Development of a Hybrid Vehicle Control System

THESIS

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The EcoCAR 3 project is a four-year competition sponsored by General Motors and the U.S. Department of Energy challenging 16 university teams to reengineer a 2016 Chevrolet Camaro to be a performance hybrid electric vehicle. The Ohio State University designed a parallel hybrid electric vehicle with a 0 to 60 mph acceleration goal of 5.6 seconds and a 44 mile all electric range.

Before the performance and emissions goals can be met the team must fully mechanically and electrically integrate their hybrid vehicle architecture. Concurrently to the vehicle integration, the controls team developed the basic vehicle controls that would be required to meet the goals for the second year of the competition. The controls development started with fully defining the vehicle controls requirements and then evaluating which requirements would be met in each part of the development process. The controls validation occurred using a team-developed vehicle model in both the Software- and Hardware-in-the-Loop environments. The main focus for this part of the development was defining and implementing the basic controls, such as controller communication and vehicle startup, which are critical to eventually having a fully functional vehicle.

With the Year 2 controls validated in the HIL environment, a vehicle implementation plan was developed to be implemented and validated by May of 2016. The full controls
development plan that was developed to meet the high level team goals included both performance and efficiency modes that will be implemented and validated in Year 3 and 4 of the EcoCAR 3 project.
DEDICATION

I would like to dedicate this thesis to my wonderful family who has encouraged and supported me throughout my educational career.
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I would like to thank the EcoCAR 3 team. Especially the great team leaders who helped make the EcoCAR 3 project a success. Andrew Huster, Dennis Kibalama, Arjun Khanna, and Sam Yacinthe each helped me better understand their areas of the EcoCAR project and just generally support the work that I have been doing. I would like to thank Dr. Shawn Midlam-Mohler who has been a wonderful advisor of the EcoCAR 3 project. I would also like to thank Dr. Giorgio Rizzoni who has encouraged my interest in automotive engineering and automotive control since I was a student in high school. I would also like to thank the past team leaders of the EcoCAR 1 and EcoCAR 2 teams who gave me the controls and system modeling and simulation foundation that allowed me to lead the controls development for the EcoCAR 3 Project.
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CHAPTER 1: INTRODUCTION

Hybrid electric vehicles offer a unique opportunity for energy management resulting in fuel and emissions reductions. The hybrid energy management optimization problem has been evaluated and solved in the theoretical and computational world, but actual real time implementation brings to light many other challenges. This paper discusses the development and implementation of a hybrid supervisory controller and low level vehicle controls for the Ohio State EcoCAR 3 post-transmission parallel plug in hybrid electric vehicle (PHEV).

1.1 EcoCAR 3 Competition

The Ohio State EcoCAR 3 vehicle was designed to compete in the four-year EcoCAR 3 competition. Sixteen North American university teams were given the challenge to re-engineer a 2016 Chevrolet Camaro to be a performance hybrid electric vehicle. The high level technical goals of the competition were to reduce energy consumption; reduce wheel-to-well greenhouse gas emission; reduce criteria emissions; maintain consumer acceptability in the areas of performance, utility, and safety; and meet energy and environmental goals while considering cost and innovation.

1.2 Ohio State EcoCAR 3 Architecture Overview

The Ohio State EcoCAR 3 vehicle is a post-transmission parallel PHEV. Each hybrid vehicle architecture allows for a unique set of vehicle operating modes. The main vehicle operating modes for the OSU EcoCAR vehicle are as an electric vehicle and a charge
sustaining hybrid allowing for a total vehicle range above 200 miles. Figure 1 is a representation of the EcoCAR 3 vehicle. The main powertrain components of the vehicle were a 2.0 L naturally aspirated E85 compatible engine, 150 kW (peak) electric motor (EM), 32 kW belted alternator starter (BAS), 5-speed automated manual transmission (AMT) and an 18.9 kWh lithium ion battery pack. The vehicle was designed to have an all-electric vehicle range of 44 miles, an improved charge sustaining fuel economy, as well as a 0 to 60 mph acceleration time of 5.6 seconds. The full set of team defined vehicle technical specifications (VTS) are included in Appendix B. The vehicle drive mode development is detailed in Chapter 4.

Figure 1: Ohio State EcoCAR 3 Vehicle Architecture
1.3 Project Timeline and Objectives

The first year of the EcoCAR 3 competition (2014-2015) was focused on architecture selection, requirement development, and system modeling and simulation. The second year of the competition (2015-2016) was the completion of the design and the integration of the hybrid vehicle powertrain. The third and fourth years of the competition include vehicle refinement and validation with a focus of controls improvements. Each year of competition is concluded with an evaluation of the project status relative to the vehicle development timeline, Figure 2.

![Figure 2: Ohio State EcoCAR 3 Vehicle Development Plan](image)

As EcoCAR 3 is a four year project, the vehicle controls development was not completed in the first two years of the project. In Year 1, a four year controls specific development plan was defined. This plan defined major controls milestones which align with the overall vehicle development timeline. The focus of Year 1, outside of the designing of the vehicle, was to develop controls requirements and vehicle operating modes. A simple
controls strategy was also defined and implemented in the model in the loop (MIL) environment. By the end of Year 2, the hybrid powertrain was fully integrated into the vehicle. All low level component controls and vehicle controls were required to be functional to meet Year 2 goals. Chapter 7 discusses the implementation plan for controls on the vehicle in Year 2 as well as the continued controls development and validation that will be done in Years 3 and 4 of the competition.

1.4 Motivation

There were a number of sources of motivation for the Ohio State EcoCAR 3 project. The first is the demand for hybrid electric vehicle due to the Corporate Average Fuel Economy (CAFE) standards set by the United States government. While the mainstream consumer market for new hybrid electric vehicles has remained around 3 percent, the number and visibility of hybrid electric vehicles has increased over the last decade. Every automotive manufacturer has a portfolio that includes hybrids to be able to meet the CAFE standards. Many technologies improving fuel efficiency were developed for hybrid vehicles and have been implemented in conventional vehicles. Automotive manufacturers will continue to invest in new and different hybrid and electric vehicles to be able to meet the 2025 CAFE standard of 54 MPG [1].

A second motivation was the lack of an affordable performance hybrid vehicle. Understandably, many of the hybrid electric vehicles on the market today are designed for fuel efficiency and not performance. While there are vehicles that have been moving towards a better balance of efficiency and performance, the conversation still remains
that hybrid vehicles are boring or no fun to drive. Part the EcoCAR 3 project was understanding who the customer for an affordable performance hybrid vehicle is, and what specifically they would want in a vehicle. The goal for a performance hybrid vehicle that is appealing to the consumer drove the high level vehicle design discussed in later sections.

The third source of motivation was the motivation for the EcoCAR program specifically, and that was to train the next generation of automotive engineers. The EcoCAR 3 program gives students an understanding of the different aspects of the vehicle design process including the high level architecture decisions. Many of the tools and processes used for this project are the same as what is used in the automotive industry.

The motivation for this thesis builds on the last part of the EcoCAR 3 motivation. It is important to learn from the project and maintain the knowledge gained from year to year. The work discussed in this thesis includes a number of the little things that may seem small, but are critical to successful vehicle operation. By documenting the Year 2 controls development process, the hope is that future teams will be able use this document as controls reference.

1.5 Outline of Thesis

This thesis focuses on three main aspects of controls development: Controls support systems, hybrid supervisory control development and validation, and fault detection and mitigation. Chapter 2 is a literature review which covers all three of these topics, as well
as briefly discussing hybrid vehicle strategies that were implemented by previous teams at Ohio State. Chapter 3 details the considerations made when integrating a new controls network with the existing stock vehicle controls network. This chapter also discusses controls support systems which are the little talked about systems that are required to have a functioning vehicle. Chapter 4 discusses the development of a hybrid operating control strategy for the Ohio State EcoCAR 3 vehicle as well as the limitations due to the Year 2 development timeline. Chapter 5 introduces the fault detection and mitigation strategies implemented in the EcoCAR vehicle. Chapter 6 includes an introduction to the controls development process as well as the tools used as part of this validation process. Chapter 6 also includes the results from the first stages of controls validation. Chapter 7 outlines the plan for controls implementation in the vehicle, as by the completion of this thesis, the EcoCAR vehicle was mechanically integrated and ready for vehicle controls testing to begin. Chapter 7 also includes a controls development plan to meet the VTS targets in later years. The full development plan includes thoughts about potential energy management strategies which could be implemented on the EcoCAR 3 vehicle.
CHAPTER 2: LITERATURE REVIEW

2.1 Vehicle Communications Networks

As automobiles increased in complexity, the number of electronic control units (ECUs) needed to control various aspects of the vehicle also increased. A typical car on the road today could have anywhere from 40 to 100 microcontrollers [2], [3]. These controllers are used for powertrain control, chassis control, and human interface controls. On average there may be more than 2500 signals sent and received over the communications networks at any given time [4]. Figure 3 is a snapshot of the complexity of the potential communications in a vehicle. The figure also highlights that not all of the controllers communicate in the same way or over the same network. A typical vehicle today would include a few high speed and low speed CAN networks, a LIN or LAN network, and a MOST network. Each of these communication networks is based on a different protocol and implemented for a specific purpose. Most of the vehicle safety critical controllers communicate over a Controller Area Network (CAN).

The CAN protocol was developed by Bosch in the late 1980’s and adopted in the United States, a similar protocol was adopted in Europe, in the early 1990’s [2]. CAN is a priority-based communication protocol, which means that messages are sent based on a predetermined priority identifier [2], [5]. A very important message, such as brake
position, would have a low identifier number and would always be sent over a message with a higher priority identifier.

In deciding to utilize a CAN network structure there are a number of considerations that are made. By its very definition CAN has the following properties: prioritization of messages, guarantee of latency times, configuration flexibility, multicast reception with time synchronization, system wide data consistency, multimaster, error detection and signaling, automatic retransmission of corrupted messages as soon as the bus is idle again, and distinction between temporary errors and permanent failures of nodes [7]. A CAN network is fault tolerant for a number of reasons, but one is that because of the expected frequency of the messages (time-triggered system) communication nodes know that if a message is not received as expected that there could be a communication failure.
somewhere else in the network [2]. Other considerations that have to be made when developing a CAN network are the actual structure of the network, the loading of the network, and how the network will interface with other communications networks (gateways).

2.2 Hybrid Vehicle Controls

The problem of optimal energy management in hybrid electric vehicles is an interesting one and many researchers have developed different ways to solve the problem. There is an exhaustive amount of literature on different techniques for hybrid energy management. The strategies range from strictly computational methods to strategies implemented on hybrid electric vehicles. At the highest level the main object of any energy management strategy is to minimize the fuel consumption (or energy usage) over a defined trip or cycle. The global minimization problem can be expanded to include minimizing emissions or a requirement to balance SOC. If the optimization is performed over a fixed drive cycle a solution can be found [8]. The energy management strategy is usually part of a hybrid supervisory controller which takes in vehicle speed and driver requests and outputs theoretical component torques to meet the driver’s requested torque. The supervisory controller makes the decisions, but the component controllers are physically controlling each component (engine, electric motors, transmission, and battery).

There are different strategies for utilizing the energy in the battery for a PHEV which plays a part in the energy management strategy selected. A blended strategy uses a combination of both the battery and the engine over the entire cycle. Another potential
strategy is to have an electric only mode, and a charge sustaining mode where the battery must stay within a certain SOC range. In a traditional HEV, the only option is charge sustaining, as any energy that is used over the cycle must be recharged through engine charging or regenerative braking.

The global minimization problem can be solved computationally; however, implementing many of these strategies in real time is impossible. Many solutions require previous knowledge of the route before it is driven, known as a priori knowledge. A few of the most often discussed solutions are summarized below.

2.1.1 Rule-Based Control

The one of the simplest types of energy management is rule-based control. There are different ways to implement this strategy, but generally it includes predefined points or thresholds for when components will be used. Often these rules are based on intuition or mathematical models [8]. Rule-based control can be subdivided into deterministic and fuzzy control. This review will focus on the former, as a form of rule based control used as part of the EcoCAR control strategy is discussed in Chapter 4. Deterministic rule based control includes on/off control, power follower control, and state machine based control. In state machine based strategy, the transition between modes is based on a change in driver demanded torque, vehicle operating conditions, or a system or subsystem fault. The full efficiency of the powertrain many not be fully utilized and it can often require a great deal of calibration. Rule-based control dependent on calibration may not be robust to all operating conditions [9], [10]. Fuzzy rule-based methods are
robust and easily tuned; however, these methods can get computationally complex with the expansion of hybrid architectures [8].

### 2.2.2 Dynamic Programming

Dynamic programming is a numerical method used for solving decision making problems. At its simplest form, it is a backwards-looking minimization performed at each instance in time. The dynamic programming solution will be the closest solution to optimal; however, it requires future (a priori) knowledge of the cycle [11]. Needing to know the upcoming drive cycle makes this method non-implementable in real time, but the dynamic programming solution is often used as a comparison tool and benchmark against real time control strategies and to developed rule based controls [11],[12].

The model, control, and state variables are defined and then minimized at each step in the cycle. Dynamic programming allows for the minimization of multiple objectives (i.e. fuel consumption and emissions) [12]. A fully defined problem will also include limits on each of the powertrain components. As mentioned above, the dynamic programming solution is nearly the optimal solution, but is computationally intense and not implementable. The biggest factor preventing real-time dynamic programming implementation is the need for a priori knowledge, but with the advances in GPS systems an adapted dynamic programming solution could potentially be implemented.

### 2.2.3 ECMS

The energy consumption minimization strategy (ECMS) offers a real-time implementable optimization that is much less computationally intense than dynamic programming. At its
core, ECMS creates a function where the cost of electrical energy is assigned an
equivalent cost value. This equivalent cost value accounts for the fact that at some point
fuel will be used to recharge the battery (for charge sustaining operation) [10], [11], and
[12]. The instantaneous minimization is performed at each point in the drive cycle based
on driver requested torque and does not require previous knowledge of the cycle. There
are many ways to implement ECMS, but the defining equations remain the same. The
equation below shows the local cost function, where the cost is the total equivalent fuel
cost used to meet a specific power request. One way to find the cost values is to create a
map of potential operating points offline and then select the minimum point on that map
during driving [6]. The cost calculation can also be done online [10].

\[ J(t, u) = \Delta E_f(t, u) + s(t)\Delta E_e(t, u) \]  \[10\]

Where \( \Delta E_f \) is the fuel energy consumed and \( \Delta E_e \) is the electrical energy consumed over
the defined time interval.

