

# Vehicle System Design Process for a Series-Parallel Plug-in Hybrid Electric Vehicle

P. Christopher Manning, Eli White, R. Jesse Alley, Jonathan King and Douglas J. Nelson  
Virginia Tech.

## ABSTRACT

The Hybrid Electric Vehicle Team of Virginia Tech is one of 15 schools across the United States and Canada currently competing in EcoCAR 2: Plugging In to the Future. EcoCAR 2 is a three year competition that mimics GM's Vehicle Development Process (VDP): design, build, then refine. The first step in the design process is the selection of a powertrain architecture. In the architecture selection process, HEVT considered three options: a Battery Electric Vehicle (BEV), a Series Plug-in Hybrid Electric Vehicle (PHEV), and a Series-Parallel PHEV. The team chose the Series-Parallel PHEV based on powertrain modeling and simulation and CAD packaging analysis. Next, the team looked at a variety of component combinations and selected the one that offered the best capacity to meet competition and team goals. These components are then packaged in the CAD model to plan for component integration. As this integration was happening, a control system was also being developed. A Hybrid Vehicle Supervisory Controller (HVSC) will be added to the vehicle along with the other hybrid components. This controller handles high level tasks and communicates with production component control modules to effectively, efficiently, and safely control the vehicle. The algorithm implemented on the HVSC simultaneously compares all possible powertrain operating and selects the most efficient mode of operation. In addition to component packaging and control system development, one more task completed during year 1 is the design of the Energy Storage System (ESS). This system houses the High Voltage (HV) battery pack and is responsible for distribution of HV power to electric components in the vehicle. This work includes thermal modeling and analysis of the battery pack and any wiring needed for power as well as structural analysis of the enclosure. Overall, HEVT has nearly completed design of a Series-Parallel PHEV that meets or exceeds all of the EcoCAR 2 competition requirements. Years 2 and 3 will be spent integrating this design into a working prototype.

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## INTRODUCTION

The various economic and environmental implications of petroleum energy usage and emissions strongly support the need for continued development and advancement of hybrid electric vehicles. Greenhouse gasses are linked to global climate change and criteria emissions are known to harm air quality, especially in urban areas. The use of fossil fuels, such as coal and petroleum, also contributes to these problems and are unsustainable in the long term. In particular, petroleum energy use also carries serious economic, balance of trade and national security concerns.

Greenhouse gas emissions resulting from the transportation sector in the U.S. account for 27% of the nation's total Greenhouse Gas (GHG) emissions. The US transportation sector also accounts for 30% of global transportation sector GHG emissions [1]. By 2035, if current energy policies are not changed and no new renewable

energy sources garner success, U.S. transportation GHG emissions could increase by about 10% and oil could reach \$200 per barrel [1]. As of April 2011, the price of oil is about \$100 per barrel. The Obama administration seeks to reduce oil imports by one third before 2025, deploy one million electric vehicles on the road before 2015, and reduce GHG emissions by 17% before 2020 and 83% before 2050 [2].

Light-duty vehicles account for more than half of U.S. transportation energy use and CO2 emissions [1]. Thus, it is clear that improvements in Well-to-Wheel (WTW) petroleum energy usage, WTW GHG and criteria emissions, and overall energy efficiency in the U.S. light duty vehicle segment will make a big impact on the U.S. in many ways. These improvements will reduce criteria emissions, improving air quality at the local and regional levels and reduce GHG emissions which are a global contributor to climate change.

Additionally, reducing petroleum energy consumption will ease national security and balance of trade concerns.

EcoCAR 2: Plugging In to the Future [3] is a three year Advanced Vehicle Technology Competition series organized by Argonne National Lab (ANL), and sponsored by General Motors and the U.S. Department of Energy. In EcoCAR 2, 15 university teams from across the U.S. and Canada are challenged to design and build a powertrain for a 2013 Chevy Malibu that will reduce petroleum energy use and well-to-wheel greenhouse gas and criteria emissions, while maintaining safety, performance, and consumer appeal.

