

An Innovative 4WD PHEV Utilizing a Series-Parallel Multiple-Regime Architecture

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ABSTRACT

The focus of this paper is the design and implementation of a series-parallel multiple-regime plug-in hybrid electric vehicle (PHEV) using a 2013 Chevrolet Malibu as a platform. The University of Victoria EcoCAR team used a 3-year vehicle development process (VDP) modeled after those used by Tier 1 automotive manufacturers, and maintained by the rules of EcoCAR 2: Plugging into the Future.

Intensive research was conducted to determine the ideal architecture selection based on overall greenhouse gas (GHG) emissions, criteria air contaminant (CAC) emissions, fuel economy, petroleum use, and vehicle performance. As a result, a series-parallel design was pursued, using a high power rear traction motor and large BAS electric machine tied to an E85 compatible 4-cylinder internal combustion engine (ICE). This architecture platform provides for multiple regimes of operation including electric only operation provided by the 14.8 kWh lithium ion battery. The architecture is very flexible in operability, allowing for use of the vehicle beyond direct competition goals to further UVic research activities on hybrid controls.

Vehicle control strategy development has relied heavily on hardware-in-loop (HIL) simulation. This allows for rapid development of control strategy concepts. Mechanical integration of new components has been conducted with the primary objectives of minimizing structural impacts to the existing vehicle, and maintaining consumer appeal. Mechanical design will continue to move forward and be refined in the implementation phase of the competition with support from General Motors regarding structural changes.

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INTRODUCTION

On April 13, 2011, the U.S. Department of Energy and General Motors announced the official launch and 15 participating teams of EcoCAR 2: Plugging in to the Future, a 3-year collegiate engineering design competition. Student teams will re-engineer a 2013 Chevrolet Malibu to reduce emissions and environmental impact while retaining performance and consumer appeal. The University of Victoria (UVic) team is the only team in Western Canada, and one of only two Canadian teams competing. UVic plans to build on existing and ongoing hybrid vehicle research, as well as a successful participation in the inaugural EcoCAR competition ending in 2011, by integrating an advanced supervisory control system, cutting-edge electric drive technology, and an advanced Lithium-Ion battery into a plug-in hybrid electric vehicle (PHEV) design.

EcoCAR 2 follows a modified version of the three-year vehicle development process (VDP) employed by Tier 1 automotive OEMs. The first year of the EcoCAR 2 VDP concluded in May 2012, and is the subject of this report. First-year design tasks included architecture modeling and comparison, component selection, high-voltage electrical system and battery design, mechanical integration design, control system specification and development, and controller hardware-in-loop (HIL) testing.

ECOCAR 2 VEHICLE DEVELOPMENT PROCESS

A rigorous VDP is implemented in EcoCAR 2 to ensure all teams reach a 99% buyoff target at the end of the competition. Year one of the VDP is focused on vehicle design, modeling, and simulation efforts. Year two involves the initial implementation of the vehicle design. Year three is concentrated on optimization and refinement to meet the

buyoff target. A simplified chart of the three-year VDP, divided into major technical categories, is given in [Figure 1](#).

YEAR & OBJECTIVE	MECHANICAL	ELECTRICAL	CONTROLS
Y1 - DESIGN	Life cycle analysis, vehicle architecture selection and performance modeling		
	CAD - Component	Define electrical requirements	Control system design
	CAD - Routing and integrations	HIL Design/Setup	Simple control and SIL/Prelim HIL
Y2 - MULE VEHICLE, INCREASED FOCUS ON OUTREACH	Finalized component selection		
	Vehicle modification	Vehicle harness/systems design	HIL finalization and communication setup
	Component integration	Vehicle harness setup	HIL testing - safety and fault mitigation implementation
Y3 - OPTIMIZATION & REFINEMENT	Controls integration and vehicle trouble shooting		
	Aero and lightweighting modifications, R&H and NVH	Refinement and optimization	Refinement and optimization
	99% Buyoff - vehicle ready for production		

Figure 1. Three-year EcoCAR VDP

Presently, the team is on track in the final stages of Year 1 of the VDP. Plant models have been developed and implemented for all powertrain components, and integrated together to form a detailed model of the team's architecture. In parallel with this, the supervisory control system has begun to be implemented, and is undergoing a systematic process of expansion and refinement, detailed in a later section. Mechanical design work to prove the feasibility of the architecture build is being completed, and ongoing work is focused on preparing a level of detail in the designs that is required for the integration work of Year 2. All difficulties which have arisen have been dealt with, with only minor deviations from the VDP.