The equivalence value mentioned above (denoted as \( s \)) is an incredibly important part of
ECMS. Generally there are two \( s \) values, one for charging the battery and one for
discharging the battery. One major concern with implementing ECMS is the sensitivity to
the equivalence value. \( s \) can be tuned for charge sustaining operation over a specific
drive cycle and then be non-charge sustaining over any other [15]. One way to deal with
this problem is to run offline simulation over many drive cycles to create a map of
optimal \( s \) values based on driving conditions. This map could then be referenced in real
time based on driving conditions. Another way to modify \( s \) is to have \( s \) as a function of
the difference between the current battery SOC and the target battery SOC. While these values of $s$ would still need to be calibrated, it would allow for a high $s$ value when the battery has dropped below the target to encourage heavy engine use.

Another problem with real time implementation of ECMS is the potential for rapid changes in requested engine operating points [10], [16]. This comes from the instantaneous nature of the optimization. In any case, the ECMS solution is close to the dynamic programming solution while being less computationally intense and implementable in real time.

2.3 Hybrid Vehicle Controls and Ohio State EcoCAR

It is important to explore the work that has been done on past Advanced Vehicle Project teams to understand the controls strategies and processes that were successful as well as potential areas that could be improved. The modern era of Advanced Vehicle Technology Teams at Ohio State began with the Challenge X Competition in 2004. The EcoCAR 1 (2008 to 2011) and EcoCAR 2 (2011 to 2014) competitions lead to far more complex vehicle architectures with opportunity for the development, implementation, and validation of more complex energy management strategies. Many high level decisions made in the EcoCAR 3 development process were based on lessons learned from these former projects.

2.3.1 Controls Strategies

Both the EcoCAR 1 and EcoCAR 2 vehicles were parallel-series PHEVs with the ability to operate as an electric vehicle, a parallel hybrid, or a series hybrid [16], [17]. The main
architecture difference between the two vehicles was the implementation of an automated manual transmission in the EcoCAR 2 vehicle. Figure 4 and Figure 5 are power flow diagrams for the EcoCAR 1 and EcoCAR 2 vehicles respectively. In EcoCAR 1, a high level rule-based control strategy was coupled with energy management strategies for electric and series operation. The architecture included two electric motors which allowed for the development of an optimal power split between the motors during electric only operation [18]. The power minimization was implemented in real time and extended the vehicle all-electric range. In series mode the team explored both a load following algorithm and ECMS. The load following algorithm calculated the power being consumed by the vehicle and requested that amount of power from the engine/generator system while the rear electric motor drove the vehicle [18]. This algorithm was tuned to maintain SOC around a specific value. An ECMS method was also investigated for series mode implementation, but ultimately the benefit of ECMS was not able to outweigh the complexity and potential drivability concerns [16].

The EcoCAR 2 vehicle controls were built on the foundation developed in EcoCAR 1 and expanded. The electric only mode utilized a similar motor power optimization strategy but was expanded to include optimal gear selection as well [17]. This optimization was moved from a real time optimization to an offline optimization that was implemented in real time through maps. These improvements also increased the electric range of the vehicle. An investigation was done into series mode improvements, evaluating thermostatic (on/off) control, load following, and ECMS. The thermostatic
series control was determined to be the most efficient mode, however, because of the previous controls validation done in EcoCAR 1, a simple load following algorithm was used [17],[19].

Figure 4: OSU EcoCAR 1 Vehicle Architecture [24]

The biggest change to the EcoCAR 2 controls strategy was the implementation of an ECMS strategy for parallel vehicle operation. ECMS, as discussed above, found a local minimum for equivalent fuel consumption while satisfying a number of other constraints. The ECMS calculations were done offline because of their computationally intense nature [17]. A torque distribution map was calculated for each gear and optimized offline.
2.3.2 Lessons Learned from Past Competitions

Both the EcoCAR 1 and EcoCAR 2 teams were successful in building and developing complex vehicle controls. The EcoCAR 3 team used many lessons learned from these successful teams. Later sections of this thesis will discuss the controls development process used in EcoCAR 3, but the core of this process has been used and refined for more than 10 years. The model-based controls design process has allowed teams to fully validate and optimize controls logic before the vehicle built [20]. Previous teams have also paid close attention to the details required to have a working vehicle, both from the controls perspective and the physical controller systems. Chapter 3 discusses the controller system design considerations made by the EcoCAR 3 team.

Lastly, and possibly most importantly, these teams were successful, but were not always able to implement the controls strategies discussed above in the actual vehicle. With this
knowledge, the controls development was divided into clear parts which could be implemented throughout the competition. This last lesson learned is what drove the segmentation between the Year 2, Year 3, and Year 4 controls requirements and helped the team set lofty but realistic goals for each year.

2.4 Fault Detection and Mitigation

Another important aspect of overall controls development is fault detection and mitigation. A fault is an unexpected or unpermitted change in a value or state of a system. There are three main types of faults, shown in Figure 6. Faults can be abrupt, incipient, or intermittent [30]. An abrupt fault could come in the form of a sudden mechanical failure, causing a component to overspeed. An incipient fault could be a component slow heating up and exceeding a predefined temperature limit. An intermittent fault could come from a faulty sensor that may read the correct value sometimes and the incorrect value other times. Each of these faults have to be detected in different ways. A fault detection strategy may be developed to detect any or all of these faults depending on the system. Fault system design can be divided into three parts: fault detection, fault isolation and fault identification [32].
Fault detection methods vary in complexity from limit-based supervisor methods to complex model-based fault detection based on the system being monitored [30]. The type of fault detection that can be used also depends on the dynamics of the system or signal. Figure 7 is a representation of a supervisor method of fault detection. In this scheme, the system is always monitoring the signals with respect to pre-defined tolerance values. In the event of a dangerous condition, action will be taken to mitigate the fault or shutdown the system. These systems are generally only able to react to a change in the system and do not necessarily anticipate that a fault state is approaching. In more complex model-based systems, a model of the system can be created and the recorded values can be continuously compared to the values from the model. If the values differ by more than a predefined amount a fault will be triggered. Research has also been done on a data-driven approach to fault detection. In this case, component tests can be designed and faults can
be inserted into the system to understand how the system will react. Based on the data, an algorithm can be created.

![Fault Detection Supervision Method](image)

Figure 7: Fault Detection Supervision Method [31]

Fault diagnosis includes not only detecting the fault, but also the type, size, and location of the fault [31]. Fault identification and classification methods are used to determine as much information about the fault as possible, including causes, symptoms, and impact on other systems. Just as there are many ways to detect a faults there are many ways to identify potential faults. A method often used to determine the causality of a fault is a fault tree analysis, which starts by identifying all potential faults and identifying every potential symptom. The reverse process is an event tree analysis (ETA), where the
evaluation begins with the symptoms and evaluates what fault could have caused the symptoms [31].

Understanding fault detection and isolation is in the scope of this thesis. The actual fault detection algorithm development was outside of the scope of this thesis; however, the fault mitigation actions triggered by the fault detection were within the scope of this thesis and will be discussed in Chapter 5.
CHAPTER 3: CONTROLS REQUIREMENTS AND SUPPORT SYSTEMS

3.1 Introduction

The first steps in the controls development process include understanding the needs of the controls system and defining requirements to meet those needs. The requirements start with basic vehicle functionality and progress through to the energy consumption of the vehicle. Another part of the controls development process that is different from the strategy and algorithm development is the actual set up of the physical controls network and the controls support systems. A number of considerations were taken into account when developing both the physical controls system and the overall hybrid control strategy.

3.2 Controls Requirements

The control system and subsystem requirements were defined in the first year of the EcoCAR 3 project. The system requirements were derived from stakeholder expectations and team high level requirements. The overall high level requirements included: the competition rules; team vehicle technical specifications (VTS); the hybrid architecture selected; and the expected use of the vehicle throughout its useful life (concept of operations). The system requirements were divided into: functional, interface, safety, and performance.
The required functionality of the Ohio State EcoCAR 3 vehicle was defined and validated through these requirements. To further clarify, there were overall competition requirements which focus on the four-year development process, as well as year-specific requirements. This section will discuss how all requirements were developed, but focuses on the Year 2 functional controls requirements.

3.2.1 Vehicle Technical Specifications and Competition Requirements

During the vehicle architecture selection process the team was required to set vehicle technical specifications for their selected architecture. The VTS targets may be goals set by the team or by the competition. The VTS values selected were validated through powertrain modeling and simulation. A selection of team VTS targets are included in Table 1. The full list of VTS targets set by the team can be found in Appendix B. From a controls perspective, most of the requirements based specifically on VTS values will not be met until Year 4 of the development process. These energy consumption targets will be met through energy management strategy implementation and refinement. Other high level requirements drove the need for unique vehicle modes and can be integrated in Years 2 and 3. The requirement of a 44 mile electric range defined the need for a vehicle mode in which only the electric motor is used to propel the vehicle. To meet the IVM to 60 acceleration target requirement, a performance mode was integrated into the overall controls strategy. The overall vehicle requirements were developed during the vehicle design process; however, as the controls development process continued, more controls requirements were added. These added requirements are, specifically for basic vehicle functionality and fault detection.
Table 1: Selected Ohio State EcoCAR 3 VTS Targets

<table>
<thead>
<tr>
<th>Specification</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration - IVM to 60 mph (Performance)</td>
<td>5.6 seconds</td>
</tr>
<tr>
<td>Acceleration - IVM to 60 mph (Normal)</td>
<td>10 Seconds</td>
</tr>
<tr>
<td>Starting Time</td>
<td>2 seconds</td>
</tr>
<tr>
<td>Total Vehicle Range</td>
<td>328 miles</td>
</tr>
<tr>
<td>CD Mode Range</td>
<td>44 miles – All Electric</td>
</tr>
<tr>
<td>CD Mode Total Energy Consumption</td>
<td>220 Wh/Km</td>
</tr>
<tr>
<td>CS fuel energy consumption</td>
<td>532 Wh/km</td>
</tr>
<tr>
<td>UF total energy consumption</td>
<td>63 mpgge</td>
</tr>
<tr>
<td>UF weighted WTW petroleum energy use</td>
<td>56 Wh/km</td>
</tr>
</tbody>
</table>

3.2.2 EcoCAR 3 Year 2 Controls Requirements

The Year 2 controls requirements were defined based on the competition events in the second year of the development process. More discussion of the EcoCAR 3 Year 2 and Year 3 competition events can be found in Appendix C. On the mechanical and electrical side of the project, all powertrain components were fully integrated into the vehicle; however, because of the short in-vehicle validation window (less than 4 weeks) the Year 2 controls focus was limited. The Year 2 controls requirements were divided into four categories listed below.

1. Basic vehicle functionality
2. Powertrain functionality
3. Mode functionality
4. Fault detection and mitigation

Figure 8 shows the overall controls development timeline for Year 2. Basic vehicle functionality includes vehicle startup and shutdown, shift lever functionality, high voltage
battery charging, accelerator pedal position sensing, and any other driver interfaces. Maintaining basic vehicle functionality is a top priority. It would be difficult to validate any other vehicle functions without first confirming that basic vehicle functions operate as expected. A requirement of the vehicle controls was that the driver interfaces are not changed. This means that the expected vehicle startup sequence and typical operation of the vehicle must be emulated in the team added controls. A good example of the development of controls requirements comes from vehicle startup. In order to startup the vehicle a number of criteria must be met. Those criteria are: the key must be present in the vehicle, the brake pedal must be depressed, the accelerator pedal cannot be pressed, the shift lever must be in Park, and the Start/Stop button must be pressed and held. Once all of these criteria are met, the vehicle enabling procedure can begin. The example of the vehicle startup procedure will be discussed in later sections, as it is a simple example of each part of the controls development process. Figure 9 is a snapshot of the requirements document for the startup process that was created and maintained by the controls team.

The VTS requirement driving the vehicle enabling procedure is that the vehicle must startup within 2 seconds. This means that the time from when the driver presses the start button to the time the vehicle is ready to drive should be around 2 seconds. When the vehicle enabling procedure is complete, the driver is notified via a vehicle ready indicator light. The vehicle startup process (brake, accelerator, etc.) was also defined through EcoCAR competition safety requirements.
Figure 8: Year 2 Controls Development Timeline
<table>
<thead>
<tr>
<th>Development Category</th>
<th>Name and Description</th>
<th>Pass/Fail Criteria</th>
<th>Primary Testing</th>
<th>SIL/HIL Test Procedure</th>
<th>Dyno/On-Road Test Procedure</th>
<th>MIL Status</th>
<th>HIL Status</th>
<th>Vehicle Status</th>
</tr>
</thead>
</table>
| **Vehicle in Park**  |                      | Vehicle does not start, Startup_complete = 0, Veh_Mode = 1 | SIL/HIL          | 1. PRNDL Position = D, R or N  
2. Accelerator Pedal = 0%  
3. Brake Pedal = 100%  
4. Turn key state to "crank" | 1. Key in vehicle  
2. PRNDL Position = D, R or N  
3. Accelerator Pedal = 0%  
4. Brake Pedal = 100%  
5. Press and hold start button | PASS         | PASS         |                |
| **Brake pedal depressed** |     | Vehicle does not start, Startup_complete = 0, Veh_Mode = 1 | SIL/HIL          | 1. PRNDL Position = P  
2. Accelerator Pedal = 0%  
3. Brake Pedal = 10%  
4. Turn key state to "crank" | 1. Key in vehicle  
2. PRNDL Position = D, R or N  
3. Accelerator Pedal = 0%  
4. Brake Pedal = 100%  
5. Press and hold start button | PASS         | PASS         |                |
| **Accelerator pedal not depressed** | | Vehicle does not start, Startup_complete = 0, Veh_Mode = 1 | SIL/HIL          | 1. PRNDL Position = P  
2. Accelerator Pedal = 4%  
3. Brake Pedal = 100%  
4. Turn key state to "crank" | 1. Key in vehicle  
2. PRNDL Position = D, R or N  
3. Accelerator Pedal = 0%  
4. Brake Pedal = 100%  
5. Press and hold start button | PASS         | PASS         |                |
| **Key in Vehicle**  |                      | Vehicle does not start, Startup_complete = 0, Veh_Mode = 1 | SIL/HIL          | 1. PRNDL Position = P  
2. Accelerator Pedal = 0%  
3. Brake Pedal = 100%  
4. Key not in vehicle  
5. Turn key state to "crank" | 1. Key in vehicle  
2. PRNDL Position = D, R or N  
3. Accelerator Pedal = 0%  
4. Brake Pedal = 100%  
5. Press and hold start button | NA           | NA           |                |

Figure 9: Year 2 Requirements Document
Other driver interface controls include the brake and accelerator pedal response. Part of the Hybrid Supervisory Controller (HSC) is the pedal mapping of the accelerator pedal to a driver requested torque. The accelerator pedal map remains the same for all normal driving. In later years of vehicle development, the pedal map for normal and performance modes will vary; however, the driver can only switch into performance mode when the vehicle is at zero speed. Braking is another important basic vehicle function. No modifications were made to the friction braking control; however, in later years of vehicle development, regenerative braking will be implemented as part of the HSC to be able to meet energy consumption requirements.