The Hybrid Electric Vehicle Team of Virginia Tech (HEVT) [4] is participating in EcoCAR 2. The competition follows the EcoCAR 2 Vehicle Development Process (VDP) which is: design in year one, build in year two, and then refine in year three. This paper will discuss the design work performed in year 1, including the powertrain architecture and component selection process, component packaging, control system development and Energy Storage System (ESS) design.

## ECOCAR 2 VEHICLE DEVELOPMENT PROCESS

HEVT is following the EcoCAR 2 VDP to complete the redesign of the 2013 Chevrolet Malibu. The end result of this process is a 99% production ready hybrid vehicle with full performance capabilities. To model the EcoCAR 2 VDP, the three years of the competition represent three distinct divisions of the process.

### Year 1

During this first year of the EcoCAR 2 competition, teams are tasked with creating an overall design for a hybrid vehicle. This design includes tasks such as selecting competition fuels and powertrain architecture, developing component integration schemes, and developing safety-critical vehicle supervisory control code among other important and detailed tasks. The competition has established minimum and target specifications for the design process. In addition, HEVT has established additional team goals based on a target environmental-minded customer base. These different goals and customer requirements are reflected in the vehicle technical specifications table shown in [Tables 1](#) and [2](#).

**Table 1. HEVT team goals**

| Goal                         | Description                                          |
|------------------------------|------------------------------------------------------|
| Petroleum Energy Consumption | Reduce petroleum consumption by > 80 %               |
| All-Electric Range           | > 56 km (35 mi) range as a pure all-electric vehicle |
| Passenger Capacity           | Retain stock 5 passenger capacity                    |

**Table 2. EcoCAR 2 Competition Design Targets and Requirements**

| Specification                 | Competition Design Target | Competition Requirement |
|-------------------------------|---------------------------|-------------------------|
| Acceleration 0–60 mph         | 9.5 sec                   | 11.5 sec                |
| Acceleration 50–70 mph        | 8.0 sec                   | 10.0 sec                |
| Braking 60–0 mph              | 143 ft (43.7 m)           | 180 ft (54.8 m)         |
| Highway Gradeability @ 20 min | 3.5% @ 60 mph             | 3.5% @ 60 mph           |
| Cargo Capacity                | 16. ft <sup>3</sup>       | 7. ft <sup>3</sup>      |
| Passenger Capacity            | >= 4                      | 2                       |
| Mass                          | < 2260 kg                 | < 2260 kg               |
| Starting Time                 | < 2 sec                   | < 15 sec                |
| Ground Clearance              | 155 mm                    | > 127 mm                |
| Vehicle Range                 | 322 km (200 mi)           | 322 km (200 mi)         |

With these goals in mind, the vehicle must be designed to have a total range of 200 miles and a maximum curb weight of 2078 kg. The stock vehicle has a Gross Vehicle Weight Rating (GVWR) of 2260 kg. To accommodate two passengers at 91 kg for the E&EC event, the vehicle curb weight therefore cannot exceed 2078 kg. There are also considerations for passenger space and cargo capacity. Stiff penalties are imposed for reducing the passenger capacity by removing seats or for reducing cargo capacity by raising the floor of the trunk. These penalties are considered when evaluating packaging schemes for powertrain architectures. In addition to certain rigid constraints, there are also various scored categories in the competition including: acceleration, braking, lateral handling, drive quality, and emissions and energy consumption. Therefore performance and handling must be balanced against vehicle emissions and energy consumption. There are minimum thresholds and target values for several of these metrics set forth by competition rules; [Table 2](#) summarizes these targets and minimums.

In addition to these EcoCAR 2 targets and requirements, HEVT has also established its own unique team goals. Reducing petroleum energy use is directly tied to fuel consumption and fuel consumption is often a trade-off with tailpipe emissions. Because of this trade-off, simultaneously reducing both tailpipe emissions and fuel consumption (and by extension petroleum energy use) can be difficult. GHGs are directly linked to fuel use, but criteria emissions are a complex phenomenon. A high level of technical prowess is required to develop systems, such as three-way catalysts, that effectively reduce criteria emissions. Contrastingly, fuel

consumption can be reduced much more directly. Additionally, lower fuel consumption means fewer GHGs. Thus, the team has chosen to focus specifically on reducing the fuel use of the vehicle and set a goal to reduce petroleum energy consumption by 80%.