The team is realizing the VDP by implementing a team structure that allows team members to work on areas of core competency, as well as interest. Many of the design tasks are, by nature, cross-discipline mechatronics projects. To complete these tasks, team members bringing the relevant skills and experience are brought together in workgroups. To encourage personal growth and learning, and to ensure sufficient experience will always be available in different areas, team members are also encouraged to take on new tasks outside of their traditional work area. For example, many team members working on mechanical design tasks have also worked on modeling and simulation of the same systems they are designing in CAD.

Progression through the VDP was initiated with a comprehensive literature review, to determine advantages and limitations of different hybrid vehicle architectures. The review also helped to identify key components, systems, and

design factors to be considered during the architecture selection process. In parallel with the review, an analysis of available fuels was carried out (detailed in the next section) to determine the impacts of the various competition fuels offered.

Three architectures were identified and studied: a Series E-REV, a Pre-Transmission Parallel PHEV, and a Series-Parallel PHEV. Preliminary modeling and simulation of the powertrains was carried out using the ANL Autonomie and dSPACE ASM software packages, and rough 'space-claim' CAD analysis was performed, to generate a quantitative comparison of the performance of the three architectures. Vehicle performance was evaluated using a blend of four standard driving cycles: US06 city, UDDS, US06 highway, and HWFET. Other factors considered included cost, team experience, difficulty of integration, and a requirement to utilize proven, off-the-shelf components to reduce design risk.

The results of the selection process indicated that the Series design, while simpler to build and integrate, did not offer the same performance advantages as the other architecture options, due to the Series' inherent efficiency limitation at higher speeds. The Pre-Transmission Parallel architecture offered excellent performance, but presented a very difficult integration challenge due to the lack of space in the engine bay to add the clutches and belt drive required. The Series-Parallel PHEV allowed for similar powertrain performance and flexibility to the Pre-Trans Parallel, but with more feasible front-end integration options. Therefore, the Series-Parallel PHEV was selected.

POWERTRAIN CONFIGURATION

The powertrain of the proposed Series-Parallel multi-regime architecture consists of a 2.4L ICE, operating on E85, coupled to a 6-speed automatic transmission, driving the front wheels, and a 100kW electric motor driving the rear wheels. A 37kW electric motor is also coupled to the ICE through the crankshaft pulley, as part of a BAS+ system.

The design goals, aside from meeting the EcoCAR 2 competition requirements, were to utilize proven, off-the-shelf components to build the architecture, and to develop a platform where ongoing research work in offline optimization and real-time optimal control could be applied to form the eventual core of the supervisory control strategy.

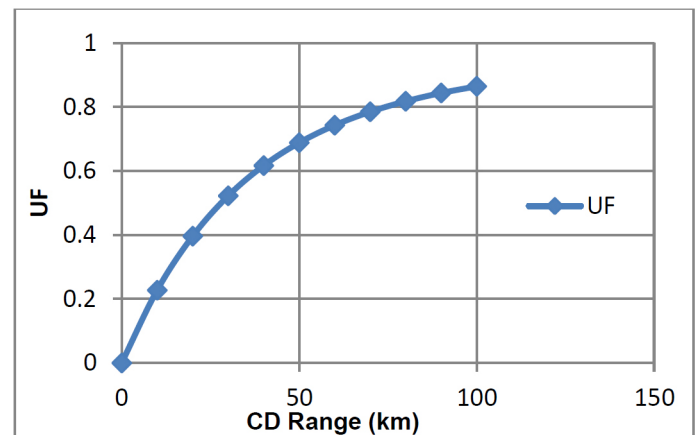
Battery Selection

The battery pack selected for the vehicle is comprised of modules and electronics units donated by A123 Systems, one of the major EcoCAR competition sponsors. The pack consists of a series string of 6 modules, each containing 45 Lithium-Ion cells, providing a nominal voltage of 292V.

Table 2. VEHICLE TECHNICAL SPECIFICATIONS - Competition and Team VTS

Specification	Competition Design Target	Team Target
Acceleration 0-60mph	≤ 9.5 sec	5.8 sec
Acceleration 50-70 mph	≤ 8 sec	4 sec
Braking 60-0 mph	≤ 43.7 m	43.5 m
Highway Gradability @ 20 min	3.5% @ 60 mph	8% @ 60 mph
Cargo Capacity	16.3 ft ³	16.3 ft ³
Passenger Capacity	≥ 4	5
Mass	< 2250 kg	< 2250 kg
Starting Time	<15 sec	<2 sec
Ground Clearance	>127 mm	>127 mm
Vehicle Range	332 km	332 km
UF-Weighted Fuel Energy Consumption	7.12 Lge / 100 km	4.86 Lge / 100 km
Criteria Emissions	Tier 2 Bin 5	Tier 2 Bin 5