Powertrain functionality requirements include communication between each powertrain controller and the HSC; startup and shutdown logic; and providing driver requested torque. The communication between the powertrain controllers and the hybrid supervisory controller was done through bench testing.

Mode functionality requirements include whether the mode selection logic works and that the components operate as expected in that mode. An example of a mode functionality requirement is that during charge depleting mode only the electric motor is providing torque to the wheels and the engine is unable to turn on. All Year 2 requirements are included in Appendix D. In the controls testing plan, Figure 8, mode functionality tests
follow powertrain functionality. The Year 3 mode functionality requirements are far more complex.

3.2.3 EcoCAR 3 Year 3 Controls Requirements
The final goal of Year 3 is to have a vehicle that is able to operate in all vehicle modes. All of the potential vehicle modes are discussed in detail in Chapter 4 but additional modes that will be implemented include charge sustaining operating, transmission shifting, and engine stop/start. The Year 3 requirements will be added to the Year 2 requirements as the work done in Year 3 will be a continuation of the controls development done in Year 2.

3.3 Controls Support Systems
Controls support systems include all of the important controls considerations that are required to have a functioning vehicle. This includes everything from the controller setup and network structure to the actual physical connections of the controllers in the vehicle. A great deal of attention was paid to the supervisory controller selection, team developed communications networks, and how the system would function in the vehicle.

3.3.1 Controller Networking
The stock EcoCAR 3 vehicle included more than twenty controllers for everything from engine control to keyless entry. Just a few of the stock powertrain controllers (engine, transmission, etc.) were removed from the vehicle with the removal of the stock powertrain components. The team added nine controllers to the vehicle including the HSC, two motor inverters, engine control module (ECM), battery management system (BMS), high voltage (HV) charger, transmission controller (GCM), DC/DC converter,
and HVAC. Figure 10 shows the overall CAN structure developed for the EcoCAR 3 vehicle including how the team added controllers are connected. The CAN networks are defined as the HVCAN, High-Speed (HS) GMLAN, Front Powertrain (FPT), and Rear Powertrain (RPT). This is a hierarchical network structure.

The team added controllers fall into two categories: team-developed and team-integrated. The team-developed controllers are the HSC, GCM, and BAS inverter. The algorithm development and testing for each of these controllers was done by the team. Chapter 4 discusses the development of the HSC. Team-integrated controllers are mostly other powertrain component controllers. To the team, these controllers are gray boxes where the inputs and outputs of the system are known. In these cases, the algorithm development and validation was done by the supplier, and has been specifically calibrated for the component. A few of these controllers do allow for further calibration by the team. These controllers include the ECM, HVAC, BMS, HV Charger, DC/DC and EM inverter. For each controller special attention was paid to the CAN message IDs to ensure that there were no conflicts on the bus they were added to.

Part of the controls development process is determining the actual controller hardware that will be used in the vehicle. The HSC is a dSPACE MicroAutoBox II which meets all of the team requirements, including having 6 CAN channels. It was selected because of the team knowledge and the software tools needed to interface with the controller. The 6 CAN channels allowed more flexibility when defining a new CAN structure. The MABX
also has the computational power required for the future, potentially complex, energy management strategies, which will need to run in real time. The general control module (GCM) partners with the MABX to send some digital signals, including the controller wake signal needed by the other powertrain controllers. The GCM is a Woodward 112 pin controller which is used for a variety of things including the transmission control. The last controller with team developed software is the BAS inverter. The team was unable to find an off-the-shelf solution to control the BAS motor, and had to make the decision to develop the control in house.

![Figure 10: CAN Network Structure](image)

There were a number of considerations made when designing the overall CAN network structure. The first consideration was how to gateway messages between the individual CAN networks. The decision was made to utilize the HSC to gateway messages between the networks. There is only one controller with this responsibility for simplicity. The
HSC is also used to recreate any messages required by stock controller from controllers that were removed from the vehicle. As a result, the HSC is also the only controller that will be added to the high speed GM CAN network, which is otherwise isolated from the team added networks. One reason that no other controllers were added to the GM network was the potential to overload the bus since the current bus loading of the GM network is presumed to be high. Another reason that additional CAN networks were added was to eliminate/reduce the number of potential CAN ID conflicts, because of the large number of messages on the GM CAN network.

Another consideration was the ability to troubleshoot each network, and the separation of CAN networks will allow the team to isolate potential CAN problems more easily as there will only be a small number of controllers on each network. For example, all controllers related to the operation of the front powertrain are on FPTCAN. The controllers were also added to networks based on their physical location in the vehicle to help the hardware implementation; for example, all of the added controllers in the front of the vehicle will be on FPTCAN. Minimizing the distance between controllers in the network minimizes the risk of potential interference or signal distortion. It was also important to evaluate the bit rate compatibility between the controllers on each network, this was accomplished by ensuring through manufacture specifications that all team added controllers are capable of a bit rate of 500 kBd.
A concern identified with this structure was the impact of the loss of CAN communication over one or more CAN networks. This is a critical concern for the controllers controlling torque-producing components. The ECM, EM inverter, BAS inverter, GCM, and BMS all have heartbeat signals which are received by the HSC. The HSC also sends a corresponding signal to each controller. In the event of lost communication, the HSC and each component controller has a procedure for safely evaluating the situation through limiting torque production and possibly limiting operating modes. This fault mitigation strategy is discussed in more detail in the fault mitigation section of Chapter 5.

3.3.2 Basic Vehicle Functionality

Before any complex supervisory control strategy can be implemented on the vehicle, all of the powertrain components must be able to communicate and function independently.

3.3.3 Establishing Communication

The powertrain functionality of the requirements section includes establishing communication between the HSC and each component controller. Much of this validation was done using the HIL as a test bench prior to implementation in the vehicle.

3.3.4 Vehicle Startup Process

The vehicle startup and enabling process is defined as the steps from when the driver presses the start button in the vehicle to when the vehicle is ready to be shifted out of park. The time requirement for this startup process was defined by the VTS to be less than 2 seconds. The requirements to key on the vehicle were discussed in a previous section; however, there are a number of other steps that must happen between the
controllers before the vehicle is ready to be driven. This process is known as the vehicle enabling procedure and is summarized in Figure 11. The vehicle enabling procedure is the process and signals required to get each controller (or component) to its normal operating state. A key aspect of this process is the handshakes between the controllers. Figure 11 is the procedure for the primary vehicle controllers. The overall vehicle startup and enabling process is triggered by a wake signal from the stock body control module (BCM). This signal will wake up GCM; however, the rest of the process defined below is not triggered until the start button is pressed. There are four main states that each controller can be in: unpowered, powered, awake-disabled, and awake-enabled. The HSC is woken up when the vehicle start button is pressed.

Each component enabling procedure includes a handshake between the HSC and the specific controller, Figure 12 is an example of this for the EM. The BMS and the EM inverter will always be enabled during the vehicle enabling process; however, depending on the current vehicle mode, the engine controller may be awake but disabled until engine power is required. Once the HSC is awake, it sends a command to the BMS to start the battery enabling procedure. Once the battery contactors are closed, the inverters (EM and BAS) and the engine can be enabled. If, for some reason, the contactors do not close, the vehicle startup procedure will be aborted. Once all of the components are enabled, the vehicle is ready to be shifted out of park, and the HSC will send out the vehicle ready signal. The HSC also sends the wake signal to other team added controllers that are not considered to be powertrain controllers, including the DC/DC converter.
Figure 11: Vehicle Startup and Enabling

Figure 12: Electric Motor Enabling Handshake
CHAPTER 4: HYBRID SUPERVISORY CONTROLLER DEVELOPMENT

4.1 Introduction

The hybrid supervisory controller (HSC) is key to EcoCAR vehicle operation as it manages driver commands as well as operation (speed, torque, power) of all of the components in the vehicle. Its job does not stop there, however, as the HSC also serves as the gateway between the team added CAN networks in the vehicle. The HSC also includes the energy management strategy as well as fault detection and mitigation. The HSC is the central controller in this system, and without it none of the control development would be possible.

The hybrid supervisory control strategy is made up of three parts. The first is the vehicle mode selection. The vehicle drive modes and transitions between modes are explored in the next section. The second part is torque distribution or energy management. Ideally, the energy management strategy is independent of the mode selection. The last part of the hybrid supervisory control strategy is the tactical control logic which includes regenerative braking, transmission shifting, and the handshakes required to command torque from each of the components.
4.2 **Hybrid Supervisory Control Structure**

The hybrid supervisory controller communicates with the three team-added CAN networks and the high speed GM CAN networks and is therefore where all major strategic and tactical decisions are made. The main inputs to the hybrid supervisory controller are divided into driver, vehicle, and component inputs. The driver inputs to the supervisory controller are the accelerator pedal, brake pedal, PRNDL, and physical switches. These inputs are translated into component requests in the HSC. The component inputs include speed, torque, temperature, etc., which are used in the HSC to make strategic decisions.

The input conditioning block also takes in the electrical signals for the accelerator pedal and PRNDL position sensors. Both of these functions were previously done in the stock engine and transmission controllers, respectively. With the removal of these controllers, the team developed control strategy must not only translate these physical signals into positions, but also check for the validity of the signals and detect any faults.

The major output from the supervisory controller is the requested torque from the powertrain components based on vehicle mode, driver requests, and current component status. As mentioned previously the HSC also sends out any signals that the stock vehicle controllers require. The output conditioning block translates and separates the signals from the HSC into the messages needed by the individual controllers. It also includes some non-mode specific tactical controls.
The core of the hybrid supervisory controller is shown in Figure 13. Each of the major blocks will be discussed in detail in the following sections. The HSC takes in the current vehicle speed and accelerator pedal position to determine the driver requested torque. The mode selection block includes a state machine which determines which vehicle mode the vehicle should be operating in at any given time. The mode functionality block contains logic which determines how the vehicle operates in each mode and how the driver requested torque will be delivered to the wheels. In later years, the mode functionality block will include the energy management strategy. The PRNDL block serves as another torque security and component check. If the vehicle is in park or neutral, no torque is transmitted to the wheels. In reverse and drive, the requested component torque and direction is compared to the component limits to ensure safe vehicle operation.

Figure 13: Hybrid Supervisory Controller Structure

4.3 Mode Development and Functionality

The vehicle operating modes were derived from the controls requirements discussed in Chapter 3, and expected vehicle operation based on the hybrid architecture selected. The vehicle operating modes can be divided into three categories: drive modes, transition
modes, and auxiliary modes. Table 2 defines and categorizes all planned vehicle modes. Green denotes that a mode was be implemented and will be validated in the vehicle. Yellow means that initial mode developed occurred but not implemented in the vehicle. Red means that no in-depth development was done. Figure 14 is a representation of the difference between the drive modes and the auxiliary modes. In Year 3, all vehicle modes will be implemented. The full mode implementation and refinement plan is discussed in Chapter 7.

Table 2: Vehicle Mode Implementation

<table>
<thead>
<tr>
<th>Category</th>
<th>Mode</th>
<th>Y2</th>
<th>Y3/Y4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive</td>
<td>Charge Depleting Normal</td>
<td>Primary Drive Mode</td>
<td>Green</td>
</tr>
<tr>
<td></td>
<td>Charge Sustaining Normal</td>
<td>Yellow</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Charge Depleting Performance</td>
<td>Yellow</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Charge Sustaining Performance</td>
<td>Red</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Series</td>
<td>Red</td>
<td>Fault Mode</td>
</tr>
<tr>
<td></td>
<td>Limited EV</td>
<td>Fault Mode</td>
<td>Fault Mode</td>
</tr>
<tr>
<td></td>
<td>Engine Only</td>
<td>Red</td>
<td>Fault Mode</td>
</tr>
<tr>
<td>Transition</td>
<td>Engine Start</td>
<td>Red</td>
<td>Fault Mode</td>
</tr>
<tr>
<td></td>
<td>Quick Engine Start</td>
<td>Red</td>
<td>Fault Mode</td>
</tr>
<tr>
<td></td>
<td>Transmission Shifting</td>
<td>Red</td>
<td>Fault Mode</td>
</tr>
<tr>
<td></td>
<td>Engine Start/Stop</td>
<td>Red</td>
<td>Fault Mode</td>
</tr>
<tr>
<td>Vehicle/Auxiliary</td>
<td>Vehicle Startup</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vehicle Shutdown</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Accessory</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Charging</td>
<td>Green</td>
<td></td>
</tr>
</tbody>
</table>
4.3.1 Drive Modes

The drive modes are charge-depleting normal (CDN), charge depleting performance (CDP), charge sustaining normal (CSN), charge sustaining performance (CSP), and charge sustaining series. Table 3 shows what powertrain components are used in each vehicle mode. Charge depleting normal mode, the power flow shown of which is in Figure 15, is the all-electric drive mode where the electric motor is used for vehicle propulsion. Charge sustaining normal mode, shown in Figure 16, is the primary charge sustaining hybrid operating mode. In CSN mode the vehicle will operate as a parallel hybrid and maintain battery SOC around a predefined set point. From a strategic controls point of view there are two performance modes; however, the driver will only know that they are in normal or performance mode. Even in normal mode, other than a potentially audible engine, the drive should not notice a difference between CSN and CDN modes. A charge sustaining series mode, Figure 17, will also be developed. In this mode, the BAS will be used as a generator converting the mechanical power created by the engine into
electrical power. In series mode, the transmission will remain disengaged and all of the power to the wheels will come from the electric motor.