Consumer acceptability is represented in a significant portion of competition points, so the team purposefully includes consumer features as a team goal. One such consumer feature is a pure Electric Vehicle (EV) mode, where the vehicle has near full performance as an EV. A fully capable EV mode is a consumer pleaser and makes the vehicle fun to drive with smooth continuous torque. The presence of a fully capable EV mode coupled with a significant EV range also greatly displaces well-to-wheels (WTW) petroleum energy and marginally reduces WTW GHG and criteria emissions. For these reasons, the team established to goal of having an EV range of >35 miles. Additionally, the team set the goal to retain the 5 passenger capacity of the stock vehicle. [Table 1](#) summarizes the additional design goals set forth by the team.

The Vehicle Technical Specifications (VTS) for the vehicle were established using these team goals and the EcoCAR 2 competition goals as a guide. The full VTS can be found in [Table A-1](#) in [Appendix A](#). Targets for acceleration were set at 8 seconds for 0-60 mph and 7.7 seconds for 50-70 mph (compared to 8.2 and 8.0 seconds for the stock Malibu). These VTS values were established to push the vehicle to be better than the production vehicle without sacrificing efficiency for performance. Likewise, the criteria emissions target was set at Tier 2 Bin 4, which is one bin better than the stock vehicle. Other values were also kept close or identical to the stock vehicle, such as 60-0 mph braking distance, passenger capacity, ground clearance and cargo capacity. The EV range target was set at 35 miles based upon the team goals previously mentioned. CD energy consumption, CS fuel consumption and the corresponding Utility Factor (UF) weighted and WTW energy consumption targets were set based upon initial powertrain modeling and prior experience with EVs and PHEVs.

## Year 2

After completing a design for a hybrid vehicle powertrain architecture during Year 1, EcoCAR 2 teams will then complete the build phase of the VDP. This phase includes physically integrating the designs laid out during Year 1 and implementing the hybrid vehicle supervisory control code which is tested using a Hardware-In-The-Loop (HIL) system. The end result of year 2 is a 65% complete prototype mule vehicle with full performance capabilities and complete safety features. Although the designs have already been completed, certain changes may be necessary during Year 2. One example of this is waivers. Since structural modifications will be necessary, HEVT must prove that any structural component modified will be twice as strong as the original component. This is accomplished using Finite Element Analysis (FEA).

## Year 3

To finish up the competition, HEVT and the other EcoCAR 2 teams will complete the refinement stage of the VDP. The third year consists of analyzing the mule vehicle created during Year 2 and trimming down the design of the vehicle to be more efficient and effective for completing team goals with a special emphasis on consumer acceptability. Some of the refinement items include lightweighting, optimizing performance both physically and from a controls standpoint, working on aesthetic appeal, as well as other more detailed tasks. This year is primarily for refining the mule vehicle into a sleek, saleable car.

## Implementation

To date, HEVT is currently working on Year 1 of the EcoCAR 2 VDP. Throughout this year, competition fuels have been selected as well as a powertrain architecture which reflects the goals laid out by EcoCAR 2 and HEVT. The powertrain architecture was selected based on a design process comparing a Battery Electric Vehicle (BEV), a Series PHEV, and a Series-Parallel PHEV. These three powertrain configurations were weighed against the goals mentioned previously and the Series-Parallel PHEV was found to most effectively meet the criteria. After this decision was made, components were chosen to meet the needs of the design and packaged within the vehicle CAD model, and hybrid supervisory control code has been completed and tested for actual implementation. As a result of this work, HEVT is on track with the EcoCAR 2 VDP and will have a completed hybrid vehicle design ready to be implemented during Year 2 of the competition.

