

Design of a Parallel-Series PHEV for the EcoCAR 2 Competition

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ABSTRACT

The *EcoCAR 2: Plugging into the Future* team at the Ohio State University is designing a Parallel-Series Plug-in Hybrid Electric Vehicle capable of 50 miles of all-electric range. The vehicle features a 18.9-kWh lithium-ion battery pack with range extending operation in both series and parallel modes made possible by a 1.8-L ethanol (E85) engine and 6-speed automated manual transmission. This vehicle is designed to drastically reduce fuel consumption, with a utility factor weighted fuel economy of 75 miles per gallon gasoline equivalent (mpgge), while meeting Tier II Bin 5 emissions standards. This report details the rigorous design process followed by the Ohio State team during Year 1 of the competition. The design process includes identifying the team customer's needs and wants, selecting an overall vehicle architecture and completing detailed design work on the mechanical, electrical and control systems. This effort was made possible through support from the U.S. Department of Energy, General Motors, The Ohio State University, and numerous competition and local sponsors.

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INTRODUCTION

The Ohio State University EcoCAR 2 Challenge Team is a multi-disciplinary team consisting of more than 40 students. The team has members ranging from high-school students to Ph.D. students who participate in a wide variety of engineering, business, and outreach tasks. As described in this report, the team's progress through a rigorous vehicle development process has led to the design of a unique vehicle for the EcoCAR 2 Challenge. The final selected architecture and vehicle technical specifications can be found in [Appendix F](#) and [Appendix B](#) respectively. The design features:

- **Multi-Mode Operation:** The vehicle's design allows for operation in series, parallel, or all-electric operation. The vehicle's supervisory control performs real-time optimization of the vehicle's engine and two electric motors.
- **High-Efficiency E85 Internal Combustion Engine:** The team has converted a high-compression ratio natural gas engine to operate on E85 resulting in greater than 40% brake thermal efficiency.
- **Automated Manual Transmission:** The team has chosen to develop an automated manual transmission. The system uses

a stock GM transmission with custom actuators and control software for the clutch and shifting.

- **Aggressive Electric Operation** - Customer requirements drove the team to design a vehicle with high all-electric range (>40 miles) and high all-electric performance.

VEHICLE DESIGN PROCESS

VDP Overview

A simplified Vehicle Development Process (VDP) was presented to the EcoCAR 2 teams by the competition organizers at Fall Workshop, which is shown in [Figure 1](#). The team used this process and unified it with the V-Diagram process used for design of complex systems, of which the team's EcoCAR 2 vehicle is an excellent example.

The team's VDP V-diagram can be found in [Appendix A](#) and shows the process that will be followed by the Ohio State team to develop both the controls system and powertrain for the vehicle. The left side of the V-diagram represents the vehicle design process, while the right side of the diagram represents the realization and validation process. The two sides are connected at the bottom with the component realization step, where the design steps from the left side are

implemented in the vehicle and then validated using the steps on the right side. Validation plans also flow from the left side of the V-diagram to the right, which provides the tools to evaluate if the realized designs meet the required design objectives.

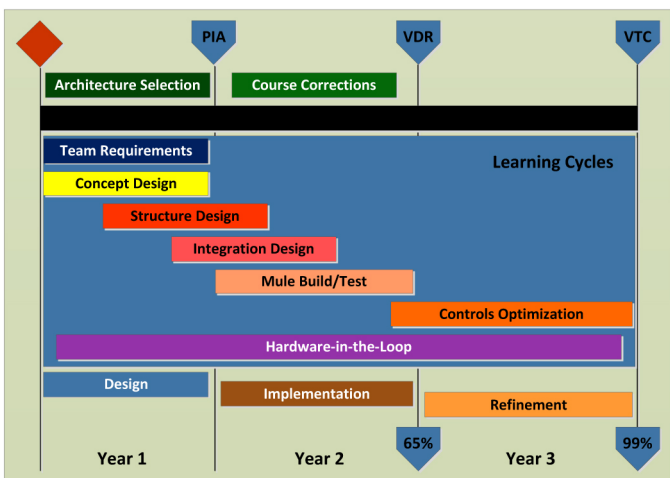


Figure 1. EcoCAR 2 Vehicle Development Process

VDP Implementation

The key to the OSU implementation of the design process is that it explicitly combines the three “swim lanes” of development into a unified diagram for electrical, mechanical, and controls efforts. On the way down the V-diagram, component design tasks form the critical path. Once a design decision is made, software design tasks then occur in the yellow area in the diagram. For instance, once the vehicle architecture is defined, it is possible to start the design tasks related to the vehicle control software. As subsystems and eventually components are defined on the critical path, the associated work on controls can begin.

On the implementation path, the right side of the diagram, controls realization is the critical path. It is usually not possible to fully validate a powertrain component or system until controls are available, thus the controls must be realized prior to full validation of the hardware. Because the control design and development was already started (in the yellow area), control hardware, software, and calibrations should be ready by the time hardware is actually realized. This approach accelerates the pace of vehicle development and is heavily reliant upon the use of SIL and HIL techniques to allow controls development without availability of hardware.