Table 3: Mode Component Usage

<table>
<thead>
<tr>
<th></th>
<th>CDN</th>
<th>CDP</th>
<th>CSN</th>
<th>CSP</th>
<th>Series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Motor</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Engine</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BAS (Start/Stop)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission (Shifting)</td>
<td>Fixed Gear</td>
<td>X</td>
<td>Fixed Gear</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ESS</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

Figure 15: Electric Only Vehicle Power Flow
Figure 16: Parallel and Performance Power Flow

Figure 17: Series Power Flow
4.3.2 Transition Modes

Transition modes are critical for vehicle operation and occur between the drive modes. The transition modes include: engine start, quick engine start, transmission shifting, engine idle, and engine start/stop. During many of these transition modes, the vehicle will still be operational and the driver should not notice that a mode change is occurring. The engine start mode requests electrically heated catalyst warm up, engine on, and engine speed up with the BAS and transmission engagement. The quick engine start mode includes the same steps as the traditional engine start mode without warming up the electrically heated catalyst. The quick engine start mode is used in two main cases. The first is when the engine has been started previously, but is not currently running. The second is when transitioning from CDN mode to CDP mode.

4.3.3 Auxiliary Modes

The auxiliary modes include vehicle startup, accessory mode, vehicle shutdown, and charging. The vehicle startup mode, as discussed in detail in the previous chapter, includes the logic to correctly and safely close the battery contactors during vehicle startup. The supervisory controller also ensures that the powertrain and other vehicle controllers are enabled and communicating. It is important that this mode occurs quickly and transitions into vehicle on state. All of the drive and transition modes occur once the vehicle is on and ready. Accessory mode starts the vehicle; however, vehicle propulsion is not active in this mode. Vehicle shutdown includes defines the steps to open the battery contactors and shut down all of the vehicle controllers. Battery charging is also
considered to be an auxiliary mode as it occurs when the vehicle is powered on, but not in run mode.

4.3.4 Simplified Mode Implementation

All of the potential vehicle modes for the vehicle have been defined; however, for Year 2 only a limited number of vehicle modes were implemented. All auxiliary modes were included, as they are critical to basic vehicle operation. The main drive mode was electric only operation. The full integration of the vehicle also allowed for the development of the series mode. The main transition mode will be the engine startup mode using the BAS.

Figure 18 shows the simplified mode selection that was implemented in Year 2. The default vehicle operating mode was the electric vehicle mode.

![Figure 18: Simple Vehicle Mode Selection](image-url)
4.4 Mode Selection

Transitions between the vehicle modes are defined through a rule-based control structure. This structure allows for clear, simple, and calibratable transition points. Many of the transitions include handshakes between the HSC and another controller. The key transitions occur between drive modes. The criteria to transition from CDN to CSN mode is that the battery SOC reaches a pre-defined level. As shown in Figure 19, once the minimum SOC criteria is met, the vehicle transitions into the engine start mode. The vehicle will continue driving on electric power, until the engine is at the proper speed and the transmission is engaged. The engine controller (ECM) will send an engine enabled signal to the HSC and the vehicle will go into CSN mode.

To transition into the performance modes, the driver must flip the performance mode switch and the vehicle must be at zero speed. The vehicle must be stationary for this transition because both the accelerator pedal and transmission shifting maps differ in this mode, and the sudden change of these maps could cause driver startle. It is important to note, that while the accelerator pedal map differs between the performance and normal mode, the brake pedal and regenerative braking maps will remain the same.

The key mode transitions to evaluate in the simplified control strategy, shown in Figure 18, include the transition from vehicle startup to vehicle on, and the transition from CD (EV only) to series. Currently, the drive mode transition will only occur when
the driver flips a physical switch (engine on or charge sustaining) or when the SOC reaches the predefined threshold.

![Complex Mode Selection Diagram](image)

Figure 19: Complex Mode Selection

4.5 Mode Functionality in Year 2

While the overall vehicle mode functionality was defined in Year 1, the short development and validation time in Year 2 only allowed for a small number of vehicle modes to be fully developed and validated. The vehicle drive modes in Year 2 are EV only and Engine start and idle. These two modes are the most basic modes and will meet goals for the Year 2 competition.

4.5.1 Electric Vehicle Operation

The main operating mode in the vehicle is electric only or charge depleting mode. Figure 15 shows the power flow when the vehicle is operating in EV mode as well as the general location of the electric motor in the vehicle. As the vehicle is a post-transmission parallel PHEV, the electric motor comes after the transmission and is coupled through a custom
power transfer unit. One reason this configuration was selected was to allow for electric vehicle operation without having to engage the transmission. This configuration also allows for EV operation in the event of a transmission failure. Transmission and other failure modes will be discussed in the next chapter.

Strategic control of the electric motor was relatively simple compared to previous EcoCAR competitions because there is only one electric motor that can provide power directly to the wheels. To meet Year 2 requirements, the vehicle can only be propelled using the electric motor. In later years, CDN mode will be the default mode when the battery SOC is above the predefined threshold. The main considerations with the electric motor were the maximum speed and torque curves and the temperature of the motor and inverter. Figure 20 shows the peak and continuous positive torque curves for the electric motor. The maximum torque for the electric motor was experimentally determined to be around 250 Nm and the maximum speed is 6000 RPM. The peak and continuous curves define the maximum range where the electric motor can operate. As the name implies, the motor could operate continuously anywhere under the continuous torque curve for as long as necessary without concern for the electric motor health. Operation above the continuous torque curve is allowed for short periods of time, but extended operation above the can cause the motor to overheat.
Two different strategies were explored for the electric vehicle operating mode with the goal of allowing the electric motor to operate close to peak whenever it was required. As mentioned previously the main consideration for the electric motor operation was the temperature. The first strategy would have incorporated a torque limiting map based on a thermal model of the motor. This strategy was not implemented after a further investigation of the motor temperature measurement design. A thermal model of the motor, based on experimental data, would have been developed to predict the temperature of the hottest part of the motor in comparison to where the motor temperature is actually measured. With this temperature prediction, as the temperature began increasing towards a dangerous level, the maximum torque would be limited until it reached the continuous torque limit or the EM temperature fault limit. After investigation into the provided motor thermal time constants given, and the location of the motor temperature measurement, it
was determined that the motor temperature sensor was located in the windings which is
generally the hottest part of the motor. Given that the motor was designed to run until the
temperature sensor reaches 150° C, concerns about potential motor hotspots were
reduced.

The second strategy, which was implemented as part of the Year 2 control strategy, was
to allow the electric motor to operate wherever needed, while actively monitoring
temperature. The decision to use this strategy was based on experimental motor data,
discussion with the electric motor manufacturer, and a study as to how often the electric
motor operates above the continuous torque curve. Figure 21 shows the impact of motor
torque and speed on motor temperature. This data was collected while the inverter was
being calibrated for the electric motor. Figure 21 confirms a number of assumptions made
about the electric motor. The first was that the nominal operating temperature of the
electric motor is between the ambient temperature and 80° C. While the data is not linear;
generally, as the torque of the electric motor (positive or negative) is increased, the
temperature of the electric motor also increases. There is uncertainty about the data at
higher points as the temperatures seems to increase around 175 Nm and then drop as the
motor reaches 250 Nm. Another assumption that the data validates is that motor speed
also has an impact on temperature.
With the temperature information collected, another study was done to evaluate how often the electric motor actually operates above the continuous torque line. The standard drive cycles (US06, FUDS, and FHDS) were used. Figure 22 shows the electric motor operating points for each of the drive cycles. It is clear that most of the operating points fall below the continuous operation line.

Table 4 shows the percent of each cycle that the electric motor is above the continuous operation line. Only the US06, which is the most aggressive cycle with the highest speeds, reaches the peak operating limits of the motor. It should also be noted that most
of these points occur during vehicle accelerations which can been seen in Figure 23 through Figure 25. Without the ability to operate above 155 Nm, the vehicle was not able to meet the accelerations in each of these drive cycles.

With this information, it became clear that the electric motor would not often attempt to sustain peak electric motor torque for an extended amount of time; thus the electric motor torque limit was defined as the peak torque limit, with an algorithm to monitor electric motor temperature. The electric temperature monitoring is discussed in more detail in the vehicle fault modes section. More development that can be done with the CD mode includes picking operating points that are in the most efficient parts of the operating map. This will allow for electric range improvements during the controls refinement in Year 3.

Table 4: EM Operation above Continuous Threshold for Standard Drive Cycles

<table>
<thead>
<tr>
<th>Cycle</th>
<th>% of Cycle Above Continuous</th>
</tr>
</thead>
<tbody>
<tr>
<td>US06</td>
<td>10.08 %</td>
</tr>
<tr>
<td>City</td>
<td>4.5 %</td>
</tr>
<tr>
<td>Highway</td>
<td>0.52 %</td>
</tr>
</tbody>
</table>
Figure 22: Drive Cycle Specific Electric Motor Operation

Figure 23: City Cycle Operation
Figure 24: Highway Cycle Operation

Figure 25: US06 Drive Cycle - Electric Motor Torque
4.5.2 Engine Start and Idle

Another controls requirement for Year 2 was to be able to start and idle the engine. This process needed to be clearly defined for future controls development, especially for the vehicle start/stop implementation. The engine is started using a small belted alternator/starter (BAS) system which has been coupled to the engine. The process of starting the engine is detailed below and in Figure 27. At this point in time, the engine will only be started if the driver flips the engine on switch. At later points in the controls development process, the engine start will be requested when the battery SOC approaches its minimum level or performance mode is activated. In both situations, if the vehicle is moving the electric motor will continue to power the vehicle as shown in Figure 26. The engine startup procedure will be tested on an engine dynamometer before implementation in the vehicle.

*Engine Start Process*

1. Engine on request from switch.
2. HSC sends ECM on signal.
3. BAS torque request is sent. This torque is the torque required to overcome the engine friction torque as well as the torque required to spin the engine up to the minimum idle speed.
4. Wait for BAS speed to be greater than minimum engine idle speed.
5. Reduce BAS torque to level required to overcome friction torque.
   a. Send engine run command to start fueling.
6. Wait for engine speed to reach idle speed.
7. Command 0 torque from BAS. Engine will now be idling.
Figure 26: Engine Start Power Flow

Figure 27: Engine Start Process
CHAPTER 5: FAULT DETECTION AND MITIGATION

5.1 Introduction

The controls, system safety, and propulsion teams worked together to identify and detect possible failures and faults, as well as what actions would need to be taken to mitigate a potential fault or safety concern.

5.2 Fault Detection

Much of the fault detection in Year 2 is based on monitoring component temperature. The component temperatures are reported to the HSC and the HSC takes action. Other fault detections implemented in Year 2 included loss of CAN communication, loss of accelerator pedal position, and loss of PRNDL position. A more robust fault detection strategy is being developed by the system safety team. This strategy will include a number of faults for each powertrain component as well as vehicle level faults. As of Year 2, both the fault detection and fault mitigation strategies occurred in the HSC. Many of the components include their own fault detection and/or mitigation; however, until each component is thoroughly bench tested the fault detection and mitigation will remain in the HSC.

Two types of fault detection methods were implemented as part of the Year 2 control strategy. The first was a supervisor fault detection strategy which monitored component
temperatures. A fault is triggered when the monitoring system detects a temperature fault above a pre-defined threshold. This type of fault detection meets team developed requirements, because component temperature should be a slow changing fault, giving the system plenty of time to react. The second type of detection was a model based detection developed to detect unintended acceleration. The team developed a mass model based on F=ma. If there is an abrupt change in the mass of the vehicle, this means that a component is generating more or less torque than requested. If the behavior is detected in the window for which the model has been calibrated, then a fault is detected. Any of the fault detection algorithms developed must go through the overall controls validation process and the focus of much of the HIL testing will be on validating the fault detection and mitigation strategies.

5.3 Overall Fault Mitigation Strategy

With a fully functioning vehicle, it is important to have a robust fault detection and mitigation strategy. The fault mitigation strategy implemented is a tiered fault mitigation strategy shown in Figure 28. The goal of this fault mitigation strategy is to maintain safe vehicle functionality as long as possible to avoid leaving the driver stranded. The first level of faults are power, limiting faults. Faults that fall under this category include approaching temperature and battery current limits. Thresholds below the temperature and current fault threshold are set to trigger a power limiting fault. It is possible that the action taken by the HSC to limit power, mitigates the problem and the vehicle can return to normal vehicle operation. An example of this kind of fault is shown in Chapter 6.
In the event that a fault is more severe, the next action would be to disable specific operating modes. In the case that a temperature limit is exceeded, a major powertrain component fails, or the transmission fails, it is possible to disable vehicle modes in a way that the vehicle can still operate. For example, if the vehicle is operating in CD mode and the EM reaches its temperature limit, the engine can be started and operated in engine only mode. Another potential failure is if the transmission shifting fails during CS operation. As long as all of the other components are functional, the vehicle can operate in series mode. Mode disabling faults cannot be cleared until the vehicle is restarted and the fault has cleared. Lastly, in the event of serious failures, such as a high voltage battery failure, brake or accelerator pedal failure, engine and EM failure, or loss of CAN communication the vehicle will shut down. The HSC threshold for shutting down the vehicle is set below the actual component limits (especially for the battery) to avoid a BMS- initiated shut down of the vehicle by opening battery contactors. If a shutdown failure is triggered, the remaining component torque is ramped down, and the battery is
shutdown properly. Once a fault is detected, the mitigation action is determined by a state machine which evaluates the type of fault and the current vehicle mode to determine what limp home mode the vehicle will need to enter. This limp home mode determination occurs after the traditional mode selection logic and will override the request from the mode selection logic. This process is shown in Figure 29.