## POWERTRAIN CONFIGURATION AND SIZING

After developing a VTS based on competition requirements as well as team goals, HEVT moved on to fuel selection and powertrain architecture selection. Past team experience was used as a guide to evaluate the various tradeoffs in this process.

## Fuel Selection

To meet the desired goals, HEVT first selected two competition fuels from a list of five, which includes E10 (10% ethanol, corn based), E85 (85% ethanol), B20 (biodiesel), hydrogen, and grid electricity. The upstream factors for these fuels are calculated using Argonne National Laboratory's Greenhouse Gas, Regulated Emissions and Energy Use in Transportation (GREET) model combined with the Canadian model, GHGenius. Calculations for grid electricity use a blend of 87% U.S. and 13% Canadian generation. The values used in this paper are taken from the EcoCAR 2 rules [3]. [Table 3](#) lists the WTW GHG factors associated with each fuel. Grid electricity has by far the worst WTW GHG factor on an energy basis because of the amount

of electricity derived from coal in the US. However, EVs are substantially more efficient at the vehicle level and can still offer a marginal WTW GHG reduction compared to a conventional vehicle which makes grid electricity an attractive fuel. The best fuel for WTW GHG factor is E85. While E85 is marginally better than B20, this difference would be negated by a slightly more efficient diesel powertrain. For the 2018 timeframe, the GREET calculations for E85 are still based on corn-derived ethanol. As cellulosic E85 becomes available, the WTW GHG reduction advantages of E85 will increase.

**Table 3. Approximate WTW GHG Factors for EcoCAR 2 Fuels. Scaled by color: red is worst, green is best.**

| Fuel        | GHG <sub>WTW</sub> (g/kWh) |
|-------------|----------------------------|
| E10         | 322                        |
| E85         | 261                        |
| B20         | 288                        |
| Hydrogen    | 392                        |
| Electricity | 648                        |

Another factor to consider is criteria emissions. Typically, criteria emissions are perceived as tailpipe emissions, but they also occur upstream in the fuel refinement process. Eliminating tailpipe emissions displaces these criteria emissions to the upstream processes and can improve urban air quality. However, many refineries and electric power plants operate in or near urban areas, so displacing criteria emissions to the upstream processes may not always result in air quality improvements. Table 4 lists the upstream or well-to-pump (WTP) criteria emissions factors for each competition fuel. Like its WTW GHG factor, grid electricity has substantially higher WTP CO and NO<sub>x</sub> factors than the other fuels due to the high amount of coal used to generate electricity in the U.S. Again, these higher upstream factors will be balanced by the substantial efficiency improvement of an EV from a pump-to-wheels (PTW) standpoint which makes grid electricity an attractive energy source. Both E85 and B20 offer improvements over E10 in upstream criteria emissions factors. Other PTW factors for criteria emissions are considered later during the selection process. These considerations will include the capabilities of available facilities and resources since B20 requires the development of an exhaust after treatment system, while E85 can be integrated into the stock vehicle with minor changes.

The last factor to consider is the WTW petroleum energy content of the fuel. This factor includes the petroleum energy that is consumed to produce or refine the fuel as well as the petroleum content of the fuel itself. Table 5 lists the upstream, downstream and total WTW Petroleum Energy Use (PEU) factors for each competition fuel. Note that the WTW values should be used to compare fuels. Grid electricity has a near-zero PE content and offers an incredible PEU reduction compared to E10. E85 has a WTW PE content of about 32% which is not zero, but is still a substantial improvement over a conventional vehicle using E10. Comparatively, B20 has a

WTW PE content of about 86%, which is only a marginal improvement over E10.