In terms of the specifics of the implementation, the OSU team maintains several documents that allow the team to track progress. The first document the team has developed is a Test Plan and Procedures (TP&P) document which tracks the propagation of design and control requirements as they cascade through the various subsystems in the vehicle. The TP&P document is structured from the high-level requirements of the vehicle. By way of example, the vehicle has a 0-60 mph time target and references the competition

rules for the execution of this particular test since it is a competition event. The document also captures how higher-level requirements trickle down into subsystems and includes hardware as well as supervisory control software.

The other document the team has developed acts as a supplement to the TP&P document that is specifically for controls related tracking. This is the Supervisory Control, SIL, and HIL Development Document. The purpose of this document is to track and document key decisions in the supervisory control development process, SIL activities, HIL activities, and fault diagnosis work. The document highlights progress, plans, and data in the following key areas of the control development: Control Requirements, System Architecture, Control Algorithms, Strategies, and Diagnostic Algorithms, Safety Critical Systems, Verification and Validation, Systems Integration, and DFMEA/FTA Results.

VDP Deviations

The team did not have any major deviations in the VDP process in Year 1. In a few cases, nearly completed subsystem designs have required extensive rework due to design objective conflicts between subsystems. In particular, the design of subsystems within the rear powertrain proved to be a challenge. The rear electric motor system, the energy storage system, and the cargo capacity aspect of consumer acceptability were all in competition for vehicle space. This was compounded by the fact that there are waiver issues involved due to structural modifications of the vehicle. In the end, the competition objectives of these three subsystems were managed by adhering to OSU's VDP process to make the best trade-off possible. This is discussed in greater detail in the Packaging and System Integration section of this report.

Current VDP Status

From a software perspective, the team is currently in the HIL Control Testing/Validation phase of the V-diagram. Software for each of the three team-developed controls is running in the target control hardware on the HIL, or in many cases, with actual plant hardware.

For electrical and mechanical subsystem development, the majority of projects are at the component or subsystem implementation phase. By way of example, the team's ambitious project to automate a manual transmission is well underway. The actuation hardware is built and is being tested with the developed control system prior to Year 1 competition. The team has already secured all other major powertrain components and confirmed delivery during summer of 2012.

Following the completion of the first year of EcoCAR 2, the controls models for the vehicle supervisory control, electrical and mechanical subsystems and component models will be validated and ready to begin the next phase of the V-diagram. In Year 2, the vehicle will be built and therefore achieve realization of the electrical and mechanical components and subsystems, as well as full, low-level control

implementation and basic high-level control functionality. In Year 3, the team will focus on further refinement and validation of the vehicle against the original targets set by the team.

POWERTRAIN CONFIGURATION

The OSU architecture selection and process is broken into four major phases: *Problem Definition*, *Specification Development*, *Concept Development*, and *Concept Selection*. Within each phase are more specific steps created to ensure thorough background research and yield the best possible architecture for the OSU team. The process is illustrated in [Appendix D](#).

Goals and Specification Developments

The team goals and specifications were set by identifying the different customers of the OSU EcoCAR 2 team, identifying the needs of each customer, and performing a competitive vehicle benchmarking assessment. This is represented in [Appendix D](#) as the *Problem Definition* phase. The team identified four different “customers” for the Ohio State EcoCAR 2 vehicle, listed below with a brief description of the reason for their selection. This phase is crucial given the inevitable tradeoffs that are necessary in designing a vehicle.

- **OSU EcoCAR 2 Students:** The vehicle designed by the Ohio State team needs to have new and challenging aspects that have not been done by the team before in order to allow both new and returning team members to learn more about hybrid vehicles.
- **Outreach Target Audiences:** The vehicle designed, built and tested by the Ohio State team needs to appeal to K-12 students, the general public, and influencers in a wide range of fields. In the coming years, all three of these groups will play a part in how hybrid vehicles are accepted into the lifestyles of the American public.
- **EcoCAR 2 Judges:** The Ohio State vehicle needs to impress the judges in EcoCAR 2 since these judges are responsible for assigning the team points based on everything from the vehicle's technical merit to its static consumer acceptability.
- **EcoCAR 2 Event Scoring:** The vehicle designed by the Ohio State team needs to maximize the amount of points the vehicle can receive in the Year 2 and 3 dynamic events. These events score everything from the vehicle's fuel economy to its performance and drivability.

Customer Needs and Wants

Each of the four different customer groups have different “needs and wants” for the team. These needs and wants are what eventually drive the concept selection and vehicle technical specifications. The engineering, outreach, and business team developed the following list for the four defined customers: 1) apply knowledge gained in the classroom to real world problems; 2) provide good design

project content; 3) provide good research project content; 4) provide good content for presentations; 5) vehicle has better fuel economy, emissions, and performance than the stock Chevrolet Malibu; 6) have strong ties to Ohio business community; 7) be aesthetically attractive to target audiences; 8) have capability to place in top 5; 9) maximize score on dynamic vehicle events; and 10) perform well on static events.