![Fault Mode Override Diagram](image)

**Figure 29: Fault Mode Override**

**Table 5: Limp Home Mode Criteria**

<table>
<thead>
<tr>
<th>Limp Home Mode</th>
<th>Selection Criteria</th>
<th>Mode Operation</th>
</tr>
</thead>
</table>
| EV Only/Limited       | 1. Engine fault  
                        2. Transmission fault  
                        3. EM/Inverter temperature warning  
                        4. Battery temperature warning | There is no way to start the engine.                     |
| Engine Only           | 1. EM/Inverter fault  
                        2. BAS fault (if the engine has already been started) | The EM/Inverter is powered down. Engine Start/Stop is disabled. |
| Series                | 1. Transmission fault                                                                  | Transmission shifting is disabled.                      |
5.4 Fault Detection and Mitigation in the Scope of Simplified Controls

The limited vehicle operating strategy implemented in Year 2 meant that not all potential faults and fault modes were included. The main vehicle propulsion mode being electric only means that most faults detected are related to the electric drivetrain. Temperature faults for the EM, inverter, and battery can be detected. The tiered fault mitigation was still implemented, in that there was a power limiting option but no disabled operating modes. The limited functionality of the vehicle also meant that if the EM were to fail, the only option was to shut down the vehicle. Two temperature thresholds were set for each component a warning threshold and a failure threshold. The warning threshold will trigger the power limiting mode, with the goal of potentially mitigating the fault. The temperature failure threshold was set below the component specific threshold, to ensure that the vehicle could follow safe shutdown procedures. The goals of this fault mitigation strategy were to keep the driver safe, and prevent any damage to the components.

A second failure that can be detected and acted upon is the loss of communication between the HSC and any team added powertrain controller (GCM, ECM, EM inverter, BMS). Some of the controllers have a heartbeat signal built in, but for the team developed controllers, a heartbeat signal was implemented to ensure communication is always maintained. In the event that communication is lost, the vehicle will shut down, as safe vehicle operation cannot be continued.

5.5 Limited EV Mode

The limited EV mode allowed for continued vehicle operation when a temperature warning threshold has been reached. Table 6 shows the temperature limits that were set;
these limits can be refined in the future. The motor inverter includes the logic to be able to ramp down motor torque based on temperature as well. During the development phase, the torque limiting will remain in the HSC for better team control.

Table 6: Component Temperature Limits

<table>
<thead>
<tr>
<th>Component</th>
<th>Warning Threshold Temperature (°C)</th>
<th>HSC Shutdown Temperature (°C)</th>
<th>Manufacturer Shutdown Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Motor</td>
<td>100</td>
<td>145</td>
<td>150</td>
</tr>
<tr>
<td>Inverter</td>
<td>80</td>
<td>93</td>
<td>95</td>
</tr>
<tr>
<td>Battery</td>
<td>50</td>
<td>55</td>
<td>60</td>
</tr>
</tbody>
</table>

The actual limits on torque were based on the temperature of the component that has triggered the fault. At this point, a simple gain based on temperature is applied to reduce the torque. As more component testing is done, both the temperature thresholds and gains will be tuned for better operation.

5.6 Safe Vehicle Shutdown

An important part of the fault mitigation strategy is to be able to safely shutdown the vehicle to avoid damaging any components. In the event that a shutdown fault is triggered two steps need to be taken before fully shutting down the vehicle. First, the component torque needs to be quickly and safely ramped down to zero. Secondly, the battery shutdown procedure needs to be followed. The vehicle shutdown points are set such that the BMS opening battery contactors is to be avoided. If the BMS detects a fault it will trigger an emergency power off, which will open the battery contactors without ramping down current and could potentially damage the battery or other high voltage devices.
CHAPTER 6: CONTROLS VALIDATION AND TESTING

6.1 Controls Development Process

The controls development process, shown in Figure 30, is a multi-step process which ensures that the software implemented on the EcoCAR vehicle is safe and functional. The first step of any vehicle design process is the development of requirements. For the controls development this also included the development of test plans. Once controls requirements were defined, the overall control architecture and logic was developed in the MATLAB/Simulink environment. The controls team worked with the system modeling and simulation team to create a full vehicle model that was utilized for Model-in-the-Loop (MIL) testing. The model, shown in Figure 31, includes a powertrain model, driver model, and the HSC. This model was used for algorithm development, to test basic logic, and evaluate simple fault detection. Once the HSC algorithm passed the Software-in-the-Loop (SIL) tests, proving that it was free of basic logic and coding errors, it was converted into discrete time and compiled. If the code is able to run in discrete time and compile, the process moves into the Hardware-in-the-Loop (HIL) phase.

In the HIL phase, the controller code is built and flashed onto the actual supervisory controller hardware. HIL testing validates that the software can run in real time and that the CAN I/O was set up correctly. It also allows for the addition of physical switches and
signals. If the algorithm fails in the HIL phase of testing, it will go back to MIL development. The HIL testing phase also allows for a larger number of faults to be tested. Once all of the tests are passed in the HIL environment the software can be implemented in the vehicle. Vehicle testing is divided into lift testing, dynamometer testing, and closed course testing. If a piece of the software fails during vehicle testing, it will go back to the HIL testing phase.

Figure 30: Controls Development Process

6.2 EcoSIM3

EcoSIM3 is a team developed vehicle model of the EcoCAR 3 vehicle developed using Simulink. EcoSIM3 is a crucial tool in the controls development process. It allows all controls algorithms to be debugged and validated before moving to the HIL. Figure 31 shows the clear division between the HSC model and the powertrain model. This separation is important to emulate the real separation and I/O requirements. The many of
the component plant models were developed based on real data. Figure 32 shows the structure of each component model, which includes both a soft ECU and a plant model.

![Figure 31: EcoSIM 3 Simple Structure](image)

![Figure 32: EcoSIM 3 Component Model Structure](image)

6.3 Developing Test Cases

Test case development was an important part of the requirements development process. From each requirement pass/fail criteria must be defined as well as a procedure to test each requirement. It is possible that a requirement cannot be tested in the MIL/HIL or vehicle environment, but most requirements are evaluated in all three environments. Testing procedures may be different for MIL/HIL and the vehicle. For each controls requirement there is a test plan document that is developed to ensure clear understanding of the testing procedures such that someone other than the person creating the software can run the test.
An example of a test procedure is the vehicle startup procedure. As mentioned previously, there are five conditions which must be met in order to start the vehicle. The test plan for vehicle startup includes attempting to startup the vehicle with each of these conditions not met. The pass criterion is that the vehicle should not start if all of the conditions are not met.

6.4 Validation

Validating each requirement was incredibly important to the process. By both thinking about how a requirement will be tested, and actually testing the requirement, a number of other potential scenarios can be determined. Finding potential holes in logic is an important part of the controls validation process. It is also important to evaluate if the logic works correctly and works the same way every time. Potential variability with the same system inputs is non-ideal. The results included here are not comprehensive, but rather show a snapshot of each of the major controls system requirements sections.

6.4.1 SIL/MIL/PIL Results

6.4.1.1 Vehicle Startup and Enabling

As mentioned in Chapter 3, the vehicle startup and component enabling procedure is a complex set of steps.

Figure 33 shows the values of the driver interfaces that must be active before the vehicle startup can continue. The vehicle starts in mode 1, startup, and once the vehicle is ready it will transition into mode 2. Figure 34 shows the controller enabling sequence. Once the key state value reaches 2, the battery enabling procedure begins. The contactors closed signal enables the BAS and EM inverters. Once every powertrain component is awake
and enabled the vehicle ready signal is sent out from the HSC. In this test, this startup occurs almost instantly; however, the controller enabling procedure will take longer in the vehicle. It should be also noted that this is the startup sequence for starting up the vehicle fully and not entering charging or accessory mode.

Figure 33: Vehicle Startup - Driver Interfaces
6.4.1.2 Mode Selection

Mode selection was challenging to visualize as there were few modes implemented in the Year 2 vehicle. A check was done to validate each of the mode transition criteria, specifically to ensure which signals were needed to transition from EV only to engine on.

6.4.1.3 Mode Functionality

Limited mode functionality in the vehicle means that only a few of the many vehicle modes were validated for implementation on the vehicle in Year 2. The two drive modes that will be discussed are the EV only mode and the engine start and idle mode.

6.5.1.4 EV Only

The requirements for EV only mode are that only the electric motor is used to power the vehicle (engine remains off) and that the vehicle is able to meet the defined drive cycles.
Figure 35 demonstrates that the vehicle can meet the aggressive US06 drive cycle without using the engine. Figure 36 demonstrates that using just the electric motor the vehicle can maintain the City drive cycle which also includes a number of aggressive accelerations. This same test was performed in the HIL environment and will be run in the vehicle on a chassis dynamometer in the future.

Figure 35: EV Only US06
6.4.1.4 Engine Start and Idle

The mode functionality requirement for engine start is that the BAS can be used to start the engine and once the engine reaches idle speed, it can continue to idle without help from the BAS. In the event that the engine was started during a drive cycle, it is also important that the electric motor continues to provide power to the wheels during this startup, and that the clutch remains disengaged.

For the engine startup validation, the vehicle was running a drive cycle when the engine on switch was activated at 100 seconds. Figure 37 shows that the vehicle will maintain operation while the engine is starting. The figure also shows that the engine eventually reaches idle speed. Figure 38 shows that the vehicle transitions from mode 2 (EV mode) back to the EV Only City mode.
operation) to mode 4 (engine start) when the switch is flipped. At this point, the BAS provides enough torque to overcome the engine friction and accelerate the engine to its idle speed. Once the engine/BAS reaches the required speed for the engine to fire, the BAS stops providing torque and the vehicle switches from mode 4 to mode 3 (Engine only). An interesting comparison of the engine model can be seen in Figure 39 and Figure 40 where an engine idle speed controller was implemented in the engine model. With this idle speed controller, the engine speed is maintained at a more reasonable level, however the torque values for the BAS and engine oscillate wildly. This behavior demonstrates that HSC development hinges on the accuracy and fidelity of the models that are used for validation.

Figure 37: Engine Start
Figure 38: Engine Start – Detail

Figure 39: Engine Start with Idle Speed Control
6.4.1.5 Fault Detection and Mitigation

Fault detection and mitigation is the easiest to visualize. Figure 41 shows the normal vehicle operation over the first 200 seconds of the city cycle. The vehicle is operating in mode 2 which is EV only and is able to maintain the drive trace. The main faults implemented in the model are temperature based, and as discussed in Chapter 5, limit the electric motor torque. Each of the temperature faults was triggered in the component model and then detected and mitigated in the controller. This separation was an important to the development as it is more representative of the actual vehicle.
The first faults tested were the motor temperature warning and shutdown. The faults were tested individually first, Figure 42 shows what would happen if the warning temperature was reached, the mitigation strategy did not work, and the motor reached shutdown temperature. The first temperature fault was inserted at 45 seconds. The fault code was triggered and the vehicle switched from mode 2 (EV only) to mode 5 (Limited EV). The torque limitations can be seen between 45 and 100 seconds as the EM cannot meet the driver requested torque. The vehicle is still able to meet the drive trace under these conditions. At 100 seconds the temperature was increased to 150°C and the vehicle enters shutdown mode (mode 6). Figure 43 shows the preferable situation, where the motor torque limiting allows the electric motor to cool down to an acceptable level. At this
point, a fault will no longer be triggered, but the vehicle will technically remain in Limited EV (mode 5) operation, with the normal motor operating limits in place. Figure 44 shows how the vehicle reacts when the electric motor reaches its shutdown temperature. In this case, the vehicle would go from EV mode (mode 2) to shutdown (mode 6).

Figure 42: EM Temperature Warning and Shutdown
Figure 43: EM Temperature Warning and Mitigation

Figure 44: EM Temperature Shutdown Fault

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The next set of temperature faults tested were the inverter and the ESS. The same
temperature fault was inserted at 45 and 100 seconds shown in Figure 45. Figure 46
shows the same fault mitigation for the ESS. The main difference between each of these
tests was the temperatures and the components that were affected. The actual action for
all of them is to go into Limited EV mode and then eventually shutdown. At this point,
the functionality of each of these modes is confirmed, but without robust thermal models
of the EM, inverter, and ESS, the amount of torque limiting may not be enough to
mitigate the fault. This is something that can be evaluated on the HIL and through further
cOMPONENT TESTING IN YEAR 3.

Figure 45: Inverter Temperature Fault Transition
6.4.2 HIL Results

The next step after MIL/SIL validation was HIL validation. The HIL setup used dSPACE ControlDesk to act as a driver interface. Figure 47 below shows the ControlDesk set up used by the team. The HIL test procedures were essentially the same as the MIL/SIL test procedures. The biggest difference was that the actual MicroAutoBox was part of the testing. To ensure that the testing set up was as close to the vehicle as possible, the system modeling and simulation team was consulted. Specific attention was paid to where all of the user interfaces (key state, PRNDL position etc.) were implemented in the HIL model. Most of the testing was the same but the HIL testing validate the requirements that the control algorithms include the correct I/O and can run in real time.
Vehicle Startup and Enabling

The testing of the startup and enabling sequence was more realistic on the HIL because the startup overrides were taken out of the supervisory controller. The figure below shows the ControlDesk interface to control the vehicle state. The same test procedure as defined for the SIL validation was used in HIL testing.

Mode Selection

For the mode selection, the engine on switch was added to the controller interface. It would be beneficial to add a physical switch to the HIL setup to have the testing be as similar to the vehicle as possible. An alternative test situation may be a bench test setup with the actual engine where the HSC sends the required signals to the ECM to start the engine. This other test would ensure that the HSC can communicate with the engine, but would not ensure that the full system is working as expected in the vehicle.

Mode Functionality

Mode functionality in all of the drive modes were also validated on the HIL as shown in Figure 48 and Figure 49. As discussed in the SIL validation the vehicle modes were EV only, Limited EV, and Engine start/idle.
Figure 47: ControlDesk Vehicle Startup Interface

Figure 48: FUDS EV Only - HIL
Fault Detection and Mitigation

The same faults temperature faults were triggered in the HIL environment. The HSC was able to respond the same way, which validates the current fault detection and mitigation. The limited EV mode will still need to be tuned based on actual component data. Figure 50 shows the EM temperature increasing to just below the max temperature threshold, then the fault being triggered when the temperature reaches $100^\circ C$. The vehicle enters limited EV mode. Once the EM temperature reaches $150^\circ C$, the vehicle shuts down.
Figure 50: EM Temperature Fault Mitigation – HIL
CHAPTER 7: FUTURE CONTROLS DEVELOPMENTS

7.1 Introduction

As discussed in great detail in previous sections, the timeline of this report falls before the completion of vehicle integration, which limited the scope of results that could be reported. Due to the short timeline for vehicle testing, having a plan for controls integration in place is key to success. The controls implementation will occur in approximately 3 weeks. The final goal for Year 2 is to have a vehicle that can safely travel above 60 mph. Years 3 and 4 will allow for a great deal of controls development and validation.