**Table 4. Upstream Criteria Emission Factors for EcoCAR 2 Fuels. Scaled by color: red is worst, green is best.**

| Fuel        | THC (g/kWh) | CO (g/kWh) | NO <sub>x</sub> (g/kWh) |
|-------------|-------------|------------|-------------------------|
| E10         | 0.0612      | 0.0119     | 0.0279                  |
| E85         | 0.0475      | 0.005      | 0.0141                  |
| B20         | 0.0101      | 0.0091     | 0.0214                  |
| Hydrogen    | 0.0025      | 0.0142     | 0.0324                  |
| Electricity | 0.0031      | 0.0326     | 0.1012                  |

Taking into account WTW GHG emissions, WTW criteria emissions and WTW petroleum energy content, grid electricity presents itself as an excellent energy source to meet the HEVT goals. It offers substantial reductions in petroleum energy use along with marginal improvements in WTW GHG and criteria emissions. An EV is also a very efficient and fun to drive vehicle, minimizing vehicle energy use and pleasing the consumer. The drawback with using electricity as a “fuel” is range. The relatively low energy density and specific energy of current battery technologies makes achieving a large vehicle range difficult. With this in mind, it makes sense to use multiple energy sources in the vehicle to achieve the range requirements of the competition. E85 offers a distinct advantage in PEU reduction compared to B20 but is comparable in WTW GHG and criteria emissions. B20 offers the potential for a more efficient diesel powertrain, but comes with the additional complexity of designing an exhaust after-treatment system. Hydrogen is great fuel in light of the considered WTW factors, but comes with substantial energy storage integration and fueling infrastructure challenges. Because of these challenges, a hydrogen powered vehicle was not considered further in the design process.

**Table 5. Petroleum Energy Use (PEU) factors. Scaled by color: red is worst, green is best.**

| Fuel        | Upstream PE content (kWh PE /kWh) | Downstream PE content (kWh PE /kWh) | WTW PEU (kWh PE /kWh) |
|-------------|-----------------------------------|-------------------------------------|-----------------------|
| E10         | 0.044                             | 0.94                                | 0.984                 |
| E85         | 0.056                             | 0.26                                | 0.316                 |
| B20         | 0.049                             | 0.81                                | 0.859                 |
| Hydrogen    | 0.01                              | 0                                   | 0.01                  |
| Electricity | 0.034                             | 0                                   | 0.034                 |

## Powertrain Selection

After analyzing the different available fuels, HEVT decided to use electricity and E85, since these fuels best balanced emissions and reduction of PEU. Having chosen



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these fuels, a powertrain architecture was then selected based on the goals of HEVT. Three separate powertrains were discussed and only one was chosen for implementation. The first architecture considered was a BEV. This design would offer great potential for petroleum energy displacement and would also provide the driver with an appealing all electric mode. However, to meet the competition range requirements, the ESS would have to be very large and certain consumer features, such as cargo space and passenger mass capacity, would necessarily be sacrificed in order to package the components for this architecture in the vehicle. In addition, this powertrain would require a significant recharge time due to the size of the battery which is not ideal for consumer acceptability.

A Series PHEV architecture solves many of the challenges presented by a BEV without losing much of the appeal. An EV mode is retained for a limited range which is designed to optimize the utility of the battery pack based on American daily driving habits [7]. This limited range dramatically reduces the size of the ESS and eases packaging, thus making it easier to retain consumer features. The competition range requirement can be met with a combination of electric range and fuel range. A pure Series PHEV is well suited for optimizing the efficiency of charge sustaining (CS) during city driving situations. While control of an engine-generator pair can be challenging, there are known solutions. One drawback of series mode is limited efficiency on the highway. Another is performance: the vehicle pays the mass penalty for carrying an engine and generator motor, but those components cannot directly assist the traction motor for acceleration performance or gradeability requirements. The generator must be sized for continuous power requirements for top speed or grade. The engine, in turn, must be able to support this generator and aid in regulating the state of charge of the battery pack.

A solution to these drawbacks is adding a path for the engine to transmit torque directly to the wheels. This path could be selectively clutched in or out and the vehicle has the capability to switch between the series mode and the parallel mode - hence it is a Series-Parallel architecture. Figure 1 illustrates the implementation of the P2-P4 Series-Parallel powertrain. The 'P' nomenclature refers to the position of the motor in the powertrain. A P1 motor is a pre-trans motor on the accessory side of the engine. A P2 motor is a pre-trans motor between the engine and transmission. A P3 motor is a post-trans motor that operates in parallel with the engine on a shared axle. A P4 motor is a post-trans motor that operates in parallel with the engine on a separate axle.