The modules were selected primarily to obtain the largest on-board energy storage capability, in order to maximize vehicle Utility Factor (UF). The UF weighting used in EcoCAR 2 (shown in Figure 2) is derived from the SAE J2841 and J1711 standards, to account for a PHEV's electric-only range capability while operating in CD mode. Although the pack was desired to be as large (in terms of energy storage) as possible, a constraint was imposed by the available space in the vehicle for integration of the pack. The energy of the selected pack design is 16.2kWh, which provides for a substantial CD range while ensuring sufficient space is available. More information is given in the ESS section of this report.

**Figure 2. EcoCAR 2 Utility Factor Curve**

Fuel Selection

The vehicle fuel selection directly impacts fuel economy, GHG emissions, petroleum use, and CAC emissions. These parameters factor heavily in the consumer acceptability of the vehicle, as well as the scoring of the EcoCAR 2 competition. The fuel choice also indirectly affects vehicle performance, as the selected engine is fuel-dependent.

The fuel selection was performed based on an analytical comparison of the available competition fuels: gasoline (E10), biodiesel blend (B20), ethanol blend (E85), and hydrogen. Emissions and energy values were derived using GREET (for US energy mix) and GHGenius (for Canadian energy mix) with 2018 as the target year (theoretically, the year the team's vehicle would enter the market if it were being produced). Electricity is also included as a fuel, for comparison purposes.

	E10	E85	B20	Elec
Fuel-specific energy by mass (kWh/kg)	11.44	7.96	11.55	N/A
Fuel Energy (kg/L)	0.746	0.7871	0.8552	N/A
Fuel energy density by volume (kWh/L)	8.534	6.265	9.878	N/A
% Petroleum	90%	15%	80%	0%
g CO ₂ / kWh	261	260	277	N/A
GHG _{WTW} (g/kWh)	322	261	288	648
Vehicle PEU _{WTW} (kWh PE/kWh)	0.984	0.316	0.859	0.034
Upstream THC (g/kWh)	0.0612	0.0475	0.0101	0.0031
Upstream CO (g/kWh)	0.0119	0.005	0.0091	0.0326
Upstream NO _x (g/kWh)	0.0279	0.0141	0.0214	0.1012

Evaluating the energy density of the competition fuels, B20 initially offers the best performance. A vehicle using B20 could carry a lower volume of fuel for the same on-board energy capacity as the other liquid fuels. This translates into a lower vehicle mass, and a smaller fuel tank, which would simplify mechanical integration. In contrast, E85 provides 63% of the energy of B20 for the same volume. In order to obtain the same vehicle range, the fuel tank of the E85-fueled vehicle would have to be 37% larger. No energy density value is presented for electricity as a fuel, as electricity is not considered for a primary vehicle fuel. This is because no currently available battery chemistry can compare with liquid fuels on an energy density basis.

The GHG emissions accounted for in EcoCAR 2 consist of carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). The grams of GHG emissions per kWh of fuel used given is the combined WTW value, consisting of both downstream and upstream emissions factors resulting from the production, transportation, and use of the fuel. Assuming the same energy conversion technology, using E85 would result in the lowest WTW GHG emissions. However, the

vehicle's powertrain components would determine the efficiency with which that energy is used. The GHG emissions from using B20 are only slightly higher compared to E85, and the inherent efficiency gain of using the diesel engine may make up the difference. Using pure gasoline would result in a higher GHG output. Although electric propulsion does not produce any downstream GHG emissions, the EcoCAR 2 weighting of GHG's from upstream electricity production provides a significant penalty in this category.

The WTW petroleum energy usage quantifies the energy derived from petroleum sources involved in the manufacture, transportation, and use of the fuel as a percentage of the fuel energy used by the vehicle. In this category, E85 is clearly the best choice of the liquid fuels. This is due to E85's low petroleum content; only 15% of the fuel blend is directly derived from petroleum sources, compared to 80% for B20. Electricity offers an even lower petroleum energy content, which suggests that designing a vehicle to have a long electric-only range is a viable strategy for further reducing petroleum energy use, with the trade-off of increased GHG emissions as mentioned above.

The criteria emissions category includes non-GHG pollutants that have a negative effect on urban air quality, primarily total hydrocarbon content (THC), carbon monoxide (CO), and oxides of nitrogen (NO_x). The downstream components of these emissions are very difficult to model, due to highly-variable engine transient conditions, as well as the cold starts and more complex operating modes imposed by different hybrid control strategies. In this category, E85 and B20 offer the lowest upstream emissions values. However, minimizing the downstream pollutant emissions from B20 would require the design and integration of a complex exhaust after-treatment and particulate filter system.

E85 was the final choice of fuel, due to its high petroleum displacement, and low GHG and CAC emissions. Although B20 and E85 are comparable in several categories, the biodiesel was ruled out due to the potential difficulty with integrating an effective particulate filter and exhaust treatment system and the team's lack of experience with diesel engines.

Engine Selection

Although a wide range of engine sizes and types are available on the market, it was decided to utilize one of the three engines provided for the competition by GM, to benefit from the accompanying technical support, available performance data, and CAD models. The 2.4L Ecotec LE9, the 1.4L LUJ, and the 1.8L LUD were compared in terms of power output, mechanical integration difficulty, and fuel compatibility.

	LUD	LUJ	LE9
Power (kW)	120	104	130
Torque (Nm)	200	167	230
Fuel	B20	Gas	E85
Displacement (L)	1.8	1.4	2.4
Volume (relative to LE9)	0.85	0.75	1.0

The LE9 was selected for the vehicle's engine. The donated 2013 Malibu ships with the LE9, which will reduce the complexity of engine mount modification. The LE9 also natively mates with the selected 6-speed automatic transmission, also from GM. The LE9 is Flexfuel-capable, and can therefore run on E85, the fuel of choice, without modification. The higher power and torque outputs of the LE9 will improve the vehicle's acceptability in performance-oriented events such as acceleration or autocross.

Motor Selection

The choice of electric drive components was based on vehicle power requirements, and a tradeoff of physical size and efficient operation. While most electric machines have a very high peak efficiency rating (>90%), this occurs at higher values of torque production. When cruising at a steady speed, the torque demand is low, leading to less-efficient operation of electric drive components. With this in mind, motors were selected based on their expected efficiency at key vehicle speeds, such as 50km/hr (urban cruising) and 90km/hr (highway cruising).

The Magna E-Drive was selected as the Rear Traction Motor of the vehicle. Donated by Magna for the EcoCAR competition, the E-Drive provides an innovative integrated design, where the motor, inverter, and a single-speed differential are combined into a single unit. This component, while not without integration challenge, offers the opportunity to utilize a solid vehicle drive turn-key solution backed by Magna support. An analysis of efficiency also showed that the E-Drive offers comparable efficiency and power density to top-end electric drive systems on the market.

CONTROL DEVELOPMENT PROCESS

Control Development Plan

The control system is under development using a systematic approach, with stages of high-level and model-based design preceding stages of incremental testing and integration with the physical vehicle systems. A high-level view of the development method employed is outlined in the modified V diagram shown in [Figure 3](#).

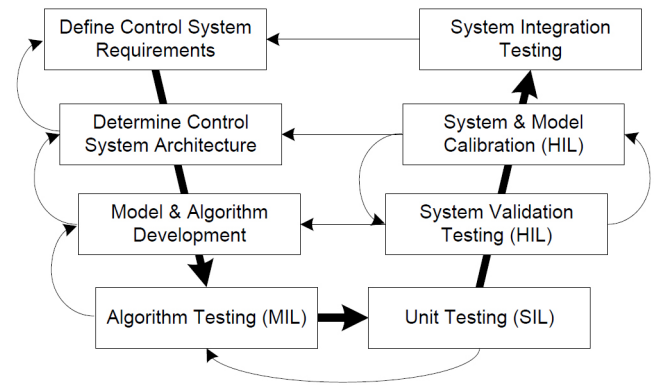


Figure 3. Control Development Plan

If a development obstacle or design failure is encountered in the descending arm of the V diagram, the previous stage is revisited and corresponding steps repeated. Failure at any stage of the ascending arm of the V results in a return to the related development stage; any revisions will always pass through all subsequent development and testing stages up to the level where the failure originated. Documentation and rigid adherence to test protocols will be crucial to the success of this process.

Starting with the left side of the V diagram, the essential vehicle control system functional requirements were determined based on team VTS. Next, all vehicle control systems requiring control input were identified and corresponding controller input/output requirements were formulated. Continuing to the next step on the V diagram, appropriate ECUs were selected based on the functional and I/O requirements of the control system. Following the completion of these steps, the foundation of the control system had been devised.

A step-by-step explanation of the V-diagram follows:

Define Control System Requirements

The vehicle control system functional requirements were determined based on the team VTS. All vehicle systems requiring control input were identified, and high level descriptions of required controller inputs and outputs (e.g. vehicle speed input, torque command output) were formulated. Component technical specifications, as well as the expertise of vendors and team mentors were used at this stage.

Determine Control System Architecture

The functional and I/O requirements of the control system were generated in order to design the sophisticated supervisory hierarchy (discussed in the proceeding section: Control System Architecture).

Model & Algorithm Development

High-level Simulink models of the vehicle systems, which reflect the team's selected architecture, were constructed using the dSPACE Automotive Simulation Model (ASM) as a base plant structure. Concurrently, a supervisory controller model was developed in Simulink. The sections of the model that were to be used in the supervisory controller were kept separate from the plant model so the two could be compiled separately into machine code for ease of use later in the development process. Both models are continuously updated as new information relating to the vehicle design becomes available or if any design changes come about.

Algorithm Testing (MIL)

Model-in-the-loop (MIL) assessments including vehicle performance tests and examining control algorithms to uncover errors and find paths to gain efficiency are performed following any significant alteration to the model. Simulink is utilized to run non-real time simulations. Messages sent between the control and plant models during this stage use physical units; intricacies related to CAN messaging are circumvented.

Unit Testing (SIL)

Software-in-the-loop (SIL) analysis, was performed once the fundamental control algorithms had been tested and validated. At this step, messages between the models are conditioned to imitate how they will be transmitted on-board the vehicle, however, the analysis is not performed in real time. For example, throttle position signals were converted to a discretized voltage range corresponding to the output of the physical throttle. In addition, communication between the vehicle control modules was modified to model CAN messages using the dSPACE RTI CAN and CANMM libraries.

System Validation Testing (HIL)

System validation testing and calibration via hardware-in-the-loop (HIL) was performed as described in the next section.

System & Model Calibration (HIL)

As vehicle hardware components, such as the EDS, become available, the components will be directly interfaced to the HIL and the corresponding section in the plant model will be replaced. In order to maximize interchangeability of HIL-interfaced components and integrated plant models, in-model hardware-enabling switches will be utilized. This process will also be used for functional unit validation of models designed for specific components and any analysis of their fidelity. By examining the differences between the modeled and observed performance, model improvements can be performed. This is the system and model calibration stage.

System Integration Testing

The final stage of control development involves full vehicle integration; the ECUs will be hooked up directly to the vehicle where possible. Testing will progress from chassis dynamometer tests to road tests. To ensure safe control development, any major code revisions will require the associated previous phases of the design cycle to be repeated.

Use of SIL and HIL

A schematic of the HIL bench is shown in [Figure 4](#). The compiled code implementing the control strategy was transferred to the dSPACE MicroAutobox II (MABx2) controller, and the corresponding plant model was transferred to the HIL The MABx2, as the vehicle supervisory controller, cannot distinguish whether it is communicating with the HIL simulator or with an actual vehicle. This step of the development process involved the use of additional software. Up to this point, Simulink and specific dSPACE libraries had been employed. Further dSPACE libraries, including RTI 1006 and RTI 1401, were required, allowing for model compatibility with the HIL simulator and the MABx2, respectively. To verify functionality and control signals passed between the controller and HIL, as well as to allow for real time parameter tuning, dSPACE ControlDesk was utilized. Through observing the vehicle's performance in real time using the HIL-MABx2 test bench system, complications caused by signal latency, discretization, and signal noise can be more easily recognized and addressed. ControlDesk was employed to perform data analysis which proved beneficial for data logging and visualization of system parameters. ControlDesk and AutomationDesk were used to develop standardized tests to compare results generated by varying different system parameters and segments of the model. AutomationDesk provides an excellent automated testing environment to increase working efficiency and time management for scheduled testing, which is necessary for the small UVic Controls and Modeling teams. Furthermore, to better conceptualize the physical meaning of the results and capture comparative controller responses to real components, a peripheral component system was interfaced to the plant model as it should be realized in the vehicle. 3D vehicle visualizations were also created in dSPACE MotionDesk to increase this conceptualization process. This peripheral component system includes accelerator and brake pedals, a steering wheel, a gear selection lever (PRNDL), a key, an in-dash display, and a designed high-voltage system replicating the designed ESS

The HIL was also used to test fault and failure mitigation routines of the vehicle's supervisory controller. This was achieved through utilization of a relay board in the HIL which allows for electrical signals to be set to open circuit and shorted to ground or a reference voltage. One additional component which will be tested in this manner is the vehicle's EDS. Also, accelerator pedal failures are tested in this