7.2 Year 2 Vehicle Implementation Plan

All of the basic vehicle functionality, discussed in Chapter 3, will be tested with the vehicle on a lift to ensure safe testing. The first task to validate is the communication between the HSC, team-added controllers, and the stock vehicle controllers.

Communication between the team-added controllers can be validated prior to installation in the vehicle. The time will be spent ensuring no diagnostic trouble codes (DTCs) exist in the remaining stock vehicle controllers. This will be done by recreating signals in the HSC. Prior to vehicle testing, a comprehensive list of signals sent by the removed stock vehicle controllers (engine and transmission) was created to minimize the number of DTCs. Most of the stock controllers remain in the vehicle. As discussed in Chapter 3, the
CAN networks were designed for tiered implementation into the vehicle to allow for individual network troubleshooting. The first step will involve working with the electrical team to ensure all of the controllers are in place in the vehicle. The HSC and GMLAN will be powered up first. Next the HVCAN, RPTCAN, and FPTCAN networks will be implemented in that order. The GMLAN and FPTCAN networks are expected to be the most complex to have completely functional.

Once the vehicle and team CAN networks are functional, the vehicle startup and shutdown processes will be evaluated. This includes being able to close battery contactors. The charging handshake will also be validated at this point in time. Next will be all of the driver interface controls including pedals and PRNDL position. The next goals are to spin the wheels using the electric motor in both forward and reverse. The engine will also be started and should be able to idle. As discussed previously, each of the powertrain components was bench tested before vehicle integration.

Once all of the controls requirements are validated on the lift, vehicle testing will continue at low speeds in the CAR parking lot. This testing will evaluate the accelerator pedal feel and creep torque. As the maximum speed of the parking lot is very low, the next step is validating the electric motor operation at higher speeds using a chassis dynamometer. This testing will check to see the electric motor and drivetrain components safely operate at higher speed. This testing will also evaluate the electric motor and battery temperatures to understand the nominal safe operating temperatures of the
components. The temperature of these components is incredibly important as the Year 2 competition is held in Yuma, Arizona where the temperatures average 105°F. The overall goal is to have tested the vehicle under many different conditions to be confident in the controls before sending the vehicle to competition and minimize the need for any controls changes at competition.

7.3 Year 3 and 4 Refinement

Years 3 and 4 will allow for full mode implementation and refinement of controls strategies to meet both performance and efficiency goals.

7.3.1 Full Mode Implementation

Year 3 will allow the team to implement and test all vehicle operating modes. The high level goal is to have robust controls for the traditional vehicle modes. In the list below at least items 1 through 4 will be developed and validated on the vehicle in Year 3. During Year 4, the team will be able to refine the vehicle controls, with a focus on meeting all of the VTS targets set by the team. The vehicle must be able to meet both efficiency and performance targets. The team will aim to drive the vehicle on a closed course as many miles as possible.

1. Series
2. Transmission Shifting
3. Parallel operation – Simple power split, charge sustaining
4. Fault Strategies
5. Performance Modes
6. Engine Start/Stop
7. ECMS or other energy management strategies
7.3.1.1 Series

As the engine will be able to operate in Year 2, and should be started with the BAS motor, the next mode for development will be a series mode. This mode will allow charge sustaining operation, without transmission functionality. While in series modes, the electric motor will continue to transmit torque to the wheels. The engine/BAS system will be generating electrical power to maintain battery SOC. The BAS was sized for the potential series operation and engine start/stop. During Year 3 and Year 4, series mode will mostly be used as a fault mode in the event that there is a transmission failure.

The limiting factor in the series mode power generation is the BAS. It is a 30 kW electric motor with a peak torque limit around 60 Nm. Based on this limit and the current battery SOC, a power level for the engine will be requested. The power limit will dynamically change with battery SOC. The engine torque point is requested based on the most efficient point, and the BAS is set to torque control mode. This initial aspects of this mode have been developed, but because of the Year 2 model priorities, could not be tested and validated. With the BAS and engine testing that will be completed outside of the vehicle during the last part of Year 2, this mode will be easily implemented in Year 3.

7.3.1.2 Transmission Shifting

Transmission shifting is a complex process to implement. Transmission shifting is considered a transition mode, and it can only be entered from CSN, CSP, or CDP mode. It requires handshakes between the HSC, GCM, ECM, and BAS. The high level process is described below. The first step is that the HSC determines that a shift is requested based on a number of criteria. Once a shift is requested, all of the driver’s torque request
is shifted to the electric motor. Then the signal is sent through the GCM to disengage the clutch. The GCM also interfaces with the transmission shifting system (MasterShift) which does the physical shift. While the new gear is engaging, the BAS is used to speed match the engine. Once both the engine and transmission are ready, the clutch is reengaged. At this point the vehicle is back in a traditional drive mode and both the engine and electric motor are used to meet the driver’s torque request. The goal throughout the shifting process is to be able to maintain the driver’s requested torque. In Year 4, drivability optimizations may be investigated.

1. Shift requested (HSC)
2. All torque to EM (HSC)
3. Disengage clutch (GCM)
4. Shift gear (GCM)
5. Speed match engine with BAS (HSC)
6. Reengage the clutch (GCM)
7. Resume normal charge sustaining operation (HSC)

### 7.3.1.3 Engine Start/Stop

Engine stop/start implementation will help meet energy consumption goals. There are a number of considerations and concerns to take into account when developing an engine stop/start strategy. Similar to transmission shifting, start/stop is a transitional mode that can only be entered from CSN and CDP modes. The criteria to enter stop/start mode is more complex than many of the other modes. The process for start/stop mode is shown below.

**Engine Stop/Start process**

1. Open clutch – request neutral torque
2. Cut off fuel
3. Ramp down engine
4. Engine remains off until requested
5. Ramp up engine speed, with BAS
6. Resume fuel
7. Use BAS to speed match engine
8. Close clutch
9. Resume normal operation

Stop/start mode is only enabled during CSN and CDP modes to reduce the fuel consumption. However, even with the fuel consumption reduction, there is potential for increased emissions or worse drivability. The strategy for allowing start/stop must take this into account. The potential fuel consumption gain can be estimated in the modeling environment. It is also possible that start/stop will be integrated into the overall energy management strategy. Once the EcoCAR baseline fuel consumption and emissions are evaluated in Year 3, a comparison can be done between different potential stop/start strategies. Drivability improvements will be a concern in Year 4.

7.2.2 Energy Management

There are a number of potential ways that the energy management strategy of the vehicle can go. Two potential energy management strategies that have already been discussed by the controls team are a simple power split with SOC control or a modified ECMS.

ECMS

In developing the CSN mode to fit with the overall control strategy, it was clear that a modified ECMS could be used to most efficiently control the various power sources. Figure 53 shows the parts of the ECMS algorithm. One goal defined was that the energy management strategy be independent of actual vehicle mode. This ECMS strategy does this by taking into account whether each component is available for operation. In CDN mode, the mode selection block would send out EM active but engine and BAS inactive.
In that case, the maximum torque of the engine would be zero, and the ECMS is just meeting the torque request through using the EM. The maximum torque limits depend on the current gear, as well as if the vehicle is in normal or performance mode. The motor and engine map blocks take this maximum torque, and output a grid of potential operating points. The engine cost is determined by using the fuel consumption map. The motor cost is determined through the use of $s$, which is an equivalence factor, calculated using the current SOC and the target SOC. The cost minimization in this case was an online minimization where at each point in time, and based on the drive requested torque, the minimum cost engine/EM torque pair was selected. Depending on the computational complexity, some of the maps could be calculated offline.

Negatives of ECMS include the complexity and potential impact on drivability. The drivability concern has been explored many times, as ECMS is offers a potentially optimal solution; however, it is finding the most optimal operating conditions at each instant in time. If not taken into consideration engine points could vary widely between calculations. If the decision is made to implement a version of ECMS into the vehicle, a great deal of validation will need to be done both in simulation and on the vehicle. Other extensions of ECMS could incorporate the engine start/stop and optimal transmission shifting into this energy management strategy.

**Power Split**

A potentially simpler energy management strategy for CSN mode would be a basic engine/electric machine power split. One potential way to implement this would be to
allow the engine to operate up to a specific torque point which has been determined offline to be “optimal” for energy usage. Once the torque request exceeds that level the electric machine would be used for the next ~1000 Nm of wheel torque (in normal mode). There is still a bit of engine torque left, and at this point that torque could be used to meet the rest of the torque demand. Figure 51 is a simple representation of this strategy. It should be noted that the EM torque is fixed in the continuous range for normal modes. A second part of this strategy would increase or decrease the EM operating range based on the battery SOC. The EM torque could also be increased if the vehicle was in performance mode instead of normal mode. Figure 52 shows the maximum engine torque in each gear, but does not take into account the fuel usage of the vehicle.

Figure 51: Power Split Representation
Figure 52: Maximum Engine Torque
Figure 53: ECMS
7.2.3 Controls Validation in Years 3 and 4

As the modes discussed in the previous section are developed and added to the overall controls software, each part will continue to follow the controls development and validation process discussed in Chapter 6. A controls validation plan for each year will be developed at the start of each year and will align with the overall vehicle development plan for the year. While each new aspect of the controls strategy will be validated in SIL and HIL environments, there will be far more in depth vehicle testing. The testing will occur in a few different environments depending on the development status of the vehicle and the type of testing. The vehicle can be tested on a vehicle dynamometer, closed course track (Transportation Research Center in Marysville, Ohio), or on public roads. The dynamometer will be the first place that high speed vehicle testing will occur. The vehicle dynamometer will also allow the team to collect actual emissions and fuel consumption data to evaluate if the energy management strategy is meeting the VTS requirements. Mode switching, transmission shifting, drivability, and performance metrics will be evaluated during closed course testing. Once the team has determined that the vehicle controls meet all safety and functionality requirements, in Year 4 the team will be able to test the vehicle on public roads. This will allow the team to drive real world city and highway driving. Extended trips (~100 miles) will be taken to ensure that powertrain components will operate safely throughout the intense emissions and energy consumption event in Year 3 and Year 4.
In EcoCAR 2 the team was able to validate the vehicle over 1000 miles during the final year of development. As this level of testing helped in ensuring a robust set of controls was implemented on the EcoCAR 2 vehicle, the EcoCAR 3 team should set a validation goal of at least 1500 miles of on-road (closed course or public road) validation.

### 7.3 Conclusions

The EcoCAR project is a study on how to design, implement, and validate hybrid vehicle controls. The process requires an understanding of all aspects of the project and the specific goals of each year of competition. Most of the discussion of hybrid vehicles focuses on the energy management strategies; however, without the most basic controls functions of a vehicle, there is no way to implement any higher-level energy management strategy. A staggered controls development approach has served the EcoCAR team well, in that controls can be developed and rolled out as required.

Having an understanding of the goals for Year 2 as compared to the overall competition goals helped set the timeline and scope for the controls development. The focus of Year 2 was to have a vehicle that could start and drive under its own power. While those goals seem simple; on the controls development side, there were a large number of controls support systems that had to be developed and implemented in the EcoCAR vehicle. The vehicle startup and controller enabling procedure may be the most complex piece of logic developed for the Year 2 vehicle, as it involves the driver inputs, the GCM, the HSC, and all of the component controllers. A great deal of attention was paid to this startup process,
as without the ability to startup the vehicle, none of the other vehicle modes would be able to be implemented on the vehicle.

While the full hybrid mode selection was defined in Year 2, the scope of the controls development simplified the vehicle drive modes to electric only and engine startup/idle. In later years of the development process all normal drive modes will be implemented and tuned for efficiency and the performance modes will be tuned to meet the performance VTS targets.

Following a clearly defined controls validation process helps ensure that the controls implemented in the vehicle were functional and free of any logic errors. The controls development process was useful for mode development in Year 2. The partnership between the controls development team and the system modeling and simulation team ensures that the requirements developed at the beginning of the controls development process were clear, and could be understood by many parts of the team.