The P4 motor or Rear Traction Motor (RTM) is the primary drive motor and is the sole form of propulsion in charge depleting (CD) or EV mode. The architecture will leverage the neutral gear in the transmission to decouple the engine and P2 generator from the wheels to enable series operation during CS mode. This mode would be used at lower speeds or during periods of low road load.

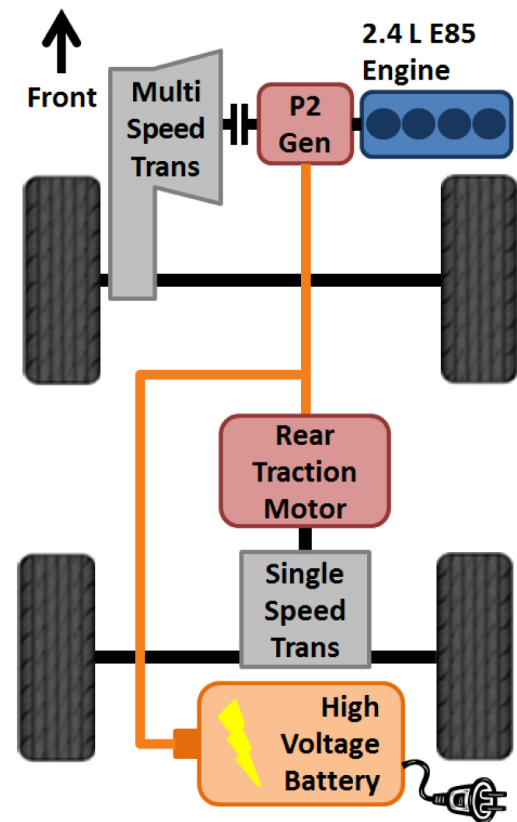


Figure 1. Series-Parallel PHEV Architecture

To couple engine torque directly to the wheels, the transmission would be engaged, most likely in 4th or 5th gear for efficiency. Because it is an automatic transmission, multiple gears could be used for performance and also to meet gradeability requirements. If the engine and gearing can meet gradeability in parallel mode without any power from the P2 or P4 motors, then the P2 generator can be downsized.

After weighing the three different architectures, the Series-Parallel PHEV was chosen as the best overall option for a hybrid vehicle design to meet the VTS. Table 6 summarizes the components and parameters for the Series-Parallel design. As discussed previously, these components were selected based on the tradeoffs being made for performance and consumer acceptability. In addition, noise, vibration, and harshness (NVH) as well as aesthetics go into the selection criteria. These components are able to reduce NVH and maximize aesthetics through effective packaging to keep as much of the stock vehicle in tact as possible. The moving and heat producing parts are to be isolated thus minimizing NVH and no changes are being made to the interior or hood of the vehicle, keeping the consumer acceptability high.

**Table 6. E85 Series-Parallel PHEV Component Specifications**

| Vehicle Parameters             |              |
|--------------------------------|--------------|
| Vehicle Test Mass              | 2050 kg      |
| A123 Energy Storage System     |              |
| Energy capacity                | 18.8 kWh     |
| Usable energy capacity         | 15. kWh      |
| Total mass including enclosure | 240 kg       |
| P4 Drive Motor                 |              |
| Peak power                     | 125 kW       |
| Continuous torque              | 45 kW        |
| Peak torque                    | 300 Nm       |
| Gear reduction                 | 7.17:1       |
| Top speed                      | 85 mph       |
| P2 Generator Motor             |              |
| Peak power                     | 30 kW        |
| Continuous power               | 20 kW        |
| Peak torque                    | 140 Nm       |
| E85 Engine                     |              |
| Peak power                     | 131 kW       |
| Peak torque                    | 230 Nm       |
| Displacement                   | 2.4 L        |
| Transmission                   | Auto 6-speed |

