). All analog and digital signaling will be routed to the MVC.