There is still a great deal of work to be done both in the vehicle implementation that will occur in Year 2 as well as the full mode development and refinement in Years 3 and 4. With plans in place the Ohio State EcoCAR 3 team has the foundation to be able to meet the lofty goals in Years 3 and 4.
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### APPENDIX A – LIST OF SYMBOLS AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMT</td>
<td>Automated Manual Transmission</td>
</tr>
<tr>
<td>AVTC</td>
<td>Advanced Vehicle Technology Competitions</td>
</tr>
<tr>
<td>BAS</td>
<td>Belted Alternator Starter</td>
</tr>
<tr>
<td>BMS</td>
<td>Battery Management System</td>
</tr>
<tr>
<td>CAFE</td>
<td>Corporate Average Fuel Economy</td>
</tr>
<tr>
<td>CAN</td>
<td>Controller Area Network</td>
</tr>
<tr>
<td>CD</td>
<td>Charge Depleting</td>
</tr>
<tr>
<td>CDN</td>
<td>Charge Depleting Normal</td>
</tr>
<tr>
<td>CDP</td>
<td>Charge Depleting Performance</td>
</tr>
<tr>
<td>CS</td>
<td>Charge Sustaining</td>
</tr>
<tr>
<td>CSN</td>
<td>Charge Sustaining Normal</td>
</tr>
<tr>
<td>CSP</td>
<td>Charge Sustaining Performance</td>
</tr>
<tr>
<td>DTC</td>
<td>Diagnostic Trouble Code</td>
</tr>
<tr>
<td>E85</td>
<td>Fuel that is 85% ethanol</td>
</tr>
<tr>
<td>ECU</td>
<td>Engine Control Unit</td>
</tr>
<tr>
<td>ECM</td>
<td>Engine Control Module</td>
</tr>
<tr>
<td>ECMS</td>
<td>Equivalent Consumption Minimization Strategy</td>
</tr>
<tr>
<td>EM</td>
<td>Electric Motor</td>
</tr>
<tr>
<td>EV</td>
<td>Electric Vehicle</td>
</tr>
<tr>
<td>FHDS</td>
<td>Federal Highway Drive Schedule</td>
</tr>
<tr>
<td>FUDS</td>
<td>Federal Urban Drive Schedule</td>
</tr>
<tr>
<td>GCM</td>
<td>General Control Module</td>
</tr>
<tr>
<td>HEV</td>
<td>Hybrid Electric Vehicle</td>
</tr>
<tr>
<td>HIL</td>
<td>Hardware-in-the-Loop</td>
</tr>
<tr>
<td>HSC</td>
<td>Hybrid Supervisory Controller</td>
</tr>
<tr>
<td>IVM</td>
<td>Initial Vehicle Movement</td>
</tr>
<tr>
<td>MABX</td>
<td>MicroAutoBox</td>
</tr>
<tr>
<td>MIL</td>
<td>Model-in-the-loop</td>
</tr>
<tr>
<td>MPG</td>
<td>Miles per gallon</td>
</tr>
<tr>
<td>MPGge</td>
<td>Miles per gallon gasoline equivalent</td>
</tr>
<tr>
<td>PHEV</td>
<td>Plug-in hybrid electric vehicle</td>
</tr>
<tr>
<td>PRNDL</td>
<td>Transmission Shift Lever</td>
</tr>
<tr>
<td>SIL</td>
<td>Software-in-the-Loop</td>
</tr>
<tr>
<td>SOC</td>
<td>State of charge</td>
</tr>
<tr>
<td>VTS</td>
<td>Vehicle Technical Specifications</td>
</tr>
<tr>
<td>Wh</td>
<td>Watt-hour</td>
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</tbody>
</table>
### APPENDIX B - VTS

<table>
<thead>
<tr>
<th>Specification</th>
<th>Units</th>
<th>OSU</th>
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<tbody>
<tr>
<td>Acceleration, IVM–60 mph (Performance Mode)</td>
<td>sec</td>
<td>5.6</td>
</tr>
<tr>
<td>Acceleration, IVM–60 mph (Normal Mode)</td>
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<td>10.0</td>
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<tr>
<td>Acceleration, 50–70 mph (Passing) (Performance)</td>
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<td>3.3</td>
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<tr>
<td>Acceleration, 50–70 mph (Passing) (Normal)</td>
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</tr>
<tr>
<td>Braking, 60–0 mph</td>
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<tr>
<td>Acceleration Events Torque Split (Front/Rear)</td>
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<td>RWD</td>
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<tr>
<td>Lateral Acceleration, 300 ft. Skid Pad</td>
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</tr>
<tr>
<td>Double Lane Change</td>
<td>mph</td>
<td>55</td>
</tr>
<tr>
<td>Highway Gradeability, @ 20 min, 60 mph</td>
<td>%</td>
<td>6%</td>
</tr>
<tr>
<td>Cargo Capacity</td>
<td>ft³</td>
<td>2.4</td>
</tr>
<tr>
<td>Passenger Capacity</td>
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</tr>
<tr>
<td>Curb Mass Added to Stock Vehicle</td>
<td>kg</td>
<td>274</td>
</tr>
<tr>
<td>Starting Time</td>
<td>sec</td>
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</tr>
<tr>
<td>Total Vehicle Range*</td>
<td>mi</td>
<td>328</td>
</tr>
<tr>
<td>CD Normal Mode</td>
<td>EV</td>
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</tr>
<tr>
<td>CD Performance Mode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CD Mode Range*</td>
<td>mi</td>
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</tr>
<tr>
<td>CD Mode Total Energy Consumption*</td>
<td>Wh/km</td>
<td>220</td>
</tr>
<tr>
<td>CS Mode Fuel Consumption*</td>
<td>Wh/km</td>
<td>532</td>
</tr>
<tr>
<td>UF-Weighted Fuel Energy Consumption*</td>
<td>Wh/km</td>
<td>188</td>
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<tr>
<td>UF-Weighted AC Electric Energy Consumption*</td>
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<tr>
<td>UF-Weighted Total Energy Consumption*</td>
<td>Wh/km</td>
<td>330</td>
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<tr>
<td>UF-Weighted Total Energy Consumption*</td>
<td>MGEge</td>
<td>63.5</td>
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<tr>
<td>UF-Weighted WTW Petroleum Energy Use*</td>
<td>Wh/km</td>
<td>56</td>
</tr>
<tr>
<td>UF-Weighted WTW Greenhouse Gas Emissions*</td>
<td>g/km</td>
<td>115</td>
</tr>
<tr>
<td>UF-Weighted WTW Criteria Emissions*</td>
<td>g/km</td>
<td>&lt;Tier 2, Bin 5</td>
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</tbody>
</table>

*Evaluated using the EcoCAR 4-cycle weighting
APPENDIX C - AVTC SUMMARY

Challenge X (2004 to 2008)

Summary From http://avtcseries.org/competitions/challengex/

In the first decade of the new millennium, the American automotive customer market trended toward larger family-sized vehicles. At the same time, an increased need to reduce energy consumption, as well as decreased vehicle emissions, was becoming imperative. As a result, the automotive and electronics industries, the U.S. and Canadian governments, and the academic community worked together to launch Challenge X: Crossover to Sustainable Mobility.

The groundbreaking four-year competition (2004-2008) gave 17 universities in North America an opportunity to participate in hands-on research and development with leading-edge automotive propulsion, fuels, materials, and emissions-control technologies.

During the competition, students were challenged to re-engineer a 2005 Chevrolet Equinox to minimize energy consumption, emissions, and greenhouse gases while maintaining or exceeding the stock vehicle’s utility and performance. Using a development process modeled after GM’s Vehicle Development Process, teams gained valuable experience in real-world engineering practices. Participating teams were provided with a variety of resources to help achieve their objectives, including technical support and mentoring from General Motors and other sponsors. Each team also received $10,000 in seed money and were eligible to receive additional production parts, software, and hardware from competition-level sponsors.

Year One (2004-2005) focused on modeling, simulation, and testing of the advanced powertrain and vehicle subsystems selected by each school. Students used computer-based math modeling tools to objectively compare and select the advanced technologies to be used for their overall design. Teams also developed and used rapid prototyping and hardware-in-the-loop (HIL) tools to validate their models and control systems. The Year One competition was held at GM University and GM’s Milford Proving Grounds, where teams showcased their design efforts.

During Year Two (2005-2006), teams developed and integrated their advanced powertrain and subsystems into the donated vehicle. This year was often dubbed the ‘mule’ vehicle build year since teams had to get to a 65% buy-off stage. The year-end competition was held at General Motors Desert Proving Grounds in Mesa, Arizona and featured an extensive set of vehicle dynamic events including braking, handling, acceleration, fuel economy, drive quality, and trailer towing performance. Teams were also judged through technical design presentations and written reports.

In Year Three (2006-2007), teams had to refine their advanced vehicles into a showroom-ready vehicle. At the end of the academic year, teams traveled to General Motors Milford Proving Grounds in Milford, Michigan for dynamic vehicle testing. Much like in Year Two, teams had the
chance to compete in several dynamic events like braking, accelerating, dynamic handling, and drive quality. The awards ceremony was held at General Motors Renaissance Center in downtown Detroit, Michigan.

The fourth and final year of Challenge X (2007-2008) featured additional refinement, as well as expansive outreach and media efforts throughout the community. The year began with a road rally through Los Angeles and a ride and drive at the Electric Vehicle Symposium 23 in Anaheim, CA in November 2007. In addition, teams showed off their vehicles to Jay Leno at his garage in Burbank, CA. Teams then had several months to refine their vehicle before taking part in vehicle testing at the Old Bridge Township Raceway in Englishtown, New Jersey in May 2008. After testing, teams began a three-day East Coast Road Rally, which began in New York City with a media event. Teams then made a stop in Baltimore for an education day, and then concluded at the U.S. Department of Energy in Washington, D.C.

Throughout the four years, students developed a strong understanding of advanced vehicle technologies that prepare them to become highly skilled engineers in the automotive industry and remain competitive in the global marketplace.

**EcoCAR 1 (2008 to 2011)**


EcoCAR: The NeXt Challenge was a three-year collegiate advanced vehicle technology engineering competition established by the United States Department of Energy (DOE) and General Motors (GM), and was managed by Argonne National Laboratory.

The competition challenged 16 universities across North America to reduce the environmental impact of a Saturn Vue by minimizing the vehicle’s fuel consumption and reducing its emissions while retaining the vehicle’s performance, safety and consumer appeal.

Students used a real-world engineering process to design and integrate their advanced technology solutions into a GM-donated vehicle. Students designed and built advanced propulsion solutions based on vehicle categories from the California Air Resources Board (CARB) zero emissions vehicle (ZEV) regulations. They explored a variety of cutting-edge clean vehicle solutions, including full-function electric, range-extended electric, hybrid, plug-in hybrid and fuel cell technologies. In addition, students incorporated lightweight materials into the vehicles, improved aerodynamics, and utilized alternative fuels such as ethanol, biodiesel and hydrogen.

Teams followed a real-world approach modeled after GM’s global vehicle development process (GVDP), which gave students valuable experience in real-world engineering practices, resource allocation and meeting deliverables. While previous student engineering competitions focused primarily on hardware modifications, EcoCAR included a unique focus on modeling and simulation, as well as subsystem development and testing.

In the first year of EcoCAR (2008-2009), participating teams used math-based design tools—such as Argonne’s Powertrain Systems Analysis toolkit (PSAT) or similar vehicle models research—to compare and select an advanced vehicle powertrain that meets the goals of the competition. Teams used software to ensure that their chosen components fit into their vehicle and that the electrical, mechanical and software systems functioned properly. Teams also used software-in-the-loop (SIL) and hardware-in-the-loop (HIL) to better develop controls and
subsystems. During the Year One competition, the teams traveled to Toronto, Canada to participate in the year-end event which featured several static presentations and a trade show display.

During the second year of EcoCAR (2009-2010), teams had to translate their design into reality by developing a ‘mule’ vehicle. By the end of the academic year, the student vehicles had to be 65% complete. General Motors hosted the teams at their Desert Proving Grounds in Yuma, Arizona for all dynamic vehicle events, including accelerating and braking, emissions and energy consumption, dynamic consumer acceptability, AVL DRIVE Quality, autocross, and more. Teams then headed to San Diego, California for several other events and the awards ceremony.

In the third and final year (2010-2011), EcoCAR teams had to refine their existing student powertrain vehicles into a 99% showroom-ready vehicle. The students vehicles were heavily tested at General Motors Milford Proving Grounds in Milford, Michigan before heading to Washington, D.C. for a ride and drive event.

**EcoCAR 2 (2011 to 2014)**

http://avtcseries.org/competitions/ecocar2/

EcoCAR 2: *Plugging In to the Future* was a three-year collegiate advanced vehicle technology engineering competition established by the United States Department of Energy and General Motors (GM), and was managed by Argonne National Laboratory.

The competition challenged 15 universities from across North America to reduce the environmental impact of the 2013 Chevrolet Malibu by improving its fuel efficiency and minimizing the vehicle’s emissions while retaining its performance and consumer appeal.

The competition was modeled after the GM’s real-world vehicle development process (VDP) and was broken down into three academic years, each focusing on a different stage in the VDP:

- **Year One:** The teams selected vehicle architectures by using modeling and simulation. They used hardware-in-the loop (HIL) simulators to develop and test their control strategies.
- **Year Two:** The teams turned virtual designs into functioning prototype vehicles.
- **Year Three:** The teams refined their vehicles to near-showroom quality.

All student-designed EcoCAR 2 vehicles were plug-in hybrid electric vehicles (PHEVs), which deplete an on-board battery to displace vehicle fuel. The powertrain components were configured to drive the vehicle in five unique combinations:

- Split-parallel,
- Series-parallel,
- Parallel through the road (PTTR),
- Series,
- Hydrogen fuel cell series.

In Year One (2011-2012) of the competition, teams designed and modified a vehicle architecture and developed their control strategy through the use of controller HIL tools. The teams also
designed major subsystems, including hybrid powertrain, energy storage, thermal management and high-power electrical systems. Year One formed the foundation for the vehicle development and refinement tasks in Years Two and Three of the competition. The year-end competition was held in Los Angeles, California where teams competed in various static presentation events as well showcased a trade show display.

The teams received their GM-donated Chevrolet Malibu’s at the beginning of Year Two (2012-2013) and began integrating their powertrain components and other subsystems to develop a running ‘mule vehicle.’ During this second year of the competition, the teams competed in engineering tests similar to the tests GM conducts to determine a prototype’s readiness for production at General Motors Desert Proving Grounds in Yuma, Arizona. These dynamic vehicle testing events included a 300-point safety and technical inspection, acceleration and braking, AVL DRIVE Quality, emissions and energy consumption, and more. Teams then traveled to San Diego, California for the final stage of the Year Two competition.

In the third and final year (2013-2014), EcoCAR2 challenged teams to refine their vehicles into near-production prototype vehicles that which would demonstrate improved fuel economy and lower greenhouse gas emissions, while also focusing on performance and consumer appeal. The Year Three Competition was held at General Motors Milford Proving Grounds in Milford, Michigan and Washington, D.C. in June 2014.

**EcoCAR 3 (2014 to 2018)**

http://ecocar3.org/

EcoCAR 3 is the latest U.S. Department of Energy (DOE) Advanced Vehicle Technology Competition (AVTC) series. As North America’s premier collegiate automotive engineering competition, EcoCAR 3 is challenging 16 North American university teams to redesign a Chevrolet Camaro to reduce its environmental impact, while maintaining the muscle and performance expected from this iconic American car. Sponsored by DOE and General Motors and managed by Argonne National Laboratory, EcoCAR is the heart of American automotive ingenuity and innovation and is the ultimate training ground for minting future automotive leaders. While this model is the most technologically advanced Camaro in the vehicle’s history, EcoCAR 3 teams will be tasked to enhance the vehicle even further by applying the latest cutting-edge technologies and incorporating new innovative ideas. Teams have four years (2014-2018) to harness those ideas into the ultimate energy-efficient, high performance vehicle. The Camaro will keep its iconic body design, while student teams develop and integrate energy efficient powertrains that maximize performance, while retaining the safety and high consumer standards of the Camaro. Teams also will incorporate alternative fuels and advanced vehicle technologies that will lower greenhouse gas and tailpipe emissions.
Year 1 – Architecture Selection

During Year 1 (2014 – 2015) of the competition teams began the vehicle development process by defining the vehicle architecture that they would design and build throughout the EcoCAR 3 Competition.