Another detail that must be considered is the fuel economy of the vehicle. [Table 7](#) presents the modeling results for the proposed Series-Parallel powertrain. This table shows how the fuel and energy consumption have played a role in the design process. The fuel economy was actually found to be higher for this architecture than for the pure series PHEV. Also shown here are the supporting details for the Series-Parallel PHEV. The performance and emissions characteristics modeled here meet the desired VTS and thus the components chosen will allow the team to build a vehicle to reach the specifications laid out in the requirements and goals. Note that these VTS goals are observed using the EcoCAR 4-cycle rating and not simply the Corporate Average Fuel Economy (CAFE) standards. The most influential difference between these two is the addition of an aggressive US06 drive schedule. This cycle demands higher accelerations and vehicle speeds than the HWFET or the UDDS drive cycles that make up the CAFE standards [8]. This is what drives the performance requirements for these different powertrain components and creates the necessity for careful design when it comes to choosing these components.

**Table 7. E85 SPS PHEV modeling results**

| Performance                         |                          |
|-------------------------------------|--------------------------|
| 0-60 mph accel                      | 8.0 s                    |
| 50-70 accel                         | 4.0 s                    |
| Gradeability                        | > 10% @ 60 mph           |
| EV mode/CD mode                     |                          |
| 4-cycle Energy Consumption          | 434 AC Wh/mi             |
| 4-cycle EV range                    | 40 mi                    |
| CS mode                             |                          |
| 4-cycle Fuel Consumption            | 1120 Wh/mi<br>30.1 mpgge |
| Utility Factor Weighted             |                          |
| UF 4-cycle Total Energy Consumption | 696 Wh/mi                |
| UF 4-cycle WTW PEU                  | 144 Wh/mi                |
| UF 4-cycle WTW GHG                  | 177 g/mi                 |

## HYBRID VEHICLE CONTROL SYSTEM DEVELOPMENT PROCESS

Control Development Process - HEVT is following the V-diagram, shown below in [Figure 2](#), as a guide for developing the control system for the vehicle. First, HEVT needed to define control system requirements. These requirements include what components need to be controlled, and how they need to be controlled. Vehicle safety is an important factor in determining the requirements of the control system. The goal is to create a control system that eliminates the possibility of safety issues, protects powertrain components from damage and, in case of failures, maintains driver control of the vehicle. The V-diagram facilitates control system design by directing the flow of development from low level requirements all the way up to high level code design and back to complete integration and testing.

As part of the control system design, HEVT has developed the hybrid control strategy that will run on the hybrid vehicle supervisory controller (HVSC). Beginning with the basic control strategy that operates a conventional vehicle and implements safety critical systems, the functionality is then extended to control the hybrid components in the vehicle. A systematic process is used to add functionality for each component one at a time to the control strategy. For each component, necessary I/O is implemented first to establish what information is reported by the component and what signals are required to control it. Next, diagnostic strategies are implemented, followed by the code necessary to operate the low level signals to the component. Finally the component is integrated into the high level strategy.