Competitive Vehicle Assessment

In addition to identifying the customers and determining each customer's unique “needs and wants” for the vehicle's performance, the team performed a *Competitive Vehicle Assessment* (CVA). The CVA is a way to benchmark the team's vehicle against vehicles being sold in the same segment as the Chevrolet Malibu (Affordable Midsize) as well as in three other segments. The complete CVA lists more than 20 key aspects collected from a variety of sources that include the US News Buyers Guide, the US News website, Yahoo Autos, vehicle manufacturer's websites, *motortrend.com*, *torquestats.com* and *zerotosixty.com*.

Affordable Midsize Cars (8 Samples)					Affordable Large Cars (6 Samples)				
	0-60 Time (sec)	Trunk Volume (ft3)	MPG (city)	MPG (highway)		0-60 Time (sec)	Trunk Volume (ft3)	MPG (city)	MPG (highway)
min.	7.5	13.3	21	31	min.	6.2	14.4	17	27
max.	9.1	16.6	26	38	max.	7.4	20	20	30
mean	8.4	15.3	22.9	33	mean	6.9	16.7	18.7	28.2

Upgraded Midsize Cars (11 Samples)					Hybrid Vehicles (6 Samples)				
	0-60 Time (sec)	Trunk Volume (ft3)	MPG (city)	MPG (highway)		0-60 Time (sec)	Trunk Volume (ft3)	MPG (city)	MPG (highway)
min.	4.8	7.4	16	26	min.	7.1	10.1	31	33
max.	7.5	15.9	22	31	max.	9.8	21.6	51	48
mean	6.2	12.7	18.8	27.7	mean	8.4	12.8	38.7	38

Figure 2. Competitive Vehicle Assessment Summary

A few relevant parameters from the CVA that helped determine the team's goals and specifications are shown in [Figure 2](#), namely: 0-60 time, trunk volume, city MPG, and highway MPG. These stats helped guide the ultimate selection of a target 0-60 time of 7 seconds as well as providing justification of some loss in trunk volume due to packaging constraints. Because of the relatively large stock trunk volume of the 2013 Malibu, some intrusion into this space would not be out of line with competing vehicles.

Establish Vehicle Design Specs

The next phase of the selection process shown in [Appendix D](#) involves developing metrics to rank different concept designs. These are similar to the VTS targets for the vehicle, but include a number of non-technical factors as well. The five categories of metrics in the table are: performance, consumer acceptability, risk, educational value, and Ohio focus. These metrics, in addition to the eventual scoring results discussed later, are shown in [Appendix E](#). The weighting for each of the metrics was determined by the EcoCAR 2 scoring system as well as the team's own goals. The composite fuel economy and the upstream/downstream

emission metrics were given weightings of 10 since the total of those two events are worth 30-34% of the points in Years 2 and 3 of the competition. The remaining metrics were assigned weights in a similar fashion to form a decision matrix. As mentioned above, these are not the full set of vehicle technical specifications at this point in the process.

Architecture Selection Process

High Level Component Design Decisions

The results of the process described above led to a list of quantitative metrics against which to evaluate the candidate architectures. However, the large freedom in the design space made it difficult to systematically define possible architectures. Free design options include: 1) fuels; 2) energy storage capacity; 3) operating modes (*i.e.* series, parallel); 4) component sizes; and other such options.

In order to reduce the number of free design variables in the architecture selection process, the team made high-level design decisions at the start of the architecture selection process to reduce the design parameters that needed to be optimized in the modeling and simulation portion of the process. The key decisions were largely made with respect to fuel and critical components and are consistent with the *Customer Needs/Wants* and *Vehicle Design Specifications* determined in the second phase of the process shown in in [Appendix D](#). Reducing the number of free parameters narrows the design space sufficiently to allow rigorous simulation studies to be used to evaluate concept vehicles.

To select fuel type and ESS capacity, the team essentially conducted a virtual EcoCAR 2 competition amongst a host of vehicle types using Argonne National Lab's Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET) Model. The team used the GREET model to analyze how each of the different fuel combinations allowed in the EcoCAR 2 competition would affect their final score in the EcoCAR 2 Emissions and Energy Consumption event, which is the highest scoring event in the competition. Once all calculations were completed, each fuel type was scored using the EcoCAR 2 competition's normalized scoring method, which scales the points awarded to each team based on the highest and lowest scores.

This analysis considered the following vehicles: a conventional vehicle with E10, E10 HEV, E10 PHEV, a conventional vehicle with dedicated E85, dedicated E85 HEV, E85 PHEV, conventional B20, B20 HEV, B20 PHEV, and a hydrogen fuel-cell vehicle. The analysis also considered the impact of varying all-electric range on the performance of the vehicle via the utility factor concept used by the competition.

Based on the results in [Figure 3](#), the hydrogen fuel-cell vehicle would be the best choice for earning points at the competition based on its excellent petroleum use reduction and WTW GHG emissions reduction. However, hydrogen is not well-aligned to the research goals of the team or Ohio State's Center for Automotive Research. Therefore, a

hydrogen fueled vehicle was not considered further by the team. If the use of hydrogen as a fuel is eliminated as an option, the best remaining fuel combination shown in [Figure 3](#) is the E85 PHEV. This decision is consistent with the design process as it matches the customer needs and wants defined earlier.

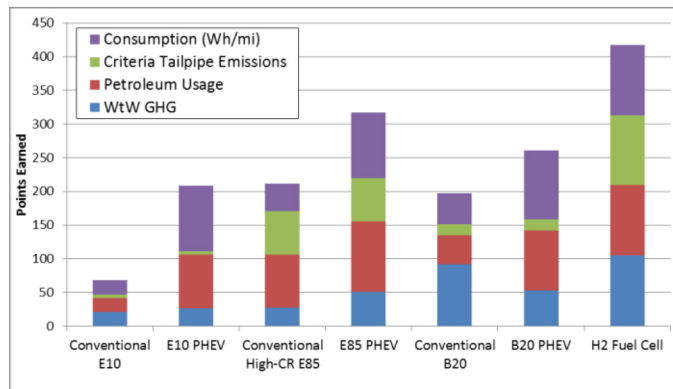


Figure 3. Estimated Total Competition Score for Fuel

Based on the choice of E85, the team decided to use a 1.8L high compression ratio Honda engine in order to take advantage of E85's high octane rating to get better efficiency from the engine. This was a practical result of the team's previous experience with this engine and the fact that it represents a best-in-class efficiency for a SI engine at 40% brake thermal efficiency. Note that these design decisions also support the Customer Needs/Wants, specifically having better fuel economy and emissions than the stock Malibu, having strong ties to the Ohio business community, performing well on static competition events, and providing good content for presentations, design projects, and research projects.

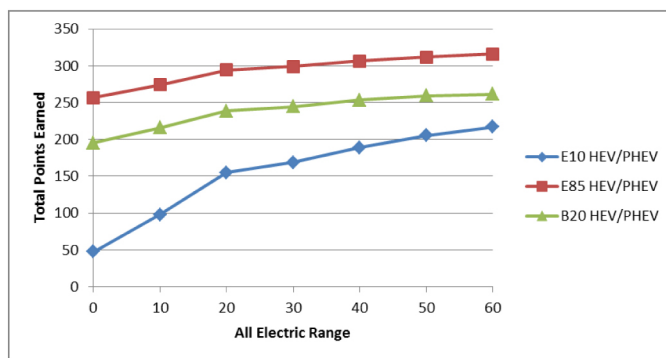


Figure 4. Estimated Total Fuel Economy and Emission Scores for Varying Charge Depleting Ranges

As seen in [Figure 4](#), increasing the charge depleting range of the vehicle has a significant effect on raising the overall score for the EcoCAR 2 Emissions and Energy Consumption event. Therefore, it is desired to maximize the charge depleting range of the vehicle by maximizing the capacity of

its battery pack. This led the team to select the largest battery pack A123 was willing to donate to the team, which was an 18.9 kW-hr battery pack.

Concept Development

With the fuel, engine, and ESS system already defined, the team was able to focus on developing concepts in a manageable design space. As shown in [Appendix D](#), this is a multistep process. In the *Internal Concept Search* phase of this process, the team started developing concept architectures over the summer of 2011, using a collaborative and private wiki website hosted by OSU to capture ideas from the returning team members who were at various locations on internships. The *External Concept Search* involved conducting a thorough literature review of relevant topics containing more than 60 references and a review of the publications and performance of top EcoCAR and Challenge-X team designs. The team used these results in the *Search Result Synthesis* section to understand what attributes and systems would deliver the best possible design.

Candidate Hybrid Vehicle Architectures

The outcome of the *Concept Selection Process* was four different architectures that the team felt would best satisfy the *Vehicle Design Specs*, and thus, the customer needs/wants. These four vehicle architectures are: 1) a series PHEV; 2) a post-transmission PHEV; 3) a pre-transmission PHEV; 4) a parallel-series PHEV. Vehicles (1) through (3) are well-known architectures. A diagram of architecture (4) is shown in the [Appendix F](#). Descriptions of each of the candidate architectures are given in [Table 1](#).

Table 1. Candidate Architectures

Option 1: Series PHEV	
Front Axle	75 kW EM coupled directly to 1.8L Honda engine
Rear Axle	145 kW EM coupled through two speed transmission to axle
Option 2: Pre-Transmission PHEV	
Front Axle	1.8L Honda engine clutched directly to an 85 kW EM, then connected to 5-speed automated manual transmission connected to the axle
Rear Axle	N/A
Option 3: Post-Transmission PHEV	
Front Axle	BAS attached to 1.8L Honda engine clutched directly to the 5-speed automated manual transmission connected to the axle
Rear Axle	150kW EM connected to axle through a single speed gearbox
Option 4: Parallel-Series PHEV	
Front Axle	1.8L Honda engine clutched directly to 82 kW EM, connected to 6-speed automated manual transmission connected to axle
Rear Axle	82kW EM and single speed gearbox connected to axle

For each of these vehicles, Argonne National Lab's *Autonomie* software was used to simulate the different vehicle architectures in addition to the stock vehicle as a baseline. The team also completed initial packaging studies on each vehicle to ensure the powertrain components they wanted to use could be packaged inside a conventional 2013 Chevrolet Malibu. The hybrid vehicle architectures considered by the team were also compared back to the conventional vehicle in order estimate how much of an improvement in fuel economy the hybrid vehicles would have.

Vehicle Model Setup

All four of the hybrid vehicle models used the same customized initialization files for the engine and battery pack. The engine initialization file was modified to reflect the 1.8L E85 Honda engine that the team had selected using data gathered by the team in the dynamometer test cell. The battery initialization file was modified to reflect the 18.9 kW-hr pack that A123 would donate to the team using the data provided by A123. All four hybrid vehicle models also used the UQM electric machine initialization files that were pre-loaded in *Autonomie*. The team decided to use all UQM electric machines in order to maintain some consistency across the four hybrid vehicle models, since a supplier for the electric machines had not yet been identified. These maps were scaled to achieve the desired power characteristics.

Once the model for each vehicle was set up, the gear ratios, control strategy parameters and electric machine size were all optimized to give each model the best possible acceleration time and fuel economy. The team did multiple parametric studies on each of the four hybrid vehicle models to learn how the gear ratios, control strategy parameters and electric machine size affected the vehicle's performance and fuel economy numbers. The results of the parametric studies allowed the team to select a set of parameters that had the best balance between acceleration times and high fuel economy.

Simulation Results

The acceleration and fuel economy results from the *Autonomie* simulations of the hybrid vehicles and the conventional Malibu are listed in [Table 2](#). All four hybrid vehicle architectures had significantly better fuel economy than the conventional Malibu. These fuel economy numbers ranged from 63.5 mpgge for the pre-transmission PHEV to 72.3 mpgge for the parallel-series PHEV vehicle. All the hybrid vehicles also had all-electric ranges greater than 44 miles which gave them utility factors of 0.654 or greater. The parallel-series PHEV had the longest all-electric range of 50 miles.

Table 2. Vehicle Simulation Results

	Conventional Malibu	Series PHEV	Post-Transmission PHEV	Pre-Transmission PHEV	Parallel- Series PHEV
Fuel Economy					
All-Electric Range [mi]	0	43.5	46.5	44.8	50
Utility Factor	0	0.645	0.666	0.654	0.689
Utility Factor Corrected Energy Consumption (Wh/km)	855.1	315.2	302.7	329.7	289.5
Utility Factor Corrected Fuel Economy (mpgge)	24.5	66.4	69.2	63.5	72.3
Performance					
0-60mph Acceleration Time (s)	8.2	10.4	7.1	7.1	7.3
50-70mph Acceleration Time (s)	N/A	5.8	3.2	4.5	3.76
Gradeability (P/F)	P	P	P	P	P

In addition to the good fuel economy and all-electric range numbers, most of the hybrid vehicles had better acceleration times than the conventional vehicle. This was by design, as this was a feature that was identified in the customer needs/wants analysis.

Decision Matrix

The results of the vehicle simulations were used with the results of the packaging studies to determine which of the four possible hybrid vehicle architectures best meet the team's goals and specifications found the previous section of this report. The decision matrix used to evaluate each of the four architectures is shown in [Appendix E](#). The reference vehicles used in the decision matrix are the conventional Chevrolet Malibu vehicle and the twin-clutch E-REV vehicle built by Ohio State in the EcoCAR 1 competition. The conventional Chevrolet Malibu was used as the reference for the performance and consumer acceptability metrics while the twin-clutch E-REV was used as the reference for the risk, education, and Ohio focus metrics.

The results of the decision matrix in [Appendix E](#) show that the parallel-series PHEV vehicle is the best hybrid vehicle architecture choice for the Ohio State team. The simulation results showed the parallel-series PHEV had the best composite fuel economy out of all four vehicles along with the longest all-electric range. Additionally, the parallel-series PHEV had better packaging attributes to it than the series hybrid and post-transmission PHEV due to the separation of the two motors into two locations.

It was also felt that there was additional performance to be obtained for the parallel-series PHEV as the *Autonomie* model developed did not take full advantage of all of the operating modes available to the parallel-series PHEV. By way of example, the model did not optimally balance the use of the electric motors nor did it take advantage of the series mode that is available to the vehicle. These extra elements of functionality could not be developed in the short time available for architecture selection - nor did they materially select the decision as it would only strengthen the parallel-series performance.

Powertrain Component Selection

Based on the discussion above, the selection of the energy storage system and the engine were decisions made upstream of the architecture selection process. These decisions were made based on sound analysis of the design goals of the

project. The remaining major powertrain components include the front electric motor and inverter, rear electric motor and inverter, rear transaxle, and front transmission.

The simulation study provided targets for component specifications for the remaining powertrain components. These included: torque and power specifications for the electric motors; gear ratio for the rear drive; desired gear ratios range for the transmission; and a number of other requirements. Additionally, major systems already selected provided constraints, such as the battery voltage range which impacted inverter and motor selection.

Beyond technical requirements, business issues also impacted component selection - primarily in the form of team budget constraints. The team was fortunate to be able to partner with Parker-Hannifin for both permanent magnet motors and inverters. They provided a limited range of options; however, they matched quite well with the targets. The transmission selection was driven by a number of factors, and is discussed in great detail in the Packaging and Integration section. The last major component was the rear transaxle. In this case, a deeply discounted unit was secured from Borg-Warner which matched the desired ratio from the design simulations.

A detailed packaging study has also driven both the choice of major components and their orientation in the Ohio State vehicle. The major components influencing the vehicle design are given in [Table 3](#) through

Table 3. Front Powertrain Component Summary

GM MF3 M32 Six-Speed Manual Transmission	- Max torque: 320 Nm - Weight: 46.7 kg - Length: 334 mm
Luk Single Disk Dry Clutch	- Static dry torque : 186 Nm - Max rpm: 7000
2008 Honda 1.8 L CNG Engine (converted to run on E85)	- Same engine used in previous competition - 100 kW peak power output
Parker Hannifin MPT 2104 Electric Machine	- 118 kW peak output power - 180 Nm peak torque
Parker PMAC Mobile Duty Inverter	- Nominal operating voltage: 350 VDC - Nominal Operating Range: 205-410 VDC - Peak Current output: 450 amps - Continuous Current Output: 200 amps
Belt Coupling Housing	- Belt Coupling used to transfer torque from front electric machine to transmission - Custom housing designed for OSU vehicle
GM DC/DC Converter	- Steps down 340V to 12V in the OSU vehicle - 2.2 kW rated power
High Voltage AC	- Operates on 290-420V - Pulls 15A at 300V and 25oC

Table 4. Rear Powertrain Component Summary

Parker Hannifin MPT 2106 Electric Machine	- 118 kW peak output power - 270 Nm peak torque
Borg Warner 31-03 single speed gearbox	- Continuous Input torque: 200 Nm - Max input speed: 14,000 rpm
Parker PMAC Mobile Duty Inverter	- Nominal operating voltage: 350 VDC - Nominal Operating Range: 205-410 VDC - Peak Current output: 450 amps - Continuous Current Output: 200 amps

Table 5. Energy Storage Component Summary

A123 7 x 15s3p Battery Pack	- Minimum Pack Energy 18.9 kW-hr - Operating Voltage of 340 volts
10 Gallon Fuel Tank	- Welded aluminum sheet design utilizing similar methods from EcoCAR competition
Brusa Charger	- 3.3kW BRUSA NLG-513
EVAP Canister	- Houses excess fuel fumes to be burned in the engine when started

Key Tradeoffs in Powertrain Design

As described in the previous sections, OSU followed a rigorous design process in order to develop the best possible design based on the constraints. Some of the key tradeoffs discussed and a summary of the impact are captured in the following list. In the relevant subsections, many more tradeoffs are discussed at the subsystem and component level.

1. Fuel Choice: Analysis demonstrated that hydrogen was actually a “better” choice based on competition point structure; however, the team did not choose this fuel. Instead, E85 and electricity were chosen as the best fuels for the team. Hydrogen poses a high financial cost for hardware as well as high technical risk - the team's design process penalized these risks in favor of E85. As shown in [Figure 3](#) and [Figure 4](#), the combination of E85 and electricity are the next strongest choice and align with the team's interest and experience.

2. Energy Storage System Size: Based on the analysis leading to [Figure 4](#), the team's choice of the largest available A123 Systems battery pack was justified. The larger pack offered with it a higher weight and packaging volume as a trade-off. The team's early packaging analysis proved that the pack could be integrated with no loss of passenger space and a moderate loss of trunk space. A decision matrix analysis proved that this tradeoff was justified for the competition.

3. Front Powertrain - The front axle powertrain presented several key tradeoffs, the most notable of which was selection of a transmission that would fit within the width of the vehicle with the selected architecture. After reviewing specifications and CAD on a number of transmissions, the

team determined that none of the available transmissions would both package in the vehicle and meet the max torque requirements. The team opted to accept a lower max torque requirement from the front powertrain, however, the rear electric motor was increased in size to make up for the reduction.

4. Rear Powertrain - The major tradeoffs in packaging the rear axle powertrain were: intrusion on trunk space, intrusion on cabin space, and interference with structural vehicle members. These issues were compounded by the requirements of a larger motor in the rear driven by the transmission issue described in (3) above. This tradeoff is discussed in greater detail later in the report; however, the eventual tradeoff was deemed appropriate given the team's design goals.

Powertrain Configuration Summary

The parallel-series PHEV architecture selected by the Ohio State team has the following characteristics that make it the right choice for the Ohio State team. The final step in the process outlined in [Appendix D](#) is the generation of VTS targets for the actual vehicle. These VTS targets are an outcome of this process, most of which are derived from the simulation model that was developed. Key features include:

- Ability to operate in charge depleting, charge sustaining series, and charge sustaining parallel operation
- Robust, fault tolerant design
- Challenging mechanical, electrical, and control system design problems
- Team-programmed engine, transmission, and vehicle supervisory controllers
- 50 mile all-electric range

CONTROLS DEVELOPMENT PROCESS

Control Development Process

The controls development process is illustrated by the yellow area of the V-Diagram given in [Appendix A](#). The development of controls software has occurred in tandem with the powertrain design throughout the entire vehicle design process. First, requirements were defined for high-level supervisory controls followed by subsystem controls and low-level controls. Next, hardware and software designs were developed for each level of controls. HIL validation and testing is being performed on all of the vehicle controls before in-vehicle implementation during Year 2.

Control Development Tools

A variety of control development tools are employed by the Ohio State team throughout the control development process. The entire control system was designed and

constructed using MATLAB and Simulink, employing a variety of toolboxes contained within these powerful tools. In addition to these tools, dSPACE's Hardware-In-the-Loop simulator was used to develop and validate the control system.

The team employed professional tools to conduct Fault Tree Analysis (FTA) and Design Failure Mode and Effects Analysis (DFMEA), using Isograph's Reliability Workbench with FaultTree+ to conduct FTA, and Byteworx FMEA software to carry out DFMEA.

To determine test coverage for the control models, The Mathworks/Simulink *Design Verifier* and *Model Coverage* tools are being used. Both are tools built into MATLAB and Simulink for analyzing Simulink models. *Design Verifier* ensures that all portions of the model are accessible and allows the team to test and prove various properties of the model. The *Model Coverage* tool measures how thoroughly model objects are tested by determining how many of all possible simulation pathways in the model have been exercised during a test. This will ensure that all of the code in the controllers has been validated through SIL and HIL before implementation in the vehicle.

Plant Model Development for SIL/HIL

The Ohio State team uses a combination of self-developed models and detailed dSPACE component models in the SIL and HIL environments for control development and fault testing purposes. Table 6 contains a description of the plant model components, lists their state in both SIL and HIL development, identifies the source of the model, and lists the reasons the features were implemented into the plant model.

The Software-in-the-Loop models used by the team are mostly self-developed and are combined into a single energy based simulator called EcoSIM. EcoSIM is an energy based hybrid vehicle simulator developed by Ohio State teams over the span of over 15 years through FutureCAR, FutureTruck, ChallengeX and EcoCAR competitions, and is adaptable to different hybrid powertrains. The EcoSIM simulator contains models for each of the powertrain components that consist of static maps, simple transfer functions and simplified soft ECU's. EcoSIM in the SIL environment is especially useful for testing the effectiveness of new control algorithms at improving fuel economy.

The Hardware-in-the-Loop (HIL) models are used with the team's dSPACE HIL equipment to test the CAN communication between the different team programmed controllers and test the controller's response to fault conditions within the vehicle. The sources for the individual powertrain component models range from the team programmed models taken from EcoSIM to the detailed ASM models created by dSPACE for the engine, transmission and battery components. The detailed ASM models have many of the sensor/actuator signals found on a real vehicle, allowing the team to conduct complex fault testing on their HIL equipment before the controller code is implemented on the vehicle. The detailed ASM models are not yet implemented

on the team's HIL equipment, but they will be implemented by the Year 1 competition in May 2012.

Table 6. Models and Hardware used by the Ohio State EcoCAR 2 Team

System/ Control	SIL	HIL	Features
Vehicle Chassis	Standard road load model with longitudinal dynamics	Standard road load model with longitudinal dynamics	Exact body dimensions required for accurate CFD
Engine & Engine Controller	Static map with simple transfer function dynamics; Simplified soft ECU	Static map with simple transfer function dynamics; Soft ECU with all safety critical I/O for initial testing and actual hardware/code for more advanced testing	Proper engine model required to model torque capability, fuel efficiency, and fault detection
Engine Controller			
Front Electric Motor	Static map with simple transfer function dynamics; Simplified soft ECU	Static map with simple transfer function dynamics; Soft ECU with all safety critical I/O	Proper electric motor and inverter model to assess electrical consumption, inverter and motor losses
Front Inverter			
Rear Electric Motor	Static map with simple transfer function dynamics; Simplified soft ECU	Static map with simple transfer function dynamics; Soft ECU with all safety critical I/O	Proper electric motor and inverter model to assess electrical consumption, inverter and motor losses
Rear Inverter			
Battery	Static maps with energy storage state; Simplified soft ECU	Static maps with energy storage state; Soft ECU with all safety critical I/O	Accurate battery model required to estimate SOC, charge depleting range, effectiveness of charge sustaining, fault detection
Battery Control Module			
Transmission	Static maps with binary clutch, simple transfer function dynamics	Static maps with binary clutch, simple transfer function dynamics; Soft ECU with all safety critical I/O for initial testing and actual hardware/code for more advanced testing	Accurate transmission model required to observe efficiency, gear selection, fault detection

Finally, the team has also created detailed physics-based, sub-system models for each of the research projects assigned to students on the EcoCAR 2 team. These detailed sub-system models include CFD models for analyzing aero improvements, a GT-Power model of the engine, and thermal models of the powertrain components.

HIL Test Bench Setup

The Ohio State team's HIL system setup will be partitioned into four separate cases, outlined in Figure 5 and summarized in Table 7. This will allow validation from the sub-system controller level to the entire controller network that will be developed by the team. Each of these cases has a specific purpose, to test and validate the three OSU-coded controllers as highlighted in Table 7. OSU will be

demonstrating the most aggressive case, Case 4, at Year 1 Competition Finals.

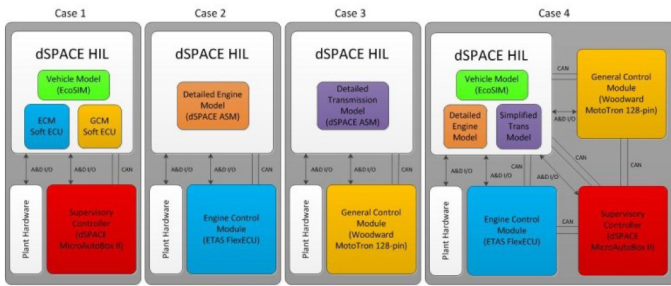


Figure 5. HIL Setup Cases

Table 7. HIL Simulation Setup

Case	Purpose	Physical Hardware	Modeled in HIL
1	Validate Supervisory Controller	Supervisory Controller	ECM + Engine, GCM + Transmission, Vehicle Model
2	Validate Engine Control Module	Engine Control Module	Engine, Supervisory Controller, GCM
3	Validate General Control Module	General Control Module	Transmission, Supervisory Controller, ECM
4	Validate OSU Control Network	Supervisory Controller, Engine Control Module, General Control Module	Engine, Transmission, Vehicle Model

Controls Development Process Summary

Due to the complexity of the Ohio State team's vehicle architecture and control architecture, an aggressive SIL and HIL development plan is necessary to ensure a robust control system that is ready for implementation in the vehicle.

CONTROL SYSTEM ARCHITECTURE

Control Architecture Design Process

The requirements for the vehicle's control system architecture, supervisory control algorithm and hardware for the supervisory, engine and transmission controllers are listed in Table 8. These high-level qualitative requirements are used to guide the selection process and eventually lead to engineering specifications.

These requirements were derived from the needs/wants the team had for each of the different controllers and the team's previous experience in the EcoCAR competition. The I/O requirements for the engine, supervisory and transmission/general control module hardware were derived from detailed the I/O lists based on plant hardware. The requirements for each controller are used in the control architecture section to select the vehicle architecture and controller hardware for the Ohio State vehicle.

Table 8. Requirements for Control Architecture and Team Programmed Controllers

	Requirements
Control System Architecture	- Contains modular design - Compatible with Hardware-in-the-Loop, Dynamometer and in-vehicle testing - Resistant to fault conditions - Has clear chain of command between controllers - Allows a single controller to manage multiple lower level controllers in an organized manner
Supervisory Controller Algorithm	- Algorithm is capable of optimizing a complex system - Optimization algorithm can be run in real time on a high performance rapid prototyping controller - Algorithm is simple enough to be designed and optimized by undergraduate, masters and Ph.D. students in less than three years - Algorithm continues the control development work started in Challenge X and EcoCAR - Algorithm does not need a large amount of real world data to initialize it before it is used in the vehicle - Algorithm is stable (does not have convergence problems)
Supervisory Controller Hardware	- Has at least 3 ADC inputs, 3 DAC outputs and 3 CAN busses - Uses Matlab/Simulink environment for algorithm code - Can execute complex control algorithms in real time) - Made for rapid-prototyping - Can build and flash code in under 30 minutes - Can wake up quickly when vehicle is put into accessory or key-on - Can withstand vibration and temperature conditions inside vehicle cabin - Low cost - Has good reliability record from manufacturer and current users
Engine Controller Hardware	- Has at least 20 analog inputs, 2 Crank/Camshaft Inputs, 1 digital input, 3 lambda inputs, 14 low side drivers, 7 digital outputs, 3 H-Bridge drivers and 2 CAN busses - Uses Matlab-Simulink environment for engine controller code - Comes with skeleton code or method of porting old engine code to new controller - High performance hardware - Made for rapid-prototyping - Can build and flash code in under 30 minutes - Can withstand vibration and temperature conditions inside engine bay - Low Cost - Has good reliability record from manufacturer and current users
General Control Module Hardware	- Has at least 14 analog inputs, 3 H-Bridge drivers, 5 digital outputs, 2 low side drivers, 1 variable reluctance/hall effect input and 1 CAN bus - Uses Matlab-Simulink environment for controller code - Made for rapid-prototyping - Can build and flash code in under 30 minutes - Can withstand vibration and temperature conditions inside engine bay or vehicle cabin area - Low Cost - Has good reliability record from manufacturer and current users

Control System Architecture

The control system architecture chosen by the Ohio State team is shown in Figure 6. The control architecture includes a high level vehicle supervisory controller that manages vehicle mode operation and the power split between the different powertrain components. Three different CAN networks are then used for communication between the vehicle's supervisory controller and the lower level controllers used to