The competition held in May of 2015 allowed the teams to share the design, modeling, and simulation work done in year one. The week long competition, held in Seattle Washington, was a chance for the teams to give technical and non-technical presentations to validate the choices made to groups of industry judges. The culmination of this project was an interactive tradeshow developed by the team to introduce the both the vehicle design and design process.

Year 2 – Vehicle Integration

During Year 2 (2015 – 2016) of the EcoCAR 3 Competition teams received their 2016 Camaro. Before vehicle disassembly in late January, the teams baseline tested the vehicle. The competition held in May of 2016 at the GM Desert Proving Grounds (DPG) in Yuma, Arizona and San Diego, California. While in Yuma, each vehicle will be inspected for safety and integration quality. Teams will also be able to demonstrate vehicle functionality. For teams that have a functional vehicle, there will be a downsized energy consumption event focused on electric only or engine only energy usage. The San Diego portion of the event will comprise of technical presentations with a focus on the vehicle integration work done in Year 2.

Year 3/Year 4 Validation, Refinement, and Optimization

In Year 3 (2016 – 2017), the team will be tested on all areas of vehicle functionality. Events will include acceleration, ride and handling, emissions and energy consumption,
and consumer acceptability. The vehicle in Year 3 will be at 65%. In Year 4 (2017 – 2018), the teams should bring a fully completed and validated vehicle to competition. At this point in time the official completion events have not been announced, however, teams are expected to have a vehicle that could compete in a longer (~100 mile) on road event. Each year at competition, teams will give technical presentations to show the judges the technical work that was completed in that year. The communications and project management teams will also give presentations each year. At the end of Year 4, the vehicle should be ready to sell to a customer both inside and outside the vehicle.
## APPENDIX D – CONTROLS REQUIREMENTS

### Year 2 Requirements and Test plans

<table>
<thead>
<tr>
<th>Dev Cat</th>
<th>Name and Description</th>
<th>Pass/Fail Criteria</th>
<th>Primary Testing Env.</th>
<th>SIL/HIL Test Procedure</th>
<th>Dyno/On-Road Test Procedure</th>
<th>MIL Status</th>
<th>HIL Status</th>
</tr>
</thead>
</table>
| **Basic Vehicle Functionality** | **Vehicle in Park** | Vehicle does not start, Startup_complete = 0, Veh_Mode= 1 | SIL/HIL | 1. PRNDL Position = D, R or N  
2. Accelerator Pedal = 0%  
3. Brake Pedal = 100%  
4. Turn key state to "crank" | 1. Key in vehicle  
2. PRNDL Position = D, R or N  
3. Accelerator Pedal = 0%  
4. Brake Pedal = 100%  
5. Press and hold start button | PASS | PASS |
| | **Brake pedal depressed** | Vehicle does not start, Startup_complete = 0, Veh_Mode= 1 | SIL/HIL | 1. PRNDL Position = P  
2. Accelerator Pedal = 0%  
3. Brake Pedal = 10%  
4. Turn key state to "crank" | 1. Key in vehicle  
2. PRNDL Position = D, R or N  
3. Accelerator Pedal = 0%  
4. Brake Pedal = 100%  
5. Press and hold start button | PASS | PASS |
| | **Accelerator pedal not depressed** | Vehicle does not start, Startup_complete = 0, Veh_Mode= 1 | SIL/HIL | 1. PRNDL Position = P  
2. Accelerator Pedal = 4%  
3. Brake Pedal = 100%  
4. Turn key state to "crank" | 1. Key in vehicle  
2. PRNDL Position = D, R or N  
3. Accelerator Pedal = 0%  
4. Brake Pedal = 100%  
5. Press and hold start button | PASS | PASS |
| | **Key in Vehicle** | Vehicle does not start, Startup_complete = 0, Veh_Mode= 1 | SIL/HIL | 1. PRNDL Position = P  
2. Accelerator Pedal = 0%  
3. Brake Pedal = 100%  
4. Key not in vehicle | 1. Key in vehicle  
2. PRNDL Position = D, R or N  
3. Accelerator Pedal = 0%  
4. Brake Pedal = 100% | NA | NA |
<table>
<thead>
<tr>
<th>Condition</th>
<th>Description</th>
<th>Steps</th>
</tr>
</thead>
</table>
| **Charger Not Plugged In**                     | The vehicle will not start if the charger is plugged in.                                         | 1. Plug On = 1  
2. PRNDL Position = P  
3. Accelerator Pedal = 0%  
4. Brake Pedal = 100%  
5. Turn key state to "crank" |
|                                                |                                                                                                 | 1. Plug In HV Charger  
2. PRNDL Position = P  
3. Accelerator Pedal = 0%  
4. Brake Pedal = 100%  
5. Turn key state to "crank" |
| **Vehicle in Park**                             | The vehicle will not shutdown if the PRNDL is not in the park position.                          | 1. Vehicle on  
2. PRNDL position ~= P  
3. Press start/stop button | 1. Vehicle on  
2. PRNDL position ~= P  
3. Press start/stop button |
| **PRNDL**                                       | The powertrain does not transmit any torque to the wheels or allow the vehicle to roll when the PRNDL is in the "Park" position | 1. Start vehicle pressing and holding start button, foot on the brake pedal  
2. PRNDL Position = P  
3. Accelerator Pedal > 15%  
4. Brake Pedal = 0% | **In vehicle test on lift**  
1. Start vehicle pressing and holding start button, foot on the brake pedal  
2. PRNDL Position = P  
3. Accelerator Pedal > 15%  
4. Brake Pedal = 0% |
| **Reverse**                                     | Torque is delivered to the wheels, vehicle moves in reverse.                                     | 1. Start vehicle pressing and holding start button, foot on the brake pedal  
2. PRNDL Position = R  
3. Accelerator Pedal > 15%  
4. Brake Pedal = 0% | **In vehicle test on lift**  
1. Start vehicle pressing and holding start button, foot on the brake pedal  
2. PRNDL Position = R  
3. Accelerator Pedal > 15%  
4. Brake Pedal = 0% |
### Basic Vehicle Functions

#### Accelerator Pedal

When the vehicle is in drive and the accelerator pedal is depressed, the vehicle will move forward.

When the accelerator pedal

| SIL/HIL |

#### Brake Pedal

*Operation*

When the brake pedal is pressed the vehicle will slow down, or not start moving

| SIL/HIL |

### Powertrain Component Functionality

#### Engine

*Communicatio* *n*

Bench
<table>
<thead>
<tr>
<th>Feature</th>
<th>Mode/State Description</th>
<th>Testing Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Engine Start</strong></td>
<td>The engine is able to start in the vehicle when the Engine on or charge sustaining switches are activated</td>
<td>Bench</td>
</tr>
<tr>
<td><strong>Engine Idle</strong></td>
<td>The engine is able to idle</td>
<td>Vehicle</td>
</tr>
<tr>
<td><strong>Engine Response</strong></td>
<td>In &quot;Engine On&quot; Mode, the accelerator pedal will proportionally increase the engine speed</td>
<td>Vehicle</td>
</tr>
<tr>
<td><strong>Transmission Communication</strong></td>
<td>The transmission shifting module will communicate with the GCM to indicate functionality</td>
<td>Bench</td>
</tr>
<tr>
<td><strong>Electric Motor Start Up</strong></td>
<td>The inverter can start up during the vehicle start up/ enabling process</td>
<td>Bench</td>
</tr>
<tr>
<td><strong>Communication</strong></td>
<td>The inverter is able to communicate with the HSC over CAN</td>
<td>Vehicle</td>
</tr>
<tr>
<td><strong>Torque Control Mode</strong></td>
<td><strong>Vehicle</strong></td>
<td></td>
</tr>
<tr>
<td>------------------------</td>
<td>------------</td>
<td></td>
</tr>
<tr>
<td>The inverter is able to request torque from the EM</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Regenerative Braking</strong></th>
<th><strong>SIL/HIL</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>The electric machine is able to operate as a generator for regenerative braking</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Battery</strong></th>
<th><strong>Vehicle</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Close Contactors</strong></td>
<td></td>
</tr>
<tr>
<td>The battery contactors must close during the vehicle start up process</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Open Contactors</strong></th>
<th><strong>Vehicle</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>The battery contactors must open during the vehicle shutdown process</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Charge</strong></th>
<th><strong>Vehicle</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>The battery must be able to enter charging mode when the charge cord is plugged in</td>
<td></td>
</tr>
</tbody>
</table>

| **BAS** | |
|----------||
| **Start Up** | **SIL/HIL/Bench** |
| The inverter can start up during the vehicle start up/ enabling process | |

<table>
<thead>
<tr>
<th><strong>Communication</strong></th>
<th><strong>SIL/HIL/Bench</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>The inverter is able to communicate with the HSC over CAN</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Speed Control Mode</strong></th>
<th><strong>Bench</strong></th>
</tr>
</thead>
</table>
The BAS inverter is able to enter speed control mode

**Torque Control Mode**

The BAS inverter is able to enter torque control mode

<table>
<thead>
<tr>
<th>Vehicle Modes</th>
<th>Bench</th>
</tr>
</thead>
</table>

**Start Up**

The vehicle shall be able to start up in 2 seconds when the start/stop button is pressed

| Start_up_com | SIL/HIL | 1. Key in vehicle  
|             |        | 2. PRNDL Position = P  
|             |        | 3. Accelerator Pedal = 0%  
|             |        | 4. Brake Pedal = 100%  
|             |        | 5. Press and hold start button |

**Shutdown**

The vehicle shall be able to shut down when the vehicle is in park and the start/stop button is pressed

| Shutdown_C | SIL/HIL | 1. Vehicle on  
|           |        | 2. PRNDL position = P  
|           |        | 3. Press start/stop button |

**EV Operation**

The vehicle will be able to meet driver requested speed when in EV only mode. The engine will remain off.

| Veh_Mode | SIL/HIL | 1. Turn vehicle on  
|          |        | 2. Start any drive cycle with SOC > 18% |

**Charging**

When the charge cable is plugged in, the charger and battery will be active to fully charge the battery fully

| Veh_Mode = Battery Charging | Vehicle | NA | 1. Plug in HV Charger |

**Fault Modes**

**Shutdown**

The battery contactors will open to power

| Veh_Mode = 4 | SIL/HIL |

PASS

PASS

PASS

NA
<table>
<thead>
<tr>
<th>down the vehicle</th>
<th>Engine Only</th>
<th>Series</th>
<th>Limited EV</th>
<th>Failures</th>
</tr>
</thead>
</table>
|                  | The engine is powering the vehicle. The electric machine is powered off and start/stop mode is inactive | Veh Mode = 5  
EM Speed = 0  
Engine Speed > 0,  
Transmission Gear > 0 | Veh Mode = 6  
EM Speed = 0  
BAS > 0  
Engine Speed > 0  
Transmission Gear= 0 (in neutral) | Veh Mode = 3  
Engine Speed = 0  
BAS = 0  
EM Speed > 0 |
|                  | Veh_mode  
SIL/HIL | 1. Turn Vehicle on  
2. Active Engine on Switch  
3. Drive Cycle  
4. Turn vehicle, off and back on  
5. Start drive cycle  
6. Trigger EM Fault | 1. Turn Vehicle on  
2. Active Engine on Switch or CS Switch  
3. Drive on dynomometer | 1. Turn Vehicle on  
2. Active Engine on Switch or CS Switch  
3. Drive on dynomometer |
|                  | NA | NA | PASS | PASS |

### Failures

**Temperature Warning**

The power request of the EM is limited if the motor temperature exceeds 100 deg C

**Temperature Failure**

The EM will be shutdown if the motor temperature

<table>
<thead>
<tr>
<th>EM</th>
<th>Temperature Warning</th>
<th>Temperature Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SIL/HIL</td>
<td>SIL/HIL</td>
</tr>
<tr>
<td>PASS</td>
<td>PASS</td>
<td>PASS</td>
</tr>
<tr>
<td>Condition</td>
<td>Mechanism</td>
<td>SIL/HIL</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------</td>
<td>---------</td>
</tr>
<tr>
<td><strong>Inverter</strong></td>
<td><strong>Temperature Warning</strong></td>
<td>The power request of the EM is limited if the inverter temperature exceeds 75 deg C</td>
</tr>
<tr>
<td><strong>Temperature Failure</strong></td>
<td>The inverter will be shutdown if the inverter temperature reaches 92 deg C</td>
<td>SIL/HIL</td>
</tr>
<tr>
<td><strong>CAN Communication Loss</strong></td>
<td>If the heartbeat signal between the HSC and EM Inverter is lost, the vehicle will be shutdown</td>
<td>Vehicle</td>
</tr>
<tr>
<td><strong>Battery</strong></td>
<td><strong>Temperature Warning</strong></td>
<td>When the battery temperature reaches 50 deg C, the HSC will enter EV limited mode to reduce the requested current on the battery</td>
</tr>
<tr>
<td><strong>Temperature Failure</strong></td>
<td>When the battery temperature reaches 58 deg C, the HSC will initiate vehicle shutdown</td>
<td>SIL/HIL</td>
</tr>
<tr>
<td>CAN Communication Loss</td>
<td>Vehicle</td>
<td>NA</td>
</tr>
<tr>
<td>------------------------</td>
<td>---------</td>
<td>----</td>
</tr>
<tr>
<td>If communication is lost between the BMS and the HSC, the vehicle will shutdown</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GCM Communication Loss</th>
<th>HIL</th>
<th>NA</th>
</tr>
</thead>
<tbody>
<tr>
<td>If communication is lost between the GCM and the HSC, the vehicle will shutdown</td>
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<tr>
<th>Limp Home Mode Determination</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EM Failure</strong></td>
</tr>
<tr>
<td>The vehicle will be safely shutdown in the event of an EM failure</td>
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</table>

<table>
<thead>
<tr>
<th><strong>Inverter Failure</strong></th>
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</thead>
<tbody>
<tr>
<td>The vehicle will be safely shutdown in the event of an inverter failure</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Engine Failure</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>The vehicle will enter EV only mode in the event of an engine failure</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Battery Failure</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>The vehicle will be safely shutdown in the event of a battery failure</td>
</tr>
</tbody>
</table>