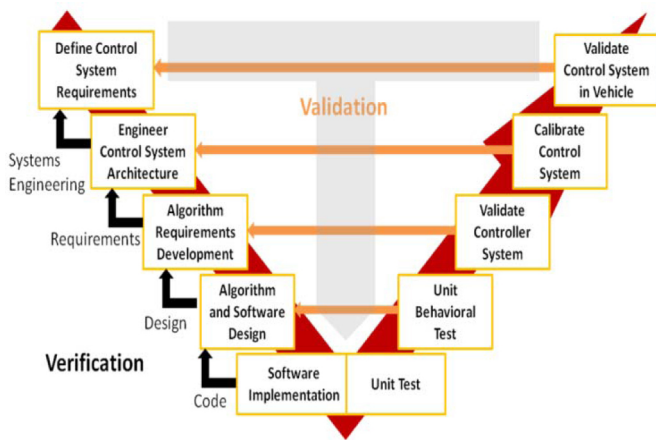


Figure 2. V-diagram

## Control System Requirements

These requirements are developed by keeping in mind the 5 technical goals of the competition: reducing petroleum energy use and greenhouse gas emissions while maintaining safety, performance, and consumer acceptability. The control system requirements are considered on a per-component basis, outlining what the HVSC needs to control for each component in the vehicle. At a high level, however, the requirements of the HVSC are to first and foremost maintain safe operation, then meet driver demand, and then to do so in the most efficient way. To protect the driver and components, there is a diagnostics subsystem built into the control algorithm that constantly monitors the vehicle components, ensuring they are operating within acceptable limits as well as checking the system for current and previous faults. There are also checks and redundancies in other subsystems of the algorithm to ensure proper functionality and safety.

## Plant Model Development

The first steps taken to modify the stock vehicle model are to introduce Simulink subsystems for the intended hybrid components and to verify their functionality. Once these subsystems are created using dSPACE Automotive Simulation Models (ASMs) and Autonomie generated models, the hybrid model is loaded into ControlDesk. The team verified that torque could be commanded to the RTM and P2 motor and that the motor speeds responded as expected. The ESS also responded correctly, regenerative braking worked, and the ESS current, voltage, and SOC behaved correctly.

The next steps in plant model development involved creating I/O between the added components and the HVSC. To verify the I/O created for the ESS and RTM, CD mode is tested. Functionality and I/O are added incrementally to the vehicle model, along with the control code, and tested after each set of additions in order to verify that the model and control code were working correctly together. This helps avoid compounding issues that would be a lot more imposing

if they are not taken piece by piece. Additionally, as the team learns more, the plant model is continuously improved to be more accurate and more representative of the actual vehicle.

## Hardware-in-the-Loop (HIL) Testing

To effectively test the control code in its entirety, HEVT is implementing controller HIL testing. The HEVT controller HIL test bench setup includes the hybrid vehicle control code running on the HVSC and a model of the selected architecture running on the HIL. The model can be driven through ControlDesk or using an input board with realistic driver input devices. The input board includes an accelerator pedal, brake pedal, key input, E-stop, and PRNDL. The safety switch on the PRNDL is actuated by a solenoid that receives a signal from the HIL. Therefore, park-neutral drive safety can be physically demonstrated as the tester is prevented from shifting the vehicle out of park without pressing the brake.

Testing of the vehicle model can also be performed exclusively through ControlDesk by bypassing the input board. To drive the vehicle manually, the ControlDesk testing interface includes key input, PRNDL, and slider gains for the accelerator and brake pedals. In addition to manual control, HEVT can run a drive cycle using ControlDesk in which the driver inputs are controlled by a driver model running on the HIL. Fault testing can be done by changing signal values in the vehicle model through ControlDesk. The Fault Insertion Unit (FIU) can also be used to fault test by changing analog signals, digital signals and CAN bus signals on the HIL. The FIU works by shorting the signals to ground, voltage sources and other signals in the HIL or create an open circuit. Determination of which faults to test was done using DFMEA in order to assess the severity of a comprehensive list of faults. This analysis determined those faults that were most severe. These faults will be the priority of the testing process to ensure that the HVSC can properly deal with these failures. To further test the functionality of the HVSC, multiple faults will be introduced concurrently to ensure the HVSC can mitigate multiple simultaneous faults. AutomationDesk is used to write scripts to automate this fault testing. Automated fault testing allows time for testing and control system development to be better managed.

In years 2 and 3, implementation of the control code into the actual vehicle will take place. Communication with each of the vehicle controllers will have to be tested individually to ensure the correct results. This testing will be done by adding the Electronic Control Units (ECUs) one at a time to the CAN busses in the vehicle while ensuring the proper signals are being read and transmitted and are not interfering with one another. As issues are discovered during integration, the vehicle model will be updated to account for behavior of the real vehicle components. The control code will be updated to properly work with the component and the test plan will be used to validate the new build of the control code before integration can continue. Year 2 will be devoted to implementing the control code and getting a mule